PICTURE OF THE MONTH

Orographic Channeling of a Cold Front by the Pyrenees

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ABSTRACT

The channeling effect of the Pyrenees on a cold front is illustrated using high resolution surface data. Satellite data support the analysis of the surface data and show that the surface front is trapped to a significant degree in the vicinity of the mountains.

1. Introduction

The southerly buster is a particularly abrupt form of a cold front that occurs frequently in the coastal regions of eastern Australia. Observations indicate that it is associated with the deformation of a cold front which interacts with the mountain ranges of south-eastern Australia (Baines 1980). While the southerly buster is a local phenomenon restricted to the coastal regions of New South Wales, there is evidence that fronts with similar characteristics occur in other parts of the world. It is likely that the "Pampero Sucio" of South America which moves northwards along the eastern side of the Andes, the "backdoor" fronts of the United States east coast (Bosart et al. 1973) and the alongshore surges of marine air of the west coast of North America (Mass and Albright 1987) are closely related to the southerly buster. The deformation of cold fronts by the European mountains (Alps and Pyrenees) is known to occur also, but documented cases are rare (Kurz 1984; Hoinka 1987). The purpose of the present note is to present an analysis of an event where a cold front was significantly trapped by the Pyrenees on 10 June 1986.

2. The observations

The Pyrenees are situated at the border between France and Spain, extending from the Atlantic Ocean in the west to the Mediterranean Sea in the east. The mean height is approximately 2000 m, while the peak height is 3200 m. The 700 hPa chart of 10 June 1986 shows a trough northwest of the Pyrenees whereas very weak gradients dominate central Europe (Fig. 1, top). A cold front approaching from the west reached western France and northern Spain at 12 UTC (time in two digit hours) as indicated by the synoptic scale surface

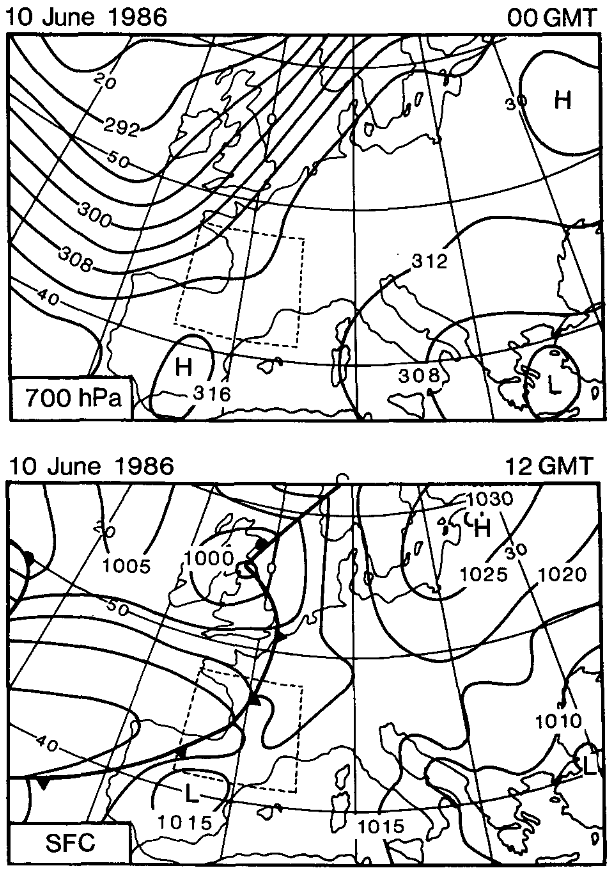

FIG. 1. Synoptic chart (700 hPa) at 00 UTC 10 June 1986 (top) and surface chart (bottom) at 12 UTC (taken from the European Meteorological Bulletin). The dashed lines mark the area shown in Fig. 2.

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analyses (Fig. 1, bottom). The behavior of this front is investigated in detail by using 3-hourly mesoscale analyses, which cover northern Spain and central France. The observation reports of about 120 stations with an averaged spacing of approximately 100 km were used to define the exact positions of the surface front. In general, what is meant by the front itself depends on the analyst, so we briefly summarize the characteristics applied to locate the surface position of the front. The front is well marked by significant changes in meteorological parameters.

