Satellites: eyes in space

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The earth and its atmosphere are continually monitored by weather satellites. Anticyclones and depressions – previously just abstractions on weather charts – have been brought to life by satellite pictures, which have also confirmed the existence of certain assumed weather systems and atmospheric phenomena. Weather photographs have, therefore, proved of particular interest to people with a taste for meteorology.

Routine observation of the atmosphere has been made possible by weather satellites orbiting at distances of either 850 km or 36000 km. Although they monitor the earth and the atmosphere in many different ways, we will restrict ourselves here to how the earth would be seen in sun-light by a human being in space. Although it appears chaotic at first sight, closer study reveals that even the atmosphere is subject to natural laws. Certain patterns recur regularly in the weather photographs, such as curling or comma-shaped banks of cloud. The hexagonal honeycomb patterns found over the oceans are also very pretty. These are just two examples of the natural beauty to be seen every day in weather photographs. As well as being aesthetically appealing, the patterns allow better charting of the current weather situation and thus assist in the compilation of the weather forecast. We will now examine a number of patterns to determine how they arise and what they can tell the meteorologist.

Large-scale weather systems

The most familiar form of cloud bank, regularly seen on satellite photographs, is a curl, a pattern linked to the depressions (low-pressure areas) that determine mid-latitude weather for a great many days each year (figure 1). These curls can be explained by the airstreams generated around low-pressure areas. In the middle of such areas there are only small variations in air pressure, and hence little or no wind. Even during the passage of active storm depressions, the wind dies away completely as the centre of the depression passes over the observer. The highest windspeeds are found in a zone some distance from the point of lowest pressure. Beyond this wind speeds decrease again. This situation is shown in figure 2. The centres of the circles in the diagram represent the centres of the depression, in a zone of weak winds. The small circle represents zones with stronger winds, and the outer one the area so far from the centre of the depression that winds have fallen off sharply in strength. On the northern side of the depression core (top of diagram), the air is colder because it is closer to the North Pole. To the south, nearer the equator, the air is warmer. The airstream around the core thrusts the cold air southwards, around the western side (left) of the depression, since airstreams around depressions always travel anticlockwise in the northern hemisphere. Warmer air moves north past the eastern edge, ahead of the depression. The

Figure 1 Characteristic cloud formations over northern Europe, as seen from a satellite. Note the typical curls (see figure 2) (Photo KNMI.)

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EURO-ARTICLE

(See p. ii)

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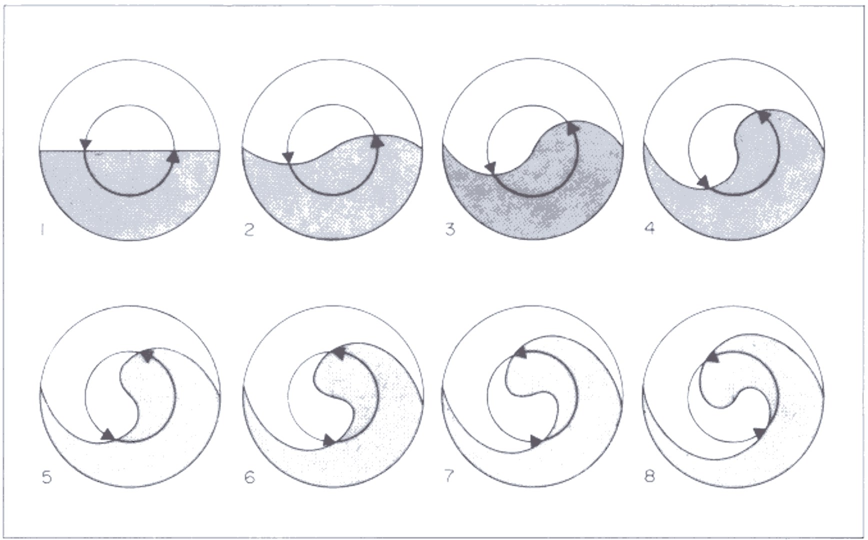

Figure 2 Schematic representation of the way in which a cloud pattern is formed round a low-pressure area.

warm air is generally moist and the cold air dry. Clouds will therefore form predominantly in the warmer air. This gives rise to the initial situation portrayed in figure 2(1): cold, dry, cloudless air to the north (top) and moist air, with thick cloud cover, to the south. The subsequent frames (2–8) show how this cloud pattern is altered by the movement of the air masses, the highest winds occurring around the small circle. Before very long, the situation becomes the one we are familiar with from satellite photographs. In older depressions, the process of curl formation has been going on for some time and the photographs will show a cloud spiral that may feature four or more loops.

