Notes on cloud streets as seen by satellite

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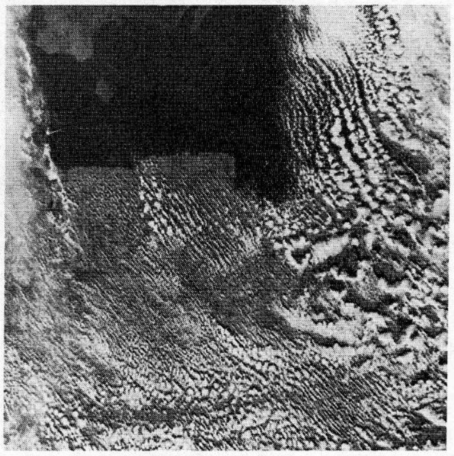
It has become possible to see cloud configurations on a scale unknown until recently. Previous investigations, particularly that by Dr V. G. Plank, were based on observations from aircraft, and could only span a few street widths. They also depended on the availability of the aircraft, and could only be conducted near to established aircraft bases, which meant that they were almost exclusively carried out over land. But with satellites it has become possible to get a good feel for the frequency of occurrence of streets in climates from the arctic to the tropics, and we can also distinguish the forms of streets typical of ocean and continental areas.

Plate I (0949 GMT, 26 October 1980) shows an inrush of cold air from Sweden, partly covered by snow into the relatively warm Baltic Sea and then across East Germany and Poland. The coldest air already forms streets over the sea close to the Lithuanian coast, behind the cold front of a cyclone over Southern Finland.

The streets contain clouds of variable size and spacing and in the east they are broken up by very large cumulus which are producing frequent showers, but even there small streets still exist. There is an area of larger cumulus near the coast where it is downwind of Bornholm and the less forested area of Skåne, but the subsidence ahead of the next frontal system which already covers Denmark damps out the convection over West Germany. The variability of the wind there reduces the forces which tend to line the cumulus in streets, namely those in the large wind shear near the ground.

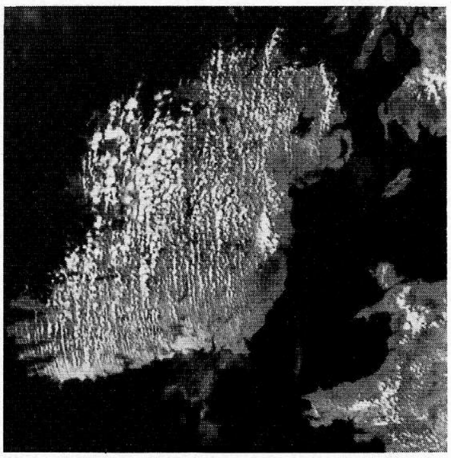
Plate II (1455 GMT, 1st June 1979) shows streets in a southerly wind over Ireland while the calm in an anticyclone over Britain locates the cumulus over the mountains only. Again we see the streets growing over the warm land into larger cumulus where the mountains aire high-

I.



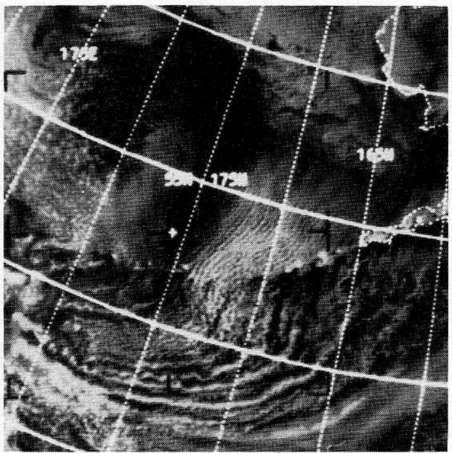
Cold air influx into central Europe behind a cold front (0949, 26 October 1980, visible): Cloud streets, with showers more prevalent in the east nearer to the centre of the cyclone over South Finland.

II.



Streets over Ireland (1455 1st June 1979, visible) in a southerly wind circulating round an anticyclone over Britain.

III.



