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The synoptic setting of thunderstorms in western Europe

Aarnout van Delden *

Institute for Marine and Atmospheric Sciences, Utrecht University, Princetonplein 5, 3584 CC Utrecht, Netherlands

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Abstract

This paper discusses the synoptic factors contributing to the formation of thunderstorms in western Europe and in particular gives reasons for the existence of the preferred areas for thunderstorms. These areas are all found in the vicinity of the Alps. The synoptic features playing a role in promoting thunderstorm formation in particular areas in western Europe are identified. The principle synoptic features or processes promoting the formation of intense thunderstorms are a high level of potential instability, convergence lines associated with frontogenesis and cyclogenesis and upper level potential vorticity advection. Additional features playing a role in thunderstorm formation are land and seabreeze circulations and (thermally) forced upward motion at slopes. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Thunderstorms; Frontogenesis; Cyclogenesis

1. Introduction

The three basic ingredients needed to produce a thunderstorm (or deep, moist convection) are potential instability (indicated by a decrease of the equivalent potential temperature with increasing height), high levels of moisture in the atmospheric boundary layer and forced lifting (McNulty, 1995). Each of these three ingredients represents a spectrum of factors (related to particular synoptic features) that affects the initiation of deep convection. This paper discusses the significance of these three ingredients with respect to warm season (April–October) thunderstorms in western Europe. This is, however, only possible with a knowledge of the thunderstorm climate for this area.

* Tel.: +31-302-533-275; fax: +31-302-543-163.
E-mail address: a.j.vandelden@phys.uu.nl (A. van Delden).

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Therefore, the paper begins with a discussion of a 4-year climatology of the summer season thunderstorms in western Europe.

2. Data

The data used to obtain the statistics discussed in this study are in part from the Global Telecommunications System. They include the six-hourly synoptic reports (surface observations) performed in the years 1996–1999 at about 220 stations distributed over western Europe,[1] as well as six-hourly upper air (radiosonde) observations on standard pressure levels, performed during the same period at Sundsvall (Sweden), Lindenberg (Berlin), Aberporth (Wales), Milan (Italy), Rome (Italy) and De Bilt (The Netherlands).

The six-hourly ECMWF analyses on a 1° by 1°lat–lon grid of three cases of severe thunderstorms over western Europe, all of which occurred in the year 1992, are selected as illustration material of typical synoptic features accompanying severe thunderstorms. These cases, which have been well documented in the literature, occurred on, respectively, 20–21 July 1992 (Haase-Straub et al., 1997; McCallum and Waters, 1993), 20 August 1992 (Kurz, 1993) and 22 September 1992 (Sénési et al., 1996; Massacand et al., 1998).

3. A 4-year climatology of warm season thunderstorm reports

The synoptic reports of the weather at the earth's surface at 0000, 0600, 1200, 1800 UTC used to construct a 4-year (1996–1999) summer season (April–October) climatology of the thunderstorm frequency. More than half a million individual weather reports were processed. The thunderstorm frequency is defined as the total number of thunderstorm reports (ww = 29 or 91–99) divided by total number of weather (ww)-reports in promille. For example, a frequency of eight promille implies eight reports of thunder and/or lightning, including precipitation, per 1000 weather reports at a particular location. With this definition of thunderstorm frequency, gaps in the timeseries do not present unsurmountable difficulties. Thunder and/or lightning reports without precipitation (ww = 13 or 17) are not counted as a thunderstorm report. It appears that ww = 13 reports (only lightning observed, no thunder heard) are more numerous during the night than during the day, especially at coastal stations. Obviously, this is due to the fact that lightning is much better visible during the night than during the day, especially when there are few obstacles, such as mountains, in the surroundings of the observer. The systematic error introduced by this effect is eliminated by excluding ww = 13 reports. In view of this, it is logical to also exclude ww = 17 reports (only thunder heard, but no precipitation observed) as a thunderstorm report.

Fig. 1 shows the distribution of total thunderstorm frequency for the period in question. The frequencies are printed in bold if they are based on a relatively complete

[1] Portugal, Spain, Italy, France, Switzerland, Leichstenstein, Austria, Belgium, Luxemburg, Germany, Czechia, Slovakia, Ireland, United Kingdom, The Netherlands, Poland, Denmark, Norway and Sweden.

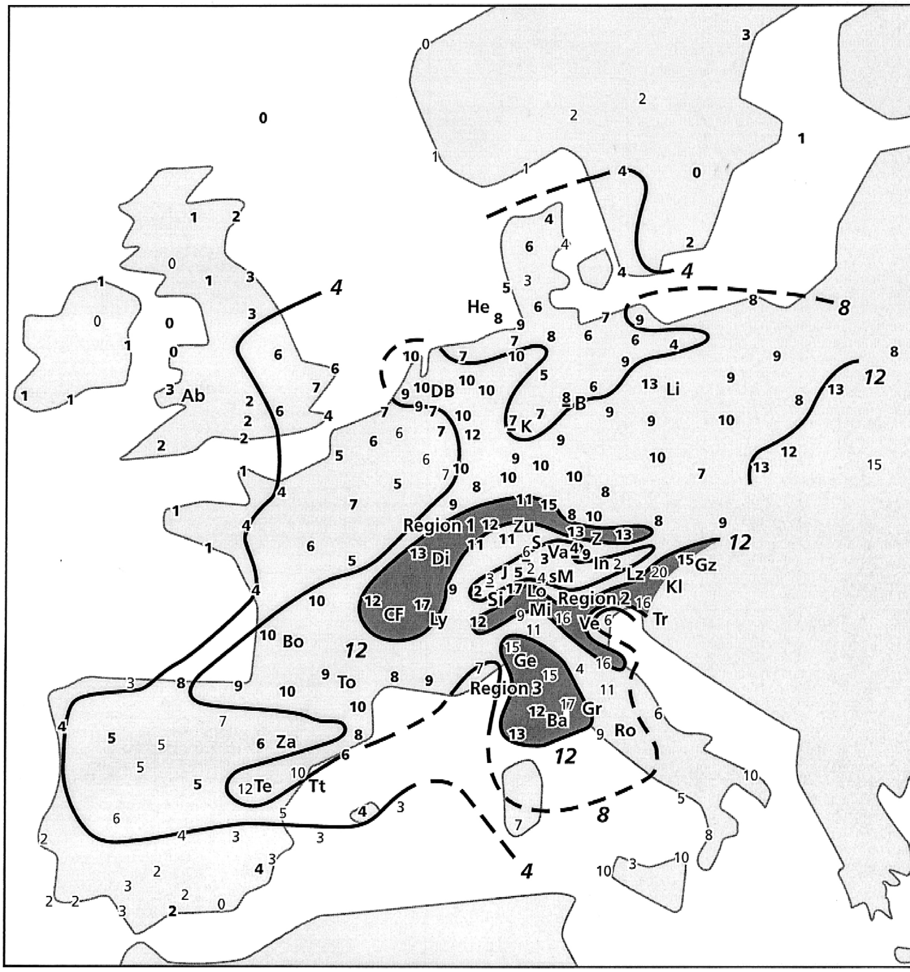

Fig. 1. Thunderstorm frequency (as defined in the text) at more than 200 synoptic weather stations in western Europe for the period April to October of the years 1996–1999 (0000, 0600, 1200, and 1800 UTC). The frequency is printed in bold if the dataset at the particular station contains more than 3000 observations (at least 88% of the maximum amount possible), whereas it is printed in plain text if it is based on a series containing between 2000 and 3000 observations. A weather-report is counted as a thunderstorm report if thunder is heard and/or lightning is observed with precipitation one hour before, or at, observation time. The names of several stations mentioned in the text are indicated in the map with the following two-letter abbreviations. Ab: Aberporth; Ba: Bastia; Bo: Bordeaux; CF: Clermand Ferrand; DB: De Bilt; Di: Dijon; Ge: Genua; Gr: Grosseto; Gz: Graz; He: Helgoland; In: Innsbruck; Kl: Klagenfurt; Li: Lindenberg; Lo: Locarno; Ly: Lyon; Lz: Lienz; Mi: Milan; Ro: Rome; Si: Sion; sM: St Moritz; Su: Sundsvall; Te: Teruel; To: Toulouse; Tr: Trieste; Tt: Tortosa; Ve: Verona; Za: Zaragoza; Zu: Zurich. Mountain top stations are indicated by one capital letter, i.e. B: Brocken (1142 m); J: Jungfraujoch (3580 m); K: Kahler Asten (834 m); S: Saentis (2490 m) and Z: Zugspitze (2962 m). The frequencies associated with mountain top stations are underlined. Regions 1 to 3 are discussed in the text.

data set of more than 3000 observations at a particular location. If the data set corresponding to a particular station is relatively incomplete (between 2000 and 3000 observations), the frequency is printed in plain text. Unfortunately, the data set for Italy and much of Spain and Portugal is relatively incomplete. The data set corresponding to Lienz, Klagenfurt and Trieste is nearly complete, but covers only the 3-year period 1997 to 1999. These locations are nevertheless included, as are Teruel and Tortosa (Spain), which transmit weather reports only three times a day (0600, 1200 and 1800 UTC). Several stations transmit a weather (ww) report only at 0600 and 1200 UTC (i.e. working hours of the observer), whereas most thunderstorms occur at 1800 and 2400 UTC. These stations were excluded from the climatology shown in Fig. 1.

