

The Break Down of Zonal Circulation during the Period January 8 to 13, 1956, the Characteristics of Temperature Field and Tropopause and its Relation to the Atmospheric Field of Motion¹

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Abstract

I. An introductory outline of earlier work (FR. DEFANT and H. TABA, 1957, 1958, 1958) on hemispheric changes in the type of General Circulation by means of tropopause maps is presented to make the reader familiar with the main features of tropopause and its intimate relation to the main windcores of the westerlies. The prehistory of the period from Jan. 8 to 13, 1956, which we studied in this paper, is described in detail.

II. Tropopause maps for each day (Jan. 8 to 13, 1956) are presented. By means of these maps it was shown, how the zonal type of Circulation (zonal with respect to a zonal polarfront jet) changes during this period into a meridional (meandering) type. The behaviour of subtropical jet (in a characteristic way different from that of polarfront jet) is simultaneously discussed.

III. A selection of soundings with respect to the breaklines in the tropopause level or according to the location of the belts of maximum wind of the westerlies was made for each day. Different characteristic groups of soundings (different with respect to the total vertical temperature distribution and the form as well as the height of tropopause) are discussed and characteristic mean soundings for each group are computed.

IV. A computation of standard deviation of the individual vertical temperature distributions from the mean one for each group is presented. An important conservatism of the sounding type in each group is shown.

Meridional temperature differences between different groups inform the reader about the possible locations of baroclinity in tropo- and stratosphere.

V. A statistical investigation of tropopause level by use of 2,513 atmospheric soundings from Jan. 1 to 13, 1956 is presented. The structure of tropopause is discussed.

VI. A synoptic vertical cross section clarifies the relationship between subtropical break in the tropopause level and the existence of the subtropical jet. Important aspects of form of subtropical jet are outlined.

I. Introduction

In three different papers (DEFANT, FR. and TABA, H., 1957) the authors investigated large-scale developments in the General Circulation by means of hemispheric maps of tropopause

height and tropopause temperature. A complete and rather careful inspection of the total radio-sonde material of the Northern Hemisphere with respect to the total vertical structure of the soundings was made.

It was found that the tropopause is not a continuous surface between the equatorial and the polar region in the atmosphere as it has

¹ This article summarizes part of the results of investigations on the General Circulation, especially with reference to the upper layers of the atmosphere.

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mostly been thought in meteorology so far. On the contrary three different tropopause levels could be distinguished appearing in different parts of the atmosphere.

From the equator northward to approximately the 30° parallel the so-called *tropical tropopause* can be found in the winter season generally at a height of 80 to 100 mb (17.5 to 16 km) and with a slow decline from the equator to 30° N latitude circle. But from there northward the tropical tropopause lifts its level and gradually disappears.

In low latitude soundings possessing the single and pronounced tropical tropopause near 90 mb the gradual decrease in temperature with height appears to be interrupted in the middle layers of the troposphere (at about 350 to 250 mb) by a layer of small vertical extent showing either a slight inversion or isothermy. Mostly, however, only a change in the uniform lapse rate appears, so that the upper tropospheric part of low latitude soundings possesses a steeper lapse rate than the lower one. This discontinuity in the uniform lapse rate should not be called a tropopause, because of the further decrease of temperature upwards and because of the existence of the tropical tropopause near 90 mb. This break in the continuous lapse rate of the low latitude soundings lifts somewhat and becomes a pronounced tropopause near the 200 mb level (12 km), when we approach the region near latitude circle 30° N. From there northward this lower tropopause level continues to exist and, while the tropical tropopause lifts and gradually loses identity in the higher stratosphere, the lower one becomes the dominant and only tropopause over mid latitudes. It lowers only gradually its level from 200 mb (12 km) near 30° N down to approximately 240 mb (11 km). This height seems to be characteristic for this tropopause level in mid latitude soundings and we called this tropopause therefore the *middle tropopause*.

From these results it is obvious that a layer with a vertical extent of about 5 km exists near 30° N, where the tropical and the middle tropopause overlap (subtropical breakline in the tropopause level). By means of this layer from 200 mb up to 90 mb (12 to 17 km) the higher part of the tropical troposphere is directly connected with the stratosphere of mid latitudes. This subtropical tropopause break allows a direct horizontal exchange of air between

tropo- and stratosphere and is therefore of utmost importance.

Immediately below the lower tropopause near 30° N a core of the maximum westerlies is found, already earlier in literature referred to as the subtropical jet stream. An intimate relation exists between this doublefold tropopause structure and the existence of this special jet phenomenon of the westerlies observed in soundings near 30° N.

The middle tropopause descends more rapidly at some northern latitude down to approximately 270–290 mb (10 to 9.5 km). There one can observe in the wind field of the westerlies the existence of the polar front jet stream near to the 300 mb level. North of this second wind maximum in the westerlies the tropopause level was observed again in lower altitudes (lower than 300 mb) (*polar tropopause level*). Therefore a further break in the tropopause level appears in connection with the polar front jet. This break does not have so much vertical extent as the subtropical one and is mostly only of 2 km vertical extent. The density of our radiosonde network does not allow a clear decision, whether the tropopause in the polar jet region is a continuous one just above or even through the jet core, but there is at least a pointwise evidence that soundings which hit the polar jet core do not show any tropopause at all. They rather show a continuous decrease of temperature with height from the troposphere upwards into the stratosphere. There are also cases with rather complicated discontinuities in the vertical temperature distribution. Here we again want to comment that polar jet soundings also show breaks in lapse rate due to intersections with the upper boundaries of the polar front surface and therefore such breaks in lapse rate can easily be misinterpreted as a tropopause. It depends very much on the exact location of the soundings relative to the polar front jet core. The complicated structure of this special kind of soundings makes it rather hard to fix the tropopause, if there exists at all a tropopause in or just above the polar jet core.

In the polar region, north of polar jet, the tropopause level is no more restricted to a certain preferred height, but is always found to exist in levels *lower than 300 mb (9 km)*. It seems from our study that in some distance (about 5 or 10° of latitude north of the polar

jet) the polar tropopause is lowest. In connection with the meandering structure of the polar jet we can clearly follow a ring-shaped depression of the polar tropopause around the earth. In the winter season, which we have studied, the polar tropopause can be realized in this ring-shaped tropopause valley as low as 370 to 450 mb (8 to 6 km). Only in polar vortices and in addition in cut-off lows of polar origin appearing frequently over much more southern latitudes, the polar tropopause drops down to extreme altitudes (near 500 mb).

The sparsity of the data in the northernmost part of the earth from latitude 75° N to the pole does not allow a definite description of tropopause conditions. But there is at least an indication that the tropopause level rises again to higher elevations (sometimes even as high as 230 mb or 11 km). There are, however, occasions when no tropopause exists in the northernmost soundings of the world and a continuous decrease of temperature may be noticed from the troposphere upwards into the stratosphere. There are other occasions when the polar tropopause lowers continuously its level from the polar front jet location to extremely low heights at the pole, mostly when a pronounced polar cyclonic vortex exists. Otherwise the high polar tropopause or even the non-existence of a tropopause over the polar cap is frequently combined with the presence of a strong and deep anticyclone over the polar region.

Summarizing these results we stress again the important fact of a threefold structure of the tropopause level in the winter season. Starting from this threefold distinction in the tropopause level we have shown in one of our previous papers (DEFANT, FR. and TABA, H., 1957), that a mean geographical location of the different tropopause levels is only a simplified average picture. In general one might agree in restricting the tropical tropopause to the region between equator and 30° N, the middle one to the mid latitude belt and the polar one to the northern latitudes, but as we pointed out earlier and in our previous papers, the breaks or breaklines in the tropopause go parallel with the main maxima of the westerlies and therefore the meandering behaviour of the jets decides about the location and latitudinal distribution of the different tropopause levels.

In the period from January 1 to January 7, 1956 we were able to demonstrate that the high tropical tropopause, which in the mean is located over the region south of latitude 30° N, sometimes in connection with strong meandering behaviour of the subtropical jet stream shifts northward towards middle and higher latitudes and appears on top of large and deep anticyclonic vortices gradually forming over these latitudes. The identity of such subtropical intrusions in its northward motion towards middle and higher latitudes could be followed from day to day on synoptic maps quite definitely. It was further shown that these intrusions from the tropical-subtropical regions appeared simultaneously during the period in question in different parts of the world. On January, 7, 1956 several of such features existed over middle and higher latitudes, whereby the region characterized earlier by the existence of a middle tropopause level diminished and nearly disappeared. In this case the high tropical tropopause level could be observed opposite the low polar tropopause. Naturally the tropical tropopause in such northward shifts did not hold its high altitude for a considerable long time, but adjusted itself at a somewhat lower level over middle and higher latitudes, but this level was well above 200 mb (near 175 mb), which is still a rather unusually high tropopause for these latitudes.

These subtropical impulses, from which each one was connected with the formation of extensive blocking anticyclones over mid latitudes, had strong effect on the structure and location of the polar jet. The polar cold air and the region with a polar tropopause level was restricted to rather northern latitudes (mostly north of latitude 60° N) with the exception of the more permanent southward extension of polar air over Eastern Asia (permanent trough). The polar front jet lost its meandering structure, which was present on January 1, 1956, and took on a more zonal form in northern latitudes (zonal circulation type). At the same time branches of the subtropical jet surround the different blocking anticyclones and come close to the polar front jet in some regions of the earth or even superimpose the polar jet maximum.

