The Strong Index Change Period from January 1 to January 7, 1956

By FR. DEFANT and H. TABA, International Meteorological Institute in Stockholm

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Abstract

In continuation of a recent paper (DEFANT, TABA, 1957) a seven days period (January 1—7, 1956) has been investigated on a hemispheric scale. During this period strong world wide changes in the circulation type occurred. Such a circulation change from a meridional into a zonal type* has been studied for the first time by means of hemispheric tropopause maps and by using a special technique of dividing the total available material of atmospheric sound ings into three different groups as described in the previous paper. The following points summarize the results:

1. The hemispheric tropopause maps are most suitable for obtaining a clear picture of three dimensional structure of the atmosphere. The distribution of cold and warm air masses can easily be seen. Breaks in tropopause heights give an immediate impression of the location and the form of the two principal westwind maxima of the westerlies (polarfront jet and subtropical jet). The concentrations in the temperature field of the tropopause level are a further guide for the location of the main wind belts. This temperature field makes it possible to picture the meandering structure of the wind belts and shows the interaction of tropical and mid-latitude circulation. Clear distinction has to be made between subtropical and polar jet.
2. By the use of this method strong northward displacements of the tropical atmosphere have been shown. At the same time a strong meandering behaviour of the subtropical jet appears. These tropical impulses play a dominating role in producing pronounced changes in mid-latitude circulation and for the generation of large blocking anticyclones.
3. During the seven days period the character of soundings in the three selected groups (north of the polar jet, between the two jets and south of the subtropical jet) remained nearly unchanged.
4. Whenever the tropical atmosphere shifted northward stations inside deep troughs having a polar isothermal structure in the stratosphere showed a strong cooling in the higher stratosphere and at the end of the period even the polar stations showed the same feature. It is thought that this cooling is mainly due to advection from the tropical regions, but outgoing radiation and vertical motion may contribute.
5. A possible cyclic change and three dimensional interaction of the three different parts of the atmosphere is outlined at the end of the paper.

Introduction

In a recent paper (DEFANT, TABA, 1957) an attempt was made by the authors to show an essential three-fold difference in the complete vertical structure of atmospheric soundings for January 1, 1956. This three-fold distinction in the structure was obtained as a result of a special selection of soundings with respect to the location of the main hemispheric west wind maxima of the westerlies (polar front jet and subtropical jet). South of the subtropical jet a typical temperature structure with a high tropopause (about 90 mbs) was observed. In the

* meridional and zonal with respect to the form of polarfront jet.

