LEE WAVES OVER EUROPE

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Summary

Lee waves resulting from airflow over mountains were first observerd and, in detail, described by glider pilots. Lee wave cloud bands on a length of up to several hundred kilometers downstream were detected in satellite images from the beginning of this new observation technique. An overview on criteria of formation of lee wave clouds and their characteristic scale and shape is presented. The reception area of the institute's satellite receiving station allows one to observe lee wave formation over whole Europe and small islands in the North Atlantic. On the basis of daily high resolution AVHRR images the mean monthly number of days with lee wave clouds for a number of regions is given and seasonal differences are shown. For the British Isles and Scandinavia the highest number of lee wave days is found.

1. Introduction

A wind crossing mountain ranges often produces lee waves which are nearly stationary. Their existence is primarily due to vertival oscillations of air induced by the obstacle. The first detailed observations of lee waves and the wave flow were provided by glider pilots between 1920 and 1940, in particular by Küttner and Förchtgott over European mountains. Since then further observations were undertaken by glider, powered aircraft, radar, lidar, constant level balloons and satellite. Since the beginning of the availability of weather satellite images in 1960 mesoscale features as lee waves were being observed and interpreted in terms of atmospheric conditions. The improvement of spectral and spatial resolution of satellite sensors led to the detection of a wider range of observable wavelengths. Satellite images furthermore revealed the great extent of lee wave trains as well as a great variety of patterns. A vast literature is available on lee wave observations and on theoretical background and numerical simulations of observed phenomena. The present paper gives a short overview of necessary conditions for the formation of lee waves and their appearance in satellite images and conclusions that can be drawn from the different size and structure of the lee wave phenomena. For different regions of Europe a statistical investigation of the frequency of lee wave cloud formation is presented, based on daily high resolution satellite data, which are received and processed at the institute.

2. Lee wave generation

When air flows over a mountain range or isolated mountain vertical displacements occur and gravity waves are excited. Their existence is based on the buoyancy forces in a stable stratified atmosphere which try to return the air to the equilibrium level. For these quasi-stationary waves in the lee of obstacles the name lee waves is in common use. Since the lower and middle troposphere usually has enough water vapor, slight ascent will bring air to saturation and condensation and lee waves could become visible as cloud formations.

From theoretical work two main parameters for the formation of lee waves have to be considered: the vertical wind profile and the static stability. They are combined in the SCORER parameter:

$$l^2 = \frac{gS}{U^2} - \frac{1}{U}\frac{\partial^2 U}{\partial z^2} + \textit{smaller terms} \qquad S = \frac{1}{\Theta} * \frac{\partial \Theta}{\partial z}$$

where U is the mean wind speed, S is stability and Θ potential temperature.

If l^2 decreases with height, lee waves can be generated. A decrease of l^2 may come from strong vertical increase of wind speed and/or from a strongly stable layer. In most cases when wave trains are seen in satellite images, these are of the type of trapped lee waves. The obstacle is the source of energy and the wave energy is found downstream and bounces up and down between the ground and the low l^2 region, i.e. the inversion layer. This leads to a standing wave pattern in the vertical. The wave energy can be advected large distances downstream.

3. Lee wave clouds

Lee wave clouds are formed predominantly behind mountains of small or medium height and width. In the case of high mountains as the Alps the humidity may be too low and subsidence too strong for cloud formation in the lee side. Lee wave cloud bands in satellite images are in most cases two-dimensional, oriented perpendicular to the air flow. They appear relatively unaffected by the underlying terrain, but in some cases complex interference patterns can be seen. It is not yet clear which criteria are deciding the regularity of the wave trains. The regularity and the large extent of lee wave cloud bands which in most cases consist of stratocumulus were a new discovery from satellite data. The stratocumulus wave clouds often originate from a continuous cloud layer which is distorted by the mountains and wave motion. The following criteria have been evaluated as favorable for the formation of lee waves (lee wave clouds):

- the wind speed increases with height, vertical wind shear is in the range 4....9*10-3 s-1
- the minimum wind speed in the height of mountain tops is between 7 and 13 m/s.
- the wind direction is within +/- 30 degrees from the perpendicular to the wave band
- they form in a region of widespread subsidence and a typical vertical profile of potential temperature is as follows: quasi-neutral layer from the ground up to the inversion, a very stable layer in the inversion and a less stable layer above.

