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THE JET STREAM

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The Jet Stream

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1. Historical. For many years there has been evidence (for instance from pilot balloon ascents and drift of cirrus clouds) of the existence of occasional very strong winds in the upper troposphere. However, it was not until about 1933, that Bjerknes, who had introduced the concept of the polar front during the first world war, produced a map of geostrophic wind deduced from upper-air temperature soundings made at a few scattered stations and showed a core of strong westerly winds at about 12 kilometres in middle latitudes in winter. No further progress was made until during the second world war when a comparatively large number of upper-air stations were set up and it was found that narrow belts of very strong winds were almost always present over some part of the Earth's surface in the 30,000/40,000 ft. altitude band. In 1944–5 American bombers encountered some rather frightening winds over the Japan area and since that time some extensive investigations of jet streams have taken place.

2. Structure. The term jet stream is popularly applied to any strong upper-wind current (of say 80–90 knots) and it is safe to assume that such winds are in fact associated with a jet stream, which may be considered as a narrow tube containing very strong winds embedded in the surrounding atmosphere. In a general way the jet stream may be said to encircle the hemisphere at middle latitudes in a wavelike pattern in much the same way as the polar front, with which it has in fact a close association. Individual jet streams differ from one another in detailed structure but they have been found to conform roughly to a standard model with the following properties:

(i) The jet core is situated above a zone of strong horizontal temperature gradient.
(ii) Above the level of maximum winds (jet core) the thermal gradient is reversed.
(iii) In the region of the jet stream core there is a rapid change of the order of a few thousand feet in the height of the tropopause; it is high over the warm air mass and low over the cold air mass. The tropopause may be discontinuous, or continuous with a steep slope or it may be 'folded' over.

In connection with (i) the more intense streams are associated with well marked fronts and it is convenient (but not strictly true) to assume that the fronts extend from the surface to the level of the jet core, not as a single surface of sharp temperature discontinuity but as a zone bounded by two surfaces some fifty miles apart. In actual fact surface fronts usually become diffuse at 10,000 ft. or so and at 18,000 ft. the air is often remarkably dry. Sawyer[1] suggests that the zone of temperature change at higher levels may arise from differential subsidence of air on the 'cold' side. Analysis of flight data from B29 and B47 aircraft of Project 'Jet Stream' operating from Florida lead Endlich and McLean[2] to the concept of a 'jet front' sloping downward from the jet core towards the warm air. The 'jet front' may be considered as an upper frontal zone where strong wind shear and horizontal temperature gradients are concentrated. Detailed frontal structure associated with the jet stream is not yet fully

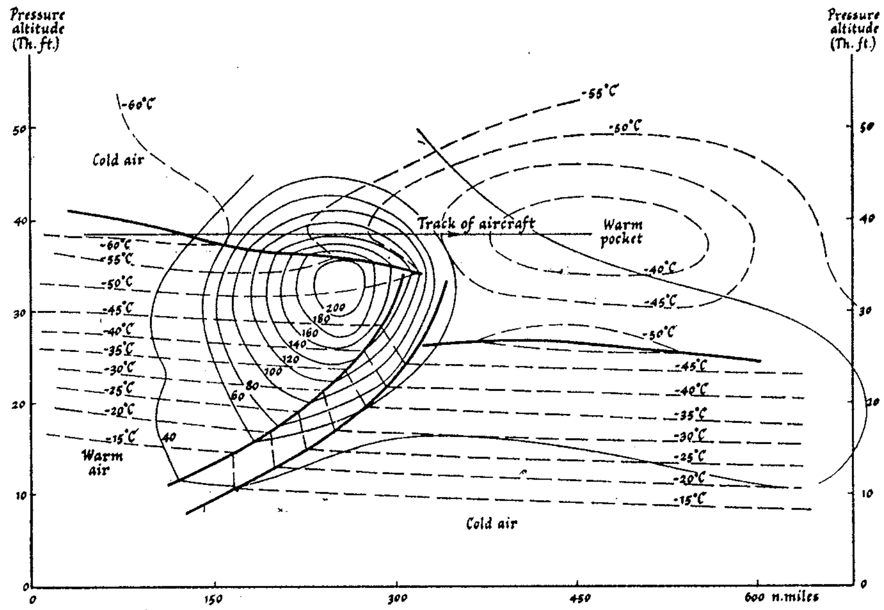

Fig. 1. Vertical section across a jet stream over the Mediterranean area on the line shown by AB in Fig. 5 at noon on 1 December 1957. The structure of the jet stream is based on the contours at 700 mb., 500 mb., 300 mb. and 200 mb. taking into account the temperature and wind ascents made at Payerne, Milan, Cagliari, Rome and Belgrade. Component of wind along 010° true. Isotachs in knots (full lines). Tropopause and frontal surfaces in heavy lines.

understood, however, and it is convenient to simplify the model by assuming a single frontal zone to exist from the surface to the jet core. The jet stream core is usually found directly above the 500 mb. position of the frontal zone and lies entirely in the warm air mass. Temperature differences across the frontal zone are frequently of the order of 10°C and in general, the greater the temperature difference the greater the wind speed.

Fig. 1 shows a cross-section of a jet stream in the Mediterranean on 1 December 1957 and comparison with a large number of other jet streams indicates that this may be considered typical of a well developed winter jet stream over NW. Europe. This jet stream is similar also to jet streams associated with the polar front in other parts of the world.

Fig. 3 shows a cross-section of a jet stream near the east coast of America at 1500 G.M.T. on 8 March 1956 and Fig. 4 shows the same jet stream six hours later. Fig. 4 has been drawn to illustrate the concept of the 'jet front' although there was only one upper-air temperature sounding (Hempstead, New York) available for that time. This jet stream illustrates the complexity of the westerlies over North America and the

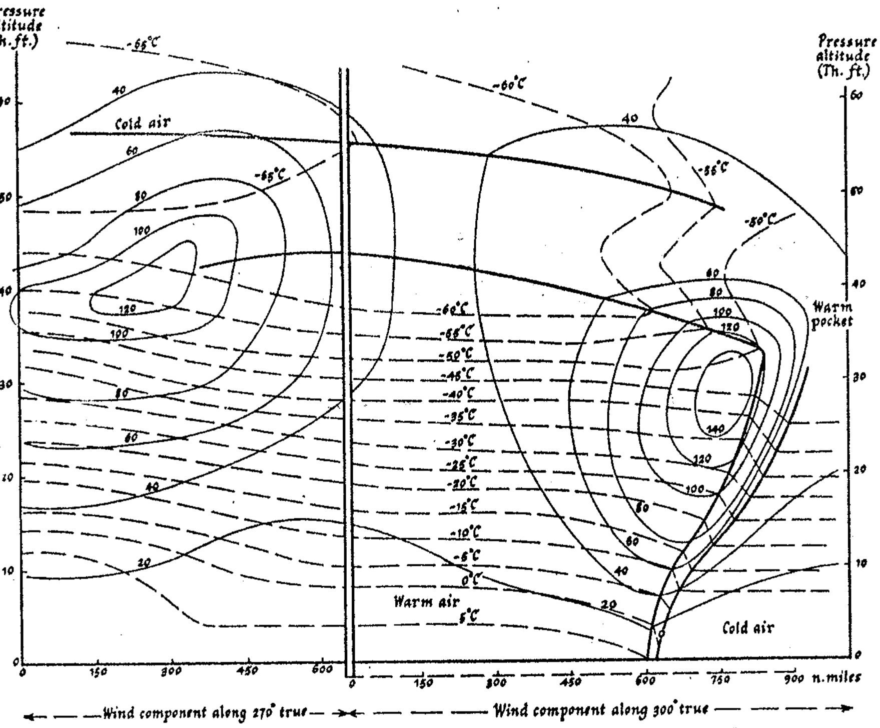

Fig. 2. Vertical section across a jet stream over the Mediterranean Sea and North Africa on the lines shown by CDE *on Fig. 5 at noon on 1 December 1957. The structure of the jet stream is based on the contours at 700 mb., 500 mb., 300 mb. and 200 mb. taking into account the temperature and wind ascents made at Tamanbasset, Aoulef, Colomb Bechar, Tripoli and Malta.*

changes which may take place during a short interval of time. It also illustrates the fact that there may be little alleviation of the wind speed over some appreciable distance to the right of the axis. This case was examined after a B.O.A.C. Stratocruiser captain had reported winds of 160 knots and upwards at 21,000 ft. on the way from Wilmington (34°N.) to New York at about 2000 G.M.T. on 8 March 1956. Heading for Idlewild from Fire Island he estimated a momentary negative ground speed and there is little doubt therefore concerning the existence of the second core along the coastline. The 'frontal' structure of this jet stream is probably much more complicated than that shown in the diagram.