Fig. 1 is based on subjective observations made by many different observers during a limited portion of time. While interpreting Fig. 1, we must be aware of the fact that there is a significant year to year variability in thunderstorm activity. A particular 4-year period may not be representative for the average conditions over a much longer period of time. We must, furthermore, be aware of the fact that many observers work inside practically sound proof buildings and have a heavy work load making them less susceptible to hearing thunder or observing lightning. Thunder is sometimes difficult to hear, because it is far away or because of other noise. Moreover, some observers are better at hearing thunder than others.

Despite these uncertainties and the gaps in the data sets, Fig. 1 clearly reveals the preferred regions for thunderstorms. Roughly speaking, the highest frequency of thunderstorms in western Europe is found in three regions. The first of these regions (region 1 in Fig. 1) spans the Massif Central (Clermond Ferrand), the Saône valley (Lyon, Dijon), the Jura mountains, the Swiss plateau and the higher ground of Wurtemberg and Bavaria (southern Germany). The second region is found in the Po valley, preferably at the foot of the Alps (Locarno and Verona) and the Apennines and further east near the southeast side of the Alps (Klagenfurt and Graz). The third region preferred by thunderstorms (region 3) spans the Gulf of Genoa (including Corsica). These areas, however, need not be the preferred areas for thunderstorm genesis. For example, the Basque country and the southwest of France (the area around Bordeaux) is the seat of the formation of many severe thunderstorms in southerly or southwesterly flow. These thunderstorms drift toward the northeast, presumably reaching their maximum intensity over region 1 (see van Delden, 1998). Indeed, the southwest to northeast orientation of region 1 suggests that this region can interpreted in this sense as a "thunderstorm track". Another important source region of severe thunderstorms is the area around the Saone valley (Lyon, Dijon).

Thunderstorms in region 1 are observed principally in late spring and early summer (May, June and July), while the preferred season for thunderstorms in region 2 is summer (June, July, August). In region 3, most thunderstorms occur in August, September and October. The preference for, respectively, summer and autumn in the latter two cases is related to high degrees of potential instability in these seasons in these areas (see Section 5).

Fig. 1 also demonstrates that there is comparatively little thunderstorm activity in Northern Europe (Norway, Sweden, Scotland) and in those parts of Europe that are more remote from continental influences (Ireland, Wales, southwestern England and Brittany).

This is clearly related to the comparatively low levels of potential instability observed in these regions (see Section 5).

According to Fig. 1, there is a distinct minimum in thunderstorm frequency over the central part of the Alps. This is related, not only to the lower moisture levels over the high ground (in April, May and October the higher parts of Alps are covered with snow), but also to the impossibility of prolonged moisture flux convergence as well as to the absence of a source of lift in several prominent, relatively deep valleys in this area, such as the upper Rhône valley and the Upper Rhine valley. Many observation points (i.e. Sion, Dissentis, Chur and Vaduz) in this area are located inside these two valleys. For example, Sion in the upper Rhône valley, which reports a thunderstorm frequency of less than two promille, is located at a height of 480 m, while it is surrounded by mountains of more than 4000-m height. Another example is Vaduz, which is located in the Rhine valley between Austria and Switzerland and reports a thunderstorm frequency of three promille, while Zurich, 85 km from Vaduz, on the Swiss plateau to the north of the Alps, reports a thunderstorm frequency of 11 promille. Another example is Lienz, which is located in the Drau valley in Austria at 659 m, and reports a thunderstorm frequency of only two promille, while Klagenfurt, about 125 km to the east, reports a thunderstorm frequency of 20 promille.

Not all deep valleys experience such as lack of thunderstorm activity. Innsbruck, for example, in the Inn valley in Austria has a relatively high thunderstorm frequency of nine promille. Two thirds of these cases of thunder and lightning at Innsbruck occur at 1800 UTC. In this context, it is remarkable that the mean pressure at the earth's surface when thunder or lightning is observed in Innsbruck is 0.8 hPa higher than the mean pressure when no thunder or lightning is observed. This is also observed at Vaduz. This is related to the failure of the development of the valley wind or the disruption by the thunderstorms of this otherwise dominant valley wind system. At almost all other locations, the pressure at the earth's surface observed when a thunderstorm is observed is in fact systematically lower than average.

In general, in nearly all areas, the preferred time of the day for thunderstorm occurrence is approximately equally distributed between 1800 and 2400 UTC. One notable exception is the east coast of Corsica (Bastia) where more than two thirds of all thunderstorms occur at 0600 and 1200 UTC, while on the other side of the Tyrrhenian sea at Grosseto near the Italian coast, more than two thirds of all thunderstorms is observed at 1800 and 2400 UTC. This suggests that the land/sea breeze circulation plays an important role in modulating deep convection in this area. Exactly how this works in this particular area remains to be investigated.

4. Moisture

We now explain the climatology presented in the previous section by relating the basic ingredients needed for thunderstorm development (i.e. moisture, potential instability and a source of lift) to specific synoptic flow-features. We will start with a discussion of the importance of moisture.

High levels of moisture near the earth's surface are typically observed over the Mediterranean sea and adjacent coastal areas and in the Po valley. Typically, the average dewpoint temperature at locations along the Mediterranean coast and in the Po valley in the period April to October is about 15°C. The dewpoint temperature at these locations exceeds 20°C on 5% to more than 10% of all cases (remember that only observations made at 0000, 0600, 1200 and 1800 UTC are considered), especially during late summer and autumn, when the sea surface temperature hovers around 25°C in the western Mediterranean and maybe around 27°C in the Adriatic sea. Presumably because of the presence of several big lakes and many rivers, the dew points observed in the Po valley are significantly higher than in other large (drier) valleys with access to the Mediterranean sea, such as the Ebro valley (on the southern side of the Pyrenees) in Spain, the Rhone valley (between the Massif Central and the Alps) in France and the corridor between the Massif Central and the Pyrenees in France. For instance at Zaragoza (Ebro valley), the average dewpoint temperature over the period in question (April–October of the years 1996–1999) is 10.5°C. Similar mean dewpoints are observed at Lyon (Rhone) and Toulouse (in the "corridor"). At these locations, the dewpoint seldomly exceeds 20°C. If it happens, however, this is frequently the forerunner of an episode of severe thunderstorms. Fig. 2 shows an example. In the afternoon of 20 July 1992 severe thunderstorms formed over northern Spain. These thunderstorms would grow out into a huge convective complex affecting the western half of France, southern England and the