Summarizing different investigations on lee wave clouds in satellite imagery it can be stated that:

- the horizontal extent of lee wave trains seems to be inversely proportional to the thickness of the stable layer;
- strong stability and low windspeed favor short wavelengths and less stability and strong winds favor long wavelengths;
- the first band behind the mountain may be the zone of rotor formation near the surface with strong turbulence;
- the wavelength range is from 1km to about 30km with a relative maximum in the range of 10-20 km, which corresponds to a resonance property of the atmosphere; and
- lee wave cloud patterns are observed up to 500 km downstream.

Figure 1 demonstrates quite clear the existence of lee wave patterns perpendicular to the flow in the middle troposphere with a variety of different wavelengths between Scotland, eastern Central Europe, former Yugoslavia down to the southern tip of Italy. The longest wavelengths of 20-23 km are found over Scotland and Czech Republic, very short wavelengths of 3-4 km are found over Wales and northeastern Germany. Figure 2 shows a large number of lee wave patterns over West and Southwest Europe with some very long wave trains and other remarkable features: over Ireland so-called ship-wave patterns are seen and in the lee of the Pyrenees lee wave clouds do not appear, but to the west and to the east of the Pyrenees they are well organized. As in Figure 1 the orientation of the parallel cloud bands is perpendicular to the flow in the lower troposphere.

4. Three-dimensional lee wave pattern

In the case of isolated mountains or mountains on small islands in the North Atlantic there appear transverse and diverging wave systems in a wedge-shaped region behind the obstacle, as can be seen over Ireland in Figure 2. These lee waves are typical for three-dimensional wave motion and are in many respects similar to the occurence of surface waves behind a ship moving in calm water. Some possible explanations for the formation of three-dimensional lee wave patterns are:

- both types appear together if air is streaming slowly in a thick layer below the inversion;
- at high windspeed in a shallow inversion the transverse waves disappear, only diverging waves occur, the orientation of crests gets close to the free stream direction;
- the topographic scale of the obstacle plays an important role: diverging waves are more dominant in the case of a small mountain profile; and
- the wedge angle of 38° as derived from theoretical work appears in some satellite images exceeded, which indicates that energy is transported beyond 38°.

In the wake of the island of Jan Mayen in the Norwegian Sea often waves and vortex streets are generated. In the eastern part the near conical mountain Beerenberg rises to