The cold, dry air drawn south by the depression past its western flank has far less cloud than the warm wet air thrust northwards ahead of the depression. It is, nevertheless, not completely cloudless, given the ease with which cumulus clouds form above relatively warm ocean water or a warm area of land. Such clouds appear on photographs as white flecks on a dark background. The forward boundary of the warm air carried along by a depression is described in meteorological terms as a warm front, while its rearward boundary (where the clear patches and cumulus begin) is known as a cold front. Meteorologists always mark the fronts on weather charts. They are significant in terms of the way the weather changes shortly before and during the passage of the depression – with changes in wind speed and direction, humidity, temperature, and height and extent of cloud cover, etc. Fronts are also shown on newspaper and television weather charts, usually as lines with semicircular or triangular symbols. In satellite photographs, the fronts are not usually as obvious as in the media charts. There are, however, exceptions – as in the adjoining photograph (figure 3)

High-pressure areas

The counterpart of a depression is an anticyclone. The scale is the same, approximately 500–1000 km, but the latter are usually more welcome in that they usually, though not always, bring fine weather. What is always true is that the weather phenomena associated with anticyclones affect the lower few hundred metres of the atmosphere. Cloudless weather in anticyclones gives satel-

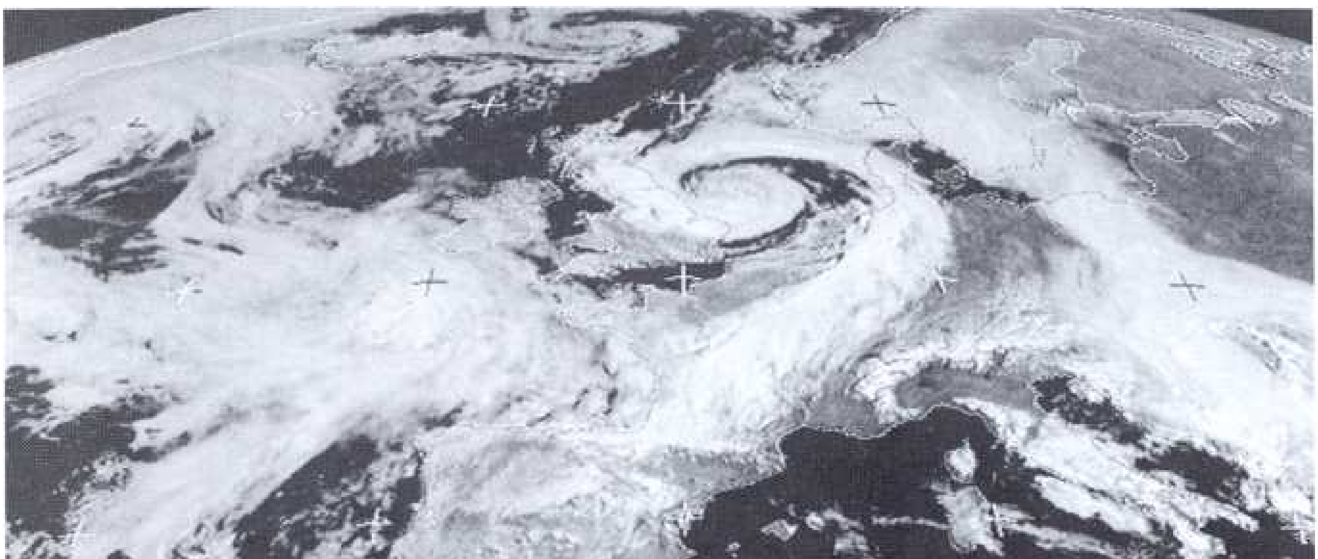

Figure 3 A low-pressure area with its centre above the North Sea. Clouds concentrate in the southeast edge, where warm air is carried northwards. (Photo EUMETSAT.)