It should be pointed out that the core of a jet stream is by no means circular, as may be imagined from a casual glance at the cross-section diagrams. The horizontal and vertical scales of these diagrams are vastly different. Thus in Fig. 4 WX is about 65 n.m. whereas YZ is less than 2 n.m. and the core is in the form of a narrow ribbon.

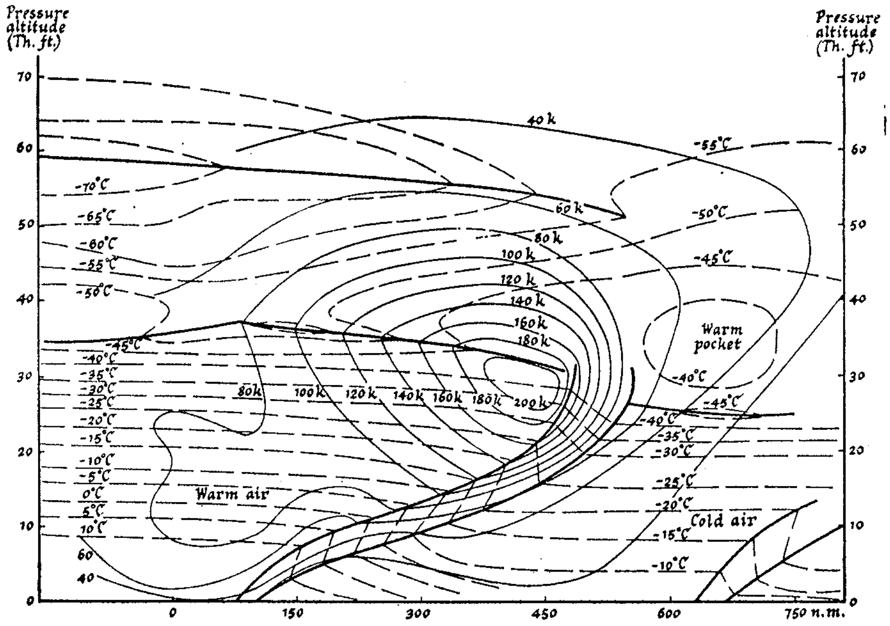

Fig. 3. Vertical section across a jet stream over North America on lines shown by F G *on Fig. 6 at 1500 G.M.T. on 8 March 1956. The structure of the jet stream is based on the contours at 700 mb., 500 mb., 300 mb. and 200 mb. taking into account the temperature and wind ascents made at Detroit, Pittsburgh, Washington, Norfolk and Hatteras.*

3. POLAR AND SUB-TROPICAL JET STREAMS. Since a kink in the tropopause is a firm feature of the jet stream, a study of tropopause height should reveal likely locations of the jet. In general, three distinct tropopauses are to be found over the hemisphere:

(1) A polar tropopause in the cold air to the north of the polar front, usually between 500 mb. and 300 mb.

(2) A sub-tropical tropopause in the warm air to the south of the polar front, usually between 200 mb. and 300 mb.

(3) A tropical tropopause usually found south of latitude 40° N. at about 100 mb. and with a temperature below − 70° C. Occasionally this tropopause may extend northwards almost as far as the polar front and may overlap the sub-tropical tropopause.

As already stated the polar jet is associated with the polar front and with tropopauses 1 and 2 and the core is usually found at about 300 mb. It is often possible to relate the position of this jet stream to the position of the surface front and provided there is a marked temperature discontinuity across the front the jet stream follows the line of the front, but it frequently flows at right angles across newly occluded fronts. It is usually 200 to 400 miles behind the surface position of cold fronts and 400 to 800 miles ahead of warm fronts, the exact position depending to some extent on the actual slope of the front.

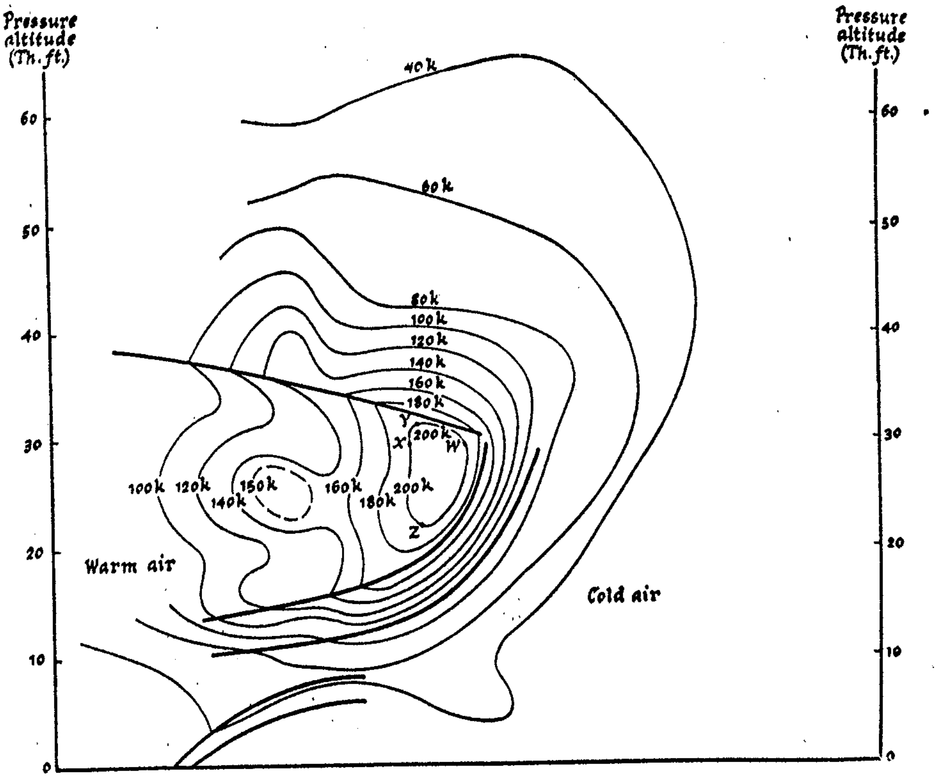

Fig. 4. Vertical section across a jet stream over North America on same line as Fig. 3 but at 2100 G.M.T. on 8 March 1956. The structure of the jet stream is based on the contours at 700 mb., 500 mb., 300 mb. and 200 mb. taking into account the temperature and wind ascents made at Detroit, Buffalo, Pittsburgh, Albany, Philadelphia, Hempstead, Norfolk and Hatteras.

Between the tropopauses 2 and 3 it is usual to find another jet stream which may be referred to as the sub-tropical jet stream with the core at about 200 mb. or a little higher. The zone of strong horizontal temperature gradient necessary for the jet usually is not associated with a front and is often confined to the higher troposphere, there being no evidence generally of its existence at 20/25,000 ft. or below.

On individual occasions the jet stream may take up many and varied positions and orientations, and it is possible to elaborate and classify them into finer detail.[3] There may be, for example, two or three jet streams at different latitudes sometimes emerging like 'fingers' from a single jet upstream, possibly reuniting downstream and each one in a variable state of development. It is rarely possible to trace a single jet stream completely round the hemisphere, however, and at any particular time a number of jets may be identified with well defined entrance and exit regions.

