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THE JET STREAM

by

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PRESIDENTIAL ADDRESS

TO THE CANADIAN BRANCH

OF THE ROYAL METEOROLOGICAL SOCIETY

January 26th, 1950

P. D. McTaggart-Cowan.

THE JET STREAM

A resumé of the scientific papers published on the Jet Stream and related phenomena up to November, 1949.

1. Once each year it is the privilege of the President of this Society to address a meeting on a subject of his own choosing. I have chosen the Jet Stream.

2. First of all I would like to make it clear that my remarks tonight contain no original contribution on my part to the mathematics or physics of the Jet Stream. The purpose of the address is to summarize in a convenient form the many excellent papers produced over the last several years up to November, 1949, on the Jet Stream and immediately related phenomena.

3. There is a further self-imposed restriction on the subject of this address in that it is intended to cover the physical aspects of the problem, only. The many excellent mathematical contributions will not be treated in detail.

4. In this latter limitation I do not for a moment mean to imply that a complete physical understanding of the features and properties of the Jet Stream can be obtained without the student digesting the mathematical theories and theorems involved.

However, the mathematical treatises are such that any attempt at substantial abbreviation below that appearing in the original papers would in most instances rob them of their apparent logic, and I can but recommend reference to the original papers.

5. Notwithstanding the exclusion of mathematics, I hope I can give you a real physical picture of the Jet Stream, and an appreciation of its anomalies and properties; and of the other phenomena which have in recent papers been associated directly with the Jet Stream.

HISTORICAL

6. As in many scientific advances, the literature preceding the basic papers contains the development of many physical and mathematical factors without which the basic concept might have been substantially delayed.

7. A list of such papers leading up to the Jet Stream, if it were to be complete would be very long. I have, therefore, kept it to a list of only those which might be considered as having an immediate and direct bearing on the fundamental papers.

8. In volume 5, No. 1, of Papers in Physical Oceanography and Meteorology, published by the Massachusetts Institute of Technology, and the Woods Hole Oceanographic Institute, there is a paper by Dr. Rossby, on the -

"DYNAMICS OF STEADY OCEAN CURRENTS IN THE LIGHT OF EXPERIMENTAL FLUID MECHANICS" (2)

There is a very striking resemblance between the Jet Stream and such major ocean currents as the Gulf Stream, and this paper by Dr. Rossby, published in 1936, forms an excellent background for the appreciation of many of the physical features of the Jet Stream.

9. Another paper by Dr. Rossby, published in 1938, in the Journal of Marine Research on the -

"MUTUAL ADJUSTMENTS OF PRESSURE AND VELOCITY DISTRIBUTION IN CERTAIN SIMPLE CURRENT SYSTEMS" (3)

is also good background reading.

Note: Numbers in brackets, thus (2), refer to the numbered list of papers appended hereto.

10. In 1944 Dr. Willett, in his book -

"DESCRIPTIVE METEOROLOGY" (6)

presented for the first time mean cross-sections clearly showing the Jet Stream, but, as was the case with Sir Napier Shaw who came so close to recognizing the physical entity of a frontal surface but just failed to name it, thus leaving to the Norwegian school of Meteorologists the honour of first propounding the mathematical and physical features and proposing the name, so Dr. Willett, with his attention undoubtedly directed to the general circulation of the earth's atmosphere, did not set forth the synoptic significance of the localized, high velocity stream of air shown on his mean cross sections.

11. In June, 1945, in the Journal of Meteorology, Albert Cahn, Jr. of the University of Chicago, published another good background paper entitled -

"AN INVESTIGATION OF FREE OSCILLATIONS OF A SIMPLE CURRENT SYSTEM" (7)

12. As a thoroughgoing mathematical treatise on many of the fundamental hydrodynamical factors which led to the basic papers, Jeremi Waisutynski's book entitled -

"STUDIES IN HYDRO-DYNAMICS AND STRUCTURE OF STARS AND PLANETS" (8).

published as volume 4 to Astrophysica Novegica, in Oslo, in 1946, is recommended.

13. As an example of how close some practising Meteorologists in the field came to recognizing the Jet Stream as a physical entity, reference should be made to Vincent J. Oliver's paper in January, 1947, issue of the bulletin of the American Meteorological Society. The paper is entitled -

"THE FORECASTING SIGNIFICANCE OF HIGH LEVEL WINDS IN SUB-ARCTIC REGIONS" (9).

14. The large changes of wind direction and speed found by observation by Oliver were used by him as criteria to determine the direction of motion of the associated surface depressions, and, thereby, in the forecasting of the weather in the Aleutians and Alaska. He thus failed to recognize the fundamental importance in the general circulation of the fast moving stream of air, itself.

THE FUNDAMENTAL PAPERS

15. The first of the fundamental papers on the Jet Stream was Dr. Rossby's paper which appeared in the Bulletin of the American Meteorological Society, February, 1947, under the title -

"ON THE DISTRIBUTION OF ANGULAR VELOCITY IN GASEOUS ENVELOPES UNDER THE INFLUENCE OF LARGE-SCALE HORIZONTAL MIXING PROCESSES" (10)

In this paper Dr. Rossby attacked the problem of Zonal wind distribution in the atmosphere from the basis of an intense thermally driven lateral mixing process, assuming that it was associated with a tendency towards equalization of the vertical component of the absolute vorticity. On these assumptions Dr. Rossby arrived at the conclusion that during the Winter season this mixing process must from time to time lead to a gradual accumulation of zonal kinetic energy at the tropopause level **South** of latitude 50°N, and the creation of strong west wind **maxima at** those heights somewhere between 50°N and 30°N. As a further consequence, the strength of such a zonal maximum would increase as it was displaced southwards towards the 30°N parallel of latitude.

16. On the basis of the war-time collection of Northern Hemisphere observations by the United States Air Weather Service, and on the basis of Dr. Willett's published cross-section, Dr. Rossby deduced that this maximum zonal wind activity was suggestive of a broad meandering river flowing around the earth.

17. Thus, Dr. Rossby's paper set the stage for the entry of the Jet Stream into meteorological writing and thinking: but he left for a second paper, published by the staff members of the Department of Meteorology of the University of Chicago, collectively, the naming and describing of the Jet Stream, itself. This paper appeared in the Bulletin of the American Meteorological Society in June, 1947, and was entitled -

"ON THE GENERAL CIRCULATION OF THE ATMOSPHERE IN MIDDLE LATITUDES" (11)

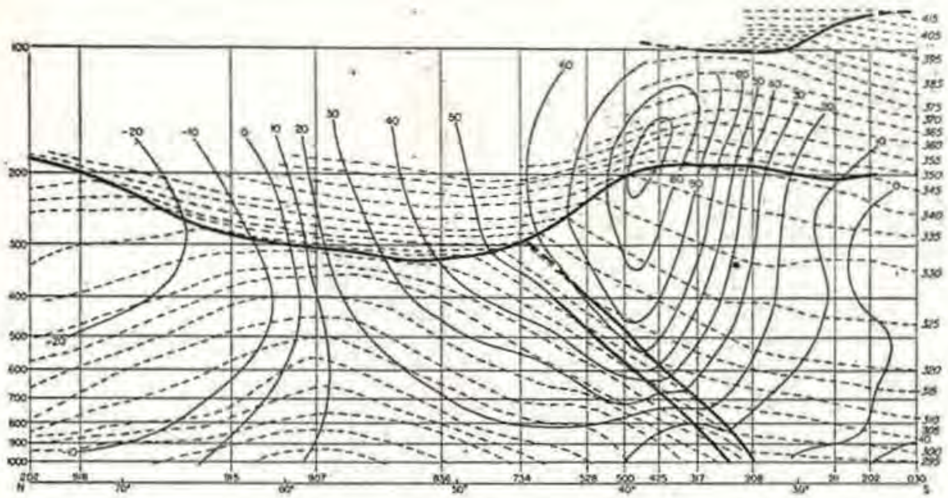

Fig. 1

Meridonal cross-section for January 17, 1947, 0300Z, from Havana in S to Thule (Greenland) in N. Heavy solid lines represent tropopause or boundaries of the frontal layer, thin solid lines constant geostrophic wind (W-wind component in mps); dashed lines represent isentropes.

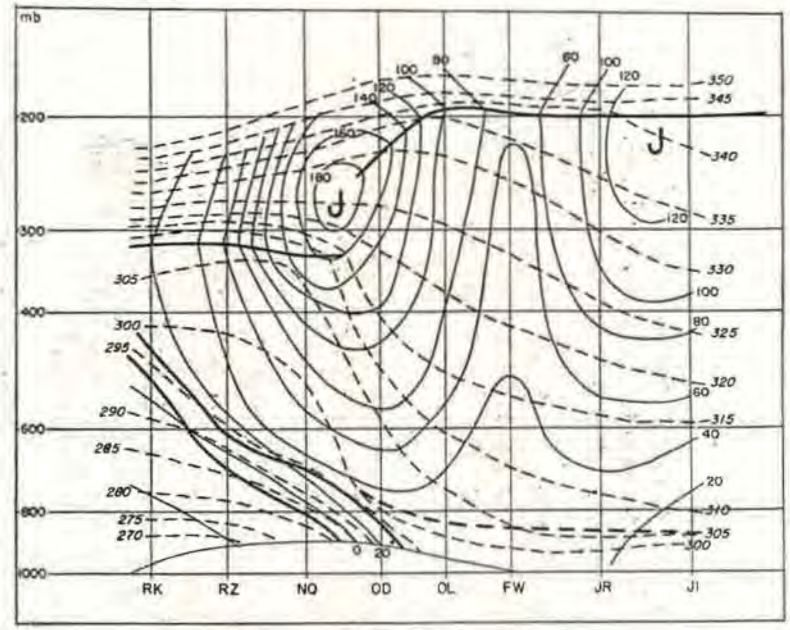

Fig. 2

Vertical cross-section, Bismarck, N. D., to Brownsville, Texas, January 29, 1947, 0300Z. Thin solid lines are lines of equal geostrophic west-wind speed (in mph), broken lines isentropes, heavy solid lines tropopauses or boundaries of frontal layer. The letter "J" (jet) indicates region of west-wind maximum. The section was taken through a current with little curvature of flow.