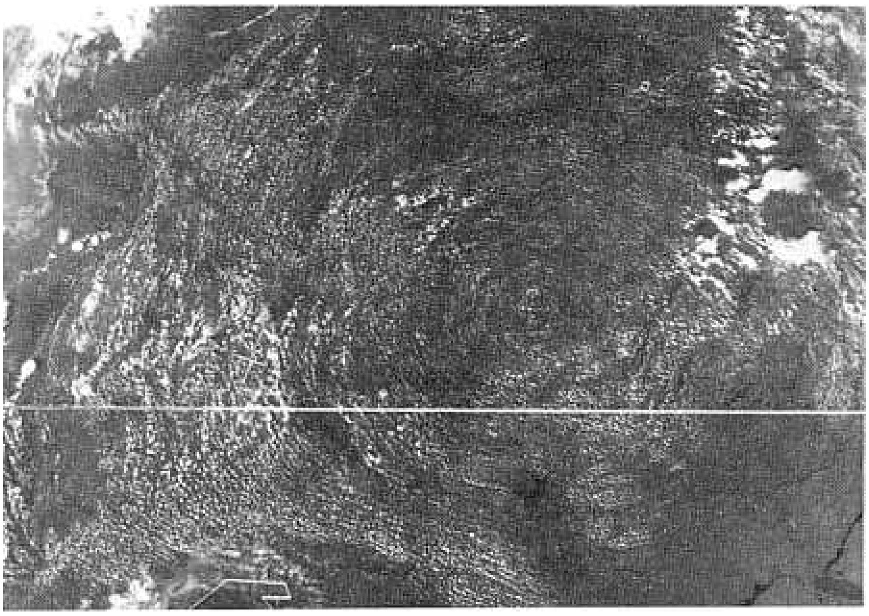

Figure 4 Exceptionally well defined anticyclone located over Russia. (Photo KNMI.)

lites an excellent view of the earth's surface, with such topographical details as mountains, coasts, and snowlines standing out on the weather photographs. If the satellite is above the sea, the water surface will appear structureless unless it is reflecting the sunlight in the direction of the satellite sensor. This kind of reflection occurs where there is a light swell. The slope of some waves will then be at exactly the proper angle to reflect the sun's rays in the direction of the satellite. With such reflections, it is often easy for the meteorologist to locate the axis of an anticyclone – where there is no wind and the sea is completely flat. The resultant absence of reflections from wave flanks therefore means that the axis of an anticyclone can sometimes be identified on weather photographs as a dark streak in a sea zone lit by reflected sunlight. Air flows around anticyclones in the same way as around depressions, but in the opposite direction; that is, clockwise. The eddy pattern around high pressure areas is usually not visible: either it is completely screened by low cloud or there is a total absence of suitable 'tracer' clouds. Views such as that in the adjoining photograph (figure 4), in which an anticyclone appears as a pancake or record shaped disc, are therefore very rare.

A third large-scale weather phenomenon is the so-called jetstream. This is an area of high windspeeds, at a height of approximately 10 km, that meanders like a river across the part of the world known as the 'mid-latitudes'. Meteorologists are interested in the jetstream because the accompanying disturbances lead with clockwork regularity to a deterioration in the weather. The northern edge of the jetstream is often marked by high cirrus, easily spotted on weather photographs.

Small-scale weather systems

Depressions, anticyclones, and the jetstream were accepted meteorological concepts before weather satellites were first launched (figure 5). Nevertheless,

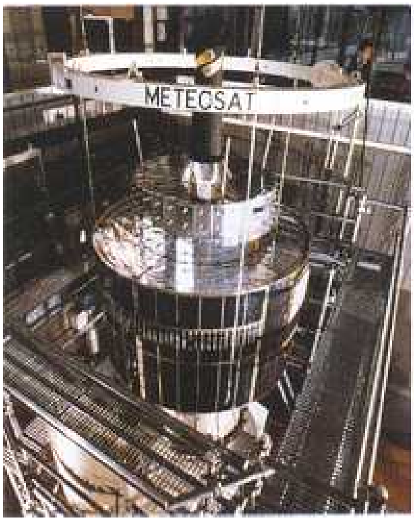

Figure 5 METEOSAT-2 being prepared for tests in the Toulouse Space Centre (France). It was launched to a geostationary orbit 36000 km above the earth on 19 June 1981. It is located approximately where the Greenwich meridian crosses the equator. Some photographs illustrating this article were taken from this satellite, others from NOAA-9 which orbits the earth at an altitude of 850 km (Photo ESA).

Figure 6 Typical satellite weather picture from TIROS-N AVHRR showing temperature variations at the sea surface, in false colour, with meteorological symbols overlaid.