For simplicity, the term 'polar jet stream' will be applied broadly to include all jet streams associated with surface fronts. The sub-tropical jet

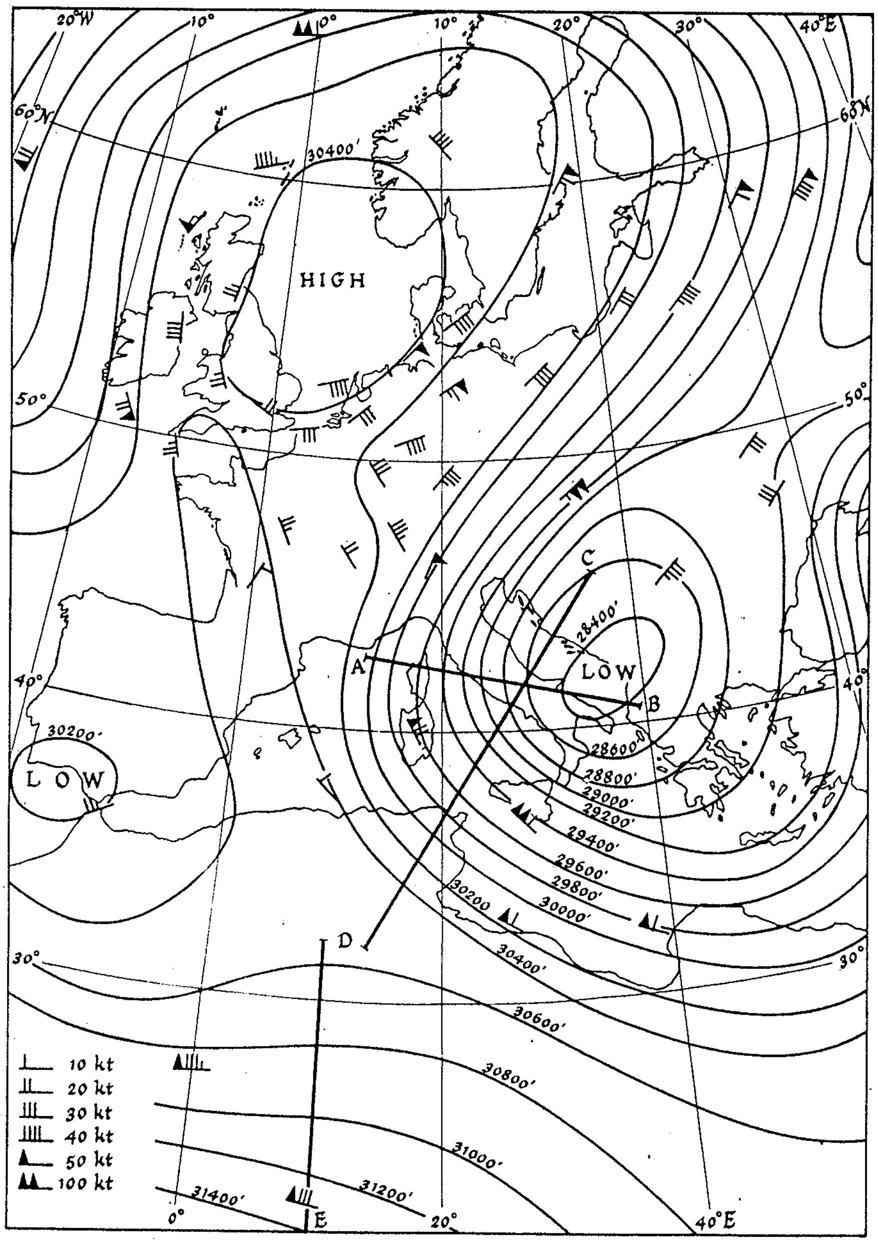

Fig. 5. Contour chart at 300 mb. at noon on 1 December 1957.

stream is considered to be a separate entity, at times encircling the hemisphere in winter, although there is evidence that it may combine with the polar jet, particularly over Africa and Asia, and the sub-tropical tropopause then disappears.

Figs. 5 and 6 show the surface and 300-mb. charts associated with the jet streams shown in Figs. 1 and 3. Fig. 2 gives a cross-section of the same

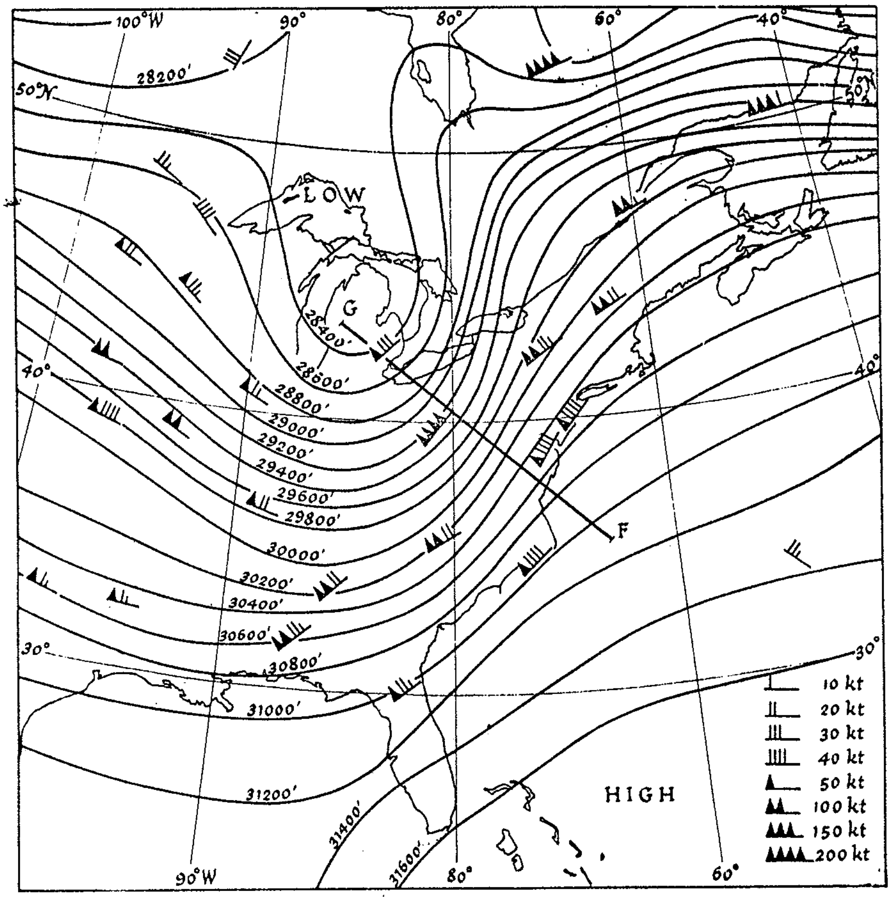

Fig. 6. Contour chart at 300 mb. at 1500 G.M.T. on 8 March 1956.

jet stream as shown in Fig. 1 but some 400 miles further downstream. The sub-tropical jet stream is also clearly shown at a distance of some 800 miles south of the polar jet. The section shown in Fig. 1 is made on the AB of Fig. 5, that shown in Fig. 2 on the lines CD and DE; the section shown in Fig. 3 is made on the line FG of Fig. 6. The cross-sections of the polar jet in the Mediterranean indicate the weakening and slight lowering of the jet core downstream and this appears to be characteristic of the polar jet. On this occasion a 'blocking' situation was present over the North Sea with an anticyclone extending from the