(i) *Surface wind:* The prefrontal wind speed is weak (<3 m s^{-1}) and the wind direction varies mainly between southeast and southwest. The postfrontal area shows stronger surface winds, 3 to 5 m s^{-1} from west to northwest.

(ii) *Pressure:* The surface front line is situated within a trough of low pressure. While the pressure has only weak gradients over the areas east of the front it rises as much as 5 hPa within a strip a few 100 km wide to the west of the front. The maximum pressure gradient occurs close to the north rim of the Pyrenees.

(iii) *Temperature and frontal weather:* The surface temperature drops continuously to the rear of the front while it is rather homogeneous over the prefrontal area. A 6/8 to 8/8 coverage of low strato-cumulus clouds is observed west of the front while east of it the sky is almost cloud free. Only weak drizzle occurs near the Atlantic coast.

Figure 2 shows the isochrones of the front position found by the mesoscale analysis between 00 and 21 UTC. The most prominent period of frontal acceleration occurs between about 03 UTC and 09 UTC. The frontal speed is estimated to be about 12 ± 4 m s^{-1} close to the Pyrenees versus 7 ± 2 m s^{-1} north of Bordeaux in central France. These estimates suggest a trapping of the cold front near the mountains. The rawinsonde data taken at Bordeaux between 00 and 12 UTC 10 June 1987 show that a cool change of 8 K in magnitude occurred at 12 UTC in the lower troposphere up to 2 km. Based on these data the slope of the front is estimated to be about 1 km in height per 100 km in horizontal distance. After the southern part of the front has left the region of the Pyrenees (at about 15 UTC) the northern part accelerates after the passing the Central Massif of France and catches up with its southern edge. On the next day a similar trapping of the same front occurred along the northern rim of the Alps (Hoinka 1987).

The frontal propagation speed along the northern rim of the Pyrenees is derived from the isochrones (Fig. 2). The speed of movement between 03 and 06 UTC is estimated to be about 19 ± 4 m s^{-1}. Between 06 and 15 UTC this speed decreased to about 5 ± 1 m s^{-1}. Why does the front decelerate in the vicinity of the Pyrenees around 06 UTC? We can only speculate about the reasons. Between 00 and 12 UTC the cross-frontal

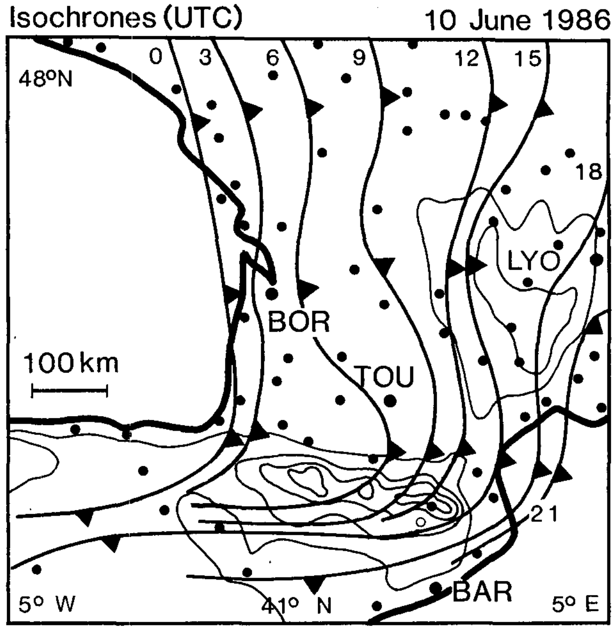


FIG. 2. Isochrones of the surface front between 00 and 21 UTC 10 June 1986. The isolines in height of the Pyrenees are given in 500 m height intervals. The dots indicate the available synoptic surface observations. The abbreviations stand for: Bordeaux/France (BOR), Toulouse/France (TOU) Barcelone/Spain (BAR) and Lyon/France (LYO).