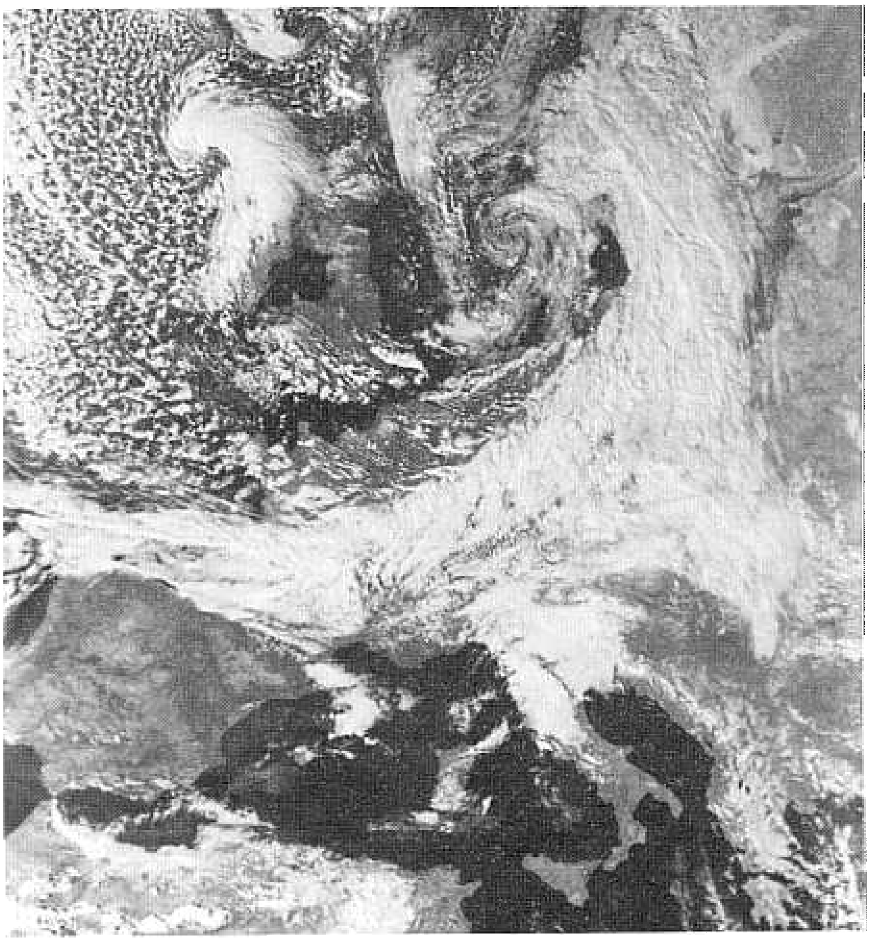

Figure 7 Clusters of showers, characteristically comma shaped, come down in succession from Scandinavia. They usually bring abundant rain, but cannot always be detected in time. The depression on the edge of which they move is above the North Sea, between Norway and The Netherlands. (Photo KNMI.)

weather photographs (available in an uninterrupted stream since April 1960) have considerably expanded our knowledge of these weather systems, and even more so in the case of small weather systems such as tropical cyclones, storm clusters in cold polar air, and polar depressions – all of which measure some hundres of kilometres in diameter.

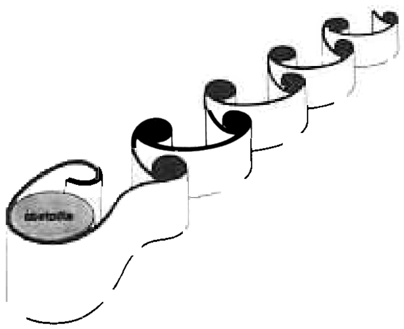

Figure 8 Schematic representation of a sequence of eddies (alternately left and right handed) forming behind an obstacle.