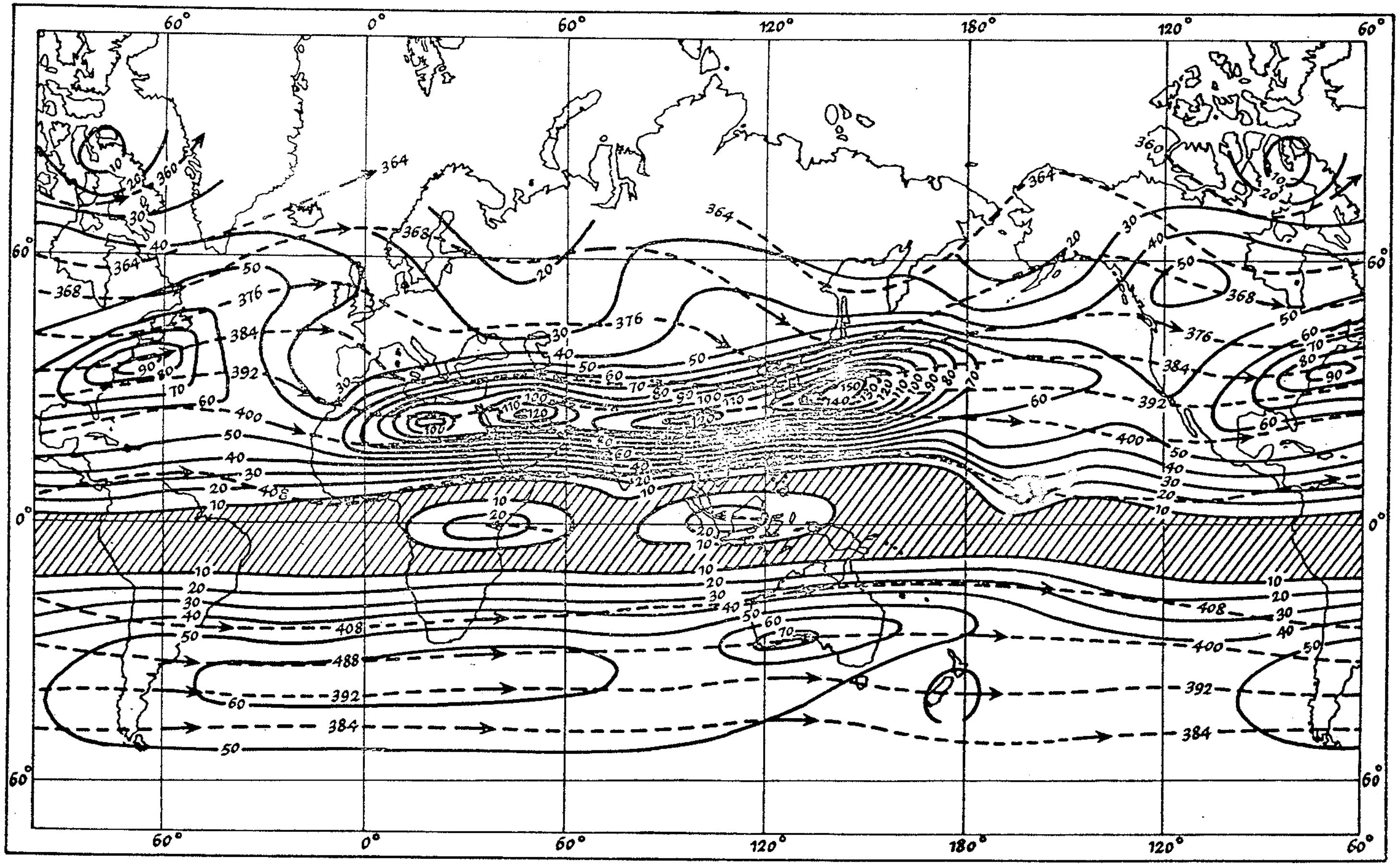

Fig. 7. The average wind speed and direction for the 200-mb. level for January.

surface to high levels causing north–south flow instead of the more usual west–east. Blocks of this type are not infrequent in eastern areas of the Atlantic and Pacific and the resulting jet streams are often intense.

4. MEAN POSITION OF JET STREAMS. Figs. 7 and 8 give the speed and direction of the average wind at 200 mb. (38,600 ft. pressure altitude) in January and July respectively. It will be seen that the average wind has maximum values over certain areas of the world with the absolute maximum in the Western Pacific in January just off the coast of Japan. It should be borne in mind that a chart depicting average winds does not indicate a typical situation except in regions where the winds show comparatively little change from day to day. Thus the average wind does not indicate a jet stream in the region of the British Isles although there are few days in winter without a jet stream somewhere in this region. The reason is that in this area the jet stream varies in direction and speed and at any given location there may be periods of strong winds followed by periods of light winds so that the average wind is comparatively light. Jet streams may occur in almost any latitude but are comparatively rare within the tropics (say 20° N. to 20° S.) whilst at higher latitudes they oscillate and recurve within wide limits.

5. GEOGRAPHICAL CHARACTERISTICS. *North Atlantic Area.* A mean upper-air trough over eastern North America, probably resulting from the effect of the Rockies on the westerly flow, causes the polar jet to reach southwards in that area to a mean winter position of about 40° N. This jet stream usually proceeds north-eastwards across the Atlantic and weakens, but often splits into two branches and its future course varies within wide limits depending on the synoptic situation. It is usually oriented between SSW. and NNW. but can occur from almost any direction, even easterly. Core height averages about 32,000 ft. but varies within the range 25/40,000 ft. whilst wind speed in the core occasionally reaches 250 knots over eastern North America and 200 knots over NW. Europe. The maximum wind recorded by an upper-air station over the United Kingdom was at Stornoway on 21 December 1954: 319° 204 knots at 307 mb. but speeds in the range 250–300 knots have been recorded over North America.

The sub-tropical jet stream is usually quite separate at about the latitude of Miami and on occasions no doubt extends eastwards to connect with the jet across Africa.

In spring the jet streams begin to move northwards and the sub-tropical jet stream often combines with the polar jet to form one broad stream. The jet continues to move north and weakens considerably in the summer and does not usually intensify significantly until late autumn. With outbreaks of cold air from the north, however, wind speeds up to 150 knots may occur in summer.

Africa and Southern Asia. The sub-tropical jet stream is a regular winter feature across Africa at about latitude 26° N. It usually moves slightly to the north across Arabia to the Persian Gulf and is then constrained along

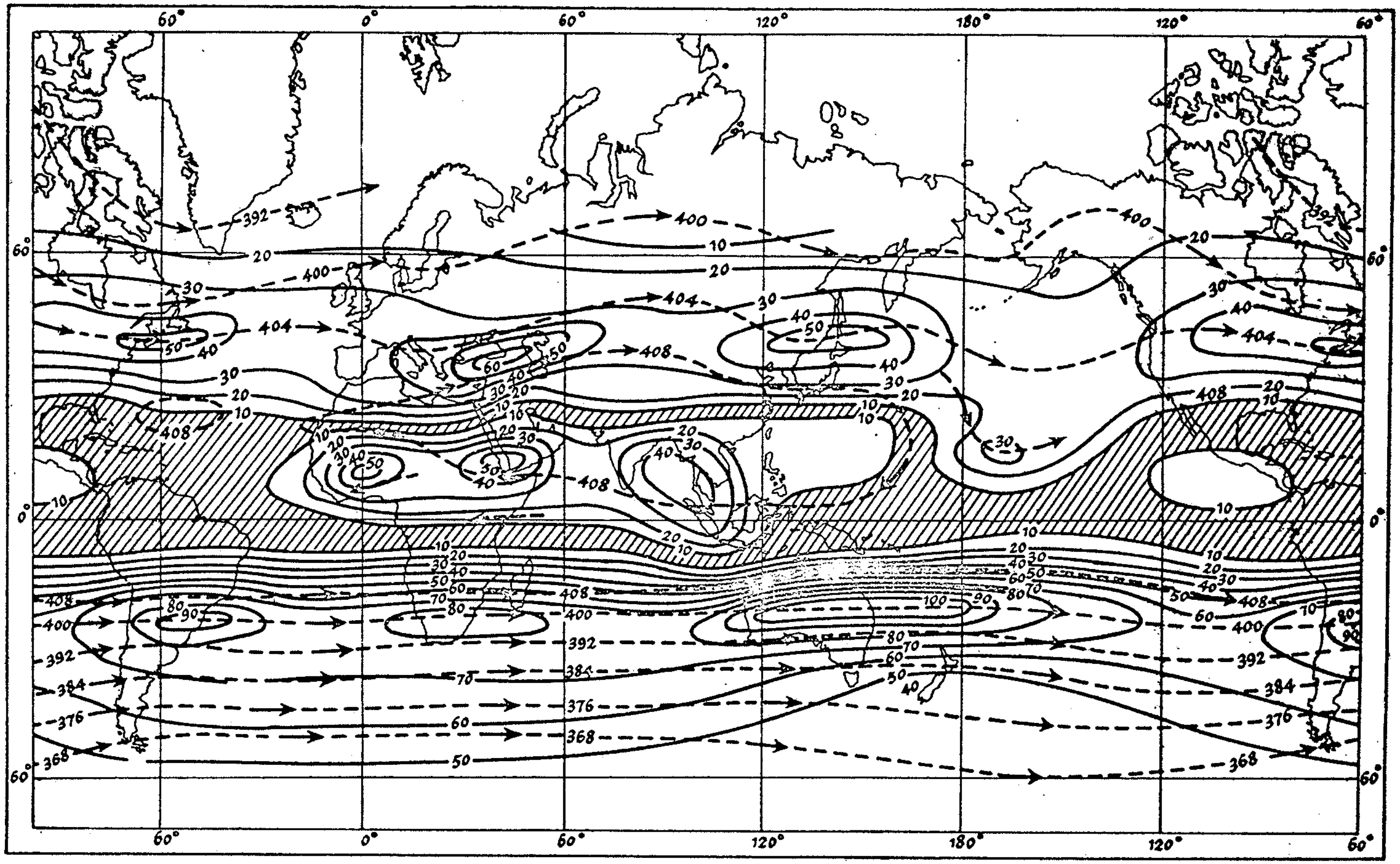

Fig. 8. The average wind speed and direction for the 200-mb. level for July.