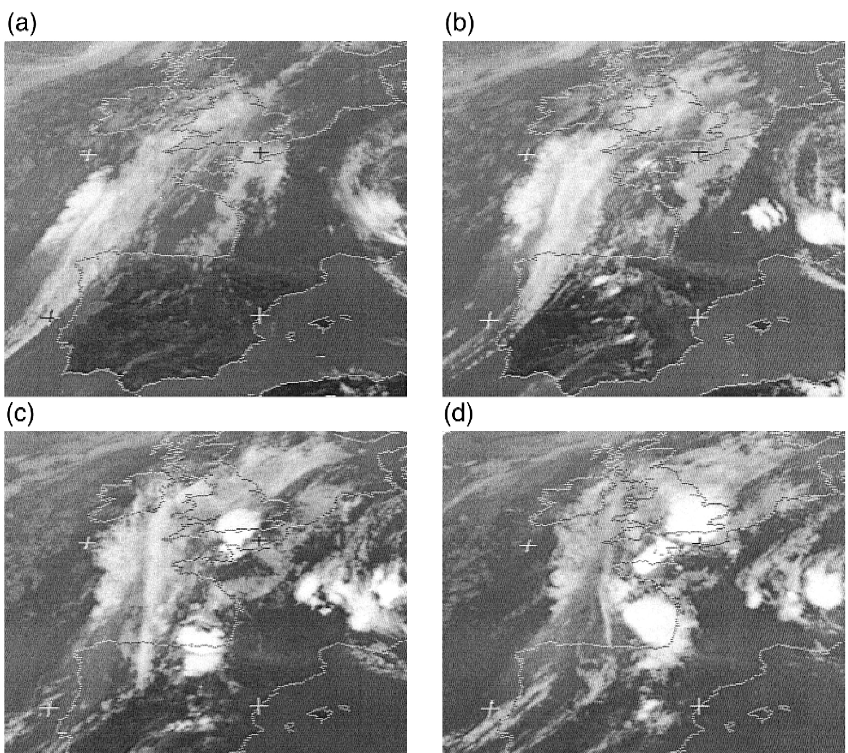

Fig. 2. Meteosat satellite images (infrared channel), 20 July 1992: (a) 1130 UTC; (b) 1430 UTC; (c) 1730 UTC; (d) 1930 UTC.

Benelux countries (see Haase-Straub et al., 1997; McCallum and Waters, 1993). At the time (15:00 UTC) of the genesis of the convective complex, many stations in northern Spain and in southern France reported dew points significantly higher than 20°C (Fig. 3).

A careful analysis of the wind near the earth's surface (Fig. 3) reveals the existence of a line of confluence stretching from south to north over Spain and western France over a distance of more than 1000 km. To the east of this line, the air is in general very humid and hot.

A computer analysis of the average horizontal moisture flux convergence at the earth's surface between 0900 and 1500 UTC (see Fig. 4), calculated from the surface data corresponding to 0900, 1200 and 1500 UTC (for the method of calculation see appendix B of van Delden, 1998), shows that the greatest moisture flux convergence is found in an oblong shaped area stretching from southern Iberia over the Bay of Biscay, along the western coast of France, over northwestern France and then towards East

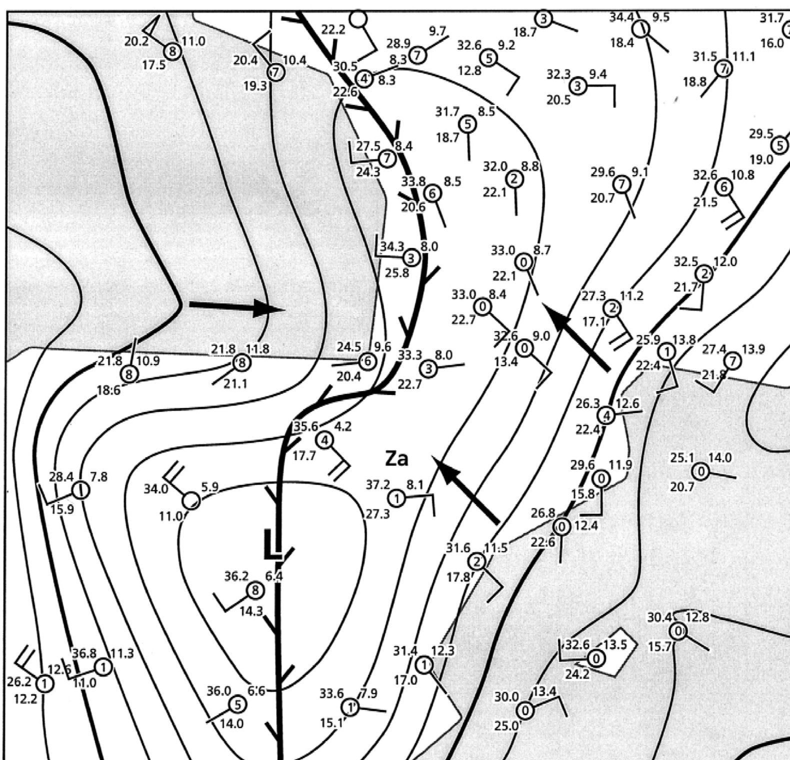

Fig. 3. Surface weather map of 20 July 1992, 1500 UTC. The position of a surface station is indicated by a circle. The number inside the circle indicates the cloudiness (in octas). Also indicated are the temperature (°C) (upper left), the dew point temperature (°C) (lower left) and the pressure (hPa-1000) (upper right). Also shown are sea level isobars drawn every hPa (thick line corresponds to 1012 hPa), according to the objective analysis scheme described by van Delden (1998). The letters "Za" indicate the position of Zaragoza. Arrows indicate the movement and sources of moisture for the thunderstorm. The confluence line is indicated by a "hooked" solid line.

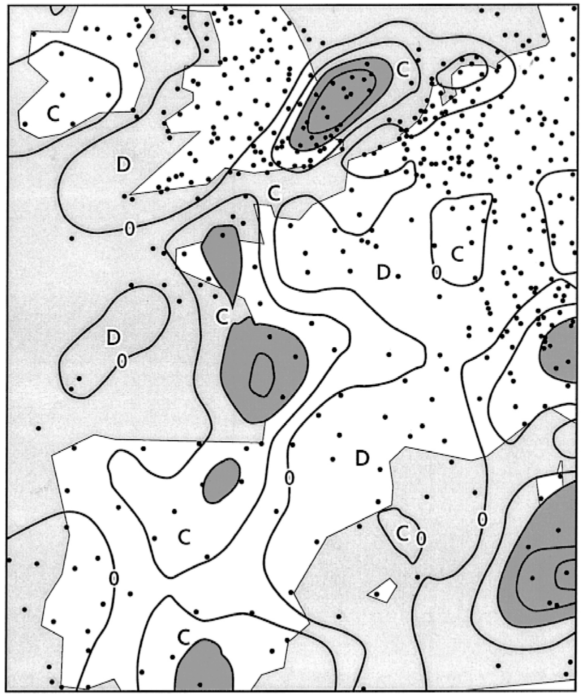

Fig. 4. Average horizontal moisture flux divergence near the earth's surface before the formation of the squall lines on 20 July 1992 between 0900 and 1500 UTC. The average is calculated from the analyses corresponding to 0900, 1200 and 1500 UTC. Only the zero contour and negative values are contoured. The contour interval is 10^{-7} s^{-1}. Regions where the mean moisture flux convergence is greater than 2×10^{-7} s^{-1} are shaded. The letters 'C' and 'D' denote moisture flux convergence and moisture flux divergence, respectively. Also shown are the locations of the measuring stations on which the analysis is based.

Anglia (England). Within this area, marked moisture flux convergence is found in the Bordeaux area and in East Anglia. Many authors (see the review by McNulty, 1995) have identified horizontal moisture flux convergence at the earth's surface as an important condition for the triggering deep convection. It can be seen in Fig. 2 that vigorous convection, coinciding approximately with this line of moisture flux convergence, develops on 20 July 1992.

5. Potential instability

It is well known that thunderstorm activity is related to potential instability. The principle factors contributing to creating high levels of potential instability are warm air advection in the lower tropospheric, blocking of cold air advection by the mountains, accumulation of moisture at low levels and strong solar radiative heating of the earth's surface.