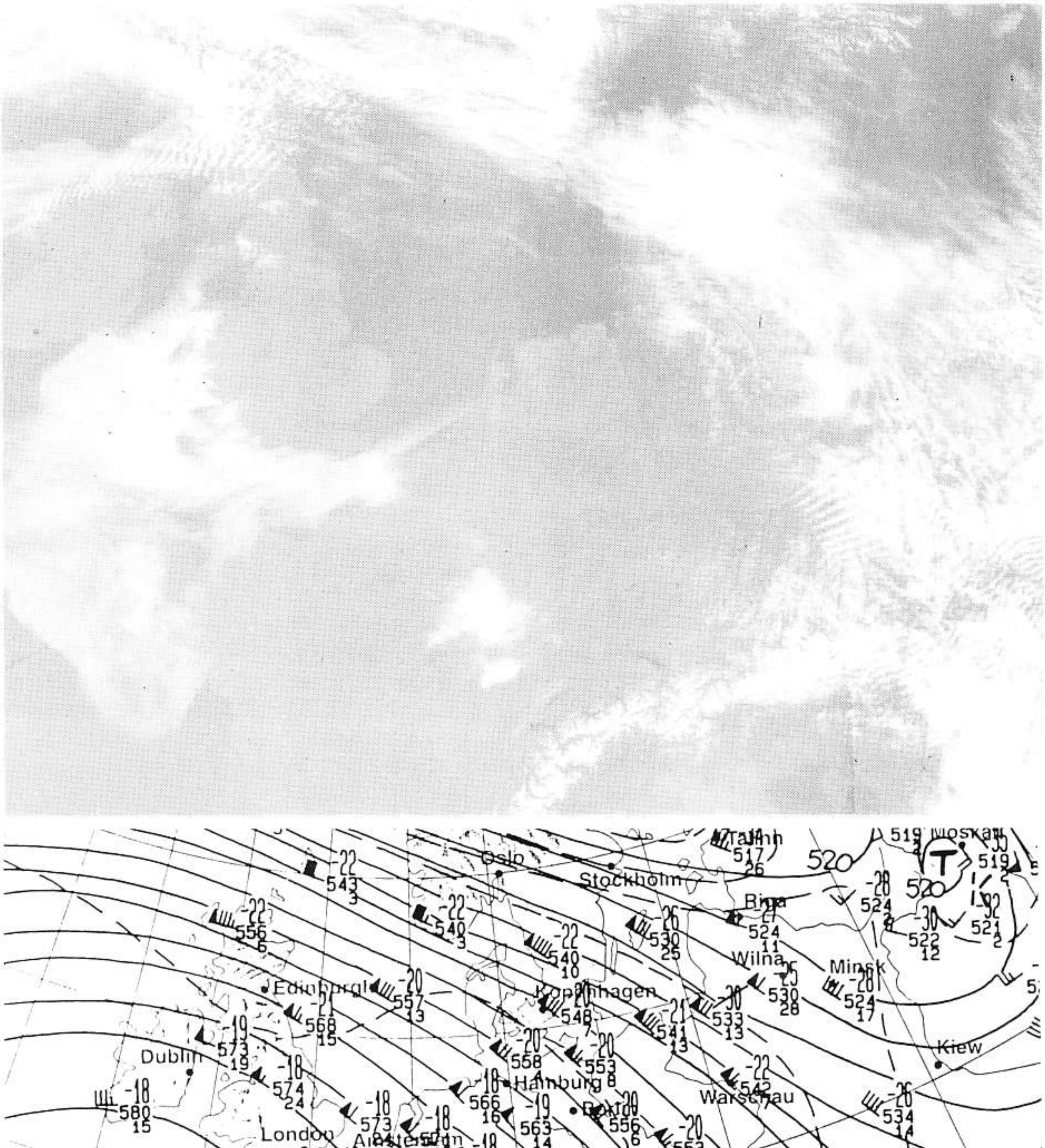

FIGURE 1. Lee wave cloud patterns over parts of Europa (above) and corresponding 500 hPa upper air chart for April 2, 1995, 00 UTC.

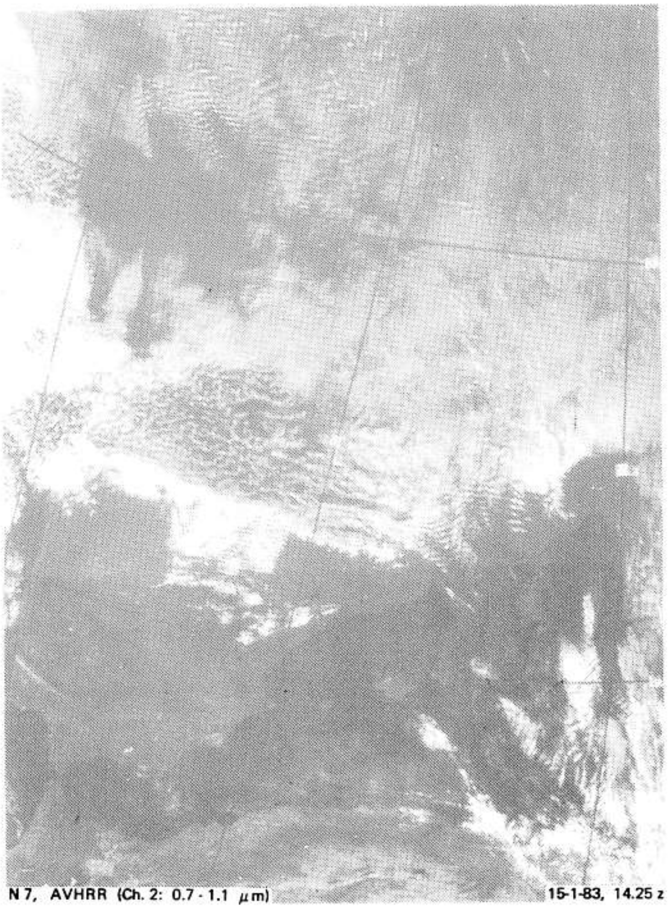

FIGURE 2. Lee wave cloud patterns over Western Europe and Western Mediterranean Area.