the southern boundary of the Himalayas where it shows little movement from day to day and gradually moves south and intensifies during the season and may reach as far south as 20° N. in February. From India it moves south across southern China to the Pacific where it is often reinforced by the polar jet. The core height is usually at about 40,000 ft. and the mean speed at core level during winter is of the order of 100 knots, occasionally reaching 150 knots. Confluence with the polar jet over northern Africa and the eastern Mediterranean, however, may produce a wind speed of about 200 knots. In general there is a persistent broad stream of strong westerlies over the Middle East region in winter and winds exceeding 100 knots are often found in a belt of 700-800 miles or more in width. Harding[4] has shown that the jet stream usually has a core width of 200 miles at about 40,000 ft. within which wind speed variations are negligible. The jet stream begins to weaken and to move north during the spring whilst in summer the mean position of the sub-tropical jet stream is at about the latitude of Cyprus. Over India the jet stream shifts north of the Himalayas just before the onset of the SW monsoon (May) and returns soon after the withdrawal of the monsoon (October). The strong westerly jet streams, however, are usually found only from December to March

Japan. The strongest mean winds in the world are found near the Japanese Islands at a height of about 40,000 ft. in winter. They result from a reunification of the westerlies, split upstream by the Himalayas. Individual jet streams also reach their greatest intensity in this area and the necessary extreme thermal gradients arise from the juxtaposition of very cold air from Siberia and warm air over the western Pacific. The relatively high temperature of the warm air is probably due to dynamical heating of the westerlies during descent over the Tibetan plateau. The sub-tropical jet stream shows little day-to-day variation near Japan in winter and is usually found at about 34° N. The wind direction is almost invariably between 240° and 290° and the speed averages about 160 knots in the core. This jet stream is frequently reinforced by a polar jet moving from the north and wind speeds of 250 to 300 knots or more may occur at core level. The maximum speed recorded in the area was on 8 February 1953 at Shionomisaki, approximately the midpoint on the international air route Tokyo–Kagoshima, when the wind observation at 33,000 ft. was given as 260° 363 knots. This observation prompted a Comet captain scheduled for Okinawa to remain on the ground at Tokyo whilst an Argonaut nonchalantly departed on schedule. It has been found subsequently that a correction for the Earth's curvature reduces this wind speed to about 310 knots and it is not expected that winds greatly in excess of 350 knots will be found anywhere in the world in the upper troposphere. As a matter of interest the Comet referred to above departed from Tokyo after a 12-hour delay and found a wind of 340 knots at about 36,000 ft. during the early part of the cruise. This is probably the strongest wind ever encountered by a transport aircraft.

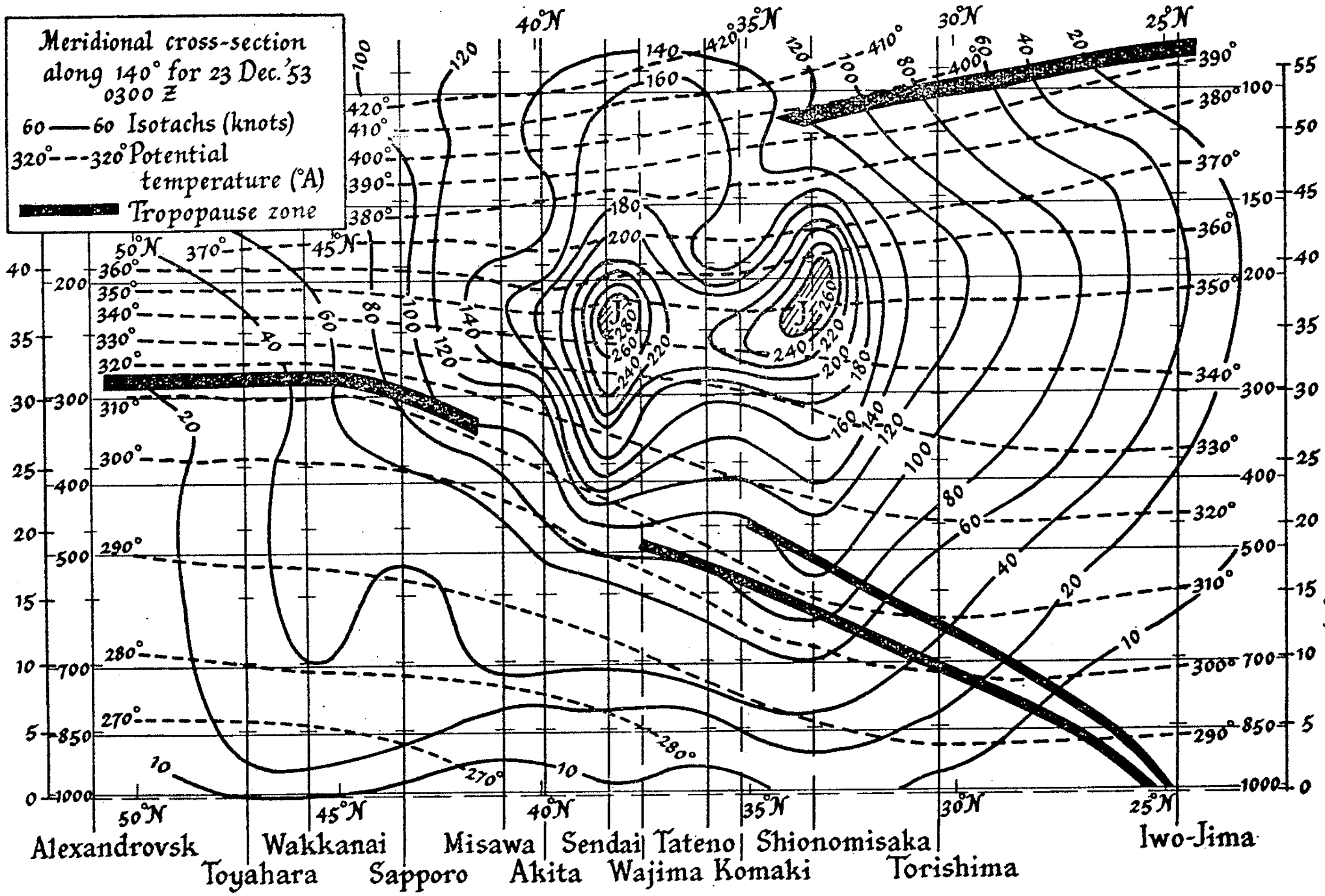

Fig. 9. Meridional cross section through the jet stream 0300 on 23 December 1953.

Fig. 9 is a north–south cross-section through the jet stream at 0300 G.M.T. 23 December 1953 and shows the polar jet and the sub-tropical jet both intense and separated by only 5° of latitude. As shown in Fig. 10