Fig. 5 shows a scatterplot of the potential instability, defined as the equivalent potential temperature at 925 hPa minus the equivalent potential temperature at 500 hPa

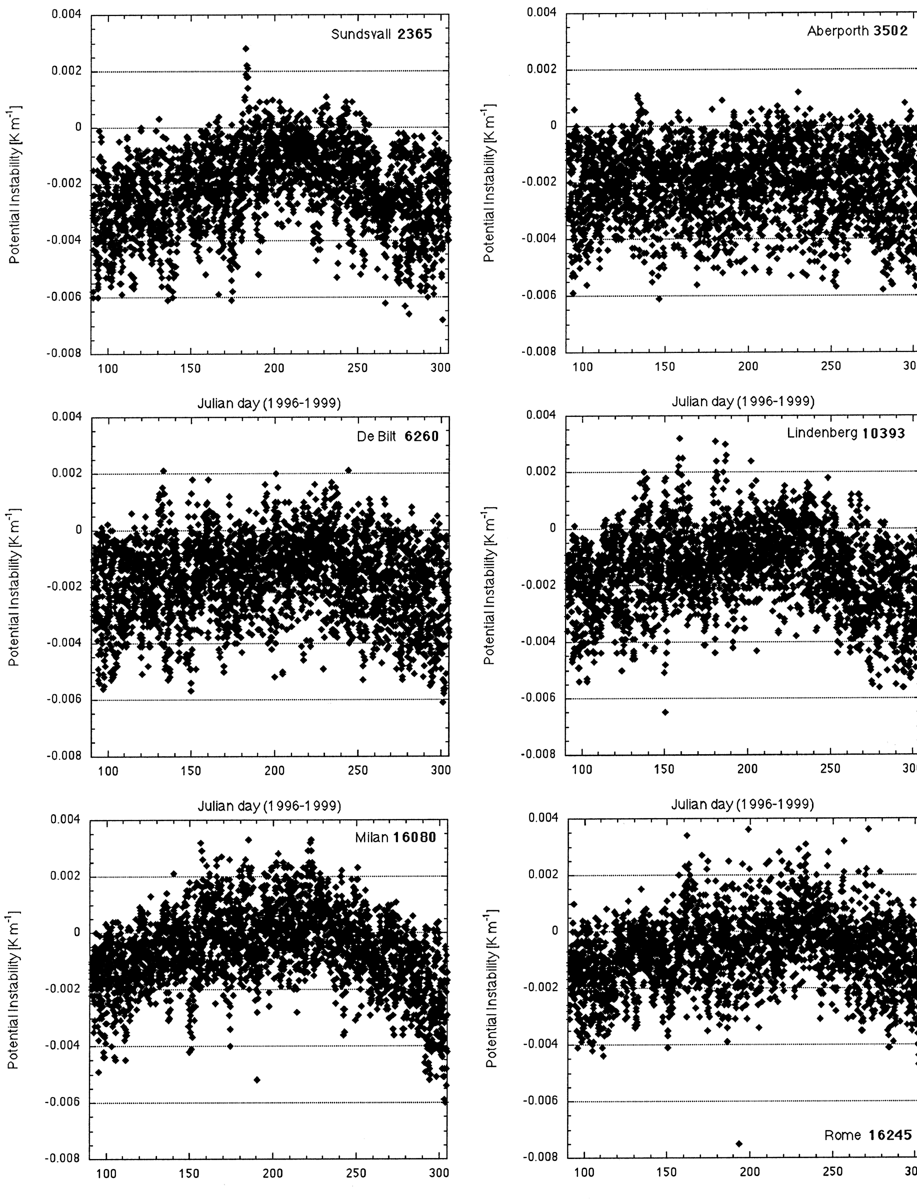

Fig. 5. Scatter plot of the observations of potential instability of the layer 925–500 hPa at Sundsvall, Aberporth, De Bilt Lindenberg, Milan and Rome (see Fig. 1 for the positions of these stations) during the years 1996–1999 (0000, 0600, 1200, 1800 UTC) as a function of Julian day, where day 91 is 1 April, and day 304 is 31 October.

divided by the difference in height between these two pressure levels, at Sundsvall (Sweden), Aberporth (west coast of Wales), De Bilt (The Netherlands), Lindenberg (near Berlin), Milan (Po valley) and Rome (Mediterranean coast). The degree of potential instability at Milan and Rome clearly depends on the time of the year. At Milan, there is a systematic preference for potentially unstable conditions during the months of June, July and August (days 150–240). In fact, during these months, the atmospheric layer between 925 and 500 hPa is potentially unstable more than 50% of the time. Obviously, this is due to solar heating of the earth's surface combined with high moisture levels within the Po valley. At Rome, the season of greatest potential instability is extended towards the autumn. This is due to the high sea surface temperature of the Mediterranean combined with the more frequent incursion of cold air from the north in autumn. Over central Europe (Lindenberg), the average value of the potential instability is significantly lower than over Rome and Milan, but there are episodes (preferably in the early summer) when the atmosphere can become extremely potentially unstable. This is related to plumes of warm air at levels between the earth's surface and 700 hPa being advected towards the north from the Iberian Peninsula or south eastern Europe. These episodes of extreme potential instability (> 0.002 K m^{-1}) are sometimes also observed as far north as Sundsvall. While the average potential stability at both Sundsvall and Lindenberg exhibits a seasonal dependence, this is hardly the case at Aberporth and De Bilt. Both these stations are close to the North Atlantic

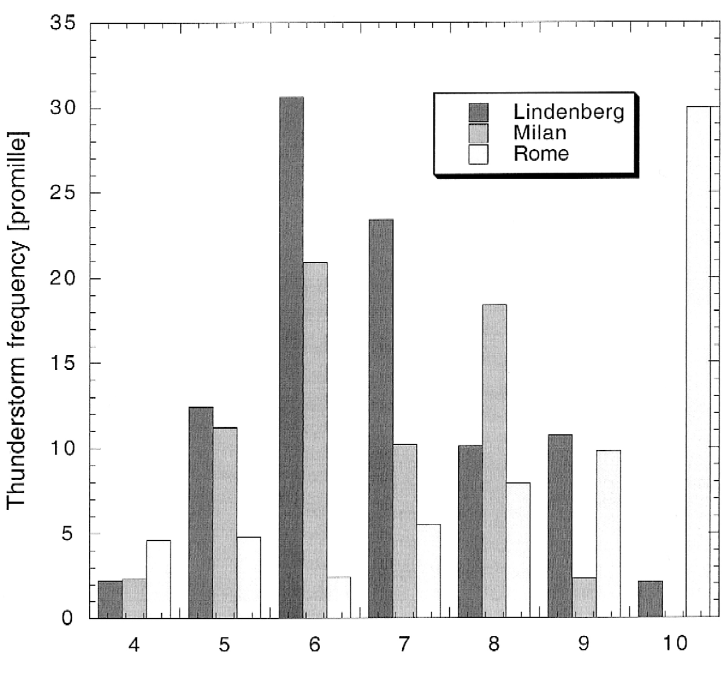

Fig. 6. Mean monthly thunderstorm frequency for the period 1996–1999 at Lindenberg (central Europe), Milan (Po valley) and Rome (Mediterranean coast).

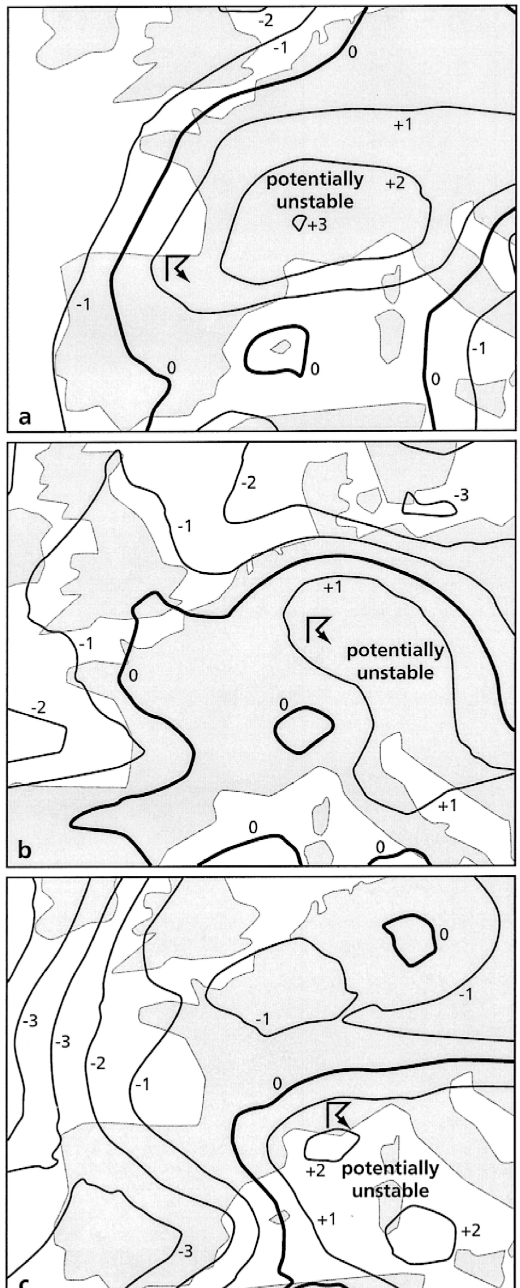

Fig. 7. Potential instability of the layer 925–500 hPa, labeled in units of 10^{-3} K m^{-1}, at the beginning of three episodes of severe thunderstorms: (a) 20 July, 1992, 1200 UTC; (b) 20 August 1992, 1800 UTC; (c) 22 September, 1992, 0600 UTC. Also indicated is the approximate position of the centre of the thunderstorm.