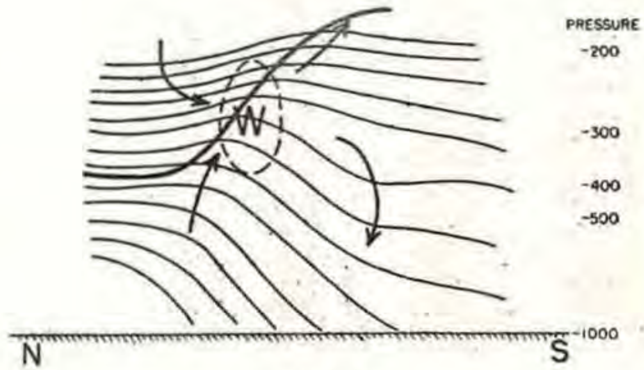

Fig. 3

Probable meridional displacements and adjustments associated with intensification of zonal wind maximum. Isentropes given by thin lines, tropopause by heavy line.

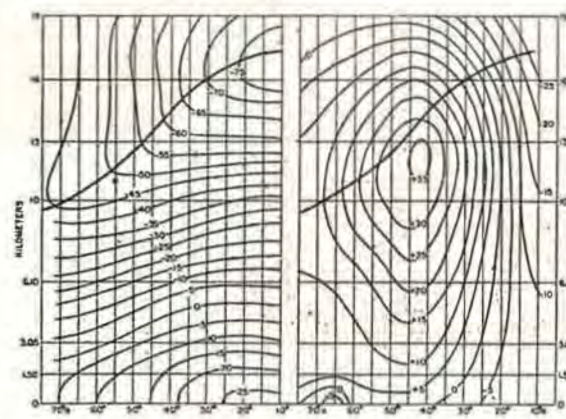

Fig. 4

Normal meridional cross sections for the entire northern hemisphere in July: left, temperature in degrees centigrade; right, west-to-east wind component in miles per hour.

Figs. 1, 2 and 3 from (11) - On the General Circulation of the Atmosphere in Middle Latitudes. Bull. Amer. Met. Soc., 28, 255-280. By - Staff Members, Department of Meteorology, University of Chicago, 1947.

Fig. 4 from (12) - Physical Nature of Some Fluctuations in the Speed of the Zonal Circulation. J. Meteor., 4, 125-133. By - Namias, J., 1947.

18. The paper was a masterly presentation by eleven outstanding scientists, led by Dr. Rossby and Dr. Palmen, As a tribute to these two project leaders, and the dynamic influence they have on modern Meteorology, it should be noted that of the papers on the Jet Stream referred to in this address nineteen out of the total of twenty-three have been written by members of that original Chicago team, or others subsequently associated with the Chicago school.

19. In this basic paper by the staff members of the Department of Meteorology, University of Chicago, the Jet Stream was initially described as follows:

> "DURING PERIODS OF REASONABLY STRAIGHT WEST WIND CIRCULATION OVER THE NORTH AMERICAN CONTINENT THERE EXISTS, NORMALLY AT LEVELS BETWEEN FIVE AND FIFTEEN KILOMETERS ABOVE SEA LEVEL A FAIRLY NARROW ZONE OF EXTREMELY STRONG WEST WIND CIRCULATION (JET STREAM) REACHING ITS MAXIMUM INTENSITY AND SHARPNESS AT THE TROPOPAUSE LEVEL, 300 MBS. TO 200 MBS."

(It will be seen later that the use of the term has been extended to cover extremely strong east wind circulations, as well as west.)

20. This paper was the first to contain synoptic meridional cross-sections clearly illustrating the existence of the Jet Stream.

21. Figures 1 and 2 are the synoptic meridional cross-sections for January 17, 1947, and January 29th, 1947, which appeared in the basic Chicago paper, and serve to illustrate several of the fundamental properties of the Jet Stream:

21.1. The change in height of the tropopause, which usually appears to be broken in the vicinity of the Jet, and not infrequently has a double structure immediately south of the axis of the Jet.

21.2. That the Jet is normally associated with a frontal surface, with the axis located in the warm air approximately vertically above the intersection of the front with the 500 mb. surface.

21.3. The very rapid decrease in wind speed north and south of the axis of the Jet.

22. The paper also deals with the association of the Jet with the long waves in the upper atmosphere, i.e. at 500 mbs. and above, on which so much work has been done by the Chicago School of Meteorology: and further parallels are drawn between the Jet Stream and the Gulf Stream.

23. Of a more debatable character are the vertical motions associated with the Jet Stream. Figure 3, taken from the paper, illustrates a possible meridional displacement pattern. This has been the subject of considerable controversy in later publications.

24. As this basic paper by the staff members of the Department of Meteorology, Chicago University, was in itself a summary report it is very difficult to do it justice by merely touching on the highlights as is done here. All who desire a thorough understanding of the Jet Stream should read this paper for themselves. Many of the subsequent papers to which reference will be made are elaborations of the various aspects summarized in the basic paper described above.

25. The next contribution was from Dr. Namias, and appeared in the August, 1947, issue of the Journal of Meteorology, under the title of -

"PHYSICAL NATURE OF SOME FLUCTUATIONS IN THE SPEED OF THE ZONAL CIRCULATION" (12)

This paper has very special significance in the light of subsequent events, in that it proposed an alternative to Dr. Rossby's vorticity theorem, by suggesting that at least in some cases the appearance of the Jet Stream could be explained as the result of large-scale confluence of cold and warm currents in the mid-troposphere. The presentation of his case is by no means as thoroughgoing as that put forward by the Chicago School of Meteorology, but, nevertheless, certain factors are presented which require very thoroughgoing study, and, as indicated by Dr. McIntyre in his address to this Society of the 27th of October, it is possible that both the mechanisms described by Rossby and by Namias play a part in the setting up of zonal circulations.

26. One diagram of special significance appeared in Namias' paper and is reproduced as figure 4. The figure

presents a meridional cross-section for the entire Northern Hemisphere in July, shown both as a thermal diagram on the left, and a west to east wind component diagram on the right. It is remarkable that the Jet should show up so clearly even when the elements are averaged over the entire Northern Hemisphere. The fact that the Jet Stream stands out so clearly is evidence that it is no transitory or infrequent occurrence, but a very frequent and fundamental portion of the zonal wind structure over the Northern Hemisphere.

27. The next paper appeared in the Journal of Meteorology of February, 1948, by Dr. Palmén -

"ON THE DISTRIBUTION OF TEMPERATURE AND WIND
IN THE UPPER WESTERLIES" (13)

28. This paper is indicative of the systematic studies of certain meridional cross-sections carried out at the University of Chicago, and is based on a detailed analysis and appraisal of the synoptic situation over North American on the 17th of January, 1947.

29. The paper is an excellent example of the clear, concise and beautifully organized presentation of material which has characterized the Chicago publications on this subject. They are a pleasure to read, and the arguments and conclusions easy to follow and understand.

30. Figure 5 shows the surface map for 0630 GMT of the 17th of January, and figure 6 the contours and temperatures of the 500 mb. surface for 0300 GMT on the 17th of January.

31. It should be noted here that the 500 mb. chart has played a fundamental role in all the studies reported in the papers on the Jet Stream and zonal circulation problems, and certainly points to its importance in the day-to-day routine of any forecast office undertaking independent analysis and forecasting: and, as a corollary, that the chart should be used in the briefing of pilots engaged in flying operations above 15,000'.

32. The synoptic features of these charts will be familiar to all. The surface chart represents a rather complex and ill-defined type of circulation: while at the 500 mb. level the circulation has taken on a very definite pattern, with a cold low situated over Port Harrison, with a secondary small vortex in the extreme southwestern United States, and well-defined west toeast zonal circulation over the entire mid-portion of the continent.

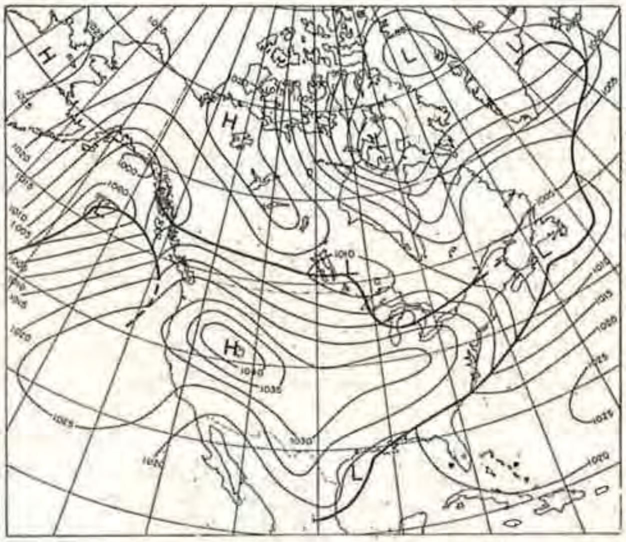

Fig. 5

Surface map 0630 GCT 17 January 1947.

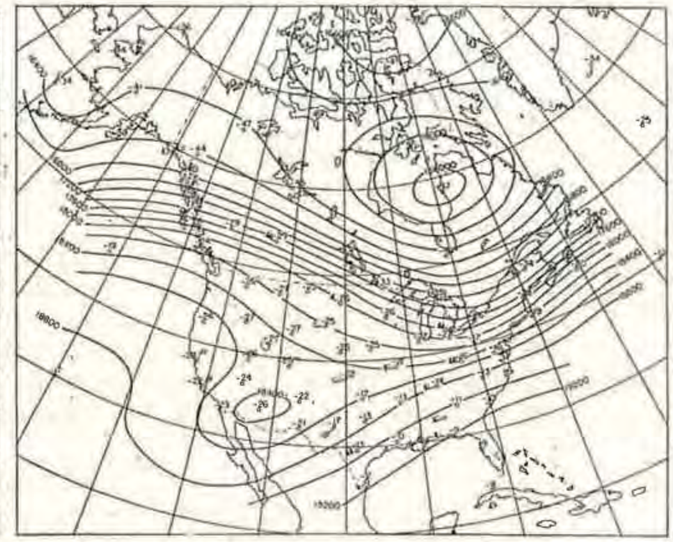

Fig. 6

Contours (ft) and temperatures (C) of the 500-mb surface 0300 GCT 17 January 1947.