temperature difference at Bordeaux is 8 K. At Brest, which is 500 km to the north of Bordeaux, a similar temperature drop occurred. At Lyon, which is about 500 km to the east of Bordeaux, the temperature decreased only by 4 K. This results from the soundings at 12 and 24 UTC 10 June 1986. The decrease in cross-frontal $\Delta\theta$ towards the east is probably due to the convective mixing occurring over the land during the afternoon. It is suggestive that a similar decrease in $\Delta\theta$ towards the east occurred close to the northern slopes of the Pyrenees which might have supported the deceleration. The theory of steady gravity currents suggests a relation between the speed of the current and the cross-frontal temperature gradient. Observations suggest that at least some fronts have the local character of a gravity current, but not all claims to this effect seem to be well-founded. Nevertheless, it is suggestive that if the crossfrontal gradients are stronger then the front might move faster.

Visible imagery from the NOAA satellite at 1358 UTC (Fig. 3, top) shows that the frontal clouds cover areas north of the Pyrenees. The basic structure of the cloud field suggests that close to the northern slope of the Pyrenees the surface front is further east than it is north of this area. The corresponding infrared satellite image of 10 June 1986 (Fig. 3, bottom) shows the upper level front as a white cloud line crossing the Pyrenees without deformation. The surface observations of the clouds north of the Pyrenees show the onset of the