These places, in which the pure polar air north of polar jet stands next to the pure subtropical air inside the large blocking anti-

cyclones and for which most of the meridional temperature contrast between 30 and 60° N appears to be concentrated in a small latitudinal interval of 5 to 10° lat. are of much interest. Here a steeply inclined polar front surface separates subtropical from polar air in the troposphere and almost no air of the intermediate type (middle air) seems to be present. But also in the higher layers of the atmosphere a steeply inclined tropopause (with an opposite inclination relative to that of the polar front) separates the higher and extremely cold portions of the subtropical blocking anticyclones from relatively warmer air of the polar stratosphere in a frontlike manner. Extremely high wind velocities from 150 to 200 km are present. A vertical study of this wind field shows either two jet maxima (polar front jet and subtropical branch) close to each other, but in different heights (300 mb, resp. 200 mb), or even on top of each other (DEFANT, FR. and TABA, H., 1957), see also FR. DEFANT (1958).

We have mentioned several reasons why we expect these regions to be favourable for exceptionally strong cyclogenesis followed later on by a complete breakdown of the zonal circulation type. This type of vertical structure of the atmosphere does not seem to be a hydrodynamic stable one, especially not in such regions with the above described features of baroclinicity of a double kind. The zonal polarfront jet in combination with a meandering subtropical one represents a critical stage, which tends towards equalization of existing contrasts or tends towards cyclogenesis and breakdown of the zonal form of polar jet in form of polar outbreaks of cold air. As a consequence the polar jet takes on a meandering form and the subtropical jet readjusts at its normal position at latitude 30° N losing all meandering structure and reassumes its normal zonal character.

It is the purpose of this paper to present another series of tropopause analyses for the period January 8 to January 13, 1956 to demonstrate how the zonal type of circulation (zonal with respect to a zonal form of the polar front jet) of January 7 was destroyed and was changed into a meridional type of circulation, which is the more frequent type over mid latitudes. On January 13, 1956 such a meridional type of circulation seemed to be re-established, characterized by a meandering

polarfront jet well separated from the more zonal subtropical jet stream, which then has formed again near latitude circle 30° N in almost all the northern hemisphere. Subtropical intrusions of the type described in form of strong anticyclonic vortices, containing pure subtropical warm air, having on top, however, rather cold air near the unusual high tropopause, gradually disappear from their unusual position in northern latitudes. They lose slowly their identity and characteristic features and the air masses in the troposphere transform into the normal type of mixed or middle air covering then the space between polar front and subtropical jet. The reestablishment of a region with middle air and middle tropopause gives rise to a complete separation of the main westwind maxima of the westerlies. Similarly to January 1, the tropopause map of January 13 shows the normal threefold structure in the tropopause level described before.

II. Tropopause maps of January 8 to January 13, 1956 and description of the breakdown of the zonal circulation type

Referring to our hemispheric tropopause analysis of January 7, 1956 (DEFANT, FR. and TABA, H., 1957), p. 240, it was pointed out that in many regions of the world polar front jet and subtropical jet branches were close together and critical conditions in the sense of the foregoing discussion were present. This was particularly true for the region southwest of Iceland in the Atlantic Ocean and at the Aleutian Islands in the North Pacific. In these regions already cyclogenesis happened and the zonal circulation type started to break down. On the tropopause map of January 8, 1956 (Fig. 1) we already notice trough-formations in the polar breakline of tropopause height due to this first outbreak of polar air from the polar region (over the North Sea and Great Britain and south of Alaska). However, in the Mid-Atlantic strong anticyclonic conditions with an abnormally high tropopause continue to exist. Under the influence of these first polar outbreaks penetrating south-eastward over Great Britain towards Central Europe, the large anticyclone over the Atlantic already starts to move westward and breaks up into separate anticyclonic cells. This preliminary activity at the polar front continues on January

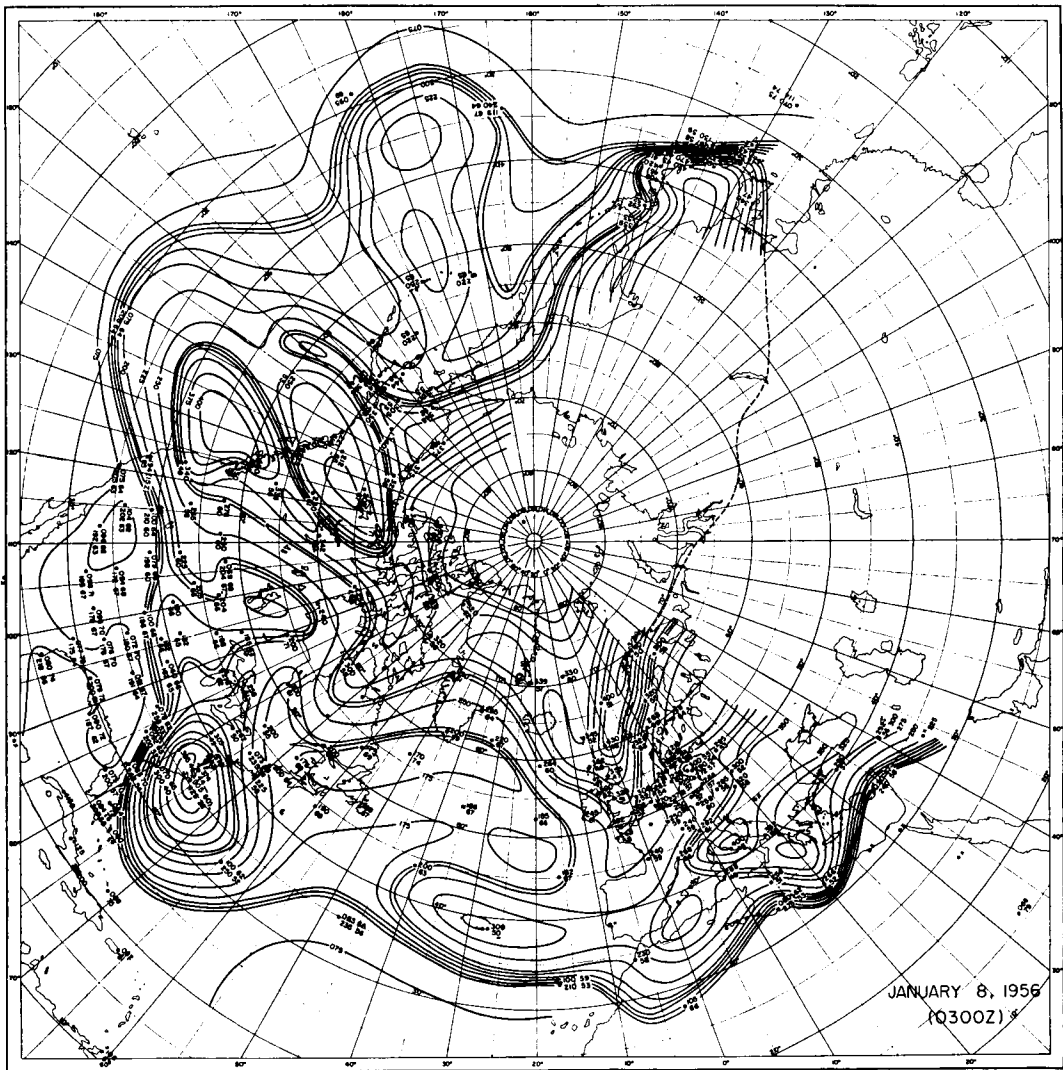


Fig. 1. Hemispheric map of tropopause level (in mb) for Jan. 8, 1956, 0300Z. Breaklines of tropopause level are shown by a concentration of isolines. (For each station tropopause height in mb (three figures) and tropopause temperature in °C (two figures) are plotted. Minus sign for temperatures omitted.)

9 (Fig. 2). Over the Mid-Atlantic southwest of Iceland critical conditions prevail and one may already visualize the formation of a new cold wave developing in the region between Iceland and Southern Greenland. A rather spectacular cyclogenesis can be observed in the surface maps of the 9th, 0000Z, 0300Z and 0600Z. Similar to this activity in the Atlantic Ocean cold outbreaks are also in progress over Alaska. On January 10, 1956 (Fig. 3) the rapid breakdown of the zonal circulation type in

both regions is clearly evident. In the Atlantic Ocean the polar breakline in the tropopause height has moved southward across the 50° parallel. This rather strong outbreak of polar cold air in the rear of the above mentioned well developed cyclone (62 mb pressure fall in 20 hours) definitely ended the anticyclonic conditions in this area. One part of the anticyclone can be seen over Northern Spain and the other one continued to move westward and appears over New Foundland. Similarly