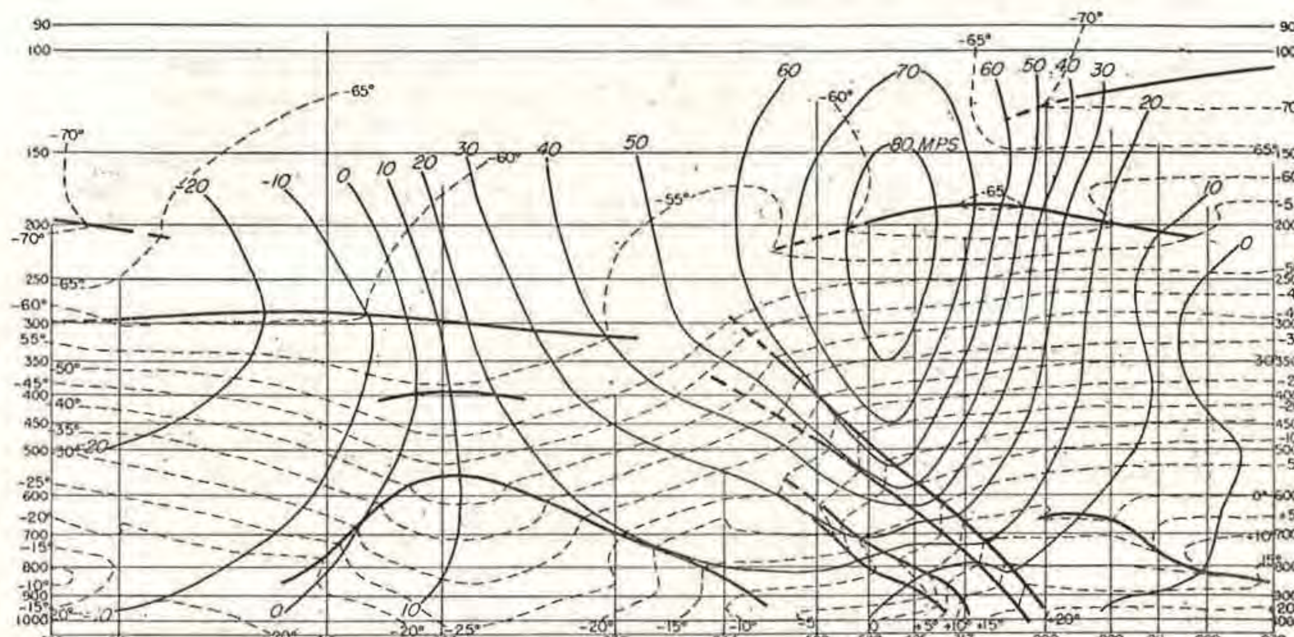

Fig. 7

Vertical cross section approximately along the meridian 80° W from Havana in the south to Thule (Greenland) in the north, Vertical lines indicate the soundings used in the diagram with the international station numbers below. Frontal boundaries, inversions or tropopause surfaces are indicated by thick, solid lines when they are distinct, and by thick, dashed lines when not distinct. Thin. solid lines indicate geostrophic wind velocity (meters per second) perpendicular to the cross section (zonal wind), dashed lines isotherms (C).

Figs. 5, 6 and 7 from (13) – On the Distribution of Temperature and Wind in the Upper Westerlies. J. Meteor., 5, 20-27. By – Palmen, E., 1948.

33. Figure 7 is the vertical cross-section for 0300 GMT, 17th January, extending from Havana to Thule, Greenland, approximately along the 80th meridian.

34. Here, again, the discontinuity in the tropopause with its apparent double structure south of the axis of the Jet, the location of the Jet vertically above the intersection of the associated frontal surface with the 500 mb. surface, and the concentration of the thermal gradient immediately to the north of the axis of the Jet, are all clearly recognizable.

35. It should be noted that the geostrophic wind velocities in figure 7 are given in meters per second. (See attachment for conversion table to miles per hour.) These show roughly that the Jet reaches a maximum of 180 miles per hour over a depth from 350 mbs. to 150 mbs. over a horizontal distance of four to five degrees of latitude.

36. Also recognizable is the very strong horizontal wind sheer south of the axis of the Jet. At around 225 mbs. this sheer reaches an order of magnitude of 10 meters per second per degree latitude between 32° and 37°N.

37. A characteristic of the meridional temperature field in the upper atmosphere, deduced by Dr. Palmén from these studies, is also put forward in this paper: that is, that at the level of the axis of the Jet Stream, in this case around 200 to 225 mbs., there is a zone of lowest temperature about 4° of latitude south of the strongest winds, and a zone of highest temperature about 7° of latitude north of the same zone.

38. Palmén suggests that this is connected with the special kind of cross-stream vertical circulation, as suggested in the basic paper (11), superimposed on the zonal motion.

39. The next paper to appear was by Cressman, in the April, 1948, issue of the Journal of Meteorology, and was -

"ON THE FORECASTING OF LONG WAVES IN THE UPPER WESTERLIES" (14)

This paper deals with the problem from the standpoint of prognostic analysis and forecasting, and should be studied by all forecasters.

Of special interest is his conclusion that for successful "progging" the area of the upper air charts must be sufficiently large to show several of the long waves.

40. Another paper in the April, 1948, issue of the Journal of Meteorology was -

"AN ANALYSIS OF THE WIND AND TEMPERATURE DISTRIBUTION IN THE FREE ATMOSPHERE OVER THE NORTH AMERICAN CONTINENT IN A CASE OF APPROXIMATELY WESTERN FLOW" (15)

by Palmén and Nagler.

41. In this paper a special situation on the 30th of November, 1946, similar in manyrespects to the situation described in Palmén's previous paper, was examined and discussed with the aid of an average cross-section, drawn with the use of all radiosonde data, for the date in question.

42. The factors brought out in Palmén's preceding paper (13) are again recognizable, and, in addition, one can see the easterly flow in the northern latitudes.

43. In the same issue of the Journal of Meteorology a short paper was presented by Ernest Hovmöller of the Swedish Meteorological and Hydrological Institute of Stockholm, entitled -

"NORTH-SOUTH CROSS SECTION SHOWING DISTRIBUTIONS OF TEMPERATURE, RELATIVE HUMIDITY AND WINDS IN A WELL-MARKED ZONAL CURRENT OVER WESTERN EUROPE" (16)

44. This was a study of a particular synoptic situation carried out in the same manner as the studies in the basic Chicago paper (11), but dealing with a cross-section from Lerwick to Bordeaux. The principal interest, perhaps, in this paper centres around the close agreement between the calculated axis of the Jet Stream and the position actually determined by means of the Rawin ascents taken over the United Kingdom. The axis of the Jet was at approximately 300 mbs. and at latitude 53°N.

45. The next paper to appear was by Riehl, under the title of -

"THE JET STREAM IN UPPER TROPOSPHERE AND CYCLONE FORMATION" (17) in the Transactions of the American Geophysical Union, April, 1948.

46. Riehl reported on an examination of cases of relatively straight westerly flow in an attempt to find criteria that might indicate the circumstances leading to cyclone genesis.

47. From the study of the development of cyclones over the central plains of the Rocky Mountains, Riehl was driven to the conclusion, as, in fact, all Meteorologists who have analyzed charts from that area must conclude, that the strength or weakness of the front in the lower portions of the troposphere cannot account fro a considerable number of the intense developments. Frontal zones of greatest intensity can be observed to remain inactive for protracted periods, while on other occasions great cyclones have developed in comparatively weak frontal zones. In attacking this problem, with the Jet Stream concept, Riehl placed considerable importance on the tropopause region.

48. Figure 8 shows the isotherms at 200 mbs. on January 28th, 1947, with the heavy arrow indicating the centre of the Jet. The temperature minimum south of the axis of the Jet, and the maximum immediately north of the axis, are very clearly illustrated in this figure. It appears inescapable that vertical motion must be primarily responsible for the observed temperature distributions near the 200 mb. level. Considerations of the magnitude of vertical motion necessary to produce this temperature distribution led Riehl to the conclusion that the generation of the cold air most probably takes place in the westerly currents, with a cross-section component of motion towards the south.

49. Similarly, he concluded that the vertical motions were of such magnitude as to necessitate their connection with events at lower levels in the vicinity of the Jet Stream maximum. This logically led to Riehl's association of low level wave development with the axis of a well developed Jet. Figure 9 shows the axis of the Jet Stream superimposed on a surface chart, in which the apparent correlation between lower tropospheric cyclonic activity and the Jet Stream appears to be very good.

50. The vertical motions associated with this well developed Jet were used to account, not only for rapid cyclonic development but also, in a great measure, for the magnitude of the rain fall associated with the development. However,

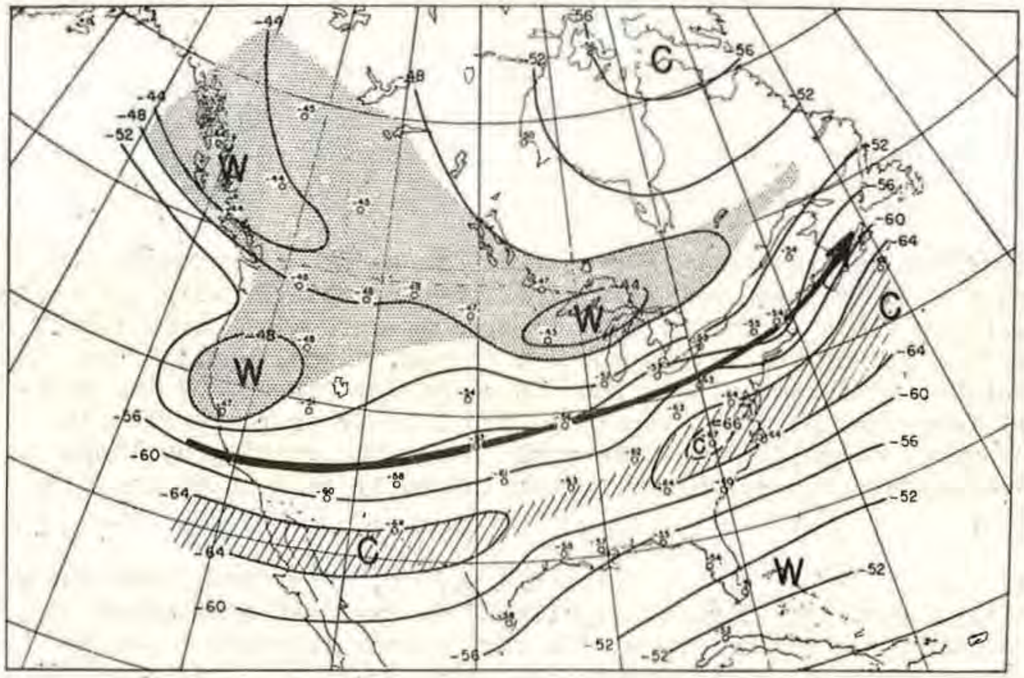

Fig. 8

Isotherms (°C) at 200 mb, January 28, 1947, 0300Z; heavy covered arrow indicates center of jet.