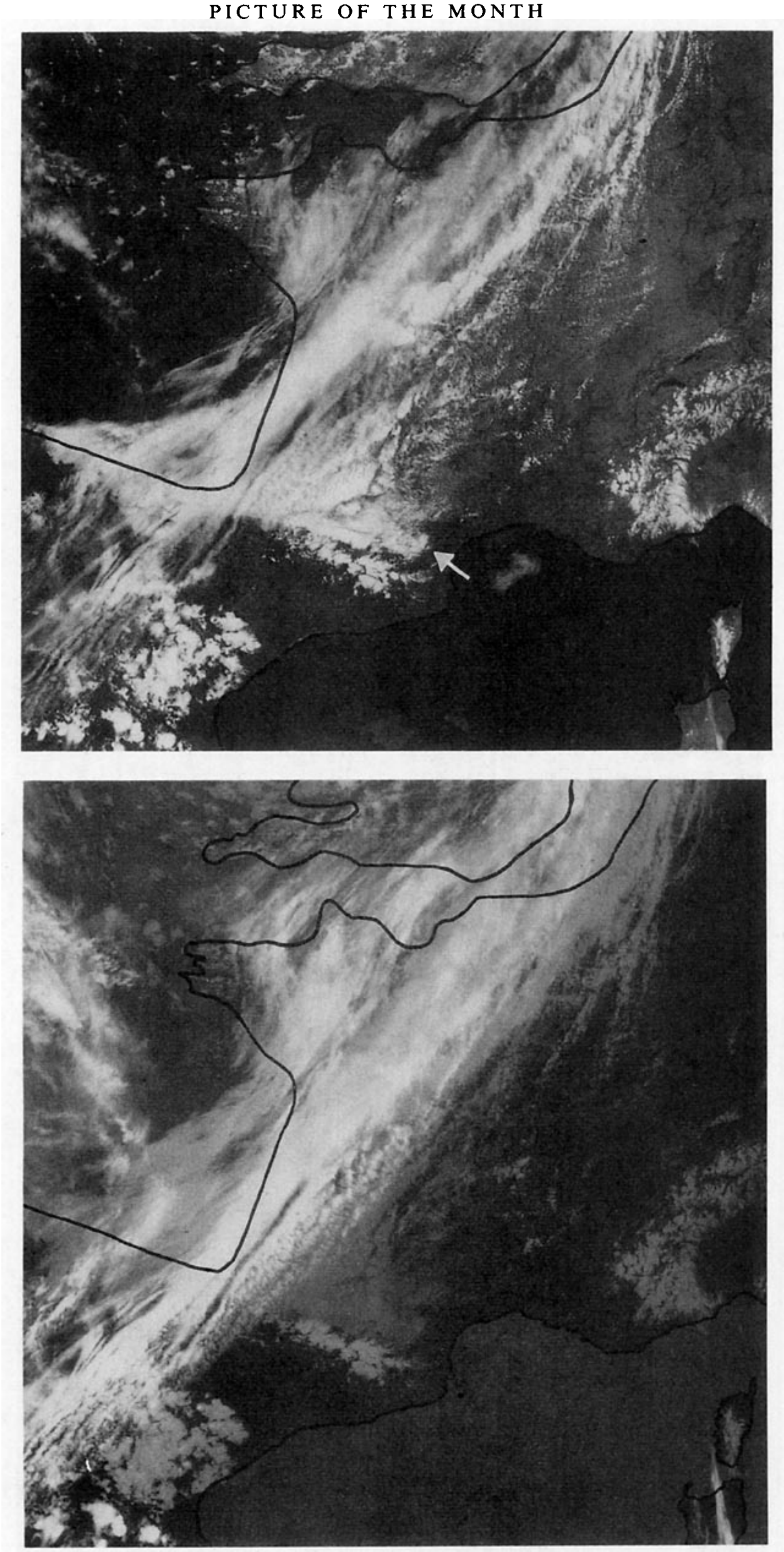


FIG. 3. NOAA-9 visible (top) and infrared (bottom) image for 1358 UTC 10 June 1986. The black lines indicate western Europe with southern England, France and northern Spain. The arrow indicates the clouds related to the trapped surface front close to the Pyrenees.