These 'weather sources' are much more difficult to chart using data from the meteorological observation network than their larger cousins (figure 6). Moreover, they are much more difficult to trace and to locate because they arise or move towards us over the sea. Tropical cyclones, moreover, are of unparalleled destructive potential. The earliest possible warning is, therefore, essential to permit the organization of defensive measures or, more particularly, the evacuation of the threatened area. Not surprisingly, one of the strongest political arguments for the maintenance in orbit of expensive weather satellites is the use made of weather photographs by the hurricane warning services. Tropical cyclones are generated above warm water near, but not too close to, the equator – usually between the 5th and 25th parallels. One of the prerequisites for the birth of a cyclone is a water temperature of at least 27°C in this zone. Consequently, the Atlantic hurricanes of the Carribean mostly occur in August, September, or October. Before the winds around the cyclone reach hurricane force, the hurricane warning service's meteorologist will already have observed 'suspicious' groups of clouds, and will continue to monitor them closely. He/she will check whether an 'eye' is developing – a windless and cloudless central zone surrounded by cumulus cloud. On a satellite photograph, the eye appears as a dark patch in the white cloud cluster – provided the viewing angle is not too flat. Satellite photographs alone are insufficient to determine whether it is a 'real' cyclone, since proof of the requisite hurricane force winds (120 km/hour or over) can be supplied only by those ground anemometers still intact. At sea, hurricanes are a threat to shipping. Usually they drift in easterly winds towards the west, and North America, where they can cause major damage through high winds, rain and tidal surges. The tracks of individual hurricanes are very erratic and it is, therefore, very difficult to predict where they will strike. The high winds of tropical storms are actually most intense out at sea where there are sufficient supplies of the warm wet air that 'powers' the cyclone and there is less friction between the air and the earth's surface than above land. Friction reduces the windspeed and alters its direction enough to let more air flow into the core of the cyclone. The tropical depression then fills up, with an inevitable fall in windspeed.

Less frightening than the tropical cyclones formed in warm air, but still quite capable of thoroughly ruining a favourable forecast, are the squall lines formed in polar air. Virtually every major depression is accompanied by one or more marginal comma-shaped disturbances with gusty winds (figure 7). Off the coast of Norway, so-called polar disturbances are sometimes formed in northerly airflows over the North Sea. Although the air pressure at the centre of such depressions is only marginally lower than in the surrounding area, very stormy weather is encountered. Given that during winter these involve very much colder episodes, and hence usually produce very heavy snowfalls, a meteorologist can scarcely afford to miss such a polar disturbance. There is usually little or no indication on a weather chart that such a disturbance has formed but weather satellites have increased the likelihood of detecting one in time to be useful.

Other patterns

The patterns so far discussed are all associated with small-scale or large-scale weather systems, but satellite photographs also reveal a number of other patterns that provide meteorologist with clues to the wind direction, and thus to the dominant airflows. Sometimes, these patterns lie parallel to the wind direction but in other cases they may in fact be at right-angles. An example of the first type occurs where cold polar air flows out

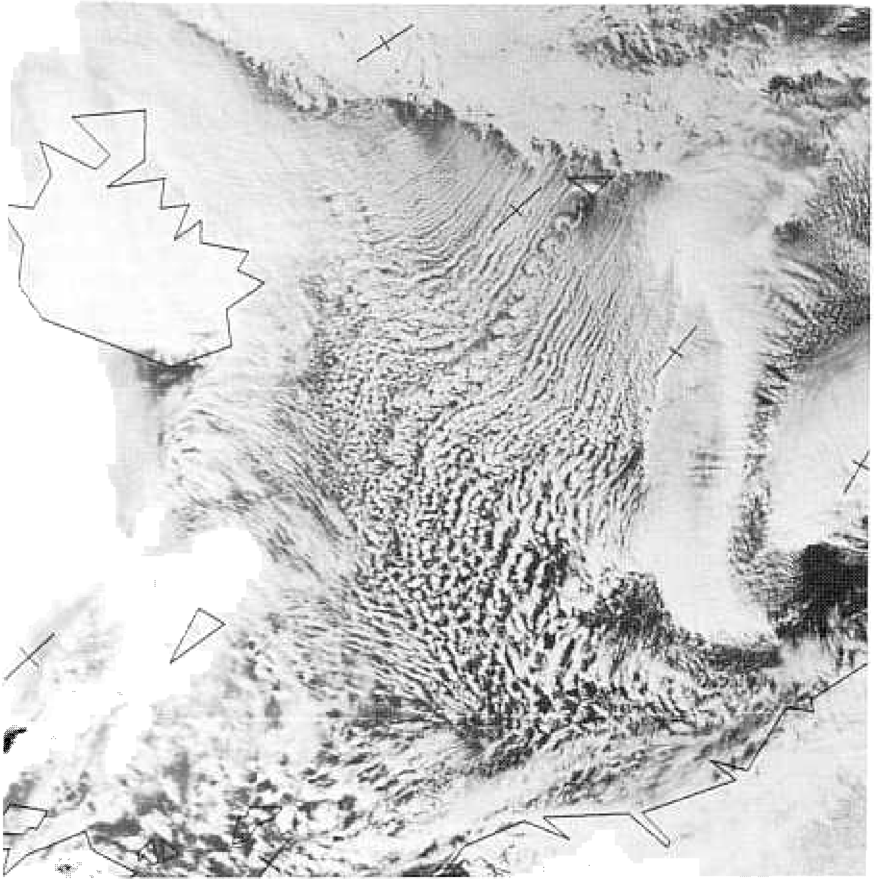

Figure 9 Example of von Karman wave. The high ground of Jan Mayen Island, between Iceland and the North Cape (indicated by black triangle) is the cause. The long-stretched bank of clouds originates from south of the Greenland ice masses. (Photo KNMI.)