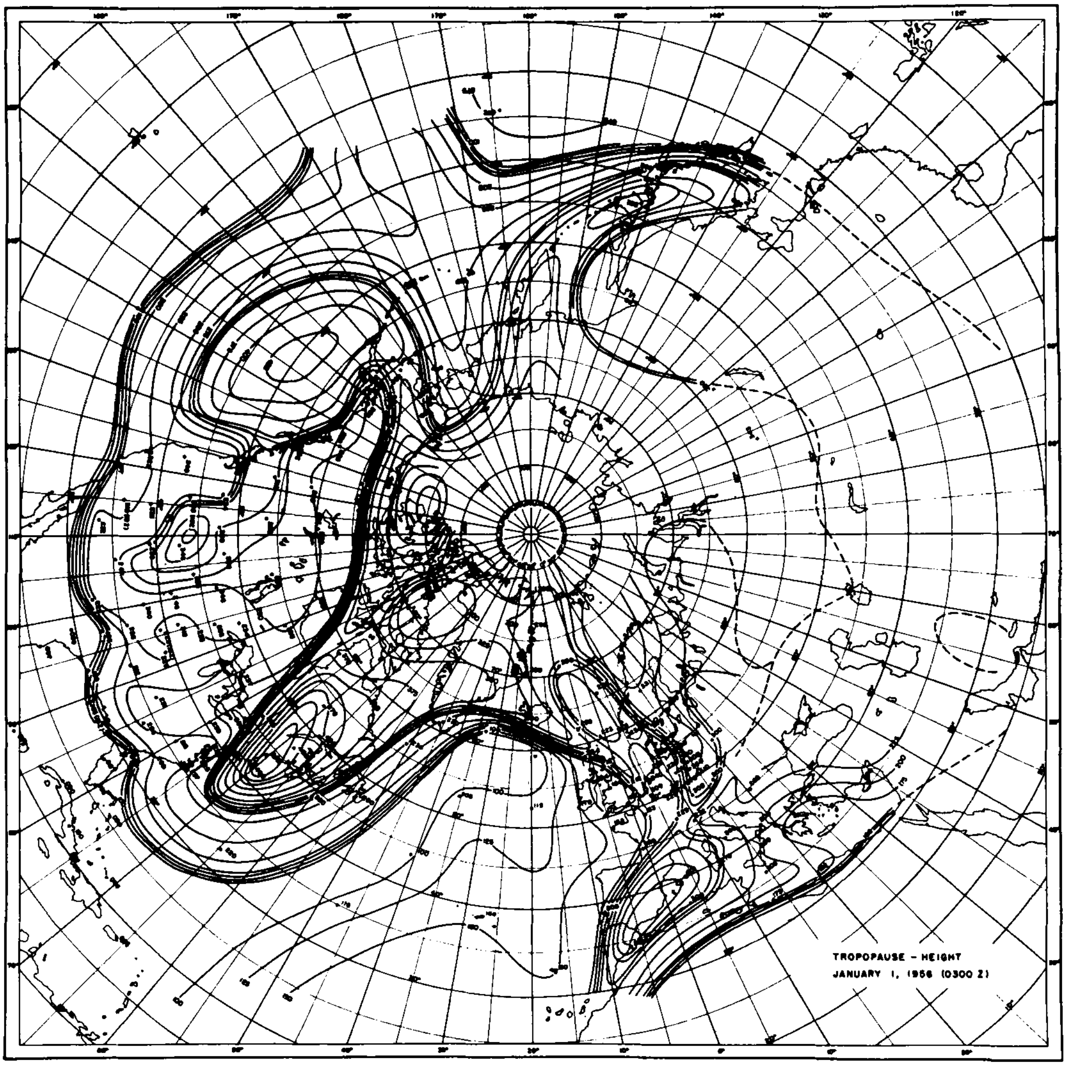


Fig. 1. Hemispheric tropopause map January 1, 1956 (0300 Z). For each station tropopause height in mb (3 figures) and tropopause temperature in °C (2 figures, minus sign omitted). In case of double tropopause levels both values are plotted. When the tropopause was not well defined no values are given. The breaklines in tropopause height are indicated by the concentration of the isolines.

area between the two jets the type of sounding was different, having a characteristic tropopause height near the 240 mb level. North of the polar front jet a third type of sounding could be distinguished by a rather low tropopause level (always lower than 300 mb, in rare cases even as low as 500 mb). It was further shown by presenting a hemispheric map of the tropopause height that the main west wind belts were closely related to the so called "breaklines" in the tropopause height which could be used as a guide in selecting stations of the different types mentioned above. Special discussion was devoted to soundings either close to the polar front or the subtropical jet. It was stated at the end of the paper, that an extension of this more or less formal discussion to a longer period (January 1 to January 7, 1956) was planned. It is the purpose of this paper to carry out such a study for this period, selected because strong changes in the world wide pattern of hemispheric circulation oc-