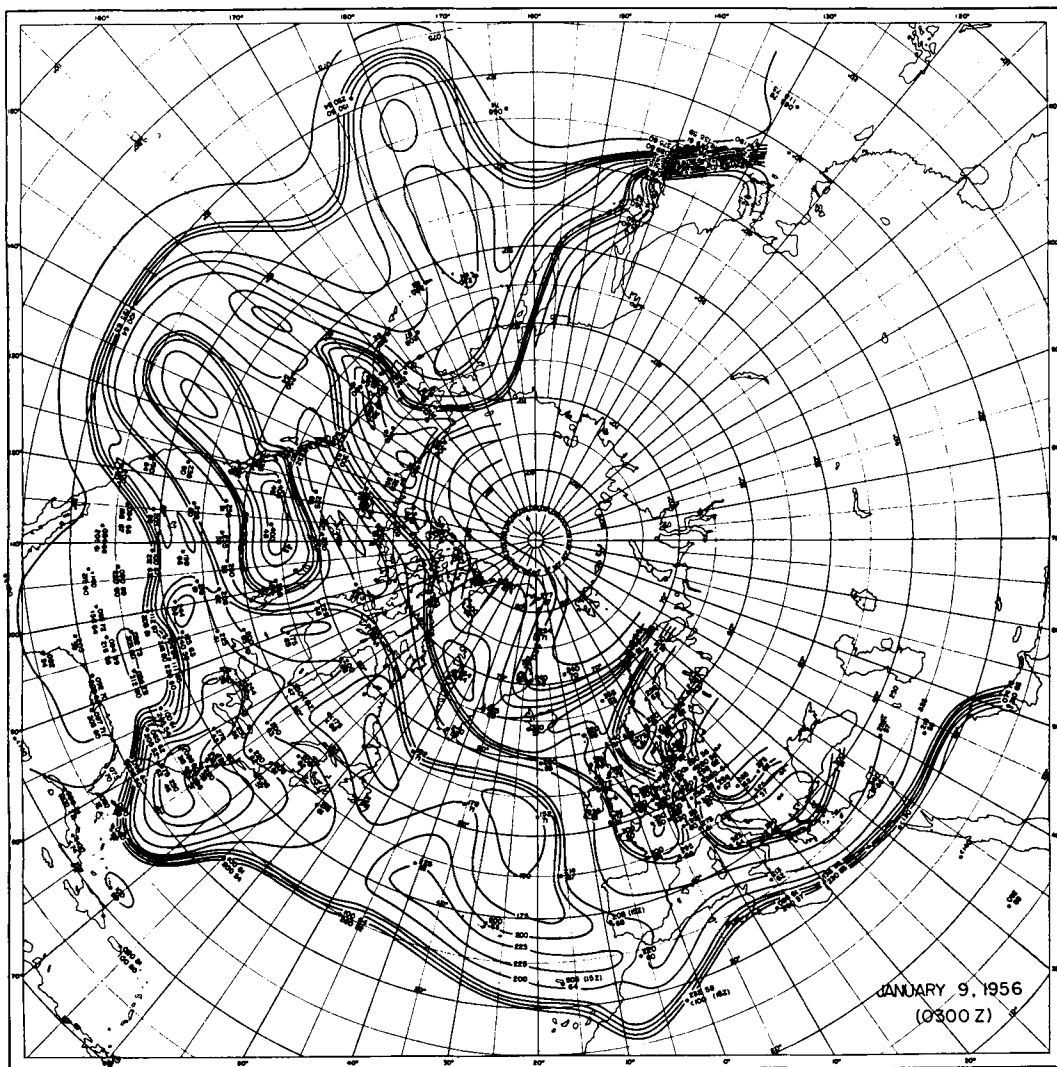


Fig. 2. Hemispheric map of tropopause level (in mb) for Jan. 9, 1956, 0300Z. Breaklines of tropopause level are shown by a concentration of isolines. (For each station tropopause height in mb (three figures) and tropopause temperature in $^{\circ}\text{C}$ (two figures) are plotted. Minus sign for temperatures omitted.)

the trough over Alaska became more pronounced and a progress of the polar jet in southern direction is equally evident in the Northern Pacific.

The tropopause map of January 10 indicates a meandering pattern consisting of three principle long waves in the polar breakline of tropopause height or what is the same, in the form of polar front jet, if one does not consider the vortex northeast of the Florida Peninsula, which according to the soundings consists only of a

shallow layer of polar air. This three-wave pattern could be seen more clearly in the 500 mb chart of January 10. We feel therefore justified to state that during the three days in question, the almost zonal circulation type present on January 7 consisting of a zonal polar front jet and a strongly meandering subtropical jet, transformed into the opposite meridional type of circulation with a meandering polar front jet and three long waves of 120° wavelength of pronounced amplitude on Janu-

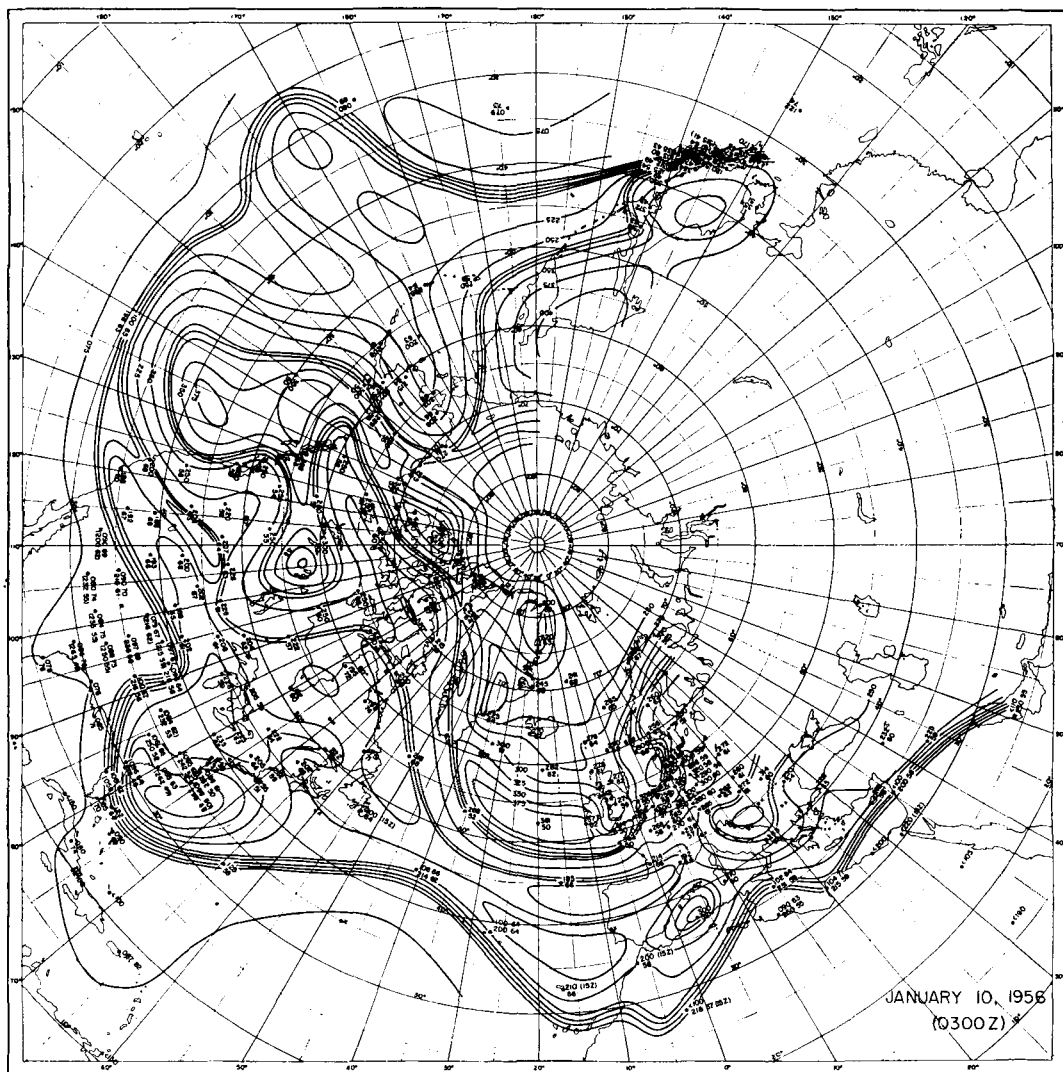


Fig. 3. Hemispheric map of tropopause level (in mb) for Jan. 10, 1956, 0300Z. Breaklines of tropopause level are shown by a concentration of isolines. (For each station tropopause height in m b (three figures) and tropopause temperature in $^{\circ}\text{C}$ (two figures) are plotted. Minus sign for temperatures omitted.)

ary 10, 1956. The subtropical jet has in the meantime reestablished itself at its normal position near latitude circle 30°N and only minor fluctuations disturb its almost zonal character.

There are other interesting features to be discussed on Fig. 1, 2 and 3. Over the North Pole itself higher tropopause values can be seen and the temperatures at the polar tropopause and higher up in the polar stratosphere are extremely low (almost as low as in the equatorial high stratosphere). Following each

outbreak a tongue of this high polar tropopause level extends southward in the rear of the developing surface cyclone showing very cold tropopause temperatures. This is clearly to be seen on January 9 and 10 between Greenland and Norway over the North Sea. It indicates well the outflow of extreme cold polar air from the polar region southward.

During this period the trough over Eastern Asia seems to have undergone a similar deepening and in the Japanese region an immensely