An early picture showing (0108 8 April 1970, visible) the effect of the Aleutian Islands on the airflow from the east Bering Sea into the north Pacific.

IV.

A cloud sheet displaying a cellular structure in a NNE'ly flow off the West coast of N. Africa (1040 30 March 1977, visible). Madeira (max ht. 1961 m, crosswind width 55 km) produces a single cloud line here seen to be 1000 km in length. Of the Canary Islands, La Palma (2423 m, 20 km) and Gran Canaria (1949 m, 45 km) have vortex streets trailing downwind. Tenerife (3718 m, 70 km), which lies between them with Gomera (1487, 20 km) produces a vortex street which seems to be absorbed into that of Gran Canaria to the east and that of La Palma to the west.

er (Wicklow, S. of Dublin) and where the subsidence is less (W. Ireland).

Plate III (0108 GMT, 8 April 1970) is mainly of historical interest as an early (gridded) satellite picture showing the very long persistent streets downstream of islands. A Northerly flow across the Aleutian islands starts as small streets in the Bering Sea but to the south becomes lines extending up to 1000 km from the islands that initiate them.

Plate IV (1040 GMT, 30 March 1977) shows a long line of cloud, in this case about 600 n.m. long stretching downwind of Madeira, with vortex streets produced by La Palma and Gran Canaria in the Canary Islands. Such vortex streets were observed in this area and recorded photographically on one of the earliest Mercury flights. An inversion lies at the top of the cool air mass originating from the far north (see plate V), in which the cellular Trade Wind cloud is formed. In such cloud there is undoubtedly some wind shear near the sea surface, but at the level of the clouds there is very often a wind maximum which, having no shear, promotes the formation of cells under the subsidence inversion rather than streets.

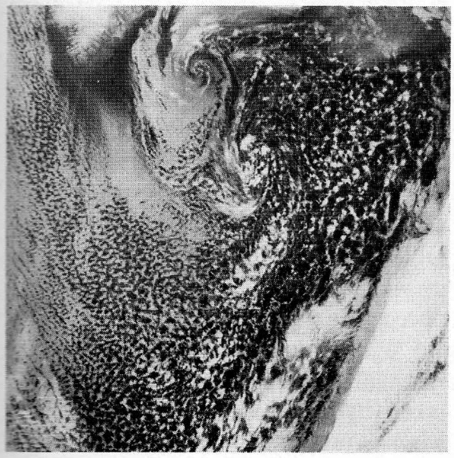
Plate V (2040 GMT, 11 February 1981) shows a typical influx of cold air from the Davis Strait into the North Atlantic behind a cold front. The clouds are lined up in streets at first but change first to individual cloud cells and then further south into empty cells ringed by cloud. In the returning cold air on the east side of the cyclone and closer behind the cold front there are large shower clouds with anvils carried to the north-north-east by the strong upper wind of the jet stream close to the front, and a mixture of large individual clouds, probably raining, with ringed empty cells in between. There is also a secondary polar air cyclone forming in a group of such storms to the south-east of the main centre, and the beginning of another beyond that. But many outflows of cold air have much more marked streets than this one.

Plate VI shows an outflow of cold air from north-east Greenland where the pack ice is breaking up and melting. It passes over the island of Jan Mayen (71N 8W) whose main peak (2277 m) reaches up above the inversion capping the arctic air and produces a vortex street similar to those shown in Plate IV. In the air above the inversion there are some «bow wave» clouds, and on the port side some lee waves can be seen in the cloud top due to the smaller peak whose top (769 m) is below the inversion.

In this case the streets are very regular and it is possible to estimate their width (w) from the satellite image. The depth (h) of the layer can be estimated from a radiosonde, so that the aspect radio (w/h) can be determined roughly. In order to get statistics to see whether the aspect is an universal constant 42 cases of cloud streets observed over the sea near the British Isles were chosen because it was easy to obtain the data. The average aspect ratio was 4.0, but there were two groups centred around the values 3.0 and 4.5.