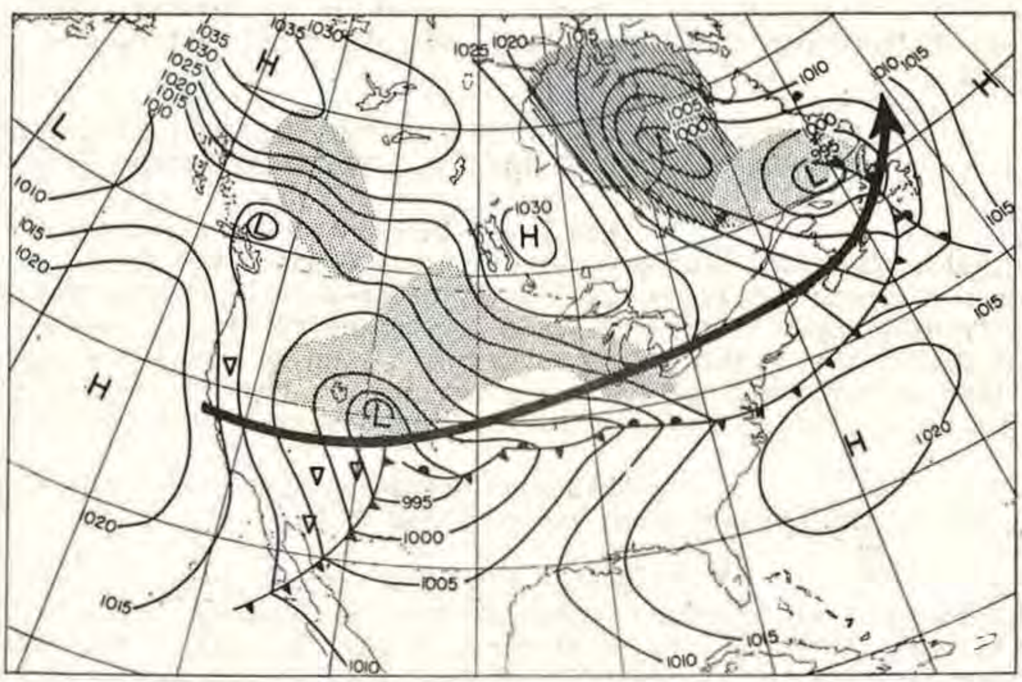

Fig. 9

--Surface map, January 29, 1947, 0630Z; heavy covered arrow indicates center of upper jet stream; shaded areas are regions of steady and intermittent precipitation

Figs. 8 and 9 from (17) - Jet Stream in Upper Troposphere and Cyclone Formation, Trans. Amer. Geo-Phys. Union, 29, 175-186. By - Riehl, H., 1948.

Riehl was careful to emphasize that his study covered only one species of cyclone formation, i.e. that associated with initially westerly flows aloft, without pronounced streamline curvature: nor was it suggested that the Jet Stream, alone, could create the cyclone. Reihl concluded that when the Jet Stream and the overall long wave pattern, together with a lower tropospheric disturbance, coincide in a favourable sense the ensuing cyclonic developments can reach very great intensity in a short space of time.

51. It would appear, therefore, that these factors should be immediately tested in day-to-day twenty-four and forty-eight hour prognostic work associated with a public weather service. They might well prove to be the criteria necessary to determine sufficiently far in advance for effective public action the developments of the more destructive of the extra-tropical cyclones, which at times literally appear to explode in the lower levels, and present considerable difficulty with the present forecasting techniques.

52. A paper appeared in the October, 1948, issue of the Journal of Meteorology, by Palmén and Newton, entitled -

"A STUDY OF THE MEAN WIND AND TEMPERATURE DISTRIBUTION IN THE VICINITY OF THE POLAR FRONT IN WINTER" (18)

53. This paper introduced a new method of analysis, wherein a mean cross-section was constructed from a number of individually analyzed daily cross-section charts, using the frontal layer as the reference for the coordinates. The advantages of this method of constructing a mean cross-section lay in that it preserved the thermal gradients observed in the individual cases, and minimized the effect of observational errors.

54. This mean cross-section is shown in figure 10, and is the section along the meridian 80°W.

55. Here, while the thermal gradients are somewhat smoothed the increase in temperature immediately to the North of the axis of the Jet is still recognizable, as well as the other properties outlined on the basis of the previous papers.

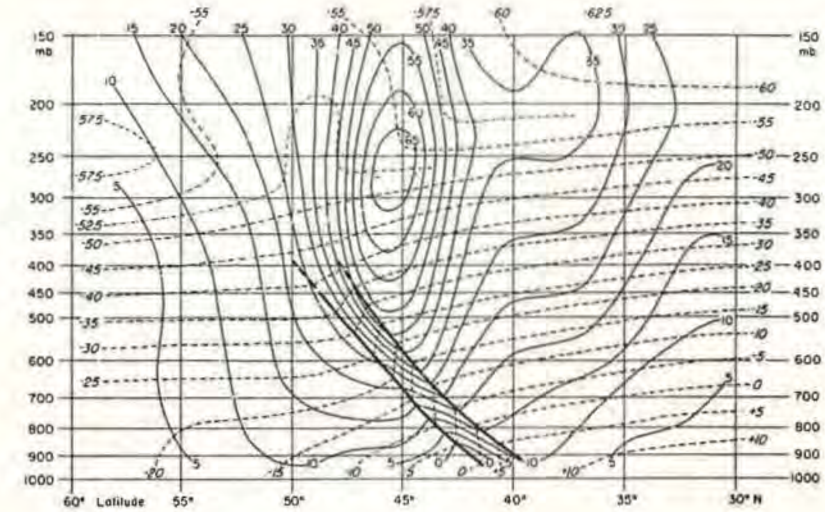

Fig. 10

Mean temperature and zonal component of geostrophic wind, computed from twelve cases in December 1946. The cross section lies along the meridian 80°W. Heavy lines indicate mean positions of frontal boundaries. Thin dashed lines are isotherms (degrees Centigrade, slanting numbers) and solid lines are isolines of westerly component of wind (meters per second, upright numbers). Means were computed with respect to the polar front in this and in the following figures.

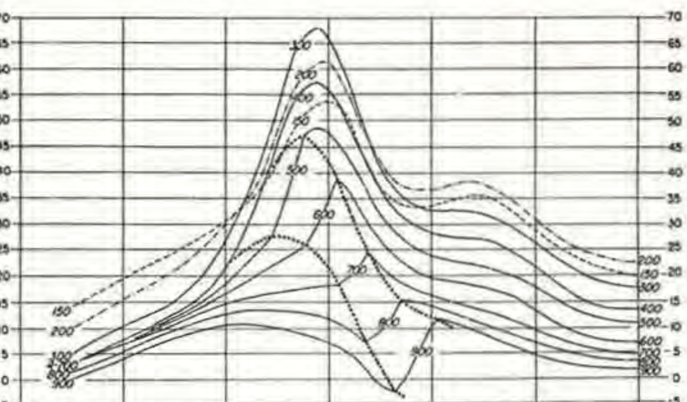

Fig. 11

Mean geostrophic wind profiles at isobaric surfaces, from fig. 1. Heavy dotted line connects intersections of frontal surface with wind profiles at different levels.

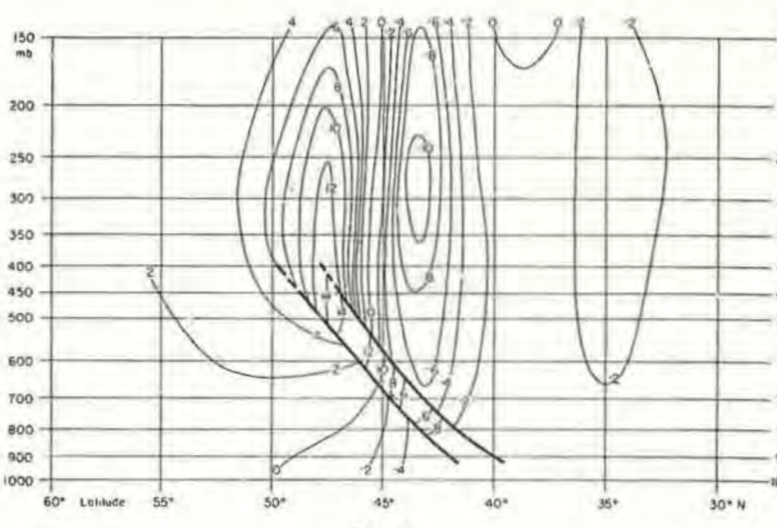

Fig. 12

Mean horizontal wind shear from fig. 1. Units are m sec⁻¹ (100 km)⁻¹, or 10^{-5} sec⁻¹. Positive numbers indicate cyclonic shear, negative numbers anticyclonic shear.

Figs. 10, 11 and 12 from (18) – A Study of the Mean Wind and Temperature Distribution in the Vicinity of the Polar Front in Winter. J. Meteor., 5, 220-226. By – Palmén, E. and Newton, C.W., 1948.

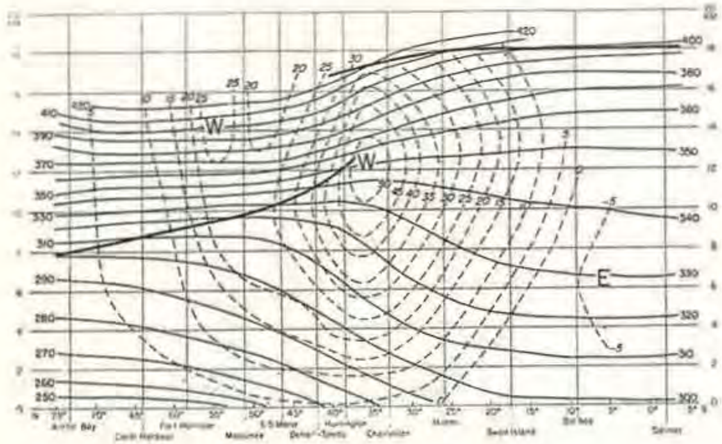

Fig. 13

Distribution of virtual potential temperature in degrees Kelvin (thin solid lines), geostrophic west wind in meters per second (dashed lines), and the tropopause (heavy lines) in winter.