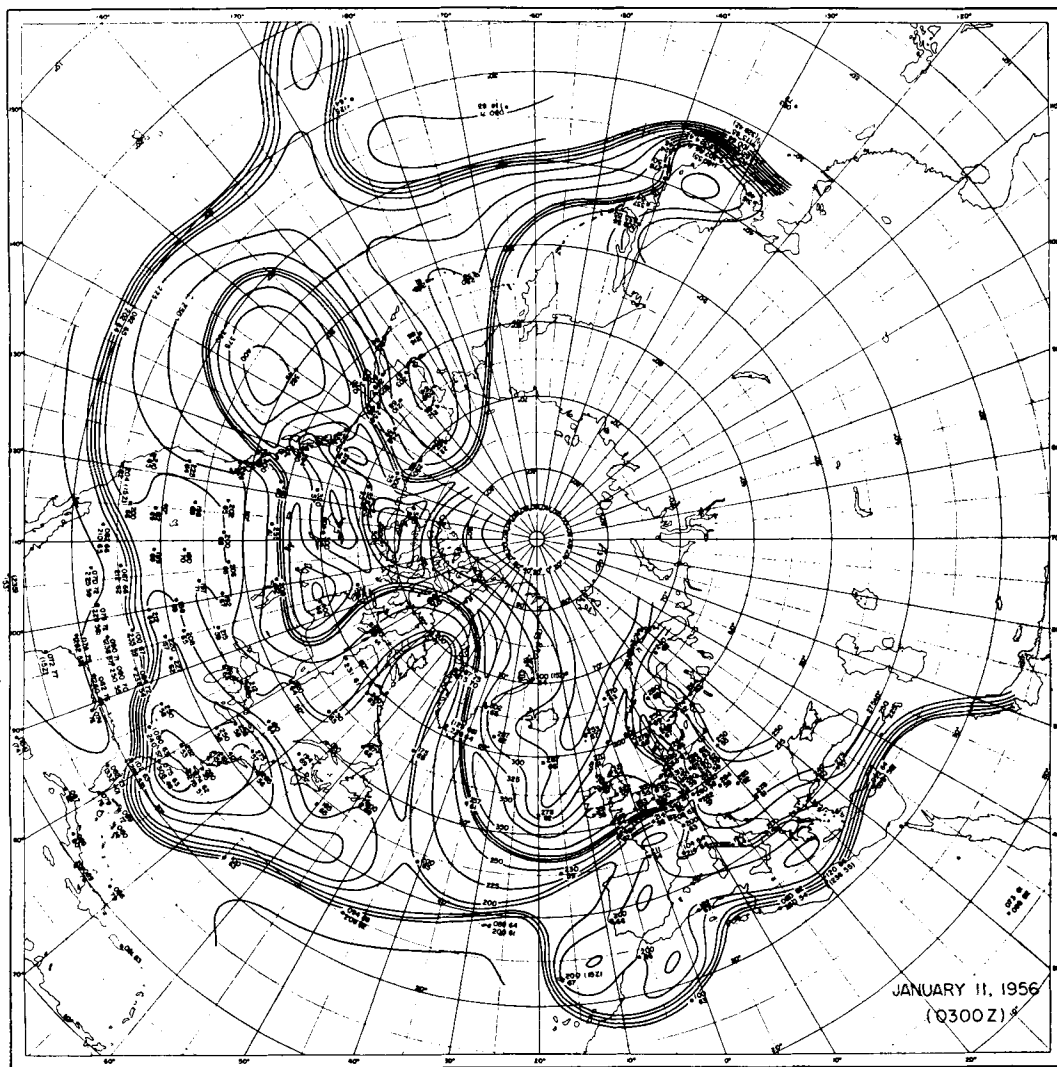


Fig. 4. Hemispheric map of tropopause level (in mb) for Jan. 11, 1956, 0300Z. Breaklines of tropopause level are shown by a concentration of isolines. (For each station tropopause height in mb (three figures) and tropopause temperature in °C (two figures) are plotted. Minus sign for temperatures omitted.)

strong gradient of the tropopause level appears, which indicates that polar front and subtropical jet are almost superimposed. This condition was not at all present during the period from January 1 to 7, which was a period of establishment of a zonal circulation type, opposite to a breakdown period, which we discuss now.

Gradually areas with a rather high subtropical tropopause disappear over the mid latitude belt and soundings between the almost zonal subtropical jet and the strongly meander-

ing polar front jet show more and more the character of middle soundings (according to our definition given in our previous papers (DEFANT, FR. and TABA, H., 1957). Therefore one may say that subtropical impulses disappear in mid latitudes and finally the two main westwind maxima of the westerlies are separated during this period by a large area with a middle tropopause level. The threefold structure of the tropopause level seems to be reestablished.

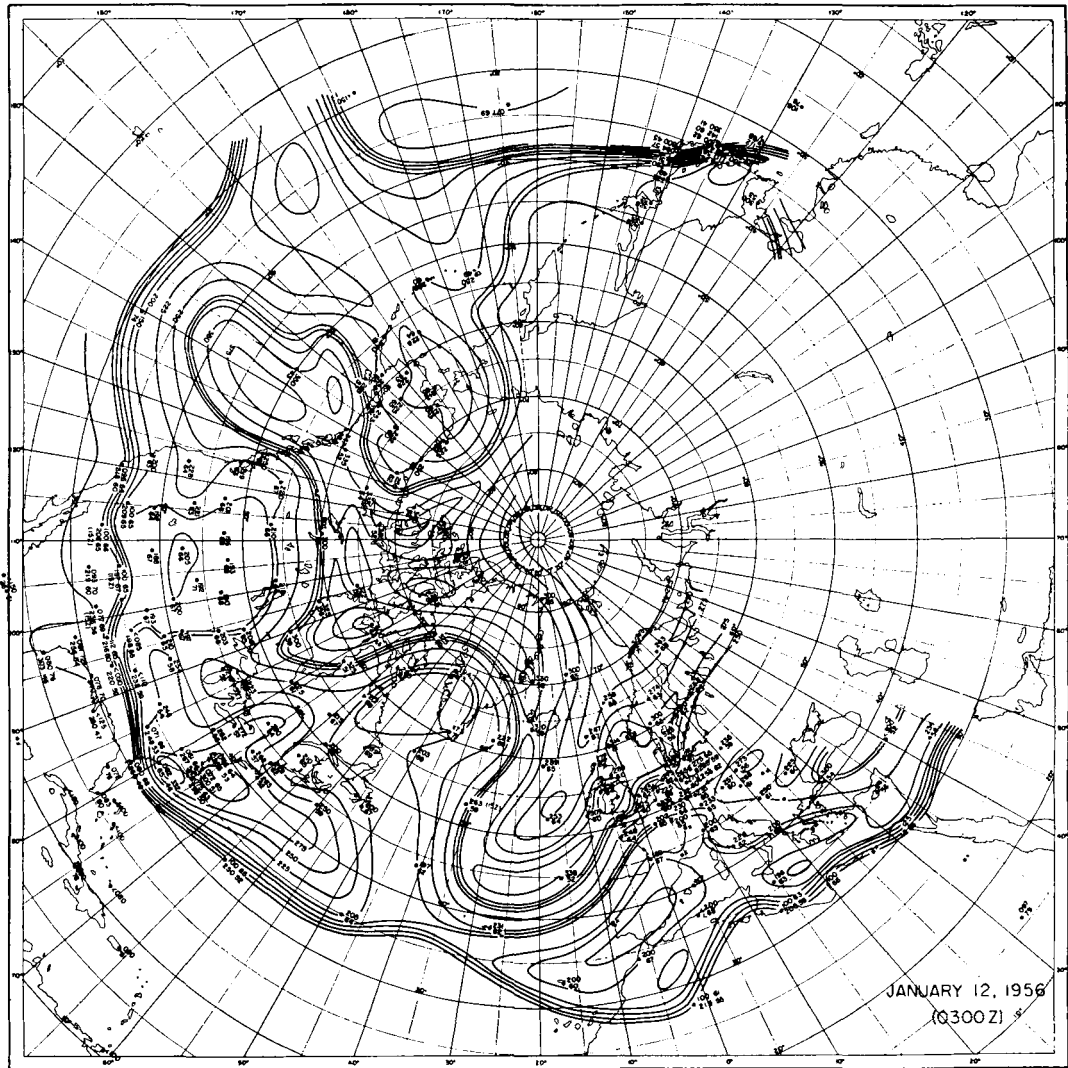


Fig. 5. Hemispheric map of tropopause level (in mb) for Jan. 12, 1956, 0300Z. Breaklines of tropopause level are shown by a concentration of isolines. (For each station tropopause height in mb (three figures) and tropopause temperature in °C (two figures) are plotted. Minus sign for temperatures omitted.)

Continuing the discussion with the tropopause maps of January 11 to 13 (Fig. 4, 5 and 6) we have little more to add, because the zonal structure of the subtropical jet continues during these days unaltered and even minor fluctuations disappear. However, the activity at the northern breakline of the tropopause height or of the polar front jet endures. The meandering pattern becomes more pronounced and a new long wave is formed over Eastern Canada to be seen on the tropopause map of January

12. There seems to be also an indication of a similar long wave formation northeast of Japan and south of the Sachalin Peninsula. Each of these newly developing long waves are connected with cyclogenesis of normal intensity at the polar front and are examples of long wave formations due to growing short waves. The 500 mb maps of January 12 and 13 show no more just three long waves around the earth, but one would rather count five or six. From theoretical reasoning one has already