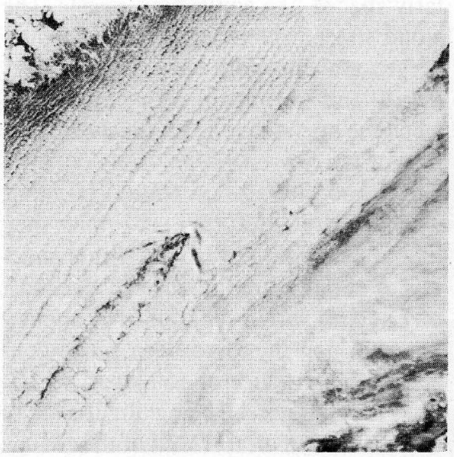
The height of the top of the stable layer ranged from 0.75 km to 2.25 km and the width from 4.15 km to 11.6 km. 12 cases were also studied when there was a cellular structure without streets and the aspect ratio varied from 8 to 33, the wider cells tending to have a wider aspect ratio. The cell width ranged from 19 to 48 km, so that cells seems to be able to occur with a much greater width than streets; or, to put it the other way round, when streets occur their width is a smaller mul-

V.



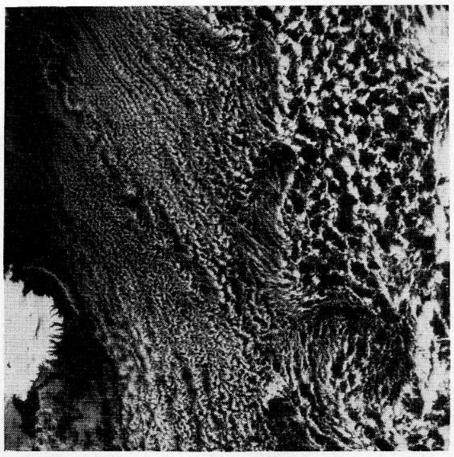
The north Atlantic (2040, 11 February 1981, infrared), from Greenland to Spain, being occupied by a rush of cold air from the Davis Strait behind a cold front stretching, in the picture, from the Azores to the Faroe Islands. The cellular structure of the convection cloud varies from streets to ringed cells and individual rainstorms. A secondary cyclone is forming in a group of rainstorms SSW of Iceland.

VI.



Air streaming from the pack ice north of Jan Mayen (71N 8W) in street formation, the street width increasing downwind (1407, 29 April 1979, visible). Over the breaking ice snow streamers can be seen. The «bow wave» of Jan Mayen is followed by a vortex street from the highest peak (2277 m) and some «shipwaves» can be seen on the port side from the lower western peak (769 m) which is below the cloud top.

VII.



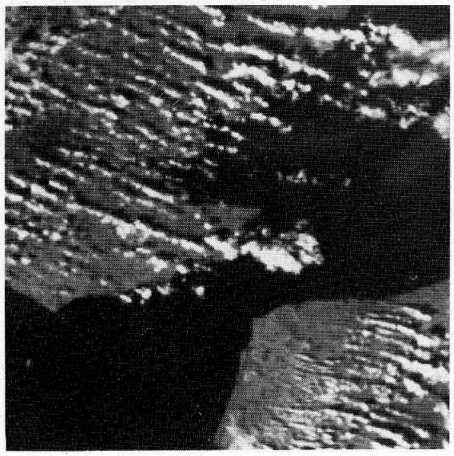
Another case (1055 27 March 1977, visible) of a vortex street produced by Jan Mayen which on this occasion (a month earlier than the case of Plate VI) lies at the edge of the ice. Streets are not so well formed and there is a much larger vortex street produced by Spitzbergen. The air coming from the east side of Spitzbergen contains much larger cells and is probably further downstream from the point of first formation of cloud.

tiple of the convection layer depth than when cells occur.