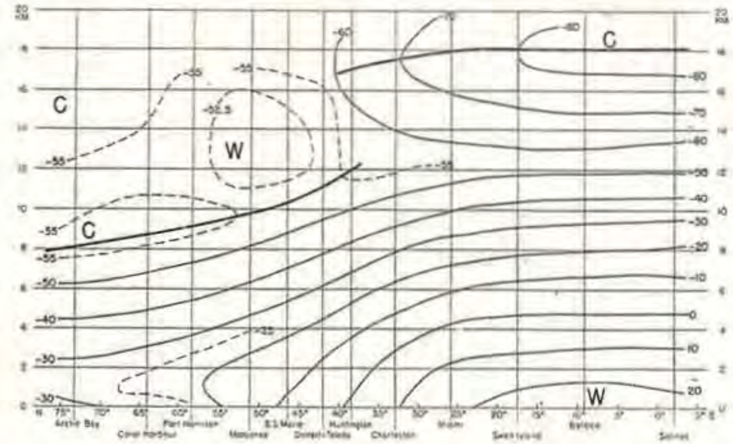

Fig. 14

Distribution of virtual temperature in degrees Centigrade (thin lines) and the tropopause (heavy lines) in winter.

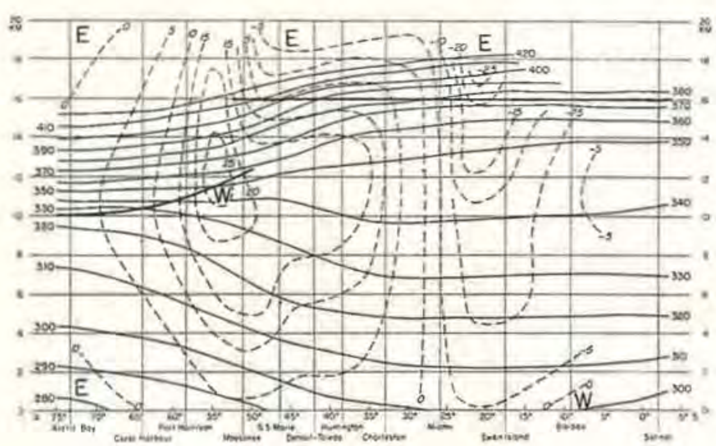

Fig. 15

Distribution of virtual potential temperature in degrees Kelvin (thin solid lines), geostrophic west wind in meters per second (dashed lines), and the tropopause (heavy lines) in summer.

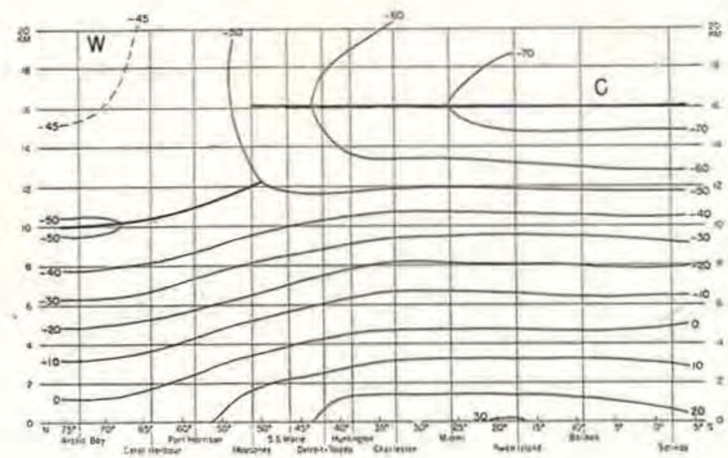

Fig. 16

Distribution of virtual temperature in degrees Centigrade (thin lines) and the tropopause (heavy lines) in summer.

Figs. 13, 14, 15, and 16 from (19) - Some New Mean Meridional Cross Sections Through the Atmosphere. J. Meteor., 6, 293-300. By - Hess, S. L., 1948.

56. Figures 11 and 12 serve to emphasize in a striking manner the intense vertical and horizontal wind sheer to the north and south of the axis of the Jet, and would certainly lead us to expect that not infrequently severe turbulence would be encountered in these regions at high altitudes.

57. In the December, 1948, issue of the Journal of Meteorology a paper was published by Hess, on -

"SOME NEW MERIDIONAL CROSS-SECTIONS THROUGH THE ATMOSPHERE" (19)

Hess presented mean meridional cross-sections along longitude 80°W for both summer and winter. These sections (figures 13, 14, 15 and 16) represented an improvement over the previous sections published by Willett and others, in that they were based upon a longer period of observation and extended over a wider range of latitude, due to the increased number of upper air stations established in the intervening years.

58. Referring first to figures 13 and 14, showing the winter cross-section, the Jet Stream is clearly recognized with its usual properties at about 36°N, and at a height of some 40,000'. In this work Hess found that the mean tropopause was not a continuous line, as shown in some of Willett's diagrams, but fell quite naturally into the pattern of separate Arctic and Tropic tropopauses. This was, of course, in accord with the results of the analysis of daily cross-sections published by others. It is indeed remarkable that this discontinuity in the tropopause is still visible in the mean maps, and lends considerable weight to its intimate connection with the Jet Stream, and that, in common with the Jet, it is a frequent phenomenon.

59. The temperature distribution in the Arctic stratosphere in winter (figure 14) was also interesting, in that a definite warm region between eleven and sixteen kilometers appeared at about 50°N. This has its counterpart in the geostrophic wind field, as can be seen in figure 13. This is even more clearly shown in Dr. McIntyre's Ph.D. thesis, (as yet unpublished).

60. Figures 15 and 16 show the cross-sections for summer. The recognizable features are the much weaker mean

Jet Stream displaced northwards to almost the 55th parallel of latitude, but remaining at approximately 12 kilometers. It was also evident that the Tropic tropopause in summer was some two kilometers lower than in winter. This was in agreement with Willett's studies of the radiosonde ascebts at Swan Island. On the other hand, the Arctic tropopause behaved in the reverse manner, and was higher in summer than in winter.

61. In the December 10th, 1948, issue of, Science, Rossby and Willett published a very readable resumé of progress up to that time -

"CIRCULATION OF THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE" (20)

62. Of necessity, the treatment in that paper was somewhat superficial, but it is interesting reading for those with a limited knowledge of mathematics who might have some difficulty in following portions of the papers previously described.

63. The next paper of interest appeared in the February, 1949, issue of the Journal of Meteorology, by Fultz, entitled -

"A PRELIMINARY REPORT ON EXPERIMENTS WITH THERMALLY PRODUCED LATERAL MIXING IN A ROTATING HEMISPHERICAL SHELL OF LIQUID" (21)

These experiments were reported upon by Dr. McIntyre in his address before this Society on the 27th of October, and no attempt will be made to resummarize the work at this time, except to state that one cannot help but be impressed with the thoroughness of the all-round approach of the University of Chicago to this problem, involving as it does the theoretical and analytical attack on the problems outlined in the previous papers, and, also, the very conscientious laboratory programme reported in Mr. Fultz' paper.

64. It is sufficient for the purpose of this address merely to indicate that Fultz' laboratory work with rotating hemispherical shells confirmed to a fair degree the theoretical and analytical work of other members of the Chicago team.

65. In volume 1, No. 1, of the new Quarterly Journal of Geophysics, Tellus, published by the Swedish Geophysical Society, in February, 1949, two papers on the problem appeared. The first is by Palmén -

"ON THE ORIGIN AND STRUCTURE OF HIGH LEVEL CYCLONES SOUTH OF THE MAXIMUM WESTERLIES" (22)

and the other by Nyberg on -

"AN AEROLOGICAL STUDY OF LARGE-SCALE ATMOSPHERIC DISTURBANCES" (23)

66. Palmén, in his paper, dealt with the development of cold cyclonic vortices, which appear first as waves in the zonal westerlies, with the trough increasing in amplitude until the southern extremity separates to form a cold vortex, with the westerly circulation and the Jet Stream reforming to the North. While this development has great importance in the general circulation of the atmosphere, it is of special importance in the consideration of the Jet Stream, in that it shows one way in which the Jet Stream can break down and re-establish somewhat later at a more northerly latitude.

67. In Nyberg's paper on -

"AN AEROLOGICAL STUDY OF LARGE-SCALE ATMOSPHERIC DISTURBANCES" (23)

stress was laid on the prognostic usefulness of the 500 mb. level as compared with the 700 mb. level, and importace was attached to two rules: first, that the pressure change areas in the 500 mb. level move with approximately 60% of the speed of the wind in that level, and, second, that advection of cold air at upper isobaric levels is followed by geopotential falls at the same level, and vice versa in the case of warm air.

68. It was also found that in a deepening trough the cold air was sinking at the same time as the Jet Stream increased in activity, and that the associated front became sharper. Thus Nyberg found a direct type of circulation, with vertical notions in the opposite direction to that shown in the first Chicago paper (11), i.e. with the cold air sinking and the warm air rising. This, therefore, supported the confluence theory put forward by Namias.

69. To reconcile these apparent conflicts it is necessaryto draw attention to the very limited number of cases studied. Nyberg's paper was written around one particular case on the 20th of January, 1947. It would not be unreasondile to suppose that the Jet Stream which intensified at that time, was due to a confluence of warm and cold air currents, and that, in itself, would not negate the indirect types of circulations propounded by the others and supported by the analyses of other synoptic situations.

70. The next paper, by Kuo, on the -

"DYNAMIC INSTABILITY OF TWO-DIMENSIONAL NON-DIVERGENT FLOW IN A BAROTROPIC ATMOSPHERE" (24)

is a solid mathematical treatise on the problem and should certainly be read by those with sufficient mathematics to handle it, but it is rather outside the scope of this address.

71. In the May, 1949, issue of Tellus, Berggren, Bolin and Rossby published a paper on-

"AN AEROLOGICAL STUDY OF ZONAL MOTIONS, ITS PERTURBATION AND BREAKDOWN" (25)

The authors dealt with a series of rapidly moving frontal waves associated with a well-developed zonal current over central Europe. The blocking action by anti-cyclonic development over Europe, so familiar to Canadian Meteorologists, played an important part in the study of this case.

72. The period studies was from February 6th through February 22nd, 1948.

73. The 500 mb. chart for February 9th at 0300 GMT, showed a well established predominantly western component in the mid-latitude flow from North America across the Atlantic to Western Europe.

74. During the period from the 6th to the 12th a series of wave disturbances passed over the British Isles and western Europe, and were of such intensity that they could not be considered as shallow phenomena.

75. Cross-sections published show a well-developed, though not particularly intense, Jet Stream.

76. Figures 17, 18 and 19 show the gradual development of the blocking action over the western approaches to Europe, with the consequent breaking off of a cold cyclonic vortex over the North Atlantic. Subsequent figures, 20 and 21, for February 18th and 20th, show the complete destruction of the established zonal westerly flow in the eastern North Atlantic, and in its place the development of an intense easterly Jet Stream over the Baltic and southern United Kingdom.