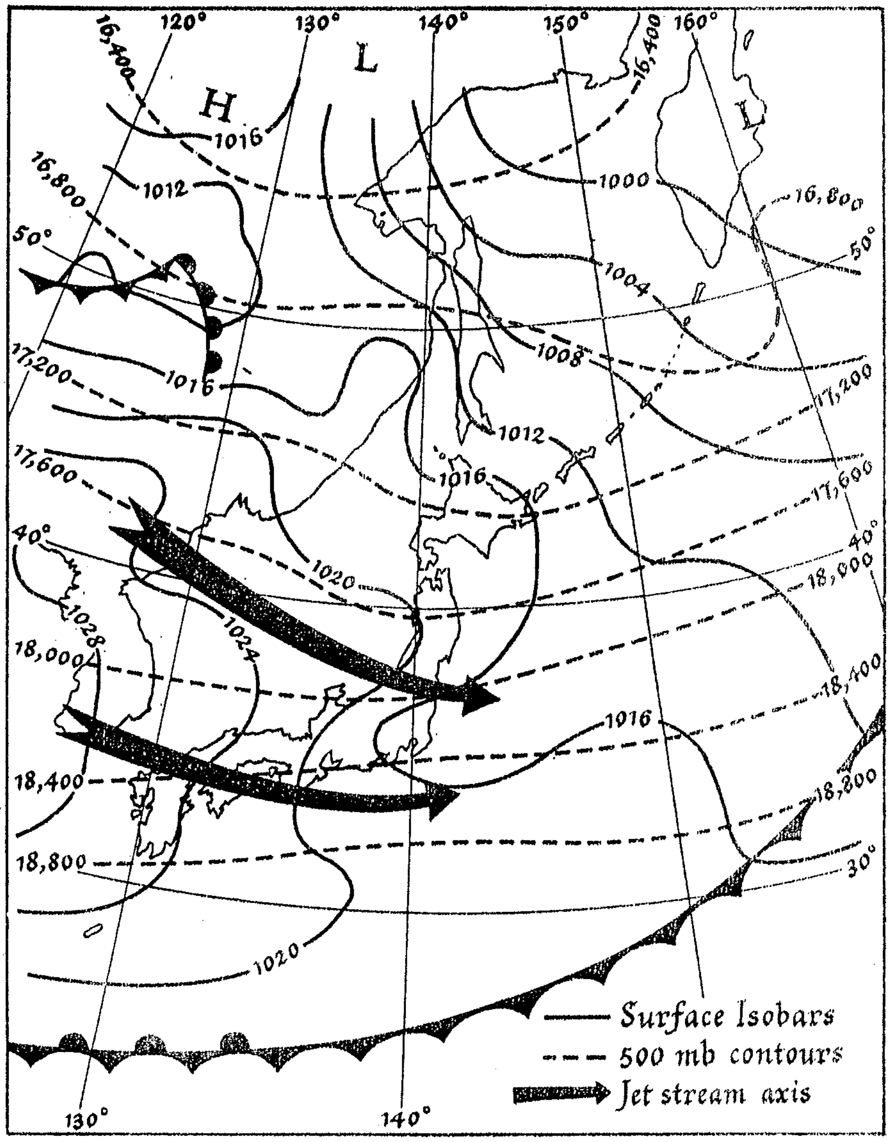

Fig. 10. Surface and 500-mb. synoptic situation for 0300, 23 December 1953.

the jet stream was associated with a well marked cold front which had crossed the south coast of the Pacific some 24 hours previously. It will be seen that there are certain similarities between this jet stream and the North American jet stream shown in Fig. 4. The strong wind speed near

34° N. and the variation with time are shown in Fig. 11 which is a time height cross-section for the last sixteen days of December 1953 at Shionomisaki. At 40,000 ft. the minimum speed is 120 knots and speeds exceeding 200–250 knots occur approximately every three days and persist for periods of 12 to 24 hours. These variations are linked with oscillations of the polar front.

Pacific. Jet-stream behaviour over the North Pacific is broadly similar to that over the North Atlantic and multiple jet streams associated with various frontal systems are frequently found, particularly in winter. The polar jet usually moves north-east from the Japan area across the western Pacific and decreases in intensity. It often splits into two streams in the west central Pacific. Serebreny and Wiegman[12] have indicated that at 35° N. in winter, winds at 200 mb. exceed 75 knots on over 90 per

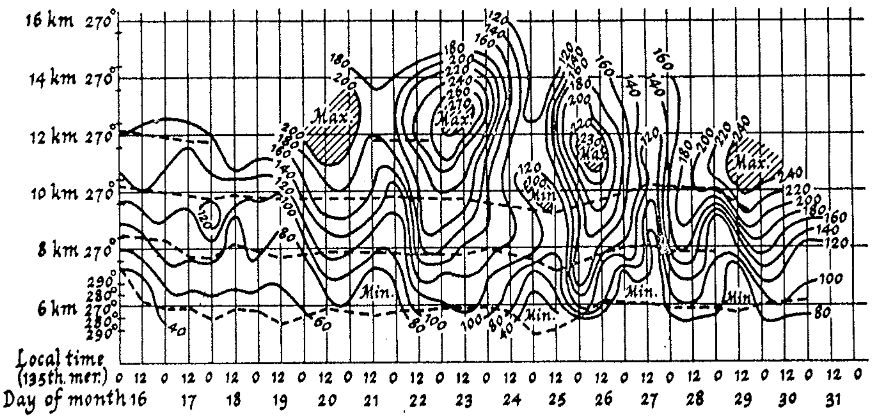

Fig. 11. Time/height cross-sections of observed winds at Shionomisaki for the last 16 days of December 1953. Solid lines give wind speed in knots. Broken lines give wind direction at each level with the baseline representing 270°. Directions above the base line are NW. and those below SW.

cent of occasions from the China coast to 160° E. whilst at 160° W. the maximum frequency is at 40° N. and is reduced to 30 per cent.

The sub-tropical jet stream is usually quite distinct from the polar jet and it appears frequently over Hawaii, particularly in winter and spring. As found in other parts of the world this jet is usually only apparent at heights above 25,000 ft. or more and winds below this height are frequently light and variable. Winds at core level (about 40,000 ft.) occasionally exceed 100 knots and it is probable that this stream is sometimes continuous across the ocean at about 20° N. Strong upper-level northerlies sometimes occur at Hawaii, however, and it may well be that the sub-tropical jet is diverted round a cold upper low on such occasions.

In summer the jet stream moves north and weakens but polar jets of 100 to 150 knots, or even higher speeds, may be found on occasions of above average cyclonic activity, whilst Riehl[6] has pointed out that westerly winds exceeding 100 knots have been observed at 40,000 ft. in July near Hawaii.

Southern hemisphere. The jet stream is also an essential part of the general circulation in the southern hemisphere where it is broadly similar to that of the northern hemisphere.

Lamb[7] has indicated that various factors subscribe to the fact that the overall wind flow is higher in the southern than in the northern hemisphere, e.g. very warm ocean surfaces in the tropics, high ground in tropical South America and Africa, low surface pressure and cold troposphere in the Antarctic. The circulation is more uniform with respect to longitude than in the northern hemisphere and in all probability the polar jet stream and the sub-tropical jet stream are continuous round the hemisphere during all seasons of the year. In the southern winter the sub-tropical jet stream is at about 25 to 28° S. over Australia and New Zealand but is further south over the eastern South Atlantic and western Indian Ocean where it averages 35 to 40° S. and on occasions combines with the polar jet. The mean speed is about 100 knots at 40,000 ft. but a speed of 300 knots was recorded at 36,000 ft. at Amsterdam Island (38° S. 78° E.) on 27 September 1956. In summer the sub-tropical jet stream moves south to about 40 to 45° S. and weakens to 50–60 knots. The polar front oscillates between 40° S. and 60° S. and the polar jet streams are often intense.

Polar-night stratospheric jet stream. Although winds are usually light at tropopause level (30,000 ft. or below) in high latitudes during winter, a jet stream exists at about 80,000 ft. and Lee and Godson[8] have described the behaviour of this jet stream during the winter of 1955–6 from an analysis of upper-air observations in the arctic regions of North America. The mechanism appears to be set up by the absorption of solar radiation in the ozone layer and the consequent sharp falling off of temperature northward across the boundary of polar darkness. This temperature gradient gives an increasingly westerly wind with height. It forms in the far north in November and reaches about 65–70° north in mid-winter then returning north and disappearing by the end of March. Speeds are about 40 knots at 50,000 ft., 80 knots at 60,000 ft. and 150 knots at 80,000 ft. A similar phenomenon is found in the Antarctic.

6. Easterly jet streams. During the northern summer a broad band of upper-level easterlies extends over southern Asia and Africa, and Koteswaram[9] has shown the existence of an easterly jet stream at about 15° N. with the axis at about 50,000 ft. although there is a tendency for the height of the axis to decrease downstream. The maximum wind only occasionally exceeds 100 knots. This jet stream is not found over the Atlantic and Pacific oceans but occasional weak jets have been noted over the Caribbean in the region of the South Bahamas, probably arising from the heating effect over the Arizona desert. The easterly jet stream almost certainly arises from the heating of the Asian land mass especially over the Tibetan plateau and its appearance and withdrawal are coincident with

those of the SW. monsoon. As in the case of the westerly jet streams, cloud and precipitation appear to the right of the axis in the entrance regions (India) and to the left of the axis in the exit regions (Africa) and oscillations of the jet stream are associated with breaks and revivals of monsoon activity. The jet stream will thus be north of its mean position during a break in the monsoon. Wind shear is usually concentrated in a relatively thin layer in the higher troposphere as observed in westerly sub-tropical jet streams and winds are mainly light below 30,000 ft.

There is also evidence of occasional weak high-level easterly jet streams over parts of the equator during the northern and southern summer seasons. Again the height of the axis appears to decrease downstream averaging about 50,000 ft. at Singapore and 45,000 ft. at Nairobi. The easterlies are particularly persistent in the Singapore area and occasionally exceed 100 knots at 50,000 ft. Above the core the winds often decrease rapidly with height and may become westerly in the stratosphere.

7. WIND SHEAR. The rate of change of wind speed (wind shear) may reach very high values in the region of the jet stream and as Fig. 1 shows, in particular, in the polar jet stream in the frontal zone. Changes averaging 10 knots per 1000 ft. have often been noted vertically (vertical shear) over ranges of up to 5,000/10,000 ft. and 1 knot per mile horizontally (horizontal shear) over distances of about 100 miles. Over somewhat smaller ranges these figures may be doubled and it is obvious that there must be local regions of exceptionally strong wind shear.