2277m, the western part is also montainous with heights up to 769m. The Figure 3 presents a three-dimensional lee wave pattern in a time interval of 100 minutes.

The wave pattern seems to be generally unchanged, typical for a quasistationary situation.

5. Geographical and seasonal distribution

At the institute AVHRR data from NOAA satellites are received and processed operationally in full 1km resolution. Based on daily data covering whole Europe the frequency of occurence of lee wave clouds has been determined for the period January 1, 1995 to April 30, 1997. The monthly distributions for January to April are therefore based on three years, for May to December on two years. Lee wave cloud patterns are found everywhere in Europa behind even hills of small height and width as well as behind islands in the Norwegian and Barents Seas. Figure 4 shows the areas which have been chosen for a study of the monthly distribution of lee wave clouds:

1. Novaya Zemlya
2. Svalbard
3. Jan Mayen
4. Iceland
5,6. Scandinavia
7. Faroe Islands
8,9. UK and Ireland
10. France
11. Central Europe
12. Alps
13. Carpathian mountains
14. SE-Europe
15. Iberian Peninsula
16. Balearic Island, Corsica, Sardinia
17. Italy
18. Greece
19. Northern Africa

The average number of days with lee wave clouds in satellite images for these regions is given in Figure 5. The highest numbers are found in UK and Ireland, Scandinavia

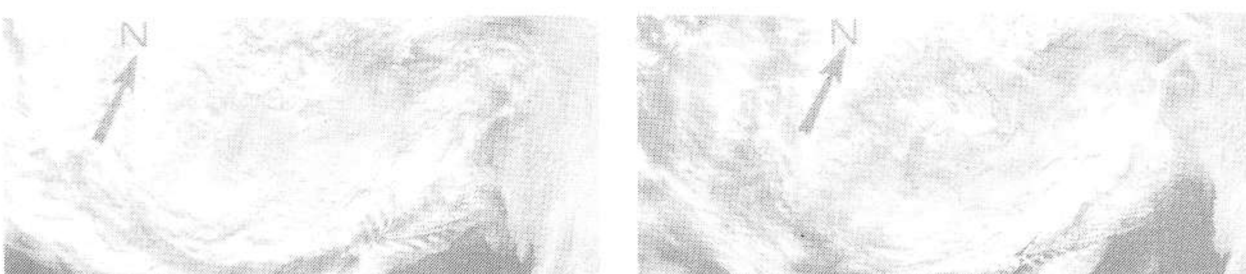

Figure 3. Three-dimensional lee waves in the wake of Jan Mayen NOAA 14 AVHRR Ch.2 (0.7-1.1 um) July 20, 1996: 11.30 UTC (left) and 13.00 UT (right)