Ocean. However, because De Bilt lies on the European continent, it experiences sporadic episodes of extreme potential instability.

Fig. 6 qualitatively demonstrates the positive correlation between the particular seasonal dependence of potential instability at Lindenberg, Milan and Rome, shown in Fig. 5, and thunderstorm frequency. At Lindenberg, the months of maximum thunderstorm activity are June and July, while at Rome the maximum thunderstorm activity is observed in October and September.

Morgan (1973) has explained how the extreme potential instability over the Po valley in summer develops. One important factor contributing to the development of potential instability is the high moisture content of the air at low levels, as was mentioned earlier. Another important factor is the blocking of cold air advection by the Alps. When a cold front approaches the Alps from the north or west, the cold air below a height of about 3000 m is blocked by the mountains and is ultimately forced to flow around the

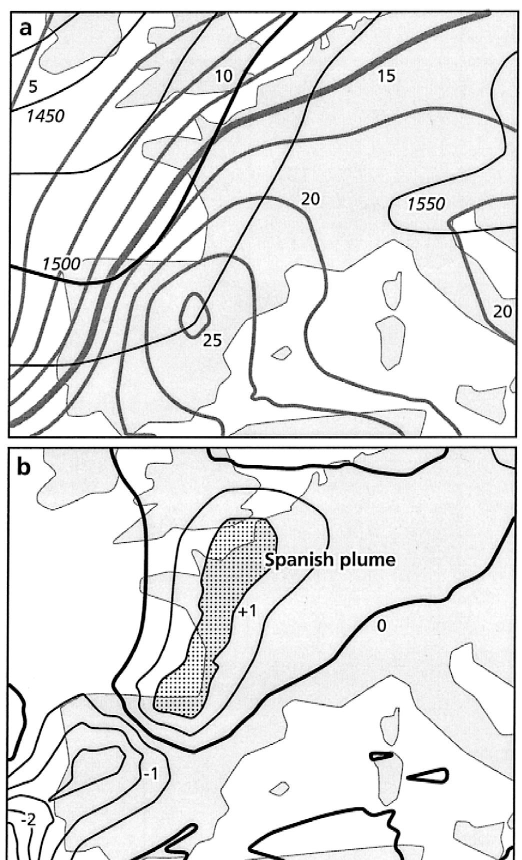

Fig. 8. Height, temperature and horizontal temperature advection at 850 hPa on 20 July 1992, 1200 UTC. The height, labeled in units of m, and the temperature, labeled in units of °C, are shown in panel (a), while horizontal temperature advection, labeled in units of 10^{-4} K s^{-1}, is shown in panel (b).

mountains. This air therefore seldomly reaches the Po valley, certainly not as cold air. Above the height of 3000 m, the cold air passes over the Alps and flows over the warm, humid and nearly stagnant air over the Po valley.

Fig. 7 demonstrates that the three cases of severe thunderstorms in 1992 were all associated with potential instability.

Another process that creates high levels of potential instability is lower tropospheric warm air advection. This effect is frequently very marked over the Bay of Biscay and France. When a trough or cut-off low approaches Iberia from the west in the summer season, the very warm air over the Iberian plateau at levels between 900 and 700 hPa (the Iberian plateau is about 1000 m high) is set into motion and travels towards the north. This is illustrated in Fig. 8 with the case of 20 July 1992. At 850 hPa, we see a zone of warm air advection, frequently referred to as the "Spanish plume" (Morris, 1986), stretching from Iberia over the Bay of Biscay and western France. Above the Spanish plume, high levels of potential static instability are created. In the American literature, the resulting thermodynamic state of the atmosphere is called "the loaded gun".

6. Sources of lift

A forcing mechanism is needed to "let the gun go off", i.e. to lift the air in the boundary layer (below the plume of warm air) to its level of free convection. This forcing mechanism is supplied by the process of frontogenesis, which in the case of 20 July 1992 is taking place over Iberia, where there is an intense horizontal gradient in the temperature advection (see Fig. 8b).

The Iberian plateau, although a frequent seat of frontogenesis and associated cyclogenesis in the warm season, is of course not the only region where an intense gradient of temperature advection can be set up. A warm plume of air can be created in other areas as well, such as Northern Africa (on 22 September 1992) or the European continent (on 20 August 1992) (Fig. 9).

The frontogenetical effect of the dipole-pattern in horizontal temperature advection (i.e. an area of cold air advection close to an area of warm air advection), seen in all three cases shown in Fig. 9, implies a disturbance to thermal wind balance. The atmosphere maintains thermal wind balance by creating vertical circulations (Holton, 1992). An impression of the forcing of vertical motion due to frontogenesis can be obtained from quasi-geostrophic theory by computing the divergence of the Q-vector. This is shown in Fig. 10 for the three selected cases of severe thunderstorms. We expect forced upward motion if there is convergence of the Q-vector. Therefore, in areas where the Q-vector is convergent the potential instability may be released. It appears that the location of the thunderstorms correlates quite well with these areas, especially on July 20 (Fig. 10a) and on September 22 (Fig. 10c).

In the case of 20–21 July 1992, frontogenesis was particularly intense, as was also shown by Prenosil et al. (1995). Fig. 11a shows the vertical motion at 700 hPa on 20 July 1992, 1800 UTC, according to the analysis made at the European Centre for Medium Range Weather Forecasts, together with the corresponding analysis of the

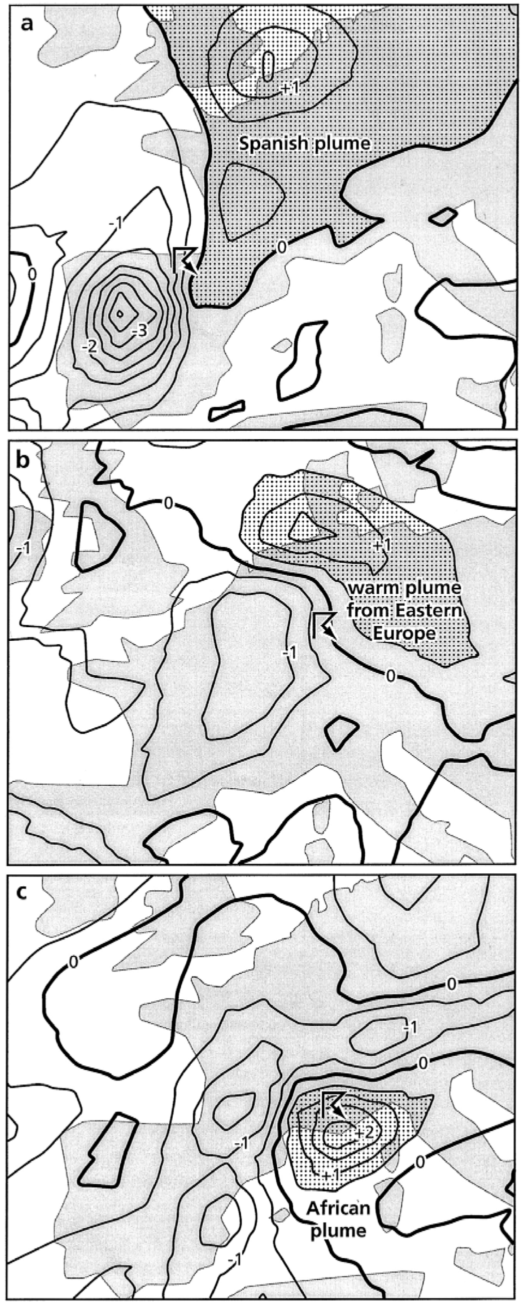

Fig. 9. Horizontal temperature advection (labeled in units of 10^{-4} K s^{-1}) at 850 hPa in the initial phase of the formation of severe thunderstorms on 20 July 1992, 1800 UTC (a), 20 August 1992, 1800 UTC (b) and 22 September 1992, 0600 UTC (c). Also indicated is the approximate position of the centre of the thunderstorm.

