

# Waves, Billows, and Wakes, as Revealed by Satellite

R.S. Scorer, Imperial College, London

Presented at the XVII. OSTIV-Congress, Paderborn, Germany, 1981

## 1. An Important Philosophical Viewpoint

The purpose of this short paper is to show that the complexity of Nature is an order of magnitude greater than the complexity of the theoretical models we use to understand its mechanisms. We are in search of new simplicities.

Within the observed behaviour there are some regularities which call for explanation. We should note that our problem is not to know the laws of Nature—the simple gas laws, the basic laws of fluid mechanics, the laws of radiative exchange: these are well known, and our failure to use them on the atmosphere with a precision matching the accuracy of the laws is due to the complexity alone. We cannot make enough measurements to act as a basis for accurate application of the laws; and even if we could have enough of such measurements we are still not capable of using them; and even if we could use them in a mega-computer the answer would be so particular to the occasion that it would be without purpose, so we might as well just wait and observe what happens, and that might even be quicker than the computation. We may nevertheless superpose in our minds several mechanisms which may be effectively analysed mathematically in isolation (For fuller treatment see Ref. 1).

We are looking for regular and recognizable features of the air motion, therefore, which can be subjected to an analysis of mechanism.

With such understanding we may hope to get to know our atmosphere better, and in the context of motorless flight, exploit and delight in its motions.

## 2. Satellite Pictures of the Wake of Jan Mayen

Satellite pictures today show a bewildering amount of detail. The infra-red indicates the relative height (coldness = whiteness) of the clouds and the relative

temperature of land and sea. Thus Fig. 1 shows a “bow-wave” produced in the clouds by the passage of the air over the narrow 55 km long island of Jan Mayen ( $71^\circ \text{ N } 8^\circ \text{ W}$ ) about 600 km north-east of Iceland, which has two peaks (see Fig. 2). Fig. 1 shows the visible image: the high cloud over the peak casts a shadow on its northerly side onto the lower layer of cloud in the midday sunshine. To the south east there appears a dark streak continuing the line of the wake edge on the starboard side. But if we look at Fig. 3 which is the simultaneous infra-red picture we see that the high (whiter) cloud casting this latter shadow is not really part of the wave pattern but is one

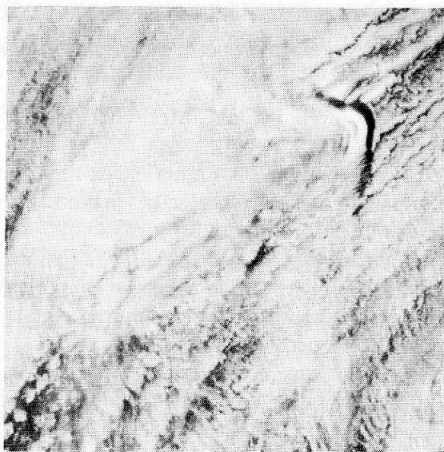


Fig. 1 Bow wave in airflow over Jan Mayen in visible light. 1338 GMT, 1st May 1979.

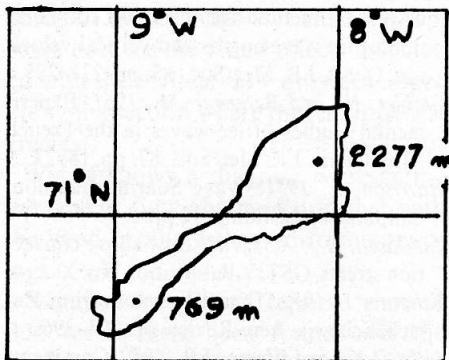


Fig. 2 Jan Mayen Island.

## Summary

A selection of satellite pictures of waves, wakes, and billows in clouds has been made to illustrate that lee waves, ship wave patterns, vortex streets and other complications can be observed simultaneously on many occasions. Trains of short lee waves can only be distinguished from long wavelength billows (dynamically unstable waves on a stable density discontinuity) by inference from the wind and topography of the occasion. Waves and convection streets sometimes occur together. Many wave trains seem to preserve their regularity over rough terrain, presumably by inducing separation of the flow from the surface.

of many streaks of high cloud in the cyclone to the east of the island.

Fig. 4 (visible) shows the wake of Jan Mayen in a rather similar situation but with the air coming more directly off the Greenland ice. Streets are well developed over the warmer sea, and a rather similar bow wave is present. There is, however, a more slowly widening wake disrupting the field of cloud streets with a vortex street down the middle.