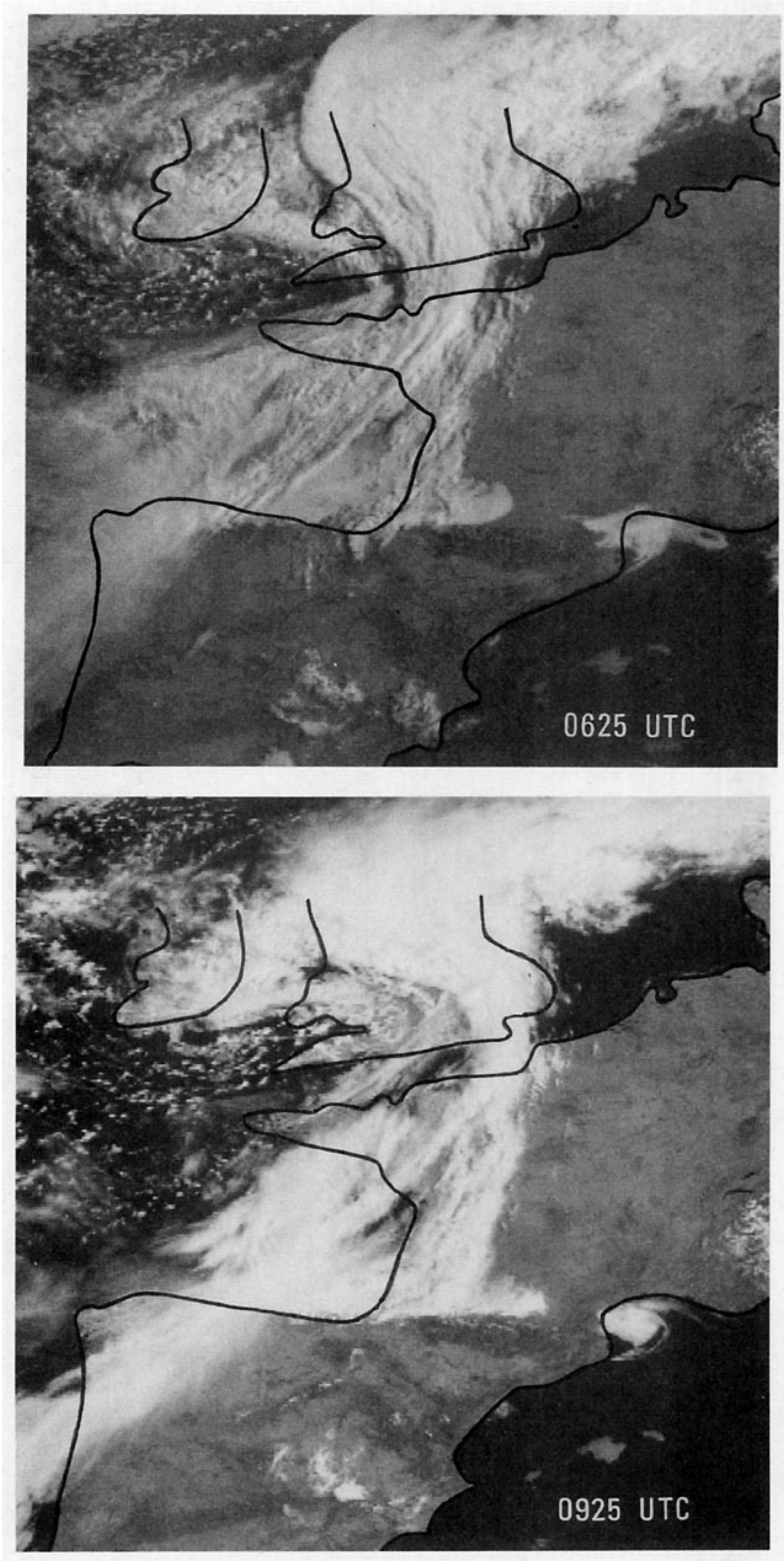
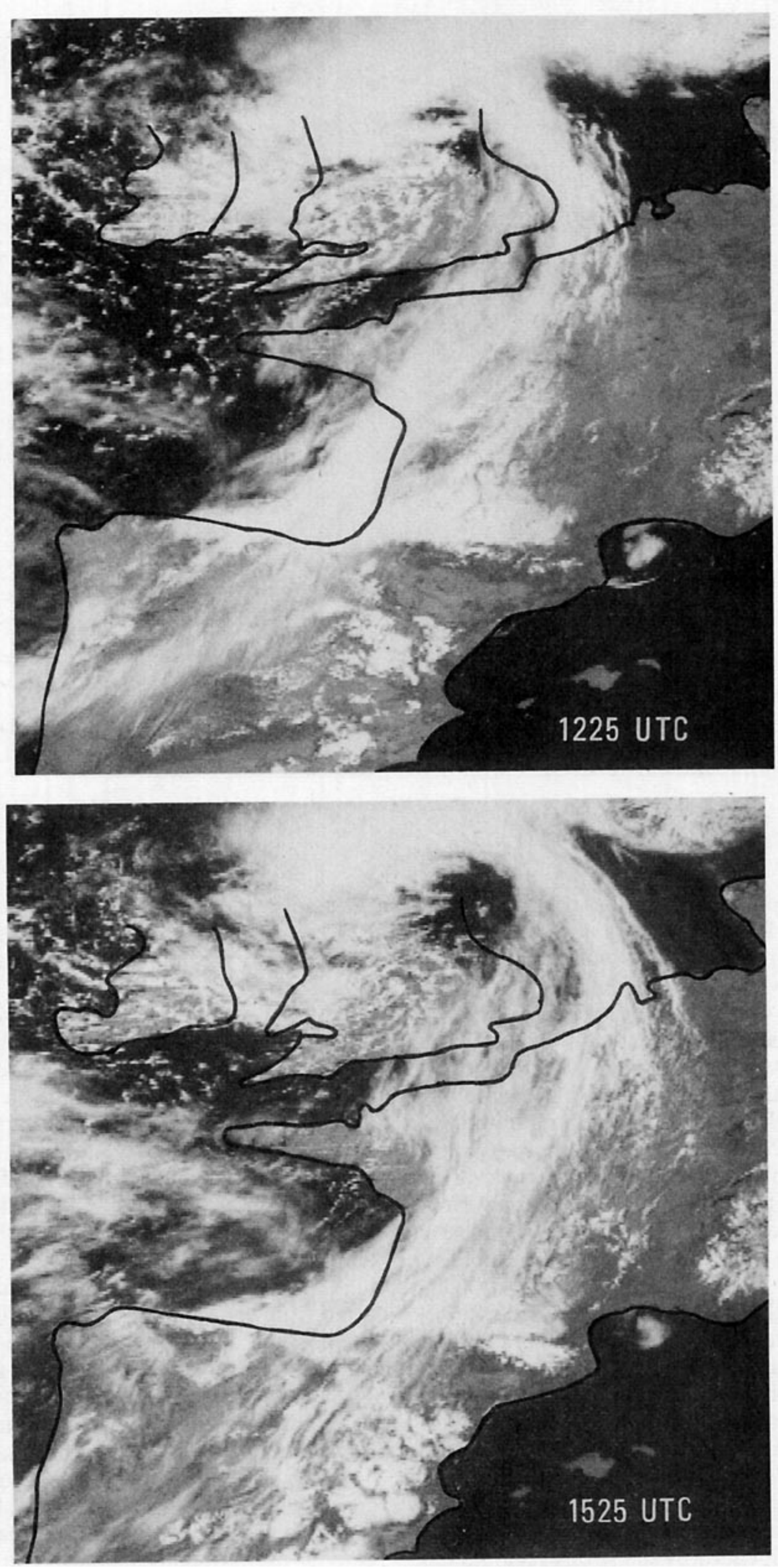