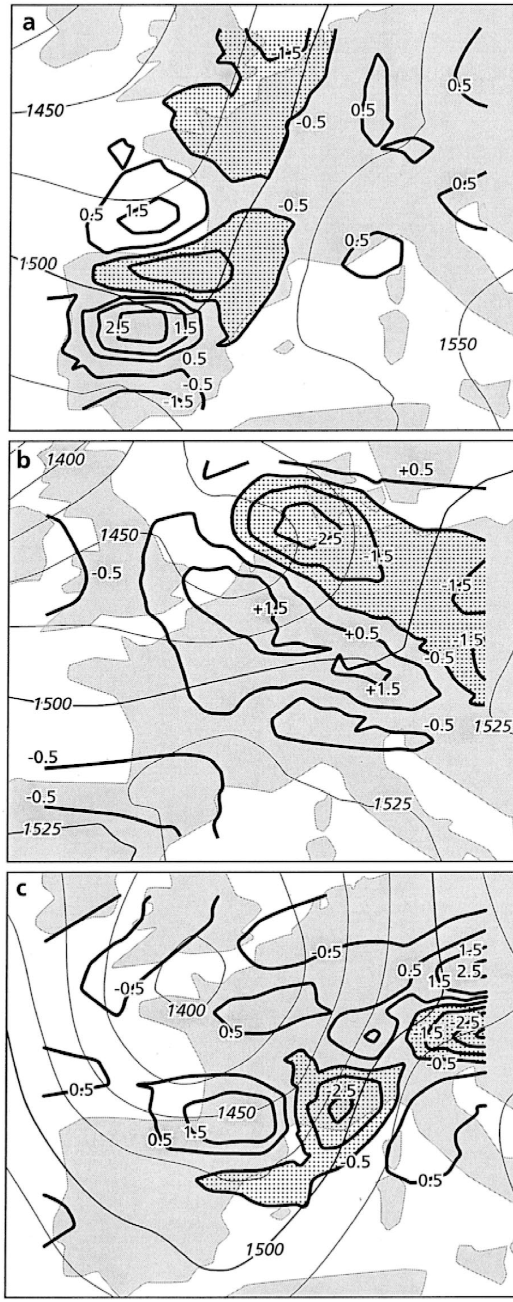

Fig. 10. Divergence of the Q-vector and geopotential height at 850 hPa on 20 July 1992, 1800 UTC (panel a), on 20 August 1992, 1800 UTC (panel b) and on 22 September 1992, 0600 UTC (panel c). The divergence of the Q-vector is labeled in units of 10^{-15} K m^{-2} s^{-1}. The most important region of Q-vector convergence is indicated by shading. The geopotential height is labeled in m.

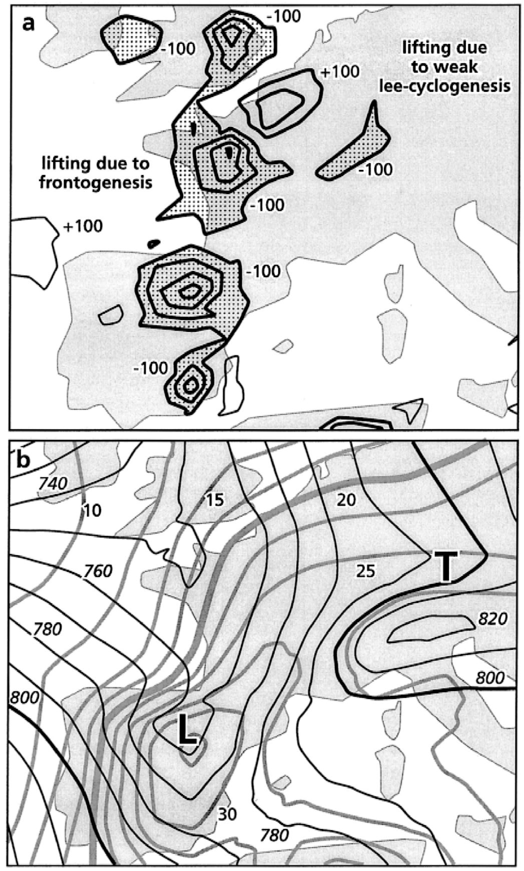

Fig. 11. Panel (a): Vertical velocity at 700 hPa (labeled in units of hPa per hour) on 20 July 1992, 1800 UTC. Panel (b): height (labeled in units of m), and temperature (labeled in °C) at 925 hPa on 20 July 1992, 1800 UTC. The letters, 'L' and 'T' indicate the thundery low and the lee-trough, respectively.

geopotential height and the temperature at 925 hPa (Fig. 11b). A comparison of Fig. 10a with Fig. 11a makes clear that the large zone of upward motion observed in Fig. 11a, is at least partly explained by quasi-geostrophic theory of frontogenesis. The zone of moisture flux convergence (i.e. the convergence line) shown in Fig. 4 is part of this vertical circulation forced by frontogenesis. The convergence line runs through the axis of a trough, marked "L" in Fig. 11b. This trough, which is frequently called a "thundery low" by forecasters in The Netherlands and the United Kingdom (Ludlam, 1980; van Delden, 1998), is formed as a consequence of mass convergence along the convergence line. It appears, therefore that frontogenesis is the process behind the formation of the thundery low and provides the source of lift for potentially unstable air.

Thundery lows formed relatively frequently throughout the summer of 1992. A preferred area of formation of thundery lows is the Iberian Peninsula and the Bay of Biscay. Fig. 12 shows the development of the thundery low on 19 August 1992, which

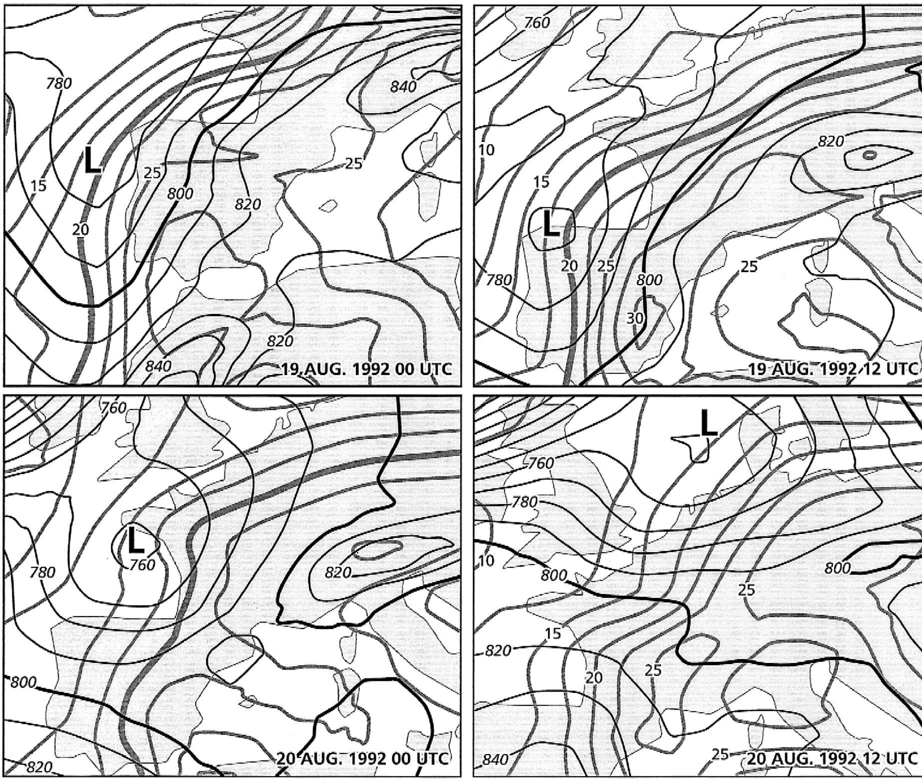

Fig. 12. An example of the formation and evolution of a thundery low (marked “L”) at 925 hPa due to frontogenesis over western Iberia on 19–20 August 1992. The times are indicated in the panels. Two fields are shown: the geopotential height (labeled in m) and the temperature (labeled in °C).

was responsible for the severe thunderstorm over Germany on 20 August 1992 (Kurz, 1993).