77. The western incursion of this blocking action is illustrated by figure 22, showing successive positions of the contour lines for 5300 geodynamic meters on the 500 mb. chart.

78. This paper is also remarkable, in that it is apparently the first occasion where the term "Jet" is applied to an easterly concentrated maximum of wind speed.

79. Figure 23 shows the vertical cross-section through this easterly Jet. The complete reversal of the temperature field by the blocking action is also worthy of note.

80. This paper should be read in detail by all practicising Meteorologists in Canada because of its very able presentation of the blocking action, and its effect on the general circulation, and the paths followed by cyclonic waves.

81. In order to make this presentation complete mention must be made of Van Mieghem's paper in Journal Scientifique de la Meteorologie, April - June, 1949, on the -

"GENERAL CIRCULATION OF THE ATMOSPHERE" (26)

82. This paper, as are many of Van Miegham's, was written for the mathematician, and no attempt will be made to summarize it in this address.

83. The first British paper on the Jet Stream was published in the July, 1949, issue of the Journal of the Institute of Navigation. It was a paper by Durst and Davis, on -

"JET STREAMS AND THEIR IMPORTANCE TO AIR NAVIGATION" (27)

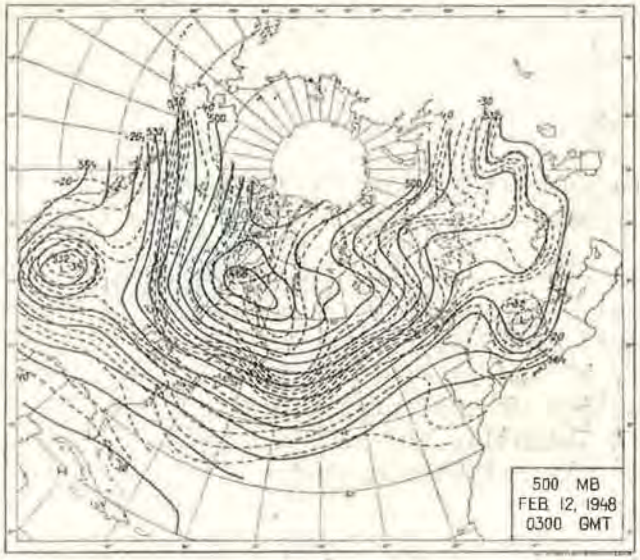

Fig. 17

Contours and isotherms on the 500-mb surface, 0300 GMT, February 12, 1948.

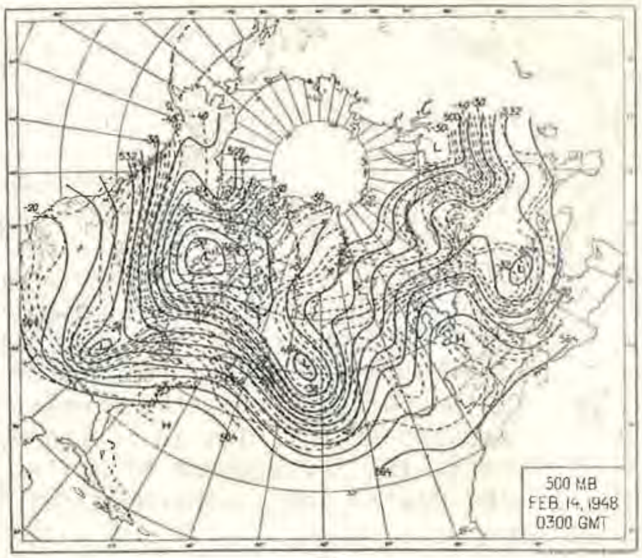

Fig. 18

Contours and isotherms on the 500-mb surface, 0300 GMT, February 14, 1948.

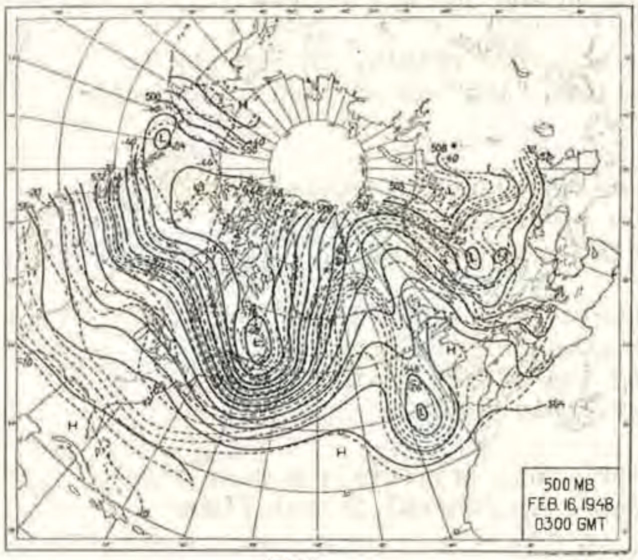

Fig. 19

Contours and isotherms on the 500-mb surface, 0300 GMT, February 16, 1948.

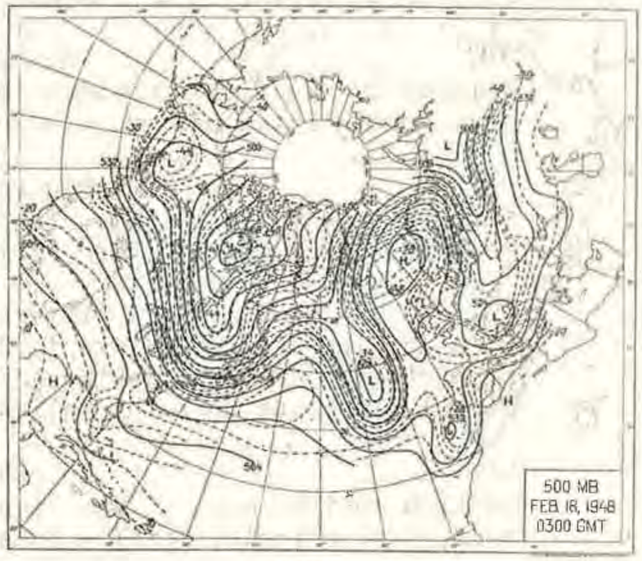

Fig. 20

Contours and isotherms on the 500-mb surface, 0300 GMT, February 18, 1948.

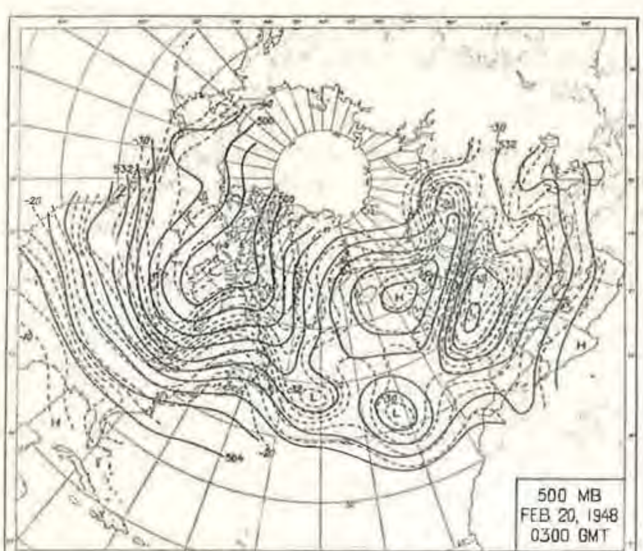

Fig. 21

Contours and isotherms on the 500-mb surface, 0300 GMT, February 20, 1948.

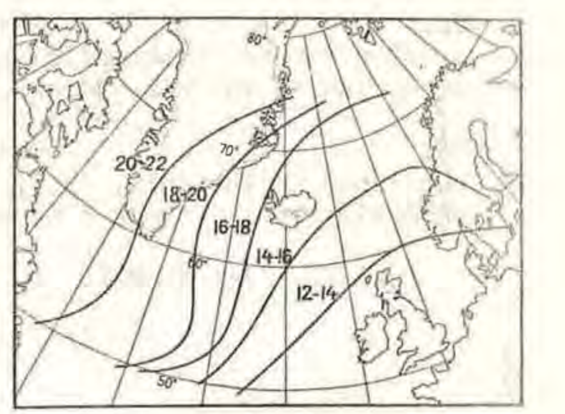

Fig. 22

Successive positions of the contour line for 5300 geodynamic meters as taken from overlapping three-day mean charts for the 500 mb level in February 1948. The numbers indicate the periods for which these mean charts were constructed.

Figs. 17, 18, 19, 20, 21 and 22 from (26) – An Aerological Study of Zonal Motion, its Perturbations and Breakdown. Tellus, Vol. 1, No. 2, 14-37. By – Berggren, R., Bolin, B., and Rossby, C. G., 1949.

84. The paper presents a useful summary of the properties of the Jet Stream, and deals specifically with certain discreet synoptic situations.

85. The cross-sections published in this paper are particularly note-worthy because of the density of the upper air information available for their construction.

86. Another excellent paper, of primary mathematical import, of which only passing mention may be made, is that presented by Platzman, on -

"THE MOTION OF BAROTROPIC DISTURBANCES IN THE UPPER TROPOSPHERE" (29)

appearing in the August, 1949, issue of Tellus.

87. In the August, 1949, issue of the Journal of Meteorology, Palmén and Nagler published a paper on -

"THE FORMATION AND STRUCTURE OF LARGE /SCALE DISTURBANCES IN THE WESTERLIES" (28)

88. This paper dealt specifically with the period from the 3rd to the 7th of February, 1947, when a very considerable change in the circulation pattern took place over North America. During that period a well-developed westerly flow, with only small perturbations, was changed to a flow dominated by large warm anti-cyclones over the northern part of the continent, and an unusually large cold cyclone covering the eastern part of the United States and south-eastern Canada.

89. The analysis was carried out using 500 and 200 mb. charts. Figure 24 illustrates a well-developed westerly flow persisting on the 3rd of February at 500 mbs. Figure 25 shows the beginning of the change on the 4th of February.

90. Figure 26 is a cross-section normal to the north-westerly upper flow, showing the position of the north-westerly Jet, which in this case reached a maximum of some 180 miles per hour at a little above 400 mbs.