FIG. 4. Sequence of visible METEOSAT pictures for 10 June 1986: (a) 0625, (b) 0925,



(c) 1225, (d) 1525 and (e) 1725 UTC. The black lines indicate western Europe with Spain, France and southern England.

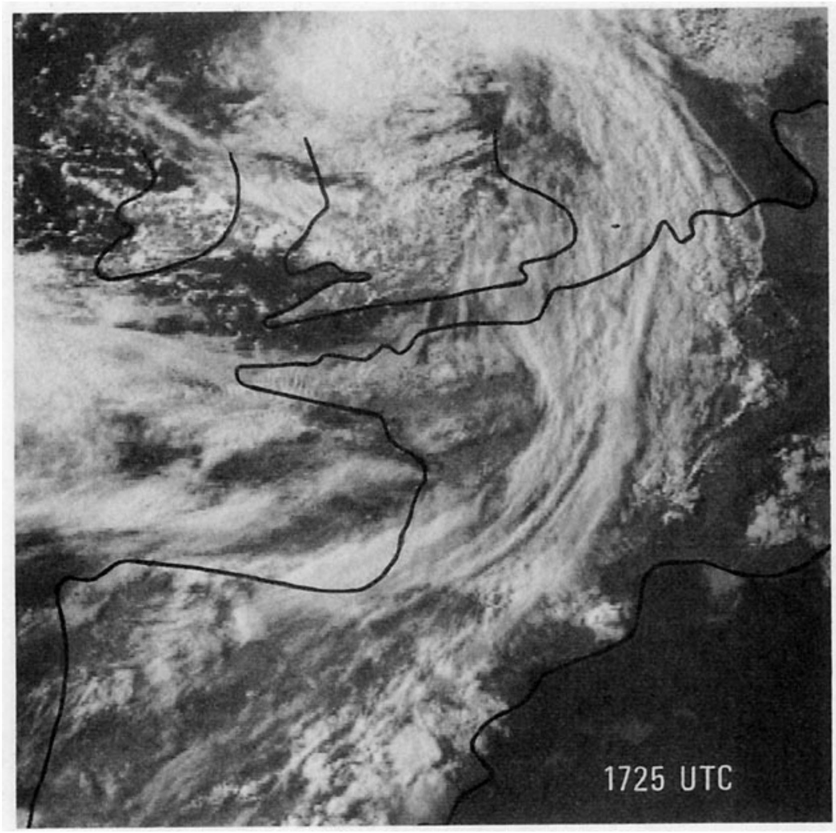


FIG. 4. (*Continued*)

stratus cloud cover with the passage of the front. Therefore, the low level clouds in grey indicate the preceding surface front close to the Pyrenees.

In order to show the temporal evolution of the low-level clouds in Fig. 4 a sequence of visible METEOSAT pictures is given between 0625 and 1725 UTC. The resolution of the METEOSAT-data is not as good as the resolution of the NOAA-data. The resolution of the METEOSAT-data for the given times in the mid-latitudes is about 2.4 and 3.4 km in the east–west and the north–south direction, respectively. However, the coarser data show the low-level cloud tongue which is particularly significant at 0625 UTC. The cloud structure coincides very well with the analyzed surface front (Fig. 2).