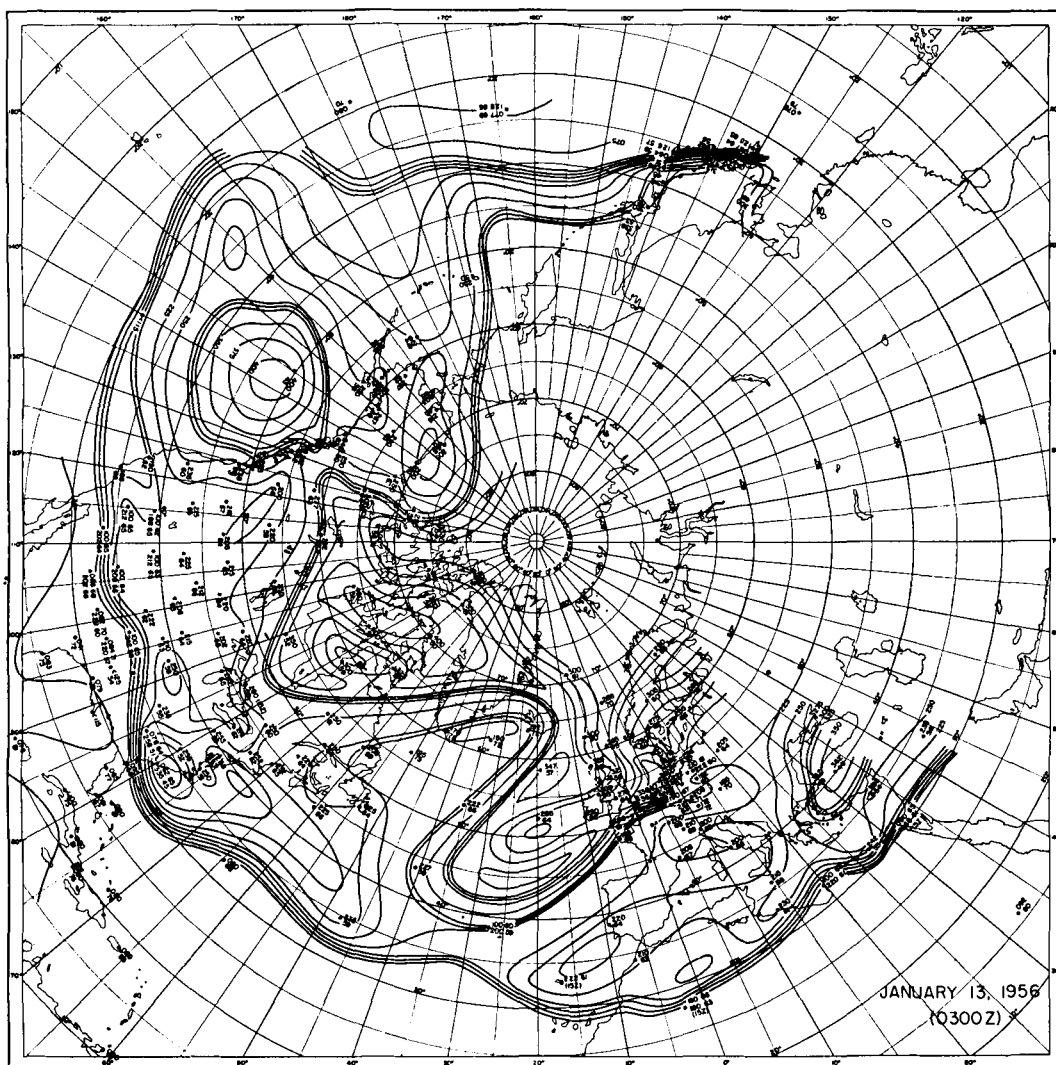


Fig. 6. Hemispheric map of tropopause level (in mb) for Jan. 13, 1956, 0300Z. Breaklines of tropopause level are shown by a concentration of isolines. (For each station tropopause height in mb (three figures) and tropopause temperature in $^{\circ}\text{C}$ (two figures) are plotted. Minus sign for temperatures omitted.)

concluded that during a period of intensification of meridional circulation and during a joint slow-down of zonal motion the number of long waves increases and the wave length shortens.

III. Presentation of different types of temperature soundings of January 8 to 13, 1956

A careful selection of soundings according to their location with respect to the main westwind maxima of the westerlies or according

to the breaklines in the tropopause level has been made for the period in question. The principles applied for this selection were the same as described in our previous papers (DEFANT, FR. and TABA, H., 1957). The following selection in the sounding type was made:

Group I: Soundings of the polar cap (soundings between 75°N and the pole). These soundings mostly possess in the lower troposphere a temperature structure characteristic for polar soundings. Strong surface inversions ap-

pear in this period, because of the anticyclonic conditions over the polar region. No definite tropopause level or isothermal structure could be found, but rather a gradual decrease of temperature continues upwards into the stratosphere. In the higher stratospheric layers temperatures of about -75°C and lower are observed. There are no indications of a temperature increase in the very high stratosphere even in extreme high ascents (see Fig. 7, *Group I*). We have separated these soundings from the polar ones, because of their different construction in the stratosphere and because of the fact that no definite tropopause was observed and no isothermal stratosphere existed. From Fig. 7 one realizes that no greater changes are present in the mean soundings of this type from day to day (the mean soundings are obtained by taking the mean of about 10 to 15 soundings per day) except in the last two days (January 12 and 13) where a gradual increase of temperature appears in the lower part of the atmosphere.

Group II: Polar soundings. These soundings (see Fig. 7, *Group II*) are taken from the area north of the polar jet or from regions surrounded by a polar breakline in the tropopause level (cut-off lows appearing over lower latitudes, polar air excluded from the polar source region). In these soundings a typical polar troposphere is separated by a definite low tropopause level (always lower than 300 mb) from the almost isothermal stratosphere. From Fig. 7 it is obvious that the mean sounding for each day keeps a nearly similar construction in the total height of the atmosphere. There seems to exist a slow temperature increase with height in the levels above 80 mb (above 18 km).

Group III: Middle soundings. These soundings were taken from regions between the polar front jet and the subtropical jet. Evidently the individual soundings of all the 6 days have rather different latitudinal position (between 30° and 60°N). Looking at Fig. 7, *Group III* we realize now a much warmer temperature in all tropospheric layers in comparison with the two previous groups. This temperature increase, which seems to be strongest in the mid troposphere from 600 to 400 mb, but is almost of the same strength throughout the whole troposphere, expresses in a clear manner that these soundings are taken south of the polar front (indicated schematically in Fig. 7).

The tropopause level appears now much higher up (at about 240 mb) in comparison with that of the mean soundings of the polar group. The height difference of the two tropopause levels amounts to about 2 km (polar breakline in the tropopause level or strong meridional gradient in tropopause height). From the middle tropopause level upwards a slow increase of temperature is observed in the mean middle soundings up to about 170 mb (12.5 km) and from there on a rather slow decrease can be noticed. In general, however, the stratosphere of middle soundings is almost isothermal.

Group IV: Subtropical impulse soundings: These soundings are taken from areas in the mid latitude belt which are surrounded by branches of the subtropical jet. Also the soundings in this group differ widely in their latitudinal position. The temperature in the whole troposphere is higher than that of the middle group (see Fig. 7, *Group IV*). This is especially true for the layer between 450 and 350 mb. The temperature distribution inside the troposphere is nearly that of the pure subtropical soundings, which we will discuss in the following paragraph. The principal difference between this group and middle or pure subtropical soundings is because of their different structure in the stratosphere and because of the different form and temperature of the tropopause. We conclude therefore that another, in comparison with the polar front much weaker frontal layer, should exist between spaces in the atmosphere characterized by these subtropical impulse soundings and others characterized by middle soundings (secondary frontal zone schematically indicated in Fig. 7). This frontal zone is never as sharp as the polar front, but can be analyzed in vertical cross sections quite definitely, and can also be found in individual soundings. It seems to be of utmost importance to realize the existence of two different warm air masses south of the polar front, which are characterized by the tropospheric temperature distributions of group III and IV. In the group of subtropical impulse soundings (IV) one observes the tropopause much higher upwards (little above the 200 mb surface). The tropopause temperature is very much lower than that of the middle group (by about 10°C or more). This clearly indicates a further discontinuity in the tropopause level related to the presence of a branch of sub-

tropical jet. Above the tropopause the temperature mostly increases in this group by 5 or 6° C up to 125 mb and from there on isothermal conditions prevail.

Group V: Subtropical jet soundings: These are soundings which pass through the subtropical breakline in the tropopause level or the region close to the subtropical jet. From Fig. 7, Group V it is quite obvious that the tropospheric temperature distribution does not show any appreciable difference compared with group IV. In all cases a double tropopause appears in each individual sounding and this is well shown in the mean soundings of the 6 days. The lower tropopause situated near 200 mb was found to be strongly connected with the existence of the subtropical jet core, situated just little below this lower tropopause. From about 200 up to 150 mb nearly isothermal conditions or even a slight increase of temperature with height is observed. This lower tropopause disappears south of subtropical jet, so that only a break in the continuous tropospheric decrease of temperature with height remains (see in this connection the tropospheric structure of group VI). From 150 mb upwards the temperature decrease continues up to the levels immediately above 100 mb where a clear cut tropopause is realized. Above this tropopause the temperature increases again upwards. In the individual soundings the two tropopauses stand out even more pronounced. The tropopause temperature at the upper and at the lower tropopause are in a characteristic way observed to be equal whenever the sounding goes through the subtropical jet core.

Group VI: Subtropical-tropical soundings: Fig. 7, Group VI. These soundings show a continuous decrease of temperature from the ground upwards to 85 mb (17 km). While the lower subtropical troposphere still keeps its character upward to about 230 mb, the higher portion of the troposphere up to 85 mb is characterized by a much weaker temperature decrease with height. The break in lapse rate around 230 mb can be considered, as was mentioned before, as an equatorward continuation of the middle tropopause level. Only in rare cases an inversion or an isothermal layer of small vertical extent exists, which should not be taken as a tropopause. Therefore the main and only tropopause level in this group is that at 85 mb. It is now extremely pronounced

(tropical tropopause). The tropopause temperature is well below -70°C and the stratospheric distribution of temperature shows a much stronger increase of temperature with height. Soundings further south (between 15°N and the equator) would not differ considerably from the type discussed in group VI. The break in lapse rate in the mid troposphere would be even less pronounced and appears sometimes as low as 300 mb. There are cases, where this last indication of the middle tropopause disappears completely. The temperature of the tropical tropopause level still decreases towards the equator and approaches values colder than -80°C (in rare cases even as low as -90°C). There is evidence in some cross sections that the lowest tropopause temperature is not reached directly above the equator, but two separate tropopause temperature minima exist on both sides of the equator interrupted by a small region just above the equator for which the tropopause temperature is little higher. There is little known, if this is true for all the regions of the world. Further data from the equatorial regions are needed to form the basis for a more complete study of tropopause conditions close to the equator. The same is true for the region close to the poles. There is still the question, if there exists a definite tropopause level close to the poles (at least for certain periods) and there is so far no definite proof for the existence of a continuous tropopause level across the equator.