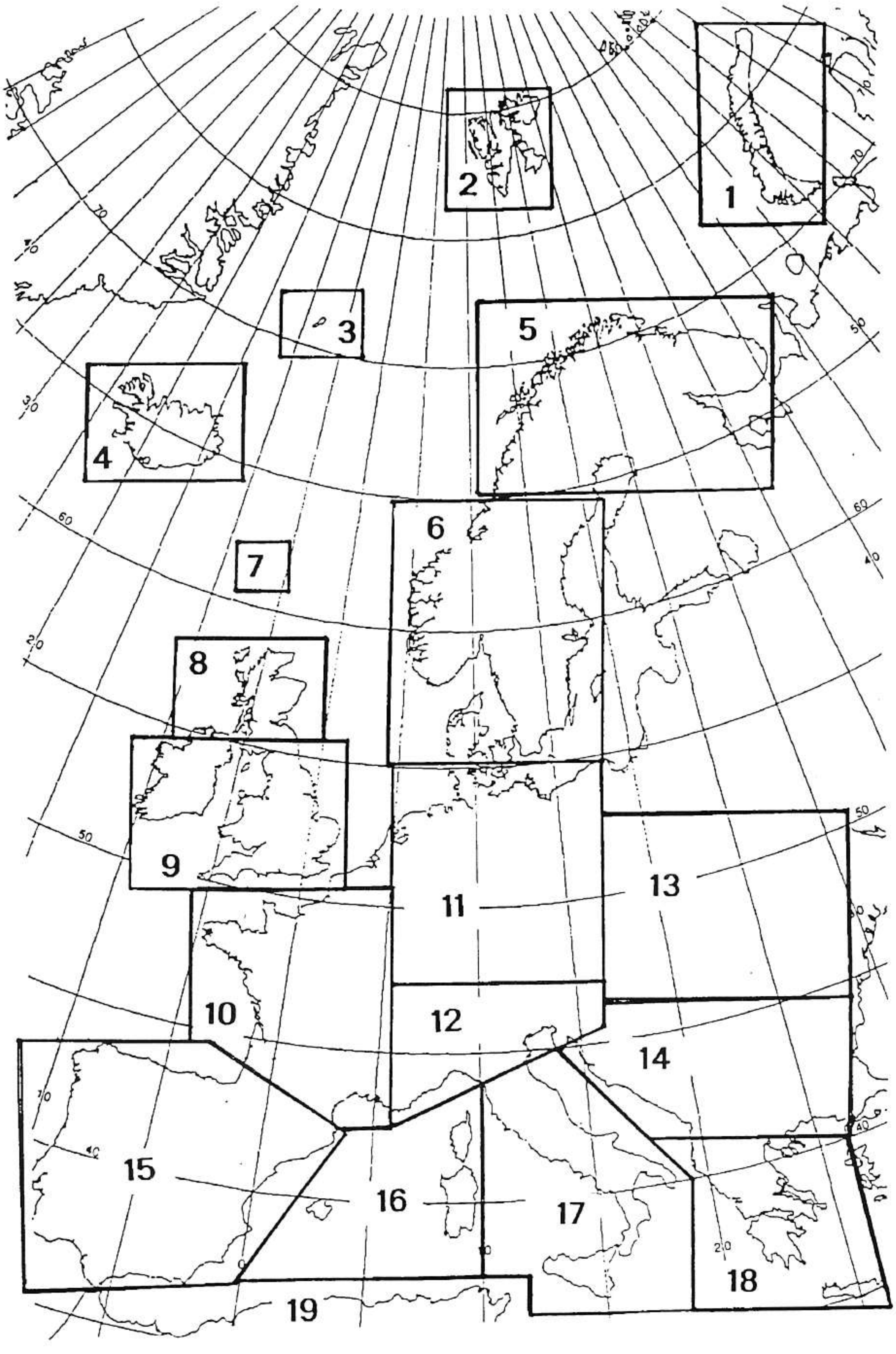

FIGURE 4. Surveyed areas of Europe.