By contrast, Fig. 5 shows some waves on the port side of the wake embedded in the cellular convection pattern, and more strikingly a single elongated clearance in the cloud downstream. Fig. 6 shows a linear clearance on the port side, a much weaker one on the starboard side, and a vortex street down the centre of the wake; while Fig. 7 shows a well developed vortex street downstream of a clearance behind the higher of the two peaks, indicating that the flow is blocked and does not pass over the peak. Yet it does pass over the lower peak, producing a pattern of seven or eight waves in its lee. The regularity of the streets generally indicates a stable layer in the air at the cloud top.

Finally, a wave pattern more similar to those seen behind many other mountains, and most justifiably called a “ship wave” pattern, is seen in Fig. 8 but it will be seen that there is a wave on the starboard side extending outwards some considerable distance at right angles to the wind. Such a wave is not included in

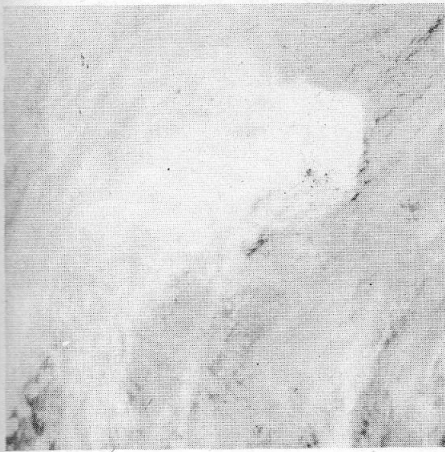


Fig. 3 The same as Fig. 1 seen in infra-red. Shadows of sunlight are not seen in the infra-red, which is an emission, not a scattered reflection.

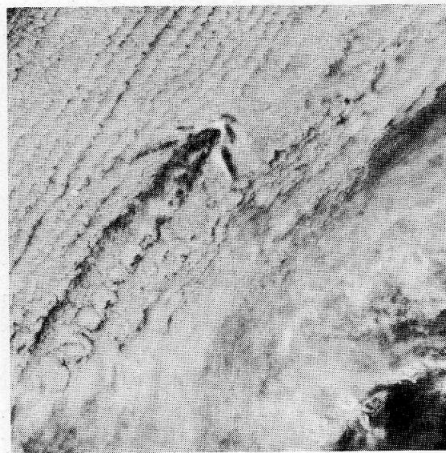


Fig. 4 The wake of Jan Mayen in visible light. 1359 GMT, 29th April 1979.

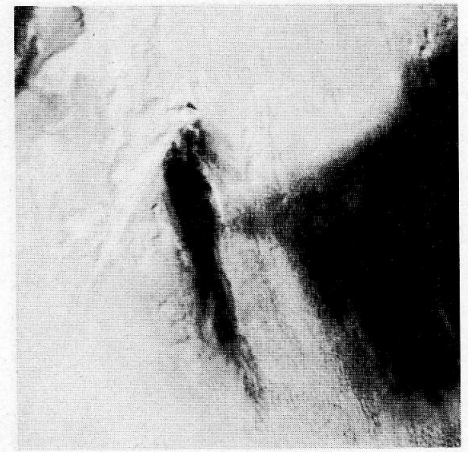


Fig. 5 Gap in cloud layer, seen in visible light, in the wake of Jan Mayen (1015 GMT, 4th July 1978).



Fig. 6 Infra-red view of the Jan Mayen wake with a stronger clearance on the port side and a feeble vortex street in the centre. A weak lee wave system is seen over the lower peak (0945 GMT, 14th November 1978).



Fig. 7 Infra-red view of a strongly developed vortex street behind the main peak and waves in the lee of the lower peak (0942 GMT, 22nd November 1978).

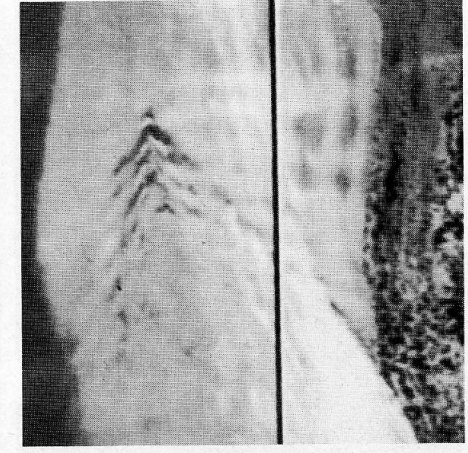


Fig. 8 Infra-red view of a Jan Mayen "ship wave" pattern that is much wider than understood by the conventional analysis of such patterns (0927 GMT, 1st September 1976, infra-red).

ordinary treatments of the ship wave pattern.