91. Figures 27 and 28 show the 500 and 200 mb. charts on the 5th of February, illustrating the breaking away of a very intense cold cyclonic vortex, with the Jet Stream forced well south to the vicinity of Charleston, North Carolina, where

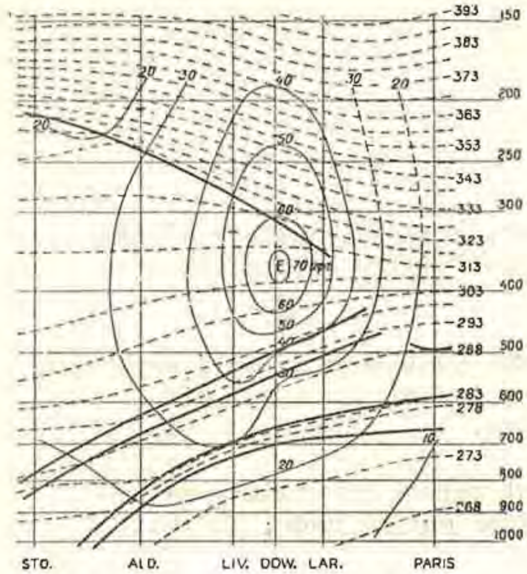

Fig. 23 Distribution of wind speed in the easterly jet over southern England on February 20, 1948, 0300 GMT. Thin solid lines indicate the wind speed normal to the section and thin broken lines the isentropes for dry air. Frontal boundaries, inversions and tropopauses are given by the thick lines.

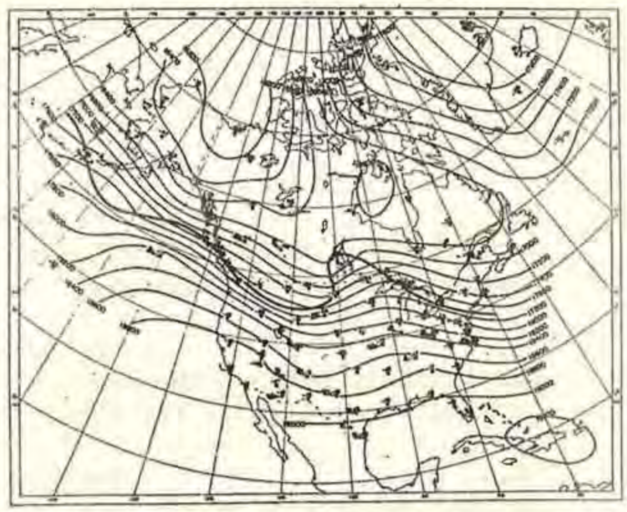

Fig. 24 Contours and observed winds and temperatures at the 500-mb surface for 0300 GCT 3 February 1947. The heavy line represents the southern edge of the frontal zone at this level. Each half barb represents a wind speed of 5 mi hr^{-1}, each full barb 10 mi hr^{-1}, and each shaded-in wedge 50 mi hr^{-1}. All temperatures are in degrees centigrade.

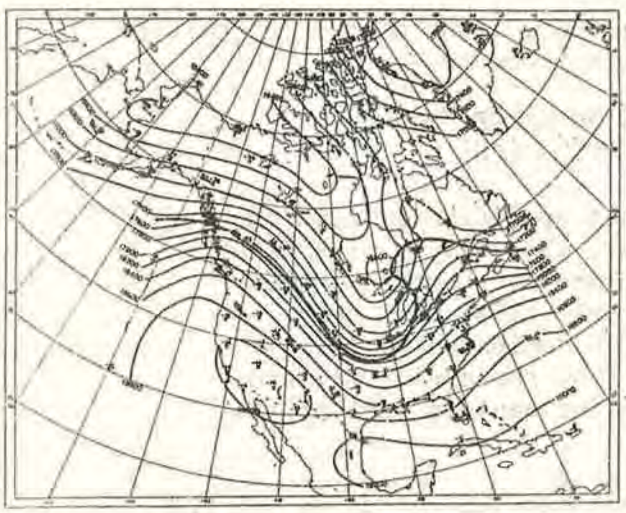

Fig. 25 Contours, front, and observed winds and temperatures at the 500-mb surface for 0300 GCT 4 February 1947.

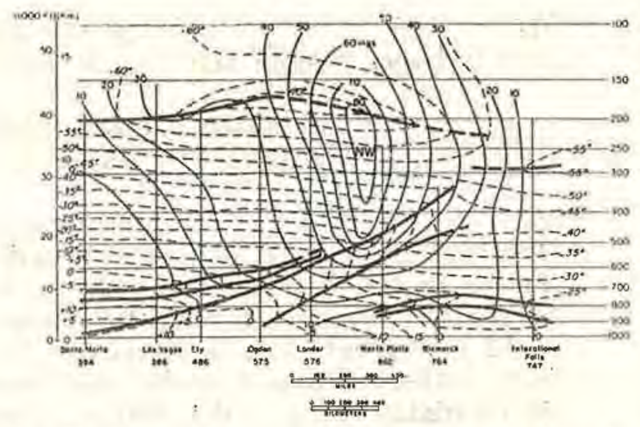

Fig. 26 Cross section normal to the northwesterly upper flow at 0300 GCT 4 February 1947. The thin solid lines give the geostrophic wind velocity (m sec^{-1}), the dashed lines are isotherms, and the heavy lines are tropopauses or boundaries of frontal layers. Where dashed, the heavy lines indicate that the tropopauses or frontal layers are not very well marked.

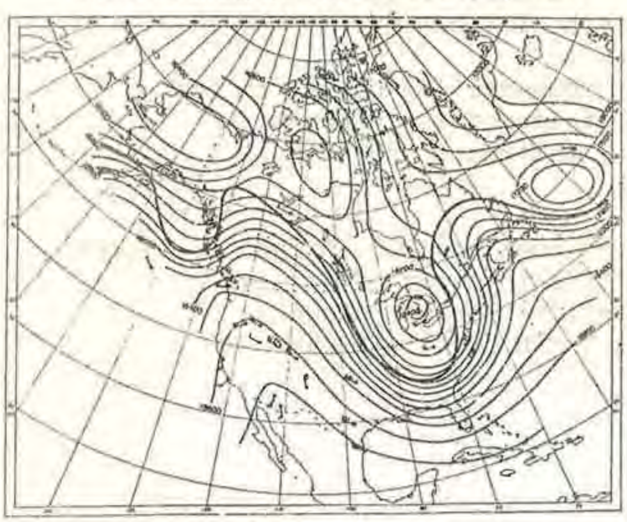

Fig. 27 The 500-mb surface for 0300 GCT 5 February 1947 showing contours, front, and observed winds.

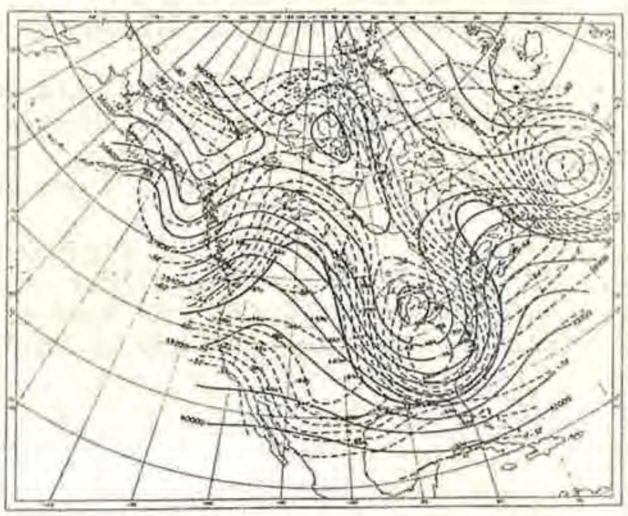

Fig. 28 The 200-mb surface for 0300 GCT 5 February 1947, showing contours (thin solid lines), isotherms (dashed lines), tropopause (heavy solid line), and observed temperatures.

Fig. 23 from (25) - An Aerological Study of Zonal Motion, its Perturbations and Breakdown. Tellus, Vol. 1, No. 2, 14-37. By - Berggren, R., Bolin, B., and Rossby, C. G., 1949.

Figs. 24, 25, 26, 27, and 28 from (29) - The Formation and Structure of a Largescale Disturbance in the Westerlies. J. Meteor., 6, 227-242. By - Palmén, E. and Nagler, K. M.

it attained, of necessity, its maximum velocity of an incredible 140 meters per second, as shown in figure 29: that is some 315 miles per hour, at a height of some 325 mbs., i.e. 28,000' approximately.

92. By February 7th figures 30 and 31 the warm anti-cyclonic ridge had pushed over northern Quebec and Baffin Island, leading to a complete reversal of the thermal gradient over Quebec: and, although an appropriate cross-section is not presented one would be led to expect the formation of an easterly Jet similar to that presented in the situation over Europe analysed by Berggren, Bolin and Rossby (25) referred to above.

93. This paper is also outstanding in illustrating the very large-scale meridional exchanges of air masses which take place in connection with the breakdown of zonal flow, and the possible vertical motions of the Jet Stream in such a case.

94. The most recent issue of the Journal of Meteorology available at the time of this address, that of October, 1949, contained no less than three papers on the Jet Stream: the first, by Sekera, on -

> "THE DISTRIBUTION OF KINETIC ENERGY IN CERTAIN TYPES OF STEADY BAROTROPIC CURRENTS" (30)

is a mathematical treatment of the problem.

95. In the second paper Namias, together with Clapp, returns to the fray with a paper on the -

> "CONFLUENCE THEORY OF THE HIGH TROPOSPHERIC JET STREAM" (31)

wherein a more thoroughgoing presentation of the confluence theory is made.

96. Namias concludes with the observations that his studies tend to confirm the theory of confluence as the origin of the Jet Stream. His paper contains one excellent diagram giving the average Northern Hemisphere position and strength of the Jet Stream for January, prepared from eighteen hemispherical meridional cross-sections.

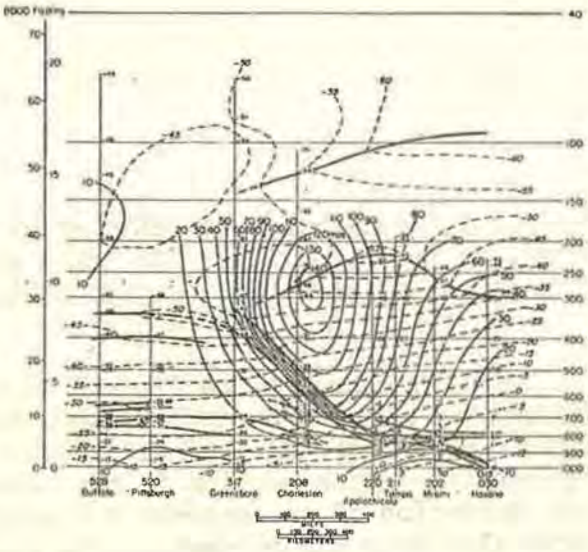

Fig. 29

North-south cross section for 1500 GMT 5 February 1947 (See fig. 26 for explanatory legend). The observed temperatures along the soundings are also shown.