The highest values of vertical shear are usually found above 15,000 ft. and very often they occur above the axis (negative shear). The horizontal shear is almost invariably greater on the cold side than on the warm side of the jet axis and is often three to four times as great whilst the respective maximum values may be located up to 150 miles or so on either side of the jet axis. The Mediterranean jet stream shown in Fig. 1 shows a vertical shear of 43 knots in 2000 ft. at 25,000 ft. at Rome and a horizontal shear of 100 knots in 130 miles on the warm side of the axis at 30,000 ft. This value of horizontal shear seems to be well above average for the warm side of a jet stream.

Values of horizontal shears measured from the cross-section of the North American jet stream shown in Fig. 3 are 80 knots in 50 miles on the cold side and 30 knots in 50 miles on the warm side and these figures appear to be representative of strong polar jet streams in the North Atlantic. In the sub-tropical jet stream (except when it coalesces with the polar jet) horizontal wind shear is much smaller and seems to average about 15 to 20 knots in 100 miles on both the cold and the warm sides. Vertical shear also is smaller in the sub-tropical jet and is usually only apparent above 20,000 ft. and sometimes only above 30,000 ft.

The true core of the polar jet stream is usually less than 50 miles wide and sometimes less than 25 miles but there is often a zone of relatively small horizontal shear just outside the true core. Variations of wind speed within the core are usually less than 10 knots whilst variations of less than

20 knots may occur in a zone of about 100 miles in width. The sub-tropical jet stream usually has a broader core of the order of 200 miles in width.

Occasionally jet streams may flow round sharp upper troughs and a northerly jet and a southerly jet may be in close proximity giving rise to exceptionally high values of horizontal wind shear. Such troughs may become closed circulations detached from the main flow and a jet stream 'ring' may result encircling a pool of cold air. Cold pools of this type tend to remain almost stationary and may persist for several days.

It may be assumed that a wind shear of at least 10 knots per thousand feet is required before a turbo-jet aircraft would increase its range by flying at a lower altitude than still-air optimum, and although such wind shears exist from time to time in certain regions of the jet stream it will usually be impossible to guarantee that the lighter winds will be found; and in any case it is unlikely that the sharp differential will be maintained over any appreciable distance. Thus, as a general rule, it will not be worthwhile to change altitude in the hope of obtaining a more favourable wind.

8. Clear-air turbulence. Turbulence sometimes experienced by aircraft flying in clear air is usually of the 'cobblestone' type, i.e. short up-and-down movements like those of a speedboat travelling through a choppy sea. In extreme cases a sudden and unexpected severe bump might occur, of intensity similar to the bumps experienced in active Cu.Nim. cloud. Considerable research has been made into this problem and it is generally agreed that severe clear-air turbulence is usually associated with large local values of vertical and/or horizontal wind shear such as may be found near jet streams. The most likely areas of the jet stream where large wind shear can be expected are:

(i) The frontal zone, particularly at the higher levels so that severe turbulence may be expected on the cold-air side of the jet and just below the core.

(ii) Above the jet core, particularly about 2000–5000 ft. immediately above the axis and also on the 'cold' edge.

In addition to these general areas of high wind shear, clear-air turbulence may be found in an area associated with a 'fork' or 'bend' in the axis of the jet and also in the exit region of the jet stream. As regards the latter, in the exit region there is an 'indirect' circulation whereby the cold air rises and the warm air descends as a result of the air being decelerated and such circulations may also be found at other parts of the jet according to its state of development. This process makes the air less stable and favours turbulence.

The force opposing turbulence is the static stability, B, and is large when the lapse rate is small (e.g. it is very large at an inversion). Large lapse rates favour turbulence whilst an air current may be dynamically unstable if the vertical shear U' is large. The ratio gB/U'^2 where g is the force of gravity is called the Richardson number (Ri) and if Ri is less than a critical (small) value turbulence is almost certain to result. *B* is reduced in jet exits and with a slowing down of the air the wind profile is irregular and contains shallow regions of very large shear. Hence very small values of *Ri* are to be found in places in the exit region and are likely to result in localized patches of severe turbulence. Exit regions of the polar jet are often found just downwind of the portion of the jet stream where the wind speed along its axis is a maximum and it is not surprising that some of the worst turbulence has been found in such regions.

As stated earlier, very high values of wind shear are sometimes found across upper lows and troughs and severe clear-air turbulence is often encountered in such areas.

Another region deserving of special mention is the tropopause, where light to moderate turbulence is almost invariably present, associated with the broad sub-tropical jet stream; moderate or severe turbulence has also been met not infrequently at tropopause levels in middle latitudes even with comparatively small values of wind shear.

In a previous paper[10] the author has drawn attention to the severity of turbulence over North-west Europe during November in southward penetrations of arctic air and it is of interest to note that the only case of severe turbulence experienced by B.O.A.C. Comet IIE flights was associated with such conditions. In fact the cross-section shown in Fig. 1 was constructed primarily to investigate the incident. The aircraft was flying to Beirut via the east coast of Italy at 38,000 ft. Cobblestone turbulence occurred in association with a rise of temperature from $-62°$ C to $-54°$ C and shortly afterwards, on approaching Amendola, temperature increased further and some sudden sharp bumps sent the accelerometer needle to the stops. It is probable that the maximum acceleration increments were of the order of $1g$. After the turbulence it was noted that the temperature had increased to $-40°$ C representing a temperature deviation from 'standard' of $+21°$ C. Allowing for adjustment of the cross-section, e.g. for curvature of the axis, it will be seen from the in-flight temperatures that bumps were experienced in the area of very strong wind shear above and on the 'cold' side of the axis of the jet stream. That such turbulence is very localized in time and space was emphasized by the fact that another Comet on the same track some 90 minutes later experienced no turbulence.

Clear-air turbulence sometimes occurs in association with mountain waves. Any range of high ground with crests of about 300 ft. or higher can produce a wave under certain conditions. The wind flow should be normal or nearly normal to the range, with speed exceeding a certain value (say 25 knots) at mountain-top level, thence increasing with height (with strong wind shear) just above mountain level and thereafter maintaining a steady speed or increasing gradually with height. In addition there should be a stable layer, preferably an inversion, below about 15,000 ft. The effects of the mountain wave may extend well into the stratosphere but the precise nature of the flow is necessarily complex and may result from interference between many separate wave trains. Organized flow with smooth up and down draughts, often encountered in well established mountain waves and resulting in fluctuations of air speed, may contain local regions of turbulence and on occasions the flow may degenerate into large-scale turbulence. Localized areas of high wind shear, e.g. in association with the jet stream, may be accentuated by the presence of lee waves and give rise to severe clear-air gusts.

The present-day position as regards forecasting of clear-air turbulence appears to be little worse than that of forecasting turbulence in cloud. As a general rule severe turbulence is forecast for those areas where large Cu. or Cu.Nim. development is expected whilst clear-air turbulence will be forecast to occur in the region of jet streams where large values of wind shear are to be expected. In the same way as many flights through Cu. Nim. have experienced nil turbulence, high-level flights through areas of very strong wind shear have also been smooth, whilst turbulence has been noted on a few occasions when cloud or wind shear has appeared to be unfavourable for turbulence. It appears unlikely that the forecaster will be able to offer much improvement to existing standards. Fortunately, the in-flight problem of avoiding severe turbulence in cloud has been largely solved with the development of airborne radar and there is little doubt that all future types of large aircraft will be fitted with such equipment. It now remains for parallel equipment to be developed for detecting clear-air turbulence and until that day arrives jet aircraft will occasionally encounter rough air and, very occasionally, some rather unpleasant bumps.