IV. The conservative character of soundings in each of the different groups and the meridional temperature gradient between them

Table I presents (a) the total mean vertical temperature distribution for all the different groups, (b) the standard deviation of the vertical temperature distribution of all the individual soundings of each group from that of the mean one in each group (c) temperature differences between the mean vertical temperature distribution of different groups (showing meridional temperature gradients in tropo- and stratosphere between different groups and the level of no meridional temperature gradient). In connection with (c) the reader is also referred to Fig. 8, where the total mean vertical temperature distributions of different groups are plotted against each other, thereby showing the

TABLE I

Sounding Types { Polar cap (PC) = Group I, Subtropical Impuls (SI) = Group IV
 Polar (P) = Group II, Subtropical Jet (SJ) = Group V
 Middle (M) = Group III, Subtropical Tropical (S) = Group VI

Height (mb)	Mean vertical temperature distributions (°C) of different groups of soundings (Northern Hemisphere Winter)						Standard deviation σ (°C) of temperature of all individual soundings from the mean one of each different group				Meridional temperature differences between different groups in °C			
	PC I	P II	M III	SI IV	SJ V	S VI	P II	M III	SI IV	S VI	Temperature decrease towards: North = positive, South = negative			
											M-P III - II	SI-P IV - II	SI-M IV - III	SJ-SI V - IV
30	-	-48.8	-58.0	-60.3	-55.6	-54.6	10.2	3.8	3.2	2.8	-9.2	-1.5	-2.3	+4.7
40	-	-53.3	-59.1	-61.2	-58.3	-58.3	9.2	3.5	3.2	3.2	-5.8	-7.9	-2.1	+2.9
50	-72.1	-55.5	-59.5	-60.9	-60.2	-62.6	9.1	3.6	3.4	3.0	-4.0	-5.4	-1.4	+0.7
60	-71.8	-56.8	-59.7	-61.2	-62.2	-66.5	8.5	3.7	3.7	3.7	-2.9	-4.4	-1.5	-1.0
70	-71.5	-56.9	-59.3	-61.4	-63.2	-69.8	7.4	3.5	3.8	3.9	-2.4	-4.5	-2.1	-1.8
80	-71.5	-57.5	-58.9	-61.4	-64.2	-72.5	7.0	3.5	3.8	4.3	-1.4	-3.9	-2.5	-2.8
83						-73.4								
90	-70.6	-57.2	-58.6	-61.3	-64.6	-72.0	7.1	3.5	3.4	4.7	-1.4	-4.1	-2.7	-3.3
95					-65.0									
100	-70.3	-56.3	-57.9	-61.1	-64.6	-70.6	6.9	3.6	3.4	4.7	-1.6	-4.8	-3.2	-3.5
125	-67.8	-55.3	-56.5	-60.3	-62.2	-65.9	6.3	3.6	3.3	4.4	-1.2	-5.0	-3.8	-1.9
150	-65.9	-54.3	-55.8	-60.8	-59.6	-61.1	6.0	3.8	3.4	3.9	-1.5	-6.5	-5.0	+1.2
175	-65.4	-53.6	-55.9	-63.8	-59.0	-56.8	5.6	4.4	4.1	3.8	-2.3	-10.2	-7.9	+4.8
200	-63.5	-53.1	-57.1	-65.4	-58.9	-52.8	5.6	5.2	3.0	4.4	-4.0	-12.3	-8.3	+6.5
208					-59.5									
250	-62.6	-53.6	-57.4	-57.7	-54.1	-46.4	5.6	3.7	2.1	5.6	-3.8	-4.1	-0.3	+3.6
270						-44.3								
300	-59.9	-53.7	-51.9	-48.6	-45.5	-39.3	5.1	3.6	2.4	5.5	+1.8	+5.1	+3.3	+3.1
320		-53.8												
350	-54.4	-50.8	-44.3	-40.0	-37.2	-32.4	3.5	3.6	2.6	5.0	+6.5	+10.8	+4.3	+2.8
400	-49.5	-45.5	-37.2	-32.7	-30.0	-26.3	3.1	3.6	2.7	4.3	+8.3	+12.8	+4.5	+2.7
500	-40.8	-35.2	-25.0	-20.5	-17.9	-14.3	4.1	3.5	2.5	3.8	+10.2	+14.7	+4.5	+2.6
600	-33.5	-26.2	-15.4	-10.9	-8.4	-5.5	5.0	3.5	2.8	3.5	+10.8	+15.3	+4.5	+2.5
700	-28.0	-19.0	-7.7	-3.6	-0.7	+1.9	6.2	3.6	3.5	3.7	+11.3	+15.4	+4.1	+2.9
800	-25.2	-13.7	-1.8	+2.4	+5.5	+7.4	7.4	3.6	3.6	4.2	+11.9	+16.1	+4.2	+3.1
900	-24.6	-9.3	+3.5	+7.2	+11.3	+12.1	9.2	3.7	3.9	4.9	+12.8	+16.5	+3.7	+4.1
1000	-24.4	-8.3	+8.4	+10.8	+14.4	+16.9	12.2	4.0	3.5	4.9	+16.7	+19.1	+2.4	+3.6

strength of baroclinicity between individual groups of soundings.

Looking first at the polar group (Table I), one observes that the standard deviation* is

* We recall that the mean m locates the centre of a distribution and the standard deviation σ measures the spread or variation of the individual measurements (in our case individual temperatures and their mean for each

smallest between the 700 mb level and the mean polar tropopause (appr. 320 mb). From there on upwards to the 100 mb level it still remains rather small. Only in the lower part of

height and each group). The concentration of the measurements close to m is emphasized by the fact that over 2/3 of the observations (66.7 %) lie in the interval $m \pm \sigma$, while 95 % of them are in the interval $m \pm 2\sigma$.

the polar troposphere and in the higher part of polar stratosphere (from 100 mb to 30 mb) we notice somewhat larger standard deviations of the individual soundings of this group from the total mean sounding (more than 7°C). This shows that individual soundings may deviate in temperature stronger in the lower troposphere from the mean temperature of the polar group, which is reasonable because of radiational effects. But also the high stratospheric layers of the individual soundings show rather strong deviations from an almost isothermal polar stratosphere during the period in question. The total height interval between 700 mb and 100 mb level, however, shows only small deviations of 3 to 5°C from the total mean vertical temperature distribution, which is surprisingly little. In this height range the polar soundings are rather conservative and the computed mean sounding is a rather representative one.

A different picture is obtained for the middle group (Table I). Here in the total atmosphere individual soundings deviate little in all the heights (standard deviation of about 3.6°C) from the mean temperature distribution of the middle group. If one considers that the soundings of this group have rather different latitudinal position (between 30° and 60°N) it is most astonishing to realize this conservative character of middle soundings. This would not be true by just selecting randomly stations of mid latitudes, computing a mean sounding and the standard deviations of the individual ones from the mean one in that case. Then one would mix soundings of different type (polar, middle and subtropical) and much larger standard deviations would appear. Therefore it is just the selection of the middle soundings always between the main westwind maxima or between the two main breaklines in tropopause height which guarantees the conservative character in this group.

The same applies equally to the group of subtropical impulse soundings (Table I). For this group as well the standard deviation in all the heights of tropo- and stratosphere remains rather small (2 to 4°C). Here the most conservative part of the atmosphere is the layer between 700 mb and the tropopause (about 200 mb).

In the subtropical group of soundings (Table I) the standard deviation remains again small with the exception of the height range between

350 and 250 mb where somewhat greater standard deviations appear (little more than 5°C). This is solely due to the break in lapse rate, which is observed in different heights in this interval (last indication or continuation of the middle tropopause in equatorward direction). This makes the temperature distribution of the subtropical soundings south of subtropical jet in this layer of small vertical extent of the troposphere more variable and the standard deviation from the mean sounding somewhat greater.

Generally we may point out that in all the groups a definite conservative character in the individual soundings exists (shown by the rather small standard deviations in temperature of each sounding from the mean ones). Most conservative is the middle and upper part of the troposphere and the form of the tropopause in each group. The only exception from this general rule appears in the polar group in the lower troposphere and in the higher part of the polar stratosphere. The non-conservative character of the latter one may not be present all the time, because, according to our opinion, only part of the time the higher portions of the polar stratosphere are influenced by advection of cold air of subtropical origin, which, in our opinion, is the main reason for the variance in temperature. Radiation may also effect the temperatures in the upper polar stratosphere but this influence would not account for such variability. At certain time intervals where no subtropical inflow of cold stratospheric air affects the polar stratosphere, the magnitude of temperature variation would not be as strong as in the period under consideration and the standard deviation of the temperature distribution of individual polar soundings from that of the mean one would also remain small.

In addition Table I contains also temperature differences between the mean vertical temperature distributions of the different groups, which indicate the strength of baroclinicity between different parts of the atmosphere. They show temperature gradients (polewards (positive) in the troposphere or equatorwards (negative) in the stratosphere) and their magnitude. They also indicate the level of no meridional temperature gradient (see also graphical representation in Fig. 8).