Similar low-level cloud tongues associated with cold air surges along a coastal orography between California and Washington are reported by Mass and Albright (1987). Although the tongue of cold air at the Pyrenees and the surges of cold air on the west coast of North America share the character of an orographically trapped flow, there are important differences. In the Pyrenees event the cold air is advected by a large-scale frontal system whereas the cold surge at the Pacific coast is mainly influenced by the strong regional temperature difference between the land and the sea and the associated heat low above California (see Fig. 9 in Mass and Albright 1987). This generates the onshore flow of cold marine air which is trapped along the coastal range.

Roughly estimating the ratio (u_1/u_2) in speed of the leading edge of the low-level stratus cloud between the area north of the Pyrenees (u_1) and central France (u_2) produces a figure of about 1.8, which confirms the estimate of 2 ± 1 derived from the surface synoptic data. The position of the surface front cannot be determined unambiguously from satellite data. In the present case, however, surface data support the idea that the surface position of the front is located at the leading edge of the clouds.

A comparison of the frontal position at 12 UTC derived from the synoptic analysis (Fig. 1, bottom) with the position derived from the mesoscale analysis (Fig. 2) shows an error of about 200 km in surface position of the front above the Pyrenees. The resolution of the three hourly standard synoptic data seems to be ade quate for a detailed study of the channeling effect.

In the presence of orography, geostrophic or quasi-geostrophic balances are not possible within approximately a Rossby radius of deformation of the topographic barrier (Baines 1980). The Rossby radius of deformation is defined by $a = cf^{-1}$, where the c is a

TABLE 1. Frontal speeds (c) and corresponding Rossby radius (a).

Comment	c (m s^{-1})	a (km)
Surface front (Fig. 2)		
$03 < t < 06$ UTC	19 ± 4	190 ± 40
$06 < t < 15$ UTC	5 ± 1	50 ± 10
$03 < t < 15$ UTC	8 ± 1	80 ± 10
Rossby radius: estimated from the surface front at 06 UTC (Fig. 2)	10 ± 3	100 ± 30
Rossby radius: estimated from the width of the low-level cloud band at 0625 UTC (Fig. 4a)	7 ± 1	70 ± 10

characteristic speed and f the Coriolis parameter. The Rossby radius of deformation is a length scale of fundamental importance for the behaviour of rotating fluids subject to gravitational restoring forces. Basically, it is the horizontal scale at which rotation effects are comparable with buoyancy effects. Thus, within this distance from the orography the flow tends to flow ageostrophically down the along-barrier pressure gradient, i.e., in the present event toward the east.

The Rossby radius can be estimated from the curvature of the surface cold front at 06 UTC from Fig. 2 and is about 100 ± 30 km; the corresponding characteristic speed is then 10 ± 3 m s^{-1}. From the satellite picture (Fig. 4a) the radius can also be estimated by counting the cloud-covered pixels normal to the Pyrenees in the cloud-tongue and multiplying this number with the resolution of 3.4 km. The radius is about 70 ± 10 km and the corresponding characteristic speed is then 7 ± 1 m s^{-1}. The observed speeds, derived from the surface frontal position, range from 5 to 19 m s^{-1} where the first value is the minimum and the second one the maximum value of the entire day (Table 1). With this enormous range in speeds during the propagation of the front on this day and with uncertainties up to 5 m s^{-1}, the comparison with a speed derived from the satellite data is questionable.

3. Conclusions

The purpose of this paper is to illustrate an event with a cold front trapped along the Pyrenees. The "surge" of cold air along the orography was identified with high resolution surface data and with satellite data. A rough estimate of the speed of this surge resulted in about 19 m s^{-1} during the phase of the maximum acceleration versus 10 m s^{-1} at the same period 500 km off the Pyrenees.

In general, the channeling of cold fronts along orography is insufficiently understood. First, what is the impact of the synoptic scale environment in generating this mesoscale phenomenon? Why does the front accelerate and then decelerate as it propagates along the barrier? Do these surges locally have the character of a gravity current? The southerly buster and the alongshore surges occurring at the mountain ranges along the coast from California to Washington are associated with rapid temperature falls and pressure rises, but rarely with precipitation. What roles do the precipitation and the associated thermodynamical processes play in modifying the effect of trapping cold air along orography?

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