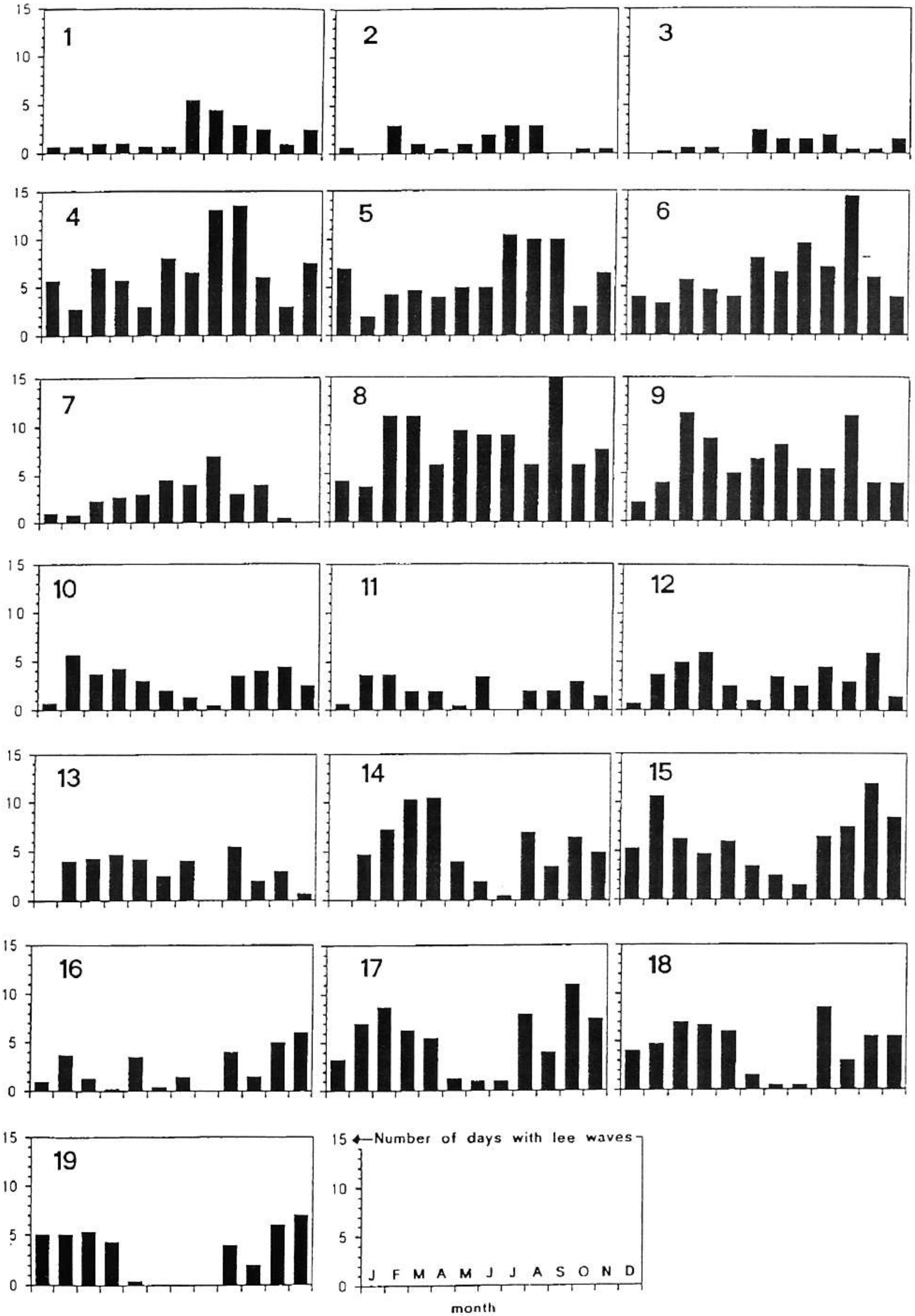

FIGURE 5. Mean monthly distribution of lee wave days derived from satellite images for the period 1995-1997 for several regions of Europe.

and Iceland, in countries around the Mediterranean Sea the number is only somewhat lower. In some of the graphs the seasonality is clearly visible. In the northernmost regions in the Arctic lee wave clouds are observed mainly in summer, whereas in the Mediterranean there is a minimum in summer and spring and autumn are preferred seasons.

Iceland and Scandinavia show a maximum number in late summer and autumn and in the UK and Ireland two maxima in spring and autumn and a minimum in January-February occur. For interpretation the following factors have to be taken into account:

a. Visible or near infrared channels are best suited for lee wave detection. In the thermal infrared channel the contrast is low due to the fact that lee wave clouds are formed in lower troposphere mainly with relative high cloud top temperatures leading to a medium grey in the images. During November to January thermal infrared images are generally used instead of shortwave channels with their illumination problems.

b. The occurence of lee waves which are visible in satellite images depends on the varying synoptic situation and circulation pattern. A longer observation period is necessary for deriving a more representative seasonal distribution. The investigation therefore will be continued.

6. Conclusions

Satellite images of 1 km spatial resolution (NOAA-AVHRR) covering whole Europe between the Arctic and Northern Africa allow continuous observation of lee wave cloud patterns. The lee wave clouds generated by mountain ranges of variable height and width all over Europe are mostly two-dimensional, isolated mountains or mountains on small islands sometimes generate three-dimensional lee wave patterns. The highest frequency of lee wave cloud formation is found over the British Isles and Scandinavia and to a slightly lesser degree over Mediterranean countries. Due to geographical position the seasonal variation shows differences.

7. References

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