Tropospheric strong temperature differences of about 10°C between polar and middle

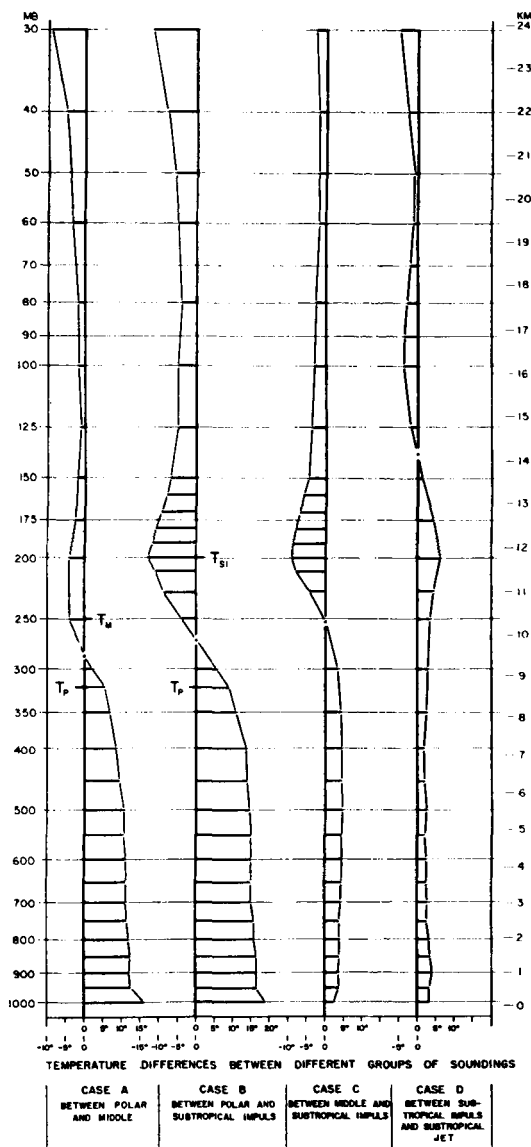


Fig. 8. Meridional temperature gradients (in °C) between the different groups of soundings for all heights in tropo- and stratosphere.

Distances to the right of vertical lines indicate temperature gradients south to north (positive).

Distances to the left of vertical lines indicate temperature gradients from north to south (negative).

Case A: Meridional temperature gradients between polar and middle groups of soundings (normal temperature concentration at the polar front in winter).

Case B: Meridional temperature gradients between polar and subtropical impulse group of soundings (extraordinary temperature concentration at the

group or of about 15° C between polar and subtropical impulse group indicate that the strongest baroclinicity of the atmosphere is concentrated in the polar front or most of the tropospheric meridional temperature gradient (directed poleward) appears at the polar front, which separates the soundings of the polar group from the ones of the middle group (group II from group III). This tropospheric baroclinicity becomes even more pronounced by some three or four degrees, when polar air comes near to subtropical air and the middle air disappears. In that case when polar and subtropical impulse groups are situated side by side the tropospheric temperature gradient amounts to about 15° C (group II opposite group IV or VI). (See both cases A and B in Fig. 8, left side.) This tropospheric baroclinicity seems to be largest in the mid troposphere but is nearly equally well pronounced in the total troposphere up to 400 mb in both cases. In the latter case a branch of subtropical jet moves towards more northern latitudes and comes close to the polar jet stream, thereby bringing subtropical air near to polar air. This results in an extreme baroclinicity at the polar front.

Tropospheric meridional temperature differences between middle and subtropical impulse group (see Fig. 8, case C, right side) is much less and has a value of about 4 or 5° C throughout the whole troposphere. This indicates the existence of a secondary frontal system dividing middle and subtropical air. This baroclinicity is never as strong as that at the polar front, but it clearly indicates two different types of warm air masses south of the polar front, earlier referred to as the same air mass (the tropical air). This subdivision seems to us of utmost importance.

Meridional gradients in the troposphere between the subtropical impulse group and the subtropical jet group remain small. This can be seen by comparing group III and IV (see Fig. 8, case D, right side). The magnitude

polar front in case of a northward advance of subtropical atmosphere (subtropical impulse)).

Case C: Meridional temperature gradients between middle and subtropical impulse group of soundings.

Case D: Meridional temperature gradients between subtropical impulse group and subtropical jet group of soundings.

of this gradient is 1 to 3° C, showing that the air in such northward advances of the subtropical atmosphere (subtropical impulses) caused by the meandering behaviour of the subtropical jet is really the same type of air usually appearing at latitude circle 30° N in the subtropical troposphere.

The level of no meridional temperature gradient lifts gradually from north to south. Between polar and middle group this level appears in 285 mb, while between middle and subtropical impulse group it is already observed at 250 mb (9.5 km, resp. 10.5 km). The height of the level of equal meridional temperature distribution increases south of 30° N to the 150 mb-level (about 13.5 km). The temperature field therefore does not show any reversal of the meridional gradient for a certain level. It is equally wrong to state that the meridional temperature gradient disappears at the tropopause, as one can read often in literature. Conditions are much more complicated and a sharp discontinuity in the level of zero meridional temperature gradient appears in connection with the subtropical breakline of the tropopause level.

We continue now the discussion with stratospheric temperature differences or negative gradients in meridional direction. Between the polar and the middle group the stratospheric temperature differences remain rather small (see Fig. 8, case A). Only in layers above 50 mb somewhat greater values appear. Therefore when the polar front separates only polar and middle air, the main baroclinicity exists in the troposphere, and stratospheric contributions to developments at the polar front remain insignificant because of a nearly uniform meridional temperature field in the stratosphere above. However, in case of a northward advance of a subtropical jet branch or in the case when subtropical air comes close to polar air at the polar front, the stratospheric meridional differences in temperature between the polar group of soundings and the subtropical impulse group increase generally in the total stratosphere and a rather strong negative temperature gradient (colder temperatures to the south) appears immediately above the strongly inclined tropopause level (order of magnitude 12 to 15° C). The numbers of Table I and Fig. 8, case B express for that special case the very important circumstance, which we already

mentioned before, that an opposite baroclinicity appears in the stratosphere concentrated near the strongly inclined tropopause and vertically above an unusually strong tropospheric baroclinicity at the polar front. Furthermore this twofold baroclinic structure of the atmosphere appears in comparatively small latitudinal regions of 5 or 10° lat. and this represents in combination with a double jet of extraordinary strength a state which can by no means be considered a hydrodynamic stable one. Due to hydrodynamic instability the equilibrium of this stratification may easily be destroyed and a new adjustment of the mass field has to be made (strong cyclogenesis). As a consequence drastic changes in the type of the General Circulation occur.

If subtropical air advances northward, but comes only in contact with middle air, we already discussed the formation of a secondary front in the troposphere (see Fig. 8, case C). But in that case stronger meridional negative gradients appear above 250 mb and also in that case stratospheric effects may be of importance.

V. Statistical investigation on the tropopause level

Looking at Fig. 7 one can easily estimate in what heights in a frequency curve high or low frequencies of appearance of a tropopause level should occur. First of all there should exist a general accumulation little above the 100 mb level up to the 80 mb level, in which height range two peaks should stand out. One near 80 mb due to the tropical tropopause level in the southernmost group. Another peak, but at somewhat lower height, should appear near to 100 mb due to the upper tropopause in the subtropical jet soundings (still the tropical tropopause).

In the height range between 100 and 200 mb the frequency curve should show nearly no sign of tropopause or extremely little.

Another accumulation can be expected between 200 and 340 mb. In this height range generally high frequencies and three pronounced peaks may be expected. The first one due to the tropopause of subtropical impulse soundings as well as the lower tropopause of subtropical jet soundings (in each case the middle tropopause level). The second peak may appear near to 240 mb because of the frequent occurrence of

the middle tropopause in that height over the mid latitude belt. The third and final peak should exist little below 300 mb due to the frequent occurrence of the polar tropopause in that height.

The diagram (*Fig. 9*) presents such a tropopause statistic. The coordinates of this diagram are: tropopause height or pressure in mb in the vertical and the tropopause temperature in degrees Celsius in the horizontal. Tropopause height and temperature from all the soundings of the period Jan. 1 to 13, 1956, 0300Z are entered in this diagram (each sounding with a dot and 5 soundings with the same coordinate by a little square). The total number of soundings is 2,513. From the distribution of the points one may easily notice that low tropopause temperatures correspond generally to greater tropopause heights and the opposite (warm tropopause temperatures—lower tropopause heights). This rule holds fairly well in the height range between 400 and 175 mb (compensation principle). Furthermore we observe clearly the expected subdivision of the total point cloud into two main families, one above 100 mb and the other below 175 mb. However, in the height range between 100 and 175 mb we realize very little points, especially between 125 and 175 mb. This outstanding characteristic feature of the distribution is a definite proof that no tropopause exists in that height range and a continuous tropopause level from the equatorial to the polar regions does not exist in the winter season (subtropical break in the tropopause level, double structure of the tropopause level across 30° N).

Concentrating on the upper point accumulation above 125 mb up to 60 mb, we notice the expected double peak (one near 80 mb, the other near 100 mb), which proves that preferred tropopause locations exist (see also frequency curve at the right side of diagram). All the points refer to the tropical tropopause level. The peak near 80 mb would shift a little higher up, if we could include more soundings from the very low latitudes. The frequency curve (right side of the diagram) shows a rapid decrease in the number of points below 100 mb down to 110 mb and also a more gradual decrease from 80 to 60 mb. In the height range between 175 and 310 mb (lower main point cloud) everywhere high frequencies

of tropopause occurrence can be noticed and as we expected three sharp peaks stand clearly out and surpass the general high frequencies of the total height range by more than double or even triple the value. As we already pointed out, the frequent occurrence of an unusually high tropopause in the subtropical impulse soundings, together with the lower tropopause of the subtropical jet soundings, give rise to upper peak near 200 mb, while the middle peak near 240 mb can be explained by the frequent occurrence of a middle tropopause level and the lower peak near 300 mb by the frequent appearance of the polar tropopause in that height. The threefold structure of the tropopause level is therefore rather well illustrated by this diagram. In this height range we must pay attention that the only relative low tropopause frequency between 280 and 300 mb, immediately above the lowest peak, demonstrates the polar breakline in the tropopause level.

Between 320 to 400 mb the frequency decreases rather rapidly and only in rare cases a tropopause can be found lower than 400 mb.