The thundery low typically forms in the exit region of the mid-tropospheric jetstreak (see Fig. 13). Jetstreaks at about 700 hPa are a rather common feature in the summer season over the Iberian Peninsula (see also van Delden, 1998). They are an intrinsic part of the recurring frontogenetic effect of the heating of the Iberian plateau adjacent to the cool Atlantic. Intense jetstreaks over this area appear when a cold front approaches from the west.

At upper levels, the flow pattern in situations when severe thunderstorms develop over western Europe is usually characterized by a zone of high potential vorticity, which slowly moves from the ocean towards the continent (Fig. 14). Hoskins et al. (1985) have explained how such a moving anomaly in isentropic potential vorticity “acts on the underlying layers of the atmosphere somewhat like a gentle vacuum cleaner, sucking air upwards towards its leading portion and pushing it downwards under its trailing portion”. Evidence of this vacuum cleaner effect of potential vorticity advection is found

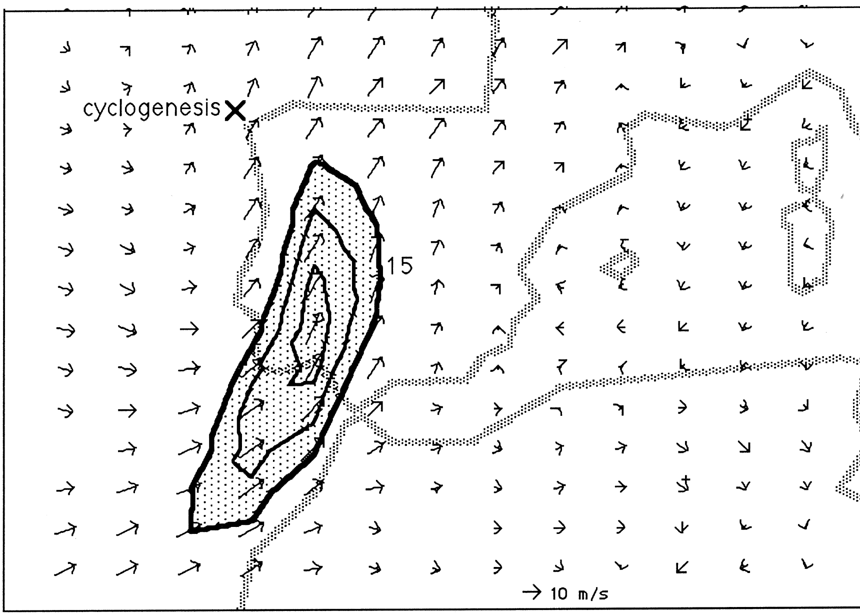

Fig. 13. The wind vectors and the absolute wind velocity (labeled in units of m s^{-1}) at 700 hPa on 19 August 1992, 1200 UTC. The contour interval is 1 m s^{-1}, starting at 15 m s^{-1}. The shading marks the approximate form and position of a jetstreak.

in Fig. 15, which, for the case of 22 September 1992, shows a zone of "horizontal" divergence in advance of the eastward moving zone of high potential vorticity, indicating that the layers of air below this layer are lifted. More evidence of this mechanism can be found in the paper by Massacand et al. (1998).

Finally, we come to the many-fold role of orography in providing a source of lift. First, there is the simple process of orographic lifting. This process plays an important role in torrential rain events in the Mediterranean, in particular in autumn (Doswell et al., 1998). Due to orographic lifting of very humid and warm Mediterranean air, huge amounts of rain can fall within a relatively short time. An example of such case was the severe weather, which struck southern France on 22 September 1992 (Sénési et al., 1996). Second, there is the process of lee cyclogenesis, which is always associated with forced upward motion. The gulf of Genoa is a well-known seat of cyclogenesis in the lee of the Alps. This may explain the high frequency of thunderstorms in the gulf of Genoa (see Fig. 1). According to Morgan (1973) and Cacciamani et al. (1995), cyclogenesis in the lee of the Alps, after the passage of a cold front, usually also provides the lift required to release the potential instability in the Po valley. Lee-cyclogenesis to the north of the Alps is in general less marked, but may nevertheless partly explain the high frequency of thunderstorms over Switzerland and southern Germany. For example, in Fig. 11b, we clearly observe a trough (marked "T" in the figure) to the north of the Alps in conjunction with thunderstorms (Fig. 2d). This effect may also explain the relatively

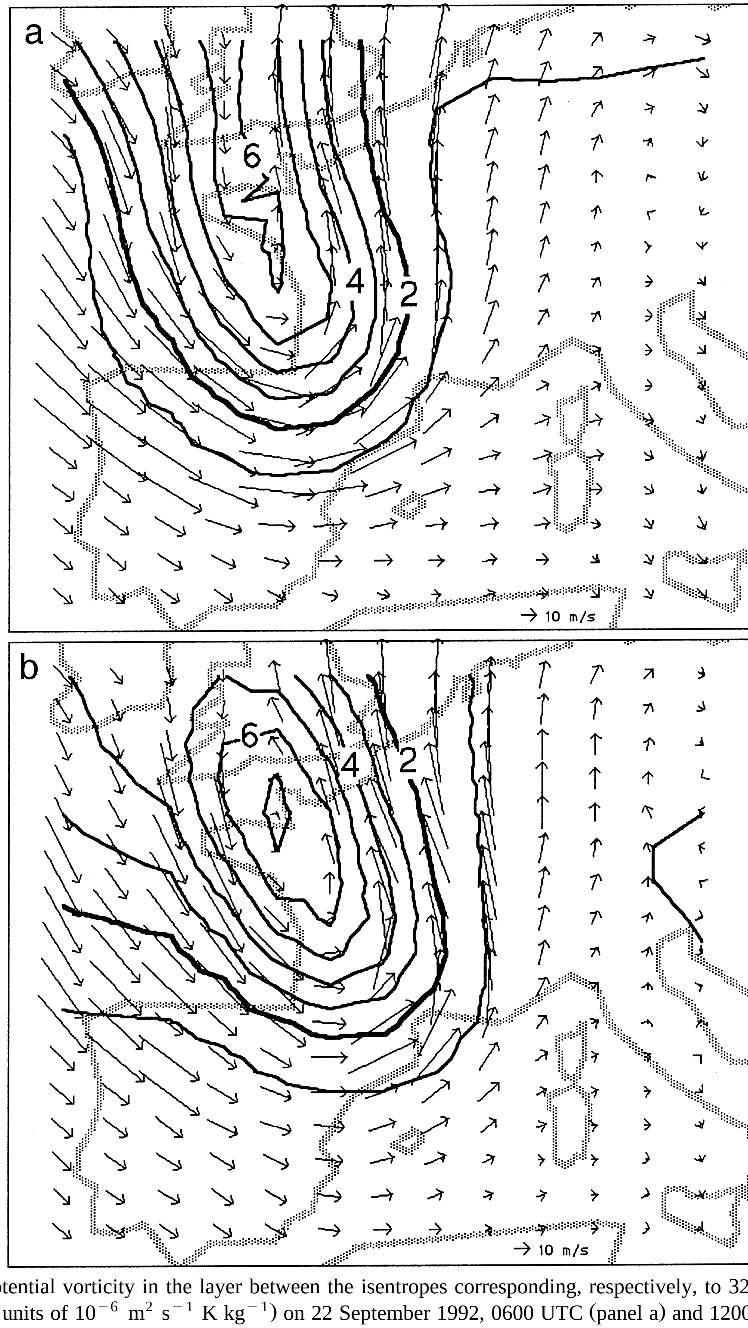

Fig. 14. Potential vorticity in the layer between the isentropes corresponding, respectively, to 320 and 330 K (labeled in units of 10^{-6} m^2 s^{-1} K kg^{-1}) on 22 September 1992, 0600 UTC (panel a) and 1200 UTC (panel b). The 325 K isentrope roughly lies at a height of 9000 m.