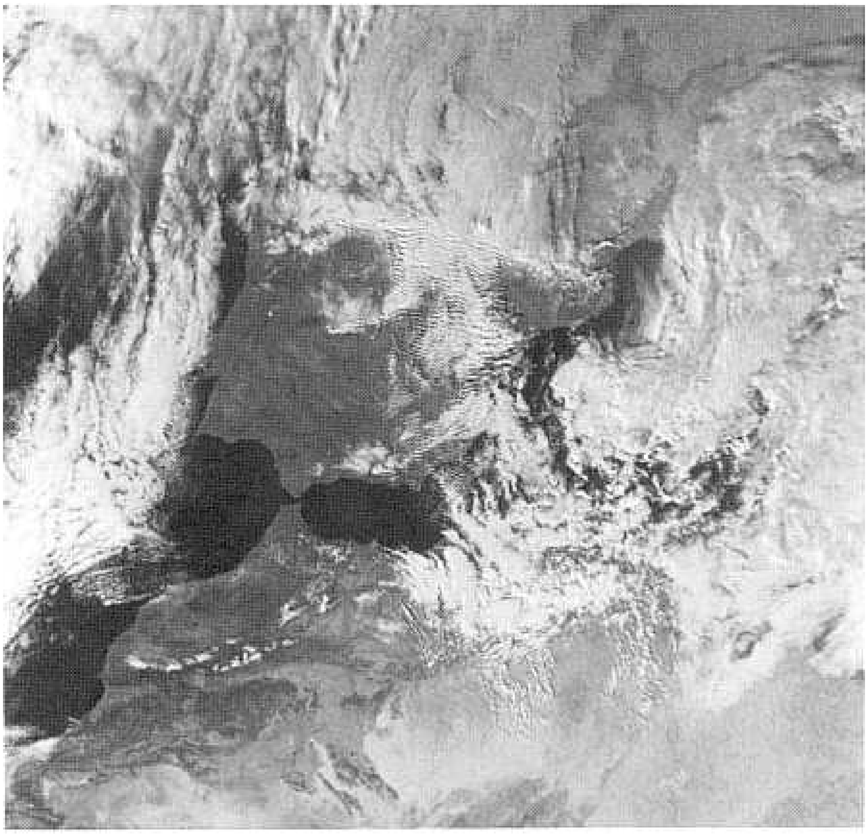

Figure 10 Cloud pattern generated by mountains (Pyrenees), lying at right angles to local airflow. (Photo KNMI.)

over relatively warm seawater. Within a short distance of the coast – or of the pack-ice boundary – a very attractive pattern of so-called 'convective cloud lines' or 'cloud streets' often forms. A cloud street is a long row of discrete cumulus clouds rather like beads on a necklace. Cumulus clouds usually form on the leeward side of a heat source (such as a city, a warm lake, or a forest fire), or in response to relief (hills and mountains). Cloud streets, by contrast, are generated by uniform warming from below and are in no way orographic in origin. Indeed, any variation in topogaphy will merely disrupt the pattern (see photograph). For this reason, cloud streets are predominantly encountered above the sea. Typically, they reach lengths of 20–500 km, the axes lying 5–10 km apart. The cloud is found in a layer bounded, at a height of 1.5–3 km, by a so-called inversion (transition to a warmer layer of air). The distance between cloud streets is usually two to three times the thickness of the lowest layer. Moreover, this layer becomes thicker with increasing distance from land. In this way, and also because of the downstream merging of cloud streets, these cloud formations are more closely spaced near land than further out to sea. The accompanying photographs clearly show that cloud streets are more finely patterned on the landward side than to seaward – where cell-shaped cloud patterns are often found.