We certainly admit that this preliminary statistical result is not a final one, because even if it includes a total of 2,513 soundings (all the soundings from the northern hemisphere except that from Russia and China for 13 days) the material does not seem to be too extensive to allow refined statistics. Considering this fact it is even more surprising how clearly definite and important features in the behaviour of the tropopause level stand out in this investigation. It is more than likely that an increase of the data would rather result in a more pronounced picture of the tropopause level, as is illustrated here. Furthermore it refers only to winter conditions and similar studies for summer periods have to be made.

VI. The subtropical breakline in the tropopause level and its relation to the core of subtropical jet stream

Fig. 10 presents a detailed analysis of the temperature and wind field in a vertical cross section, oriented from south to north through the subtropical jet over the North American Continent. This example from Jan. 8, 1956, 0300Z may convince the reader about the connection between the break or the double

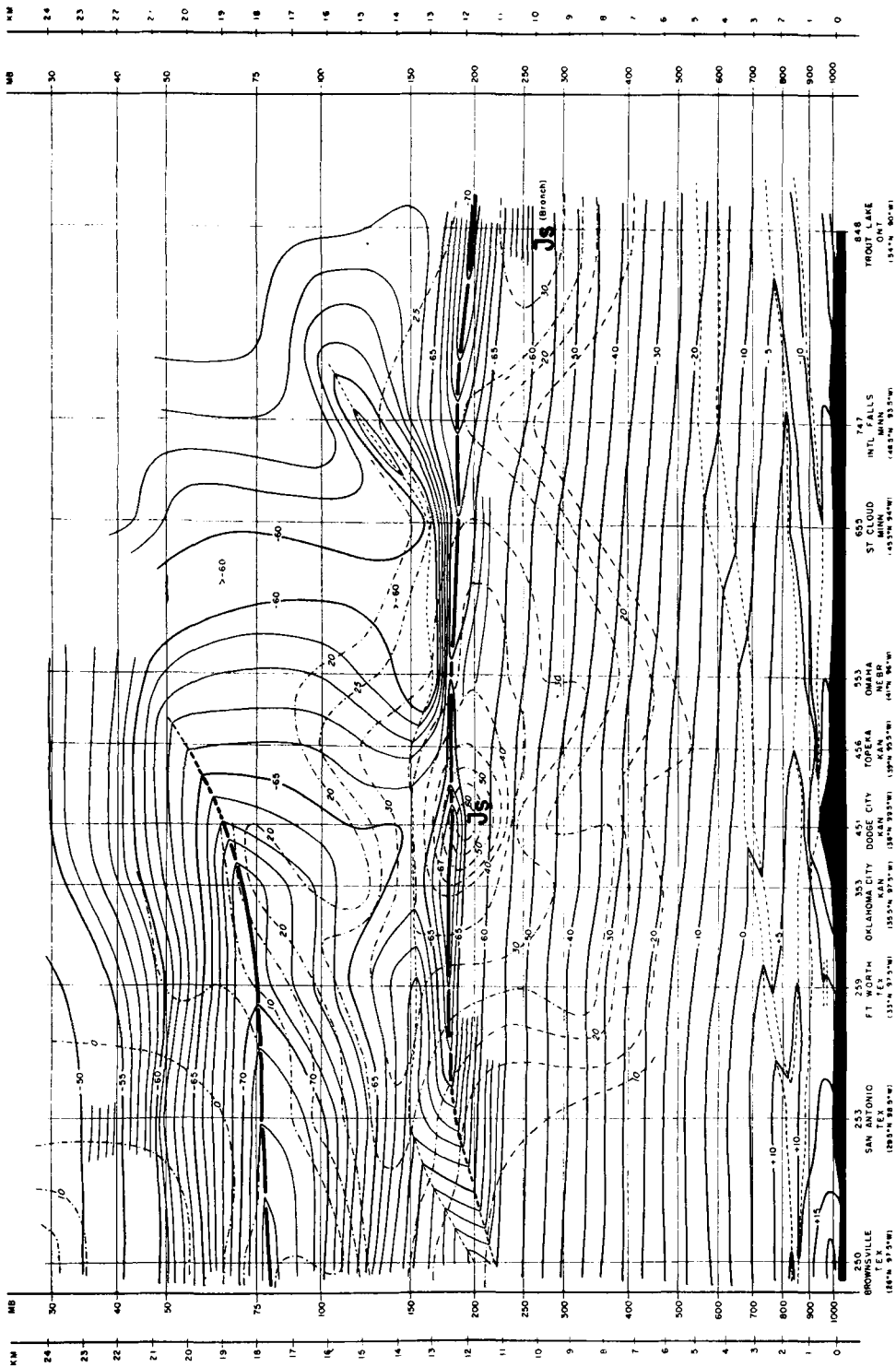


Fig. 10. Vertical cross section over North America for Jan. 8, 1956, 0300 Z through the subtropical break in the tropopause level and the subtropical jet stream. Thick full lines = tropopause levels. Thin full lines = isotherms in °C (vertical oriented numbers). Dashed dotted lines = lines of equal wind speed (actual wind in m/sec (slanted numbers)). Thin dashed lines near ground = frontal boundaries. Thin dashed line above middle tropopause = upper limit of inversion above tropopause. J_s = main subtropical jet core (63 m/sec = 122 knots). J_s (branch) = northern branch of subtropical jet (33 m/sec = 64 knots). Numbers, names and position of radiosondes are given beneath picture.

structure of the tropopause level near latitude circle 30° N and its intimate relation to the existence of a sharp and well defined westwind core inside the general westerlies of subtropical latitudes (subtropical jet). This section running from Brownsville, Texas (250) northward to Dodge City (451) and Int. Falls (774) and from there to Trout Lake (848) in Canada was taken inside such a subtropical impulse or a ridge region existing on Jan. 8, 1956 over the central part of North America. Here one can distinguish between a branch of the subtropical jet and the main subtropical jet core (the first one is seen in the picture at 250 mb in the northernmost station and the second one in the soundings of 353, 451 and 456 in the central part of the section).

Little above the 200 mb level a tropopause level is observed in all the stations of the section, which can be considered as the southernmost part of the middle tropopause level, but already appearing above or close to the 200 mb level in the region of a northward advance of subtropical air (subtropical impulse). The tropospheric temperature field indicates only a very gradual decline of the isothermal layers in northward direction. We may conclude from this almost barotropic stratification that subtropical air is present in the troposphere from the tropopause level downward to a certain frontal layer, which slopes upward from south to north. This secondary frontal layer is characterized by an inversion in its southern part and a break in the vertical lapse rate in the northern soundings. Below this frontal layer, a certain ground space is filled with middle air which is again separated by a sharp inversion from a much colder air mass covering all the ground layer of the section. This ground inversion can therefore be considered as a continuation of the polar front southward and the shallow ground layer contains a modified but typical polar air.

The temperature distribution at the tropopause indicates two separate places with extremely low tropopause temperatures (lower than -67° C). The first of these can be seen on top of the northern branch of subtropical jet and the second one appears immediately on top of the main subtropical jet or little south of it. In the region between the two jet maxima the temperature at the tropopause is somewhat higher.

From the tropopause, where the temperature is coldest in all the soundings, a general increase in temperature with height appears, the upper limit of which is indicated by a dashed line in the section (inversion above the tropopause). Higher up the temperature decreases again with height, especially in the region south of the main subtropical jet core. Here we are able to analyze clearly a tropical tropopause level near 80 mb. Along this tropical tropopause level the temperature increases from south to north and the height of the tropopause increases steadily in this direction. The more horizontal orientation of the isothermal layers over the southern part of the section around the tropical tropopause slowly disappears in northward direction and the northern part of the section is characterized by a more vertical orientation of the isotherms or by an isothermal stratosphere.

The tropical tropopause rises to somewhat higher elevations in northward direction and loses gradually its identity. The lower (middle) tropopause level lowers and loses identity in southward direction. In the region of overlap of both tropopauses the main subtropical jet maximum or jet core appears just little below the lower tropopause. Here the temperatures at both tropopauses are equal.

It is obvious from this section that a height interval of 5 km vertical extent between the two different types of tropopauses remains, which allows a connection between the higher portions of the subtropical troposphere and the lower portions of the stratosphere of mid latitudes. The importance of this gate has been stressed earlier.

Looking at the wind field of this section, which was analyzed solely by the use of actual winds, one may distinguish between the main subtropical jet and its northern branch, which are interrupted by a region of much lighter winds of the stations 655 and 747. While in almost all the parts of the section the maximum westwind appears immediately below the middle tropopause level, we observe, that south of the main subtropical jet the maximum wind appears above the middle tropopause, which gradually loses identity southward. Much stronger winds are observed for the main subtropical jet core (about 122 knots) than for its branch (64 knots). Unusually vertical and positive wind shear is observed below the main

subtropical jet core and equally or even stronger vertical and negative wind shear can be noticed above it. Such shear values don't exist elsewhere in the section and can hardly be observed at the polar jet stream. They cannot be explained by use of the thermal wind relationship. Another explanation has to be offered for the narrow peak of subtropical jet in vertical direction.

An analysis of the subtropical jet, solely based on winds from a main isobaric surface (conveniently the 200 mb level), will never allow to place the subtropical jet core correctly on a horizontal map, because the winds close to the jet core would be almost of the same strength. Therefore one would rather conclude from such an undertaking (as has often been

said in other papers) that the subtropical jet is a broad westwind maximum surrounded by weaker westwinds. Only by means of careful vertical cross sections, making use of all information about maximum wind speed, the subtropical jet core can be detected because of its narrowness in horizontal and especially in vertical direction. Already some 20 mb difference in the vertical can result in quite different wind speeds. Investigations on the structure of subtropical jet need therefore utmost care and only vertical sections allow to describe its principal form. Finally we may point out that the section presented here (Fig. 10) serves only as an example but numerous similar sections have strongly supported the same general picture, unfolded in the discussion.

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