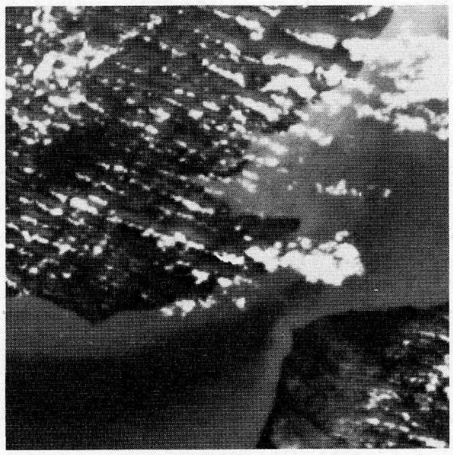
These small samples showed great variability even over the sea, where convection was rather weak, in a restricted neighbourhood. All the cases of cells without streets were in the winter of 1977–78 except one (August 1977). The streets were mainly from the same season (only 4 being from Summer 1977 and 2 from summer of 1979).

There is however a direct relationship observable in single pictures between the width and depth because the width clearly increases downwind when the air moves inland from cold sea or from frozen land on to warmer sea.

VIII.a



VIII.b



Cloud streets over land cast shadows on the ground which can be seen as dark areas in visible light (a) and as light grey areas in the infared (b) (1451 10 February 1980). At this time of day, with this orientation of streets, and with this cloud height and solar elevation the shadows fall in the space between the clouds. The infrared picture shows that the clouds (white, coldest) lie over the middle of the warmest land (black, hottest).

Plate VII shows a flow of arctic air off Greenland across Jan Mayen (1055 GMT 27 March 1977), with great variation in convection structure. On the west side of the vortex street the first clouds to appear have a ringed cell structure, but have streets on the east side. Further east is another vortex street of larger proportions produced by Spitzbergen with larger cells beyond. The vortices in the street of Jan Mayen show an effect which has been observed also in low latitudes, namely the formation of starlike cells.

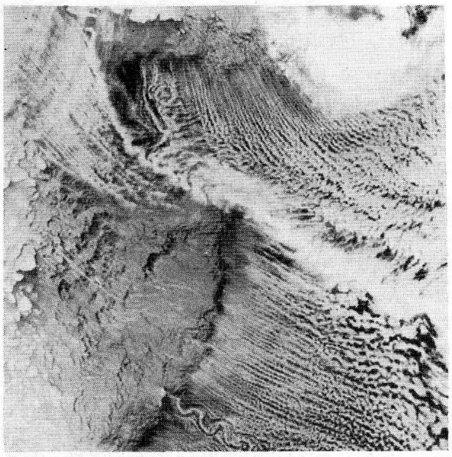
Plates VIII (a) and (b) (1451 GMT 10 February 1980) show that where the shadows lie between the streets the ground may, as a consequence, be warmest under the streets. The aspect ratio will then be influenced by the elevation of the sun, the wind direction, and the cloud base height. This cannot be an influence over the sea, but it might cause a sideways migration over land.

Plate IX (1144 GMT 17 February 1978) shows a beautiful pattern of clouds in the far north. The streamers of ice cloud over the region of ice are very long but are not usually observed to be regularly spaced like convection streets. The cloud streets which begin West of Spitzbergen grow in width but disappear over the ice and start again with small width when the open sea is again reached to the East of Jan Mayen.

It is of interest, in plate VIII, that when the streets reform over France they first appear south of Calais with a spacing of about 2 km, having left the coast of England with a separation of about 9 km at which they had been fairly constant for a distance of 150 km. This implies that the streets, being aligned along the wind, are a direct result of the change of wind with height. The convection which begins when air crosses the coast on a sunny day is accompanied by an increase in the drag, and the streets cease to be organised when the convection occupies a layer much deeper than the layer containing the wind shear.

Over the sea, because of the much slower warming rate than over the land in the middle of the day, the convection may have an un-streeted cellular pattern over a much bigger area. Furthermore, the rain showers over the sea are usually lighter and can participate in the mechanisms which shape the cells. Some ringed cells are undoubtedly due to the downdraughts in showers spreading out on the ground or sea surface and covering the centre of the cell with cooler air in which no convection cloud is produced for a time.

IX.