Between the cloud streets on the photographs, we can also see a whirl-shaped disturbance created by Jan Mayen Island. This pattern, too, is parallel to the wind direction and, therefore, also provides the meteorologist with useful information. The phenomenon of eddies forming in a steady flow behind an obstacle is known from fluid mechanics. The eddies form alternately on the left and right-hand sides of the obstacle, detach themselves and are then replaced by a new eddy (figure 8). The resulting pattern comprises two almost parallel rows of eddies, the distance between the centrelines of the eddy rows matching the diameter of the obstacle. In each row, eddies follow one another at almost regular intervals and rotate in the same direction. The rotation is reversed in the other row. Such a flow pattern is known as a 'Karman vortex street', after the Hungarian physicist Theodore Von Karman who was the first to describe the phenomenon. Such eddy patterns are frequently seen on weather photographs. They form in the lee of mountainous islands in stratified cloud to the east of subtropical anticyclones. They are also found at higher latitudes, such as near Jan Mayen Island (figure 9). As with cloud trails, a Karman vortex street can occur only in the presence of a strong inversion. The island provoking the eddies must be high enough to project

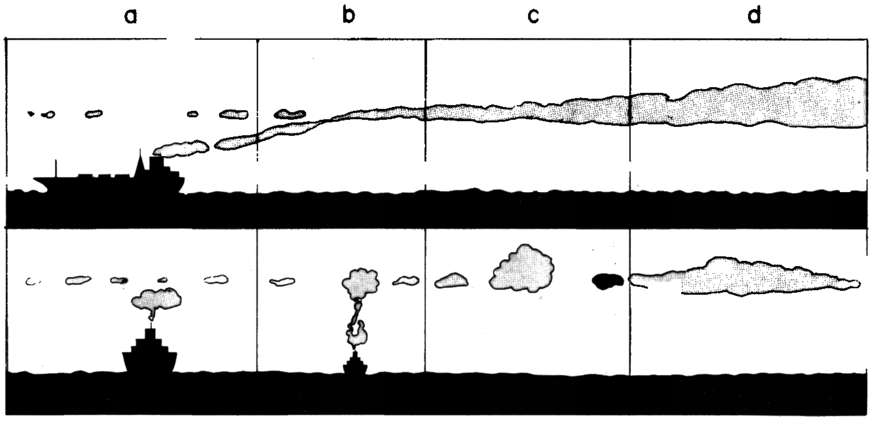

Figure 11 Clouds can be created by ships when their exhaust gases serve as nuclei for condensation in a moist bottom layer with a dry layer on top in a high pressure area. Originally the trace is very narrow but this can widen in a matter of hours. These clouds do not rise very high, as they are contained within the moist bottom layer.

through the inversion and, therefore, the effect is almost entirely restricted to islands 1500 m or more in height. Moreover, the airflow must be a steady 5-15 m/s. At lower windspeeds, eddies are not always formed, and formed eddies cannot persist in higher winds. Once formed, the eddies move along in the airflow, disappearing when they reach any area where the airflows or temperature distribution within the atmosphere, differ too much from those near the island where they formed. They can also disappear by merging with a neighbouring eddy, since two eddies from different rows rotate in opposite directions and thus cancel each other out.

Figure 10 illustrates a cloud pattern lying not parallel but at right-angles to the local airflow. This pattern is generated by mountains, which force the air