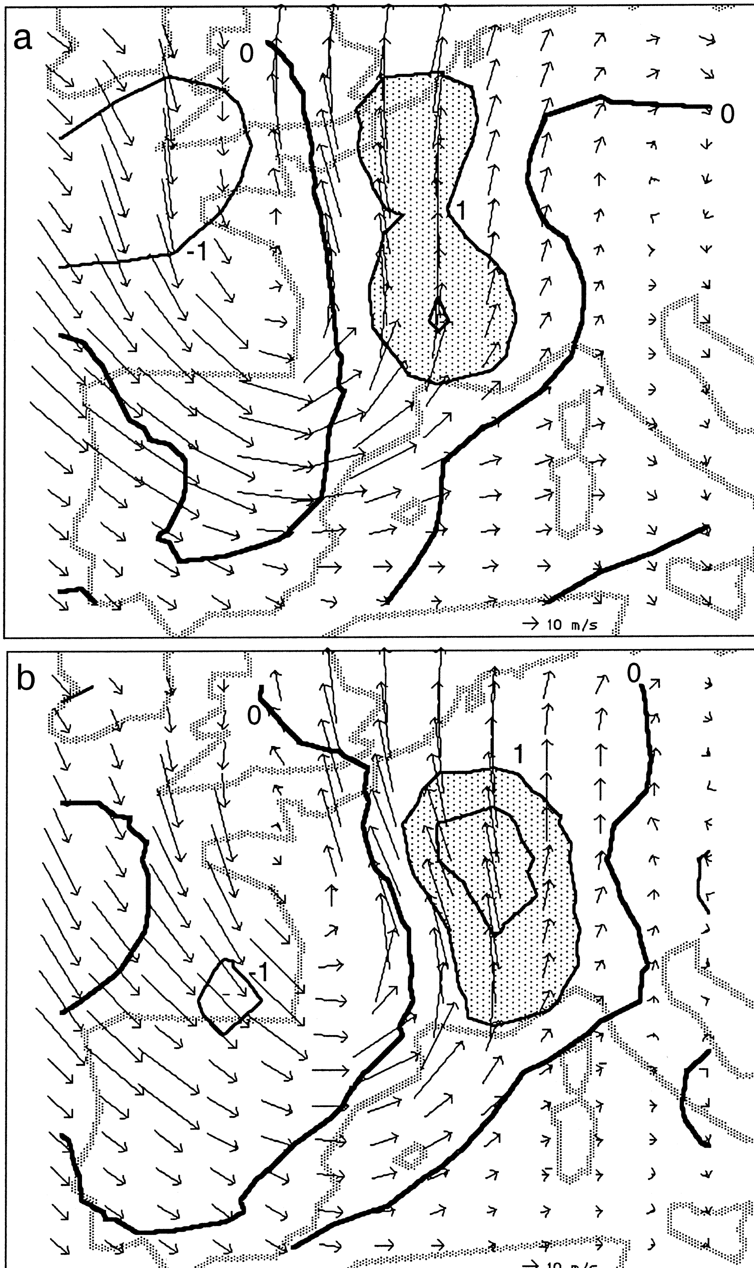

Fig. 15. Mean horizontal wind vectors and associated mean divergence of the flow in the layer between the 320- and 330-K isentropes (labeled in units of 10^{-5} s^{-1}), assuming there is no cross-isentropic flow at these levels, on 22 September 1992, 0600 UTC (panel a) and 1200 UTC (panel b).

high thunderstorm frequencies found over southern Poland, to the north of the Carpathian mountain range.

Another effect of orography was discussed by Schmid et al. (1997) who showed that the lower mountain ranges, such as the Jura mountains and the mountains in the Pre-Alpine region in Switzerland play an important role in determining the location of developing storms. Convective clouds appear first over these lower mountain ranges.

Other sources of lift for potentially unstable air can be found in the updraught of a sea breeze circulation over land or in the updraught of a land breeze circulation over sea during the night. The former effect is of importance in the spring and early summer, while the latter effect is of importance in the autumn. For example, there is a clear preference for thunderstorm formation during the night and early morning over the southern part of the North sea in September and October. At Helgoland, a tiny island in the German Bight (see Fig. 1), only 16% of all thunderstorms, observed at 0000, 0600, 1200 and 1800 UTC, are observed at 0600 UTC in the period April to August. However, in the months of September and October, when a relatively well-developed land breeze induces convergence over sea, 45% of all thunderstorms, observed at 0000, 0600, 1200 and 1800 UTC, are observed at 0600 UTC.

7. Conclusion

A 4-year thunderstorm climatology reveals that thunderstorms during the warm season (April to October) in western Europe are most numerous in the vicinity of the Alps. This is related to the relatively high levels of potential instability occurring in this area. To the south of the Alps, the Mediterranean sea is an important source of warm moist air at low levels, especially in the second half of the summer season. At levels below about 3000 m (700 hPa), the atmosphere over northern Italy and the Gulf of Genoa is sheltered by the Alps from the cool Atlantic air. Cold air may still penetrate into this area at upper levels from the west and from the north, thus creating extremely high levels of potential instability. This instability is released by forced lifting which, in this area, is usually provided by lee-cyclogenesis or mesoscale circulations, such as the sea breeze or thermally forced upslope flow. To the north of the Alps, potentially unstable conditions are associated with warm air advection at levels below 700 hPa, such as in the so-called "Spanish plume". The most important mechanism contributing to the release of this potential instability is frontogenesis. Frontogenesis is frequently accompanied by cyclogenesis. Severe thunderstorms to the north of the Alps and the Pyrenees are usually associated with a low pressure area termed "the thundery low".

The central Alps exhibit a minimum in thunderstorm frequency. This is related to the relative absence of potential instability over the higher ground during a major part of the period (April–October) investigated, and presumably to the absence of significant moisture convergence as well as to the absence of a sustained source of lift in the inner Alpine valleys. Thunderstorms are also relatively infrequent along the western and northern edge of Europe, presumably due to the absence of significant potential instability.

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References

Cacciamani, C., Battaglia, F., Patruno, P., Pomi, L., Selvini, A., Tibaldi, S., 1995. A climatological study of thunderstorm activity in the Po valley. Theor. Appl. Climatol. 50, 185–203.

Doswell III, C.A., Ramis, C., Romero, R., Alonso, S., 1998. A diagnostic study of three heavy precipitation episodes in the western Mediterranean. Weather Forecast. 13, 102–124.

Haase-Straub, S.P., Hagen, M., Hauf, T., Heimann, D., Peristeri, M., Smith, R.K., 1997. The squall line of 21 July 1992 in Southern Germany: an observational study. Beitr. Phys. Atmos. 70, 147–165.

Holton, J.R., 1992. An Introduction to Dynamic Meteorology. 3rd edn. Academic Press, New York, 507 pp.

Hoskins, B.J., McIntyre, M.E., Robertson, A.W., 1985. On the use and significance of isentropic potential vorticity maps. Q. J. R. Meteorol. Soc. 111, 877–946.

Kurz, M., 1993. Severe thunderstorms over western Germany—a case-study of the weather situation on 20 August 1992. Meteorol. Mag. 122, 177–188.

Ludlam, F.H., 1980. Clouds and Storms. Pennyslvania State Univ. Press, University Park, 405 pp.

Massacand, A.C., Wernli, H., Davies, H., 1998. Heavy precipitation on the Alpine southside: An upper level percursor. Geophys. Res. Lett. 25, 1435–1438.

McCallum, E., Waters, A.J., 1993. Severe thunderstorms over south-east England 20/21 july 1992: satellite and radar perspective of a mesoscale convective system. Weather 48, 198.

McNulty, R.P., 1995. Severe and convective weather: a central region forecasting challenge. Weather Forecast. 10, 187–202.

Morgan Jr., G.M., 1973. A general description of the hail problem in the Po valley of Northern Italy. J. Appl. Metereol. 12, 338–353.

Morris, R.M., 1986. The Spanish plume—testing the forecaster's nerve. Meteorol. Mag. 115, 349–357.

Prenosil, T., Thiel, D., Kraus, H., 1995. Frontogenesis and cross frontal circulation in a strong summertime cold front. Meteorol. Atmos. Phys. 181–196.

Schmid, W., Schiesser, H.-H., Bauer-Messner, B., 1997. Supercell storms in Switzerland: case studies and implications for nowcasting severe winds with Doppler radar. Meteorol. Appl. 4, 49–67.

Sénési, S., Bougeault, P., Chéze, J.-L., Cosentino, P., Thepenier, R.-M., 1996. The Vaison-La-Romaine flash flood: mesoscale analysis and predictability issues. Weather Forecast. 11, 417–442.

van Delden, A., 1998. The synoptic setting of a thundery low and associated prefrontal squall line in western Europe. Meteorol. Atmos. Phys. 65, 113–131.