Thus we find a complexity of patterns in the simple case of Jan Mayen, where there are several simultaneous possibilities of which the basic theories and analogue experiments do not yet explain the relative magnitude.

### 3. Patterns of Trapped Wave Trains over Mountainous Land

The ship wave patterns of lee waves sometimes seen behind Jan Mayen are frequently seen elsewhere also to be set up by isolated mountains. Fig. 9 shows Ireland in a north-easterly airstream, with several overlapping such wave

trains. Particularly noticeable is the wake of Mourne mountains and another such widening pattern extends over the sea NW of the land. In this case the airstream was capable of trapped oscillations of two distinct wavelengths which can be seen existing close together, although no mountain seems to excite both wavelengths at the same time.

It appears from Figs 9-12 that the waves achieve a particular amplitude and are maintained with about the same amplitude and few changes of phase for long distances over rather variable terrain. This is surprising in the sense that all theories lead to a calculation, both for a two-dimensional ridge, and an isolated

peak, of a lee wave amplitude quite specifically related to the mountain size and shape. It may be that a mountain which would, according to theory, change the phase and amplitude of the lee waves, merely causes a separation of the flow somewhere at the surface with reattachment further downstream so that the lowest continuous streamline does not follow the ground contours. The particular amplitude which seems dominant may be determined by the fact that (in the theory) the strict periodicity of the waves is only ensured by small (infinitesimal) amplitude, but some finite amplitude periodic waves seem often to be possible. The amplitude may be very de-

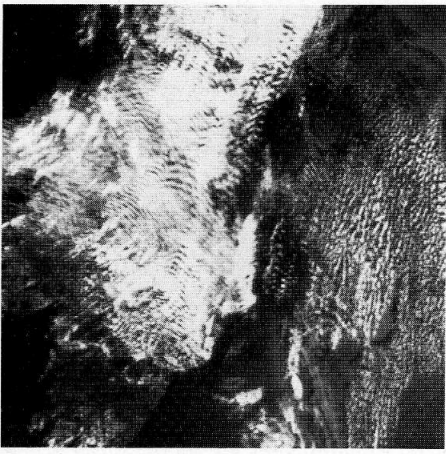


Fig. 9 Waves seen over Ireland in a north-easterly airstream (1000 GMT, 24th April 1976, visible). The ship wave pattern of the Mourne and Wicklow mountains have a shorter characteristic wavelength than the surrounding waves which could have been set up over Scotland. Of particular interest in connection with gliding is the wave train beginning in Cumbria (Coordinates marked with C on the edge of the picture, where Cross Fell and the Eden Valley produce the "Helm wind" and "Helm bars" of cloud when a deep north-easterly wind is blowing. The picture from this satellite is stretched slightly because the view direction is oblique to avoid sun-glint off the sea surface.

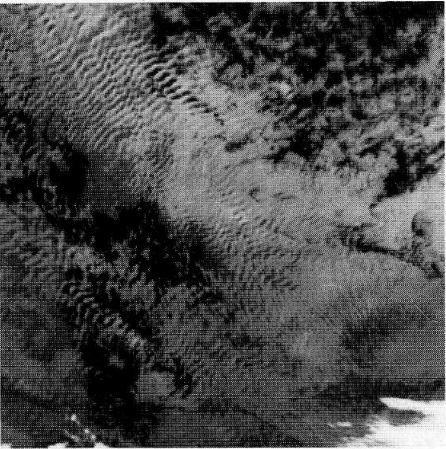


Fig. 10 Waves showing almost two-dimensional regularity over Scotland and Ireland in a north-easterly airstream. There are only small changes in amplitude and very little in phase evident in spite of the irregularity of the terrain, and the waves in the lee of Ireland extending towards South Wales have about the same amplitude over the sea as over the land (0855 GMT, 2nd December 1980, infra-red).

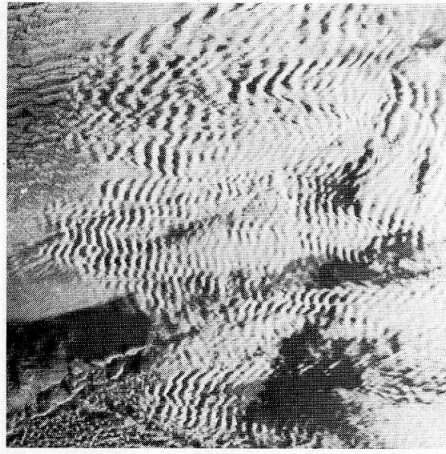


Fig. 11 Similar features are displayed in this case as in Fig. 10. The upstream edge of the land is very clearly the place where the waves begin, and the West coast of Ireland is well delineated. The waves also cover the Irish Sea. The wind increases towards the NE and so the wavelength is longer over Scotland where they are traversed by streets along the wind direction (0928 GMT, 5th December 1980, visible).