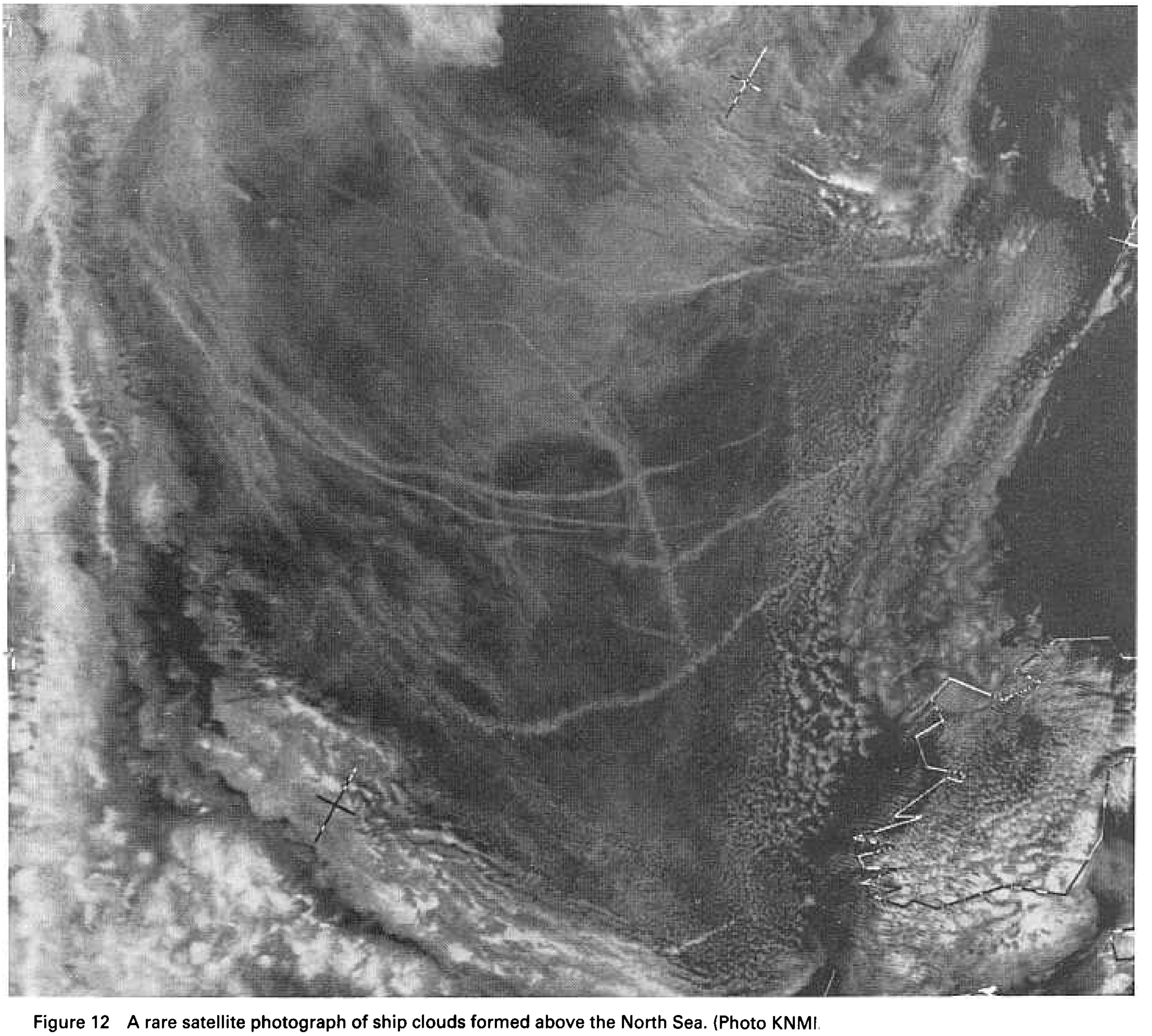

Figure 12 A rare satellite photograph of ship clouds formed above the North Sea. (Photo KNMI

first to rise and then oscillate in a wave-like pattern until it regains its definitive equilibrium. Provided the air is sufficiently humid, long lens-shaped clouds will form in the crests of the waves parallel to the mountain ridge, together forming a ripple pattern.

If the pattern detected on satellite photographs are to be used to deduce the wind direction, it is, therefore, necessary to know what kind of airflow is associated with a given cloud pattern. This is all the more important in that some cloud formations seem totally unrelated to the airflows. This is true of the well-known 'contrails' left by aircraft, and of their lesser-known counterparts generated by ships. 'Ship trails' are generally encountered near anticyclones, where the atmosphere is usually warm and dry, with the exception of a very humid lower layer within a few hundred metres of the sea (figure 11). The hot gases from the ship's funnel slowly rise to the top of the humid layer. Among the constituents of the exhaust gases from a marine engine are water vapour and so-called condensation nuclei. The latter are necessary for the formation of cloud droplets in saturated air, and hence encourage the formation of clouds. Upward expansion and thinning of the cloud trail is hampered by the stable structure of the warm air above it. When the cloud-forming process has been proceeding for some time, the ship is so far away that no further exhaust gases can reach the cloud. The cloud trail expands, becoming thicker than more recent sections and so adopting a plume shape. The accompanying photograph (figure 12) shows trails over the Atlantic Ocean, west of Ireland.

The above overview of cloud patterns observed by satellites is not exhaustive, being intended merely to provide an impression of the beautiful phenomena recorded in the photographs and of the way satellite observations can assist meteorologists in making the weather forecast. The coverage has been restricted to what would be seen by 'a human eye in space', although further computer processing of the satellite pictures has pushed the meteorological frontiers a good deal further back.

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