9. JET STREAMS AND WEATHER. In view of the association between jet streams and fronts it is not surprising that there should be some relationship between cloud formations and jet stream locations. As regards high cloud, Ci. types are considerably more frequent and extensive on the warm side of the axis than on the cold side and the edge of a Ci. or Cs. sheet frequently parallels the axis of the jet stream. Although Ci. is not unknown in the stratosphere, it is very rare for cloud to be found above the axis of the jet stream. On the cold side the tops of cloud are almost invariably at or below the level of the tropopause whilst on the warm side tops are usually one or two thousand feet below the warm air tropopause. In general, the higher the tropopause the greater is the distance between tropopause level and cloud tops. On the cold side of the jet stream, Ci. appears much more frequently than Cs. whilst the reverse is true on the warm side. At times Cs. may appear on the warm side sloping upwards towards the core with anvil Ci. some 200 miles on the cold side. In the case of jet streams associated with well-marked surface fronts of maritime air, there is a belt of frontal cloud arising from interaction of the air masses involved and apart from any Cu.Nim. the tops of such clouds are usually below 18,000 ft. where, as mentioned previously, a region of very dry air is often found. At much higher levels, say 25,000–

30,000 ft., a different regime of clouds (Ci. types) usually appears with properties as described above. Large areas of Ci. cloud are often found in association with cold upper lows or in the forward regions of deep troughs whilst nil or only small amounts may be found above surface highs or ridges. The distribution of clouds depends to some extent therefore on the location of the jet stream in relation to the synoptic situation.

At times the jet stream extends for hundreds of miles in a more or less constant direction and long roll type cloud streaks of Ci. and Cc. may be observed all along its length. Captain Bernard Frost of B.O.A.C. has taken some very convincing photographs of such clouds over the North Atlantic. These streaks are almost invariably found on the warm side of the jet and the upper boundary usually extends to the edge of the core and is sometimes 100 to 200 miles in advance of the forward edge of a lower sheet of Cs. Over the United Kingdom it has been noted by Murgatroyd and Goldsmith[11] that jet streams from a northerly point, for instance those associated with a well-marked warm front approaching from the west, often have a sharp boundary of Ci. along the axis. On some occasions the line of cloud may even follow the curvature of the jet stream axis when it finally changes course. When there is insufficient moisture for Ci. to form, a thin haze layer may be present instead of cloud and indeed haze is often noted in the warm air even when clouds are present. Thus the cold side of the jet stream at core level very often may be identified by the clear, cloudless atmosphere associated with general subsidence in the lower stratosphere which contrasts sharply with the haze and cloud associated with ascent of air on the warm side.

Valuable information regarding the location of the jet core may be obtained therefore from observations of cloud and visibility at levels near the jet axis and such observations are often possible from the ground. However, as a general rule there seems to be no very simple relationship between jet streams and weather observed on the ground and, except in certain well-defined cases such as the Ci. streaks described above, the interpretation of clouds in association with jet streams demands caution.

10. FORECASTING JET STREAMS. The dimensions of the jet stream are such that a dense network of upper-wind reporting stations is required in order to locate the axis, and over most of the world the network is totally inadequate for this purpose. In particular, over the oceans and desert areas upper-wind reports at jet core levels are very sparse and the wind field is largely determined by indirect methods such as contour analysis of constant-pressure surfaces. However, considerable advances have been made in recent years in jet stream analysis in different parts of the world and it is fortunate, perhaps, that on the whole the jet stream axis moves comparatively slowly. Forecasting the position of the polar jet amounts to forecasting the position of the associated polar front and recent work in the United Kingdom and in the U.S.A. indicates that cold fronts move with a speed equal to the component of the wind at 700 mb. across the frontal surface. This is a useful empirical rule, therefore, for

forecasting the position of the cold front polar jet. However, there are the additional problems of forecasting the height profile of the axis, the position of wind maxima along the core and of associated wind shears and these present considerable difficulties. It should normally be possible, however, to indicate approximate positions and intensities of jet streams in areas with a reasonable coverage of upper-air stations, especially if these can be supplemented by accurate reports from aircraft. With modern aids such as Dectra and doppler radar, upper winds can be measured accurately in flight but there is still the problem of disseminating the information from the air to the various meteorological offices on the ground. Factors such as cockpit workload, air/ground traffic congestion and inadequate A.F.T.N. facilities point to the necessity for providing a fully automatic means of transmitting the information from the measuring device in the aircraft to meteorological collecting centres on the ground.

11. IN-FLIGHT ASPECTS. Assuming that a good approximation to the position of the jet stream can be given by the forecaster it still remains to be able to identify its precise position and intensity in flight. The reason for this is twofold. First, the captain at all times should be in a position to assess the fuel requirements for the remainder of the flight. For this purpose the item of greatest importance undoubtedly is terminal weather and this will continue to be so until automatic landing techniques are in general service. Significant changes of weather at the flight-planned destination occur all too frequently, for example in North Atlantic operations, particularly in the case of westbounds, and such changes often involve rapid reassessment of the flight plan in relation to fuel reserves. In such cases it becomes necessary to provide a close estimate of the equivalent headwind over the route to be flown and the course of action may well hinge on the strength of the upper winds, particularly when the track of the aircraft is roughly parallel to the axis of the jet stream. Apart from the time lag involved in obtaining information from the ground, the crew navigator of an aircraft fitted with reliable wind finding equipment may well be in a position to make a better estimate of the wind than that indicated by the latest forecast, provided he can identify the position of the aircraft relative to the jet stream. Secondly, as mentioned previously, certain preferred regions of the jet stream are often associated with clear-air turbulence and it is important to reduce the time in such turbulence to a minimum. With a normal Comet IV operation for example, the mach number is reduced in rough air from cruising mach number, say 0·73, to 0·66 (indicated). If the turbulence is severe or prolonged a loss of altitude of the order of 2000–3000 ft. is involved in order to fly at the indicated air speed recommended for severe turbulence and this loss of altitude is a matter of great importance to A.T.C. It is not practicable therefore to reduce air speed on every occasion when flying through a jet stream even in regions of strong wind shear, and indeed the overall incidence of turbulence does not justify such a procedure. However, there is obvious value in being prepared to take certain action in the

event of a sudden onset of turbulence. With the knowledge of the structure and location of the jet stream small changes in altitude (say a few hundred feet) and/or course will often avoid the turbulence. Nevertheless if pronounced cobblestones are experienced in or near to a region where marked wind shear is known to exist this should be looked upon as a warning sign to throttle back and order seat belts to be fastened, since there is a definite risk of severe bumps in the shear region. This rule applies particularly to the case of jet streams associated with penetration southwards of deep cold air (i.e. flowing round a very cold upper-air low or trough) since these are probably the most vicious of all jet streams. There is a requirement, therefore, to develop a simple procedure for indicating position relative to the jet stream and for this purpose constant wind measurement is essential. The best means of doing this at the present time would be by presentation of drift and ground speed from an automatic computer on a doppler radar system. Wind measurement alone will not necessarily provide sufficient information to identify the position of the aircraft relative to the axis of the jet stream but when coupled with reliable ambient-temperature readings the position will usually be apparent. Continuous recording of temperature readings would be very useful for this purpose although a few well chosen spot readings would be adequate in most cases to identify the relative position of the jet stream. On occasions cloud formations and haze layers may prove very useful in identifying the jet stream core but in the present state of knowledge it must be looked upon as a means of providing preliminary information to be confirmed or disproved by subsequent wind and temperature observations.

In planning a flight over a route where jet stream activity is known to exist it is recommended that the following routine should be observed:

(i) Pre-flight examination of surface and upper-air charts to locate positions of active fronts and wind-speed maxima.

(ii) Briefing from the forecaster regarding:

- (*a*) Location and likely movement of jet streams over or near the route.
- (*b*) Approximate height of axis.
- (*c*) Temperature deviation from standard on both cold and warm sides of the axis at cruising altitudes.
- (*d*) Heights of associated tropopauses.
- (*e*) Regions of large wind shear.

It would be desirable to have this information recorded for inclusion in the meteorological forecast folder.

(iii) Long routes involving track selection.

In the case of head-winds, plan the flight to evade the core. In many cases this will result in the selected track being different from the best time track indicated on the forecast upper-air charts as it will include a safety factor in order to reduce the risk of encountering prohibitive headwinds. In the case of tail-winds there should be reasonable certainty that a significant saving of flight time will result before deviating from the great circle (or other standard routing) since there is no guarantee that the aircraft will be assisted by core strength winds.

With the present A.T.C. problems associated with the separation of aircraft, the importance of track selection and planned altitudes at the pre-flight stage cannot be over-emphasized. It is likely to become increasingly difficult to obtain A.T.C. clearances in flight for changes in altitude or track and therefore increasingly important that meteorological services should provide accurate information to the flight planners.

(iv) Constant monitoring of upper-wind readings and a few spot temperature observations as measured by the aircraft coupled with current meteorological information supplied prior to departure will normally be sufficient to provide a good estimate of the position of the jet stream axis relative to the aircraft. Reference to a model cross-section of a typical jet stream applicable to the route in question would be of great assistance for this purpose.

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