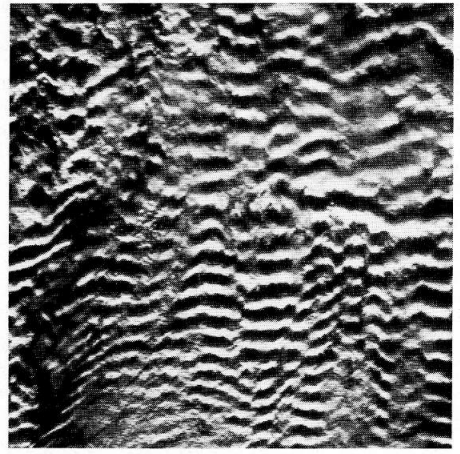


Fig. 12 An enlargement of the waves over Scotland seen in the yellow (visible) on the occasion of Fig. 10 but about two hours later, when there is still a significant change of phase over the Cairngorms, which are the highest peaks in the eastern highlands (1057 GMT, 2nd December 1980, Channel 5, yellow).

pendent not only on the airstream temperature and wind profile but also on the depths of the clouds which reduce the stability of the stratification in the wave crests. If there is a discontinuity of relative humidity in the undisturbed airstream, as there is likely to be at the top of a cloud layer, then this becomes a stable discontinuity of temperature but is reduced in magnitude at the wave crests because the presence of cloud causes the air to be warmer, when lifted, than if it were clear.

The shipwave pattern is not always dominant, and often a backbone of cloud justifies the description «fishbone» pattern applied to trapped mountain waves. This together with the refraction of wave fronts at a wind discontinuity are illustrated in Fig. 13.

On the occasion of Fig. 14 and 15 a southerly airstream becoming south westerly to the north of the British Isles decreased in strength to the east over England where the wavelength seen in the extensive sheet of low cloud was much less. In Fig. 14 we see good ship-wave patterns due to the Faroe Islands and the Outer Hebrides. Fig. 15 shows a very short wavelength over south west England.

#### 4. Billows

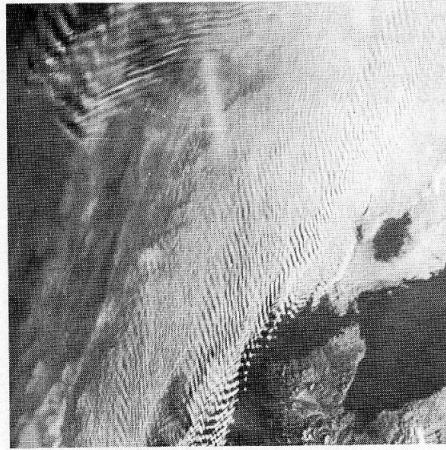
Besides occurring in waves where stable density discontinuities are tilted by the wave motion (See Scorer 1979), billows also occur on frontal surfaces where there is downslope or upslope motion of the upper layer relative to the layer beneath the front. Billows are not often visible in satellite pictures because of their much shorter wavelength. They are unstable waves, and therefore overturn completely in most cases and may or may not leave a residual pattern in a cloud layer. In the examples shown here they are nearly along the wind direction, and are normally along contours of the sloping surface and perpendicular to the direction of shear generated by the tilting of the stable layer. In plate XI they may be on the frontal surface revealed at a lower level by the "refraction" of the lee waves. Fig. 16 and 17 were taken on the same occasion as Fig. 11 and a large region of billows is seen to lie upstream of Ireland over the Atlantic where there is no orographic influence and no standing waves.