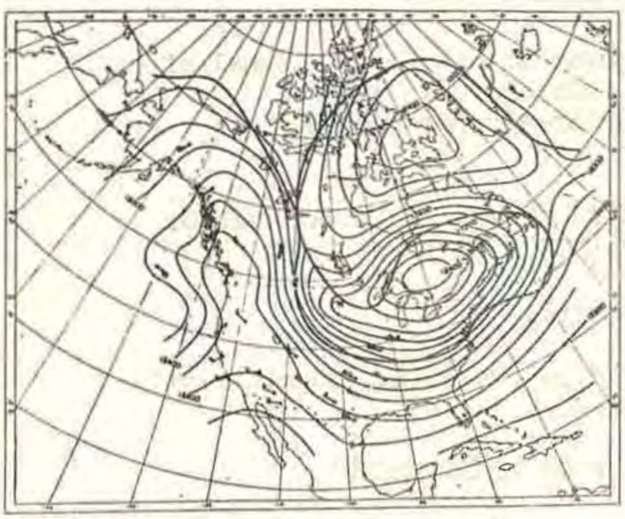

Fig. 30

The 500-mb surface for 0300 GCT 7 February 1947, showing contours, fronts, and observed winds.

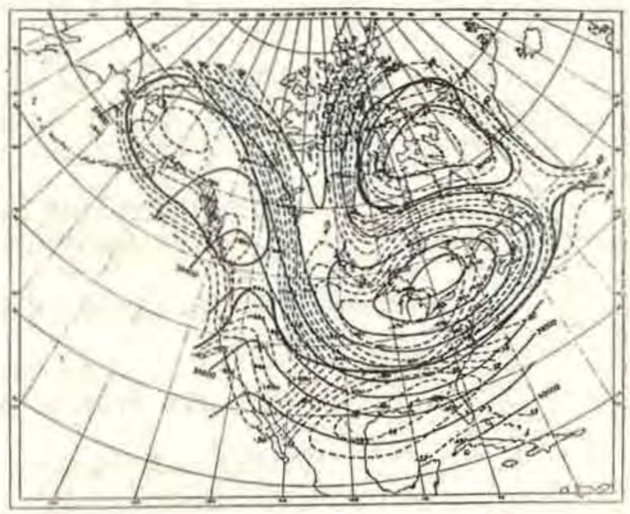

Fig. 31

The 200-mb surface for 0300 GCT 7 February 1947, showing contours (thin solid lines), isotherms (dashed lines), tropopauses (heavy lines), and observed temperatures.

Fig. 29, 30 and 31 from (28) – The Formation and Structure of a Large-scale Disturbance in the Westerlies. J. Meteor., 6, 227-243. By – Palmén, E. and Nagler, K. M.

97. Namias' paper will undoubtedly result in considerable discussion.

98. Perhaps the most controversial paper is the third one, on -

"THE RELATION OF PRECIPITATION PATTERNS IN NORTH AMERICAN TO CERTAIN TYPES OF JET STREAMS AT THE 300 MB. LEVEL" (32)

presented by Captain Starrett of the United States Air Weather Service.

99. Much importance is attached by those in opposition to Namias' confluence theory to the precipitation pattern to be found associated with a Jet Stream. According to the Rossby school of thought, rising air should be found just to the North of the axis of the Jet Stream, thus requiring a maximum of rainfall to the North of the Jet.

100. Studies of this nature are full of pitfalls and are very difficult to make entirely objective because of the variety of other causes which result in substantial amounts of precipitation. However, Starrett bases his paper on the study of twenty-four hour rainfall amounts in fifty-seven synoptic situations.

101. All one can conclude, from the method used by Starrett and the published results, is that there appears to be some slight evidence of the precipitation pattern favouring the northern side of the axis of the Jet Stream, but it is certainly not as convincingly demonstrated as many of the other properties of the Jet Stream.

CONCLUSION

102. In conclusion, the following is a brief summary of the physical properties of the Jet Stream as set forth in the preceding array of scientific papers.

103. For clarity of exposition, the summary is based on the simplest possible definition of the Jet as:

"A JET STREAM IS A NARROW ZONE OF EXTREMELY STRONG WINDS IN THE UPPER TROPOSPHERE"

PROPERTIES

104. Location and extent

104.1. Vertically, the Jet Stream lies approximately between 15,000' and 50,000' above sea level, with its maximum intensity lying normally between 350 and 200 mbs. i.e. approximately between 25,000' and 40,000', at about the tropopause level.

104.2 In winter, over North America, the latitudinal location of the Jet varies between 50°N and 30°N, approximately. In summer there is a northward shift to at least 55°N.

104.3 South of 30°N the Jet Stream appears to break down due to inertia instability.

104.4. The Jet is normally associated with a Polar front.

104.5. The axis of the Jet is approximately vertically above the intersection of the Polar front and the 500 mb. surface.

104.6. A Jet Stream does occasionally appear as completely circling the Northern Hemisphere, but more frequently is broken at various points.

104.7. It does not follow a straight horizontal course around the hemisphere, but meanders north and south and vertically over several thousand feet in altitude.

104.8. The wave-length of this meandering varies between 50° and 120° of longitude.

104.9. With excessive meandering, that is, considerable amplitude of the waves, the Jet Stream breaks down and cold vortices are formed in the southern portions of the troughs, with the zonal westerly circulation reestablishing farther north. This leads to intense meridional mixing and the cold vortices aloft are of great importance in the forecasting of the associated low troposphere weather phenomena.

104.10. Successive waves in the Jet Stream are dynamically linked, so that an intensification in one has an effect downstream on the next. Similarly, the deepening of one upper trough will in some cases lead to a second deepening down-stream.

105. Movement

105.1. The extension of the Jet Stream along its length has not yet been adequately documented, but it appears that such extensions can be carried out over great distances, leading occasionally to the establishment of a complete hemispherical Jet.

105.2. From day to day the Jet Stream can move in the direction at right angles to its axis, with a speed of around ten knots. This motion can be either towards the Polar air or towards the tropical air.

105.3. The mean position of the Jet Stream shifts south in the winter and north in the summer.

106. Wind Speeds

106.1. Wind speed in the Jet Stream can reach values in excess of three hundred miles per hour, especially in low latitudes, i.e. between 30° and 35°N.

106.2. The Jet Stream normally has a strong westerly component, but with the reversal of temperature gradients, due to intense mixing in the horizontal plane, a Jet can appear with a predominantly easterly component.

106.3. The intensity of the Jet Stream increases with decrease in latitude.

106.4. Wind speeds decrease very rapidly to the north and south of the Jet Stream, reaching values as high as 100 knots decrease in 100 miles on the north side of the Jet, and 100 knots in 300 miles on the south side of the Jet. This constitutes a very strong horizontal wind sheer.

106.5. There is also a strong vertical wind sheer, particularly in the vicinity of the associated frontal surface. A decrease of 80 knots in 12,000' below the centre of the Jet Stream is by no means uncommon, and is exceeded substantially in certain places along the Jet. Decrease with altitude above the Jet is similar in magnitude, but more uniform.

107. Temperature field

107.1. When associated with a front the Jet Stream is located in the warm air, either in or just south of the maximum temperature gradient between the polar and tropical air.

107.2. The Jet Stream is associated with a break in the tropopause, with the tropopause in the polar air being substantially lower than the tropopause on the warm air side. Not infrequently the tropopause on the warm air side has a double structure.

107.3. At the level of the axis of the Jet Stream, i.e. approximately 250 mbs. on the average, there is a zone of lowest temperature approximately 4°S of the Jet Stream, and a zone of highest temperature approximately 7°N of the Jet Stream.

107.4. This zone of warm air in the lower stratosphere immediately to the north of the Jet Stream leads to the establishment of a secondary maximum west wind to the north of the Jet Stream.

107.5. An intensification of the Jet Stream can lead to an intensification of the associated front in the lower troposphere.

108. Turbulence

108.1. There is reason to believe that severe high level turbulence will occur on occasion along the boundaries of a well-developed Jet Stream, and that light or moderate turbulence will normally be expected in this area.

109. Precipitation

109.1. There is some evidence that there is a precipitation maximum vertically below, or slightly to the north of, the Jet Stream, but from available published data the magnitude of this maximum is such that it might easily be disguised by orographic and frontal precipitation patterns, and, therefore, cannot be conclusively associated with the Jet Stream at the present time.

110. General

110.1. When an intense Jet Stream, a long wave in the westerlies and a perturbation in a front in the lower troposphere are in phase in the favourable sense, very intense and rapid cyclogenesis can be expected, even though the front itself is relatively weak.

110.2. There is evidence that both directly and indirectly driven Jets occur. The process of large scale confluence of cold and warm air currents frequently contributes to the intensification of the Jet Stream, but there appears to be other mechanisms of equal, or possibly greater, importance leading to a well-developed Jet Stream.

110.3. There is evidence of the steering of frontal waves in the lower troposphere by the Jet Stream.

110.4. The retrograde blocking action, which not infrequently develops over Europe and extends westward to affect North America, leads to a complete destruction of the westerly Jet Stream, intense mixing in the horizontal plane, and can result in the establishment of an easterly Jet.

CLOSING REMARKS

111. In closing, it is desired to stress again that the remarks in this paper have been confined to the practical, physical properties of the Jet Stream, as discovered by researches in the field. With this limitation the address has, of necessity, ignored very important portions of some of the papers, and other papers have had to be passed over almost in toto.

112. I hope I have been able to give you a clear physical picture of this latest meteorological problem child, If, in addition, I have alerted you to the need for both Meteorologists and aviators to pay close attention to subsequent literature on the Jet Stream I have accomplished my purpose.

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APPROXIMATE CONVERSION FROM METRES PER SECOND TO MILES PER HOUR

Metres per second	Miles per hour
10	22
20	45
30	67
40	90
50	112
60	134
70	157
80	179
90	202
100	224
110	246
120	269
140	314

VERY APPROXIMATE CORRESPONDENCE OF PRESSURE IN MILLIBARS AND HEIGHT IN FEET

Millibars	Feet
700	9,000
500	18,000
400	23,000
300	30,000
250	35,000
200	40,000
150	46,000
100	54,000