Cold outflow from the snow-covered ice and the Greenland plateau (1144 17 February 1978, infrared) on to warmer sea, with ice cloud streamers over the ice north of Jan Mayen. On the ice floes the whitest areas are freshly fallen snow insulated from the ice below and the very dark areas which appear rather like shadows of the ice edges are areas of exposed water which is unfrozen. The whitest clouds are the coldest and highest, and to the SE of Jan Mayen are some cirrus streamers generated over Knud Rasmussens Land (69N 29W, 3700 m) South of Scoresbysund.

We may summarise some of the main mechanisms which determine the form taken by convection when there is a wind:

(1) Wind shear, which may not occupy the whole depth of the convection layer.

(2) The presence of a stable layer, usually at a cloud top, which is uniform over a large area, setting a dimension for the spacing of the convection elements.

(3) Cloud shadows, the magnitude of the effect of depending on the relation of wind direction and sun direction, street width and sun's elevation.

(4) Rain, producing downdraughts which delay convection where they spread out on the surface. Sometimes new narrow streets appear in the downdraught air from large shower clouds.

(5) The ratio of the depth of the layer below cloud base, which has a stratification close to neutral with buoyant air rising in it, to the depth of the cloud layer, in which the cloud is unstable and the clear air between clouds is stably stratified.

(6) The motion in cloud streets is not simply a wind with longitudinal rolls superposed on it. If that were the case the layer above cloud base would be filled with a complete layer of cloud. There is probably some rather vigorous subsidence taking place which is continuously evaporating the cloud at its edges where it is diluted by mixing with clear air. This evaporation causes a stronger downdraught at the edges of the clouds than in the middle of the clear lanes between cloud streets.

Since the relative importance of these factors, and perhaps others too, may differ from occasion to occasion the resulting aspect ratio is not likely to be an universal constant but a number which may vary from case to case by a factor of 2 or 3 quite easily.

Mrs Hadithi's work shows that considerable variation occurs even in situations which were deliberately chosen to be fairly similar in many respects. The subject is one of considerable complexity and is not to be understood in the simple terms of laboratory experiments and mathematical theories of slow cellular convection in fluids of nearly uniform viscosity. There are many geographical factors peculiar to each occasion which cause variations in the phenomenon over short distances.

Bemerkungen zu Strukturen von Wolkenstrassen aus Satellitenbildern

Anhand von Wolkenstrassenaufnahmen wird gezeigt, dass jetzt auch in Satellitenbildern Feinstrukturen der Wolkenformationen in hoher Auflösung erkennbar sind. Es wird versucht, zu analysieren, welche Faktoren die Struktur von Wolkenstrassen beeinflussen, insbesondere welche Randbedingungen für das Verhältnis des Abstandes der Wolkenstrassen zur Tiefe der Konvektionsschicht massgebend sind. Als Ergebnis wird festgestellt, dass dieses Verhältnis keine universelle Konstante ist, sondern von Fall zu Fall schwankt und sich um den Faktor 2 bis 3 ändert, d. h., dass das Problem doch relativ komplex ist und nicht in einfachen Laborexperimenten und mathematischen Theorien langsamer Zellularkonvektion in Flüssigkeiten einheitlicher Viskosität dargestellt werden kann.
Viele geographische Faktoren modifizieren das Verhalten der Wolkenstrassen schon auf relativ kurze Entfernungen.

References

H. T. Al-Hadithi, M. Sc thesis, University of Dundee, 1982

V. G. Plank, Ph. D. thesis, Massachusetts Institute of Technology, 1962.

Advanced texts containing reference to the subject:

J. S. Turner, Buoyancy effects in fluids, C. U. Press, 1973.

R. S. Scorer, Environmental Aerodynamics, Ellis Horwood (& John Wiley Halstead Press) 1979.

Illustrative texts:

R. S. Scorer, Clouds of the World, David & Charles 1972, reprinted 1983.

forthcoming (1983–4)

R. S. Scorer, Clouds natural and artificial, Ellis Horwood (with emphasis on pictures obtained by satellite.)