#### 5. Conclusion

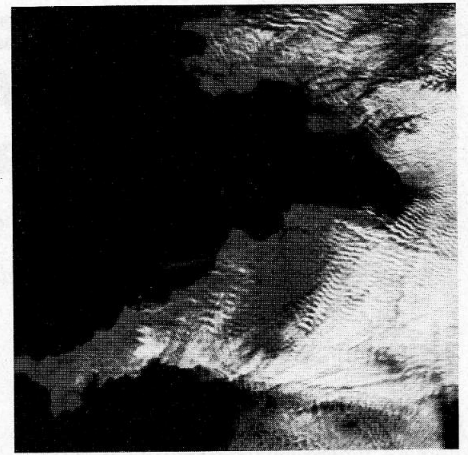
Although close inspection reveals some unexpected regularities in cloud forma-



**Fig. 13** Here we see a "fishbone" rather than a "shipwave" pattern of waves over SW Ireland. A central "backbone" is sometimes seen. Over Central and NW Ireland there are billows (see Fig. 16 and 17). (1158 GMT, 2nd January 1981, Channel 5, visible yellow).



**Fig. 14** Waves in low cloud produced by the mountains of the north western British Isles and the Faroe Islands (0923 GMT, 28th January 1981, visible).



**Fig. 15** Very short waves over South West England on the same occasion as Fig. 14 (1124 GMT, 28th January 1981, Channel 5).

tions seen by satellite we also find plenty of perplexing complications. Which simple mechanisms can combine to produce. It seems unlikely that we shall ever be able to predict these details, but their mechanisms are not entirely elusive; and having observed these phenomena we can be more perceptive in future.

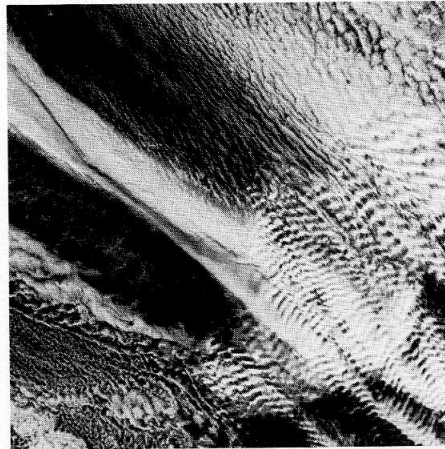
Nevertheless, we must not presume too much. Regularities in the form of streets, lines, vortices, waves and billows have been picked out from total scenes of indescribable complexity, whose beauty becomes more attractive as we probe deeper into its details.

## 6. Acknowledgement

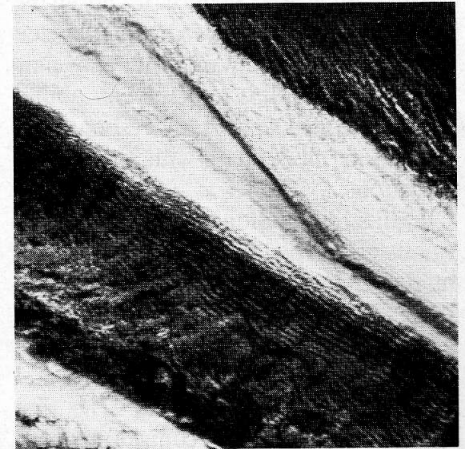
Thanks are due to the Director and staff of the Satellite Laboratory in the Department of Electrical Engineering & Electronics, in the University of Dundee, by whose permission these pictures are reproduced.

### Reference:

*R.S. Scorer, 1979, Environmental Aerodynamics, Published by Ellis Horwood (distribution outside UK by John Wiley).*



**Fig. 16** An enlargement of an area seen to the west of Ireland about 2½ hours after Fig. 11 (1152 GMT, 5th December 1980, Channel 5).



**Fig. 17** A further enlargement of part of Fig. 16 reveals an area of billows over the sea (1152 GMT, 5th December 1980, Channel 5). The dark diagonal line on the cloud street to the north of the area of billows is the shadow cast at the edge of a higher layer. The billows extend under this upper sheet, and are visible on both sides of it.

## Zusammenfassung:

Eine Reihe von Satellitenbeobachtungen von Wellen, Nachlaufströmungen und Wogen im Wolkenbild zeigt, dass in vielen Fällen Leewellen, schiffswellen-ähnliche Strömungsformen, Wirbelstrassen und andere komplizierte Strömungen gleichzeitig beobachtet werden können.

Wolkenzüge kurzweiliger Leewellen können von Wogenwolken relativ grosser Wellenlänge, die sich als dynamisch instabile Wellen zwischen stabilen Schichten mit einem Dichtesprung bilden, nur durch Beurteilung des Wind- und Topografieeinflusses in jedem Einzelfall unterschieden werden. Wellen und Wolkenstrassen treten manchmal zusammen auf. Manche Wellenzüge scheinen die Eigenschaft der Regelmässigkeit auch über rauhem Untergrund, vermutlich durch Trennung von unterer und oberer Strömung, beizubehalten.