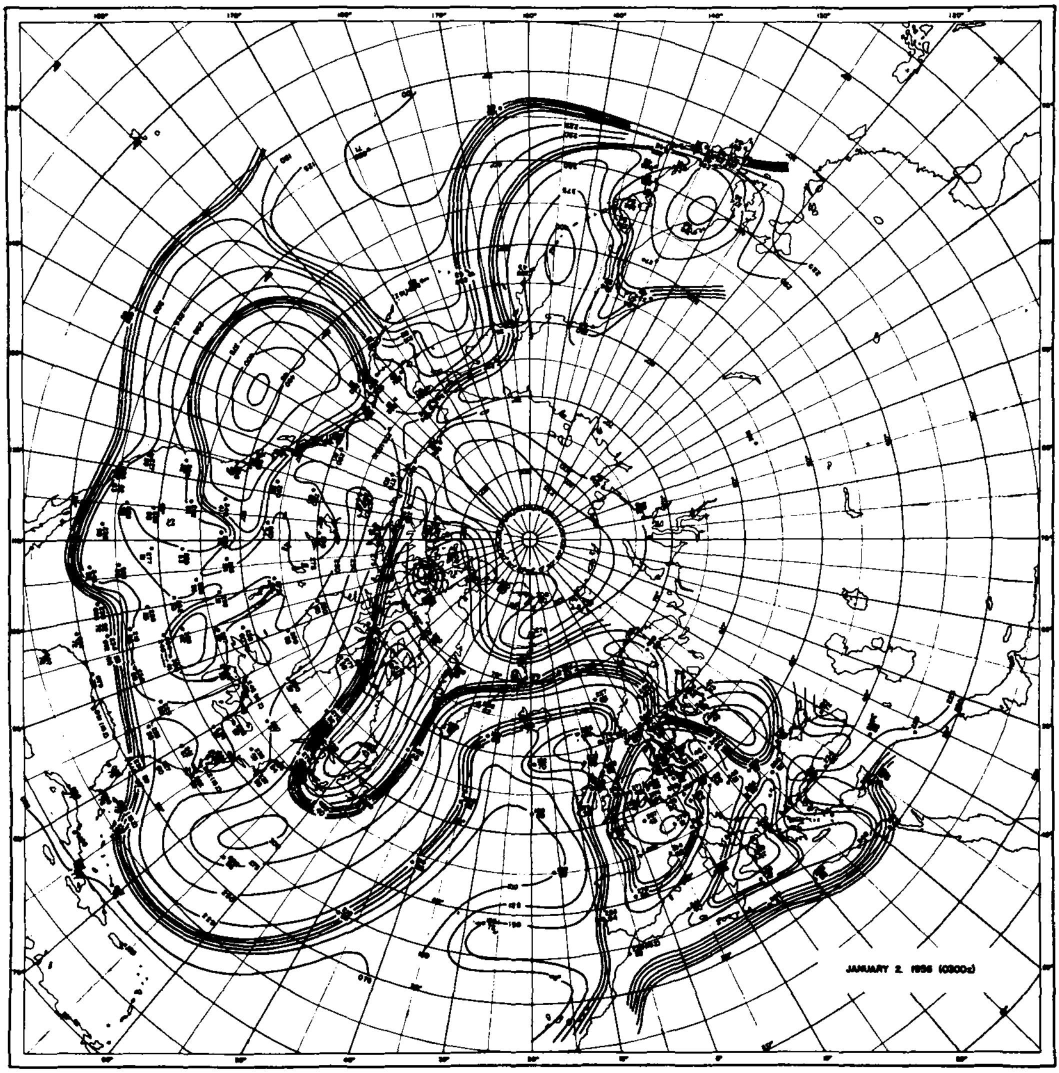


Fig. 2. Hemispheric tropopause map January 2, 1956 (0300 Z). For each station tropopause height im mb (3 figures) and tropopause temperature in °C (2 figures, minus sign omitted). In case of double tropopause levels both values are plotted. When the tropopause was not well defined no values are given. The breaklines in tropopause height are indicated by the concentration of the isolines.

curred and which offered certain advantages for studying their nature and the mechanism of such index changes.

For each day of this period (7 days) tropopause maps similar to those in our previous paper have been prepared and a similar grouping of soundings according to their location was made. For each day and each group of soundings mean values have been computed. The number of soundings in each area changes from day to day according to the fluctuation of the breaklines north and southward or according to the meandering of the two west wind belts. We have been well aware of the fact that for instance a southward movement of the polarfront jet over the continent with a denser coverage of soundings meant the inclusion of more soundings of the cold type. This did not effect the correctness of the averaging process as inside each part, the latitudinal change effects only the lower tropospheric layers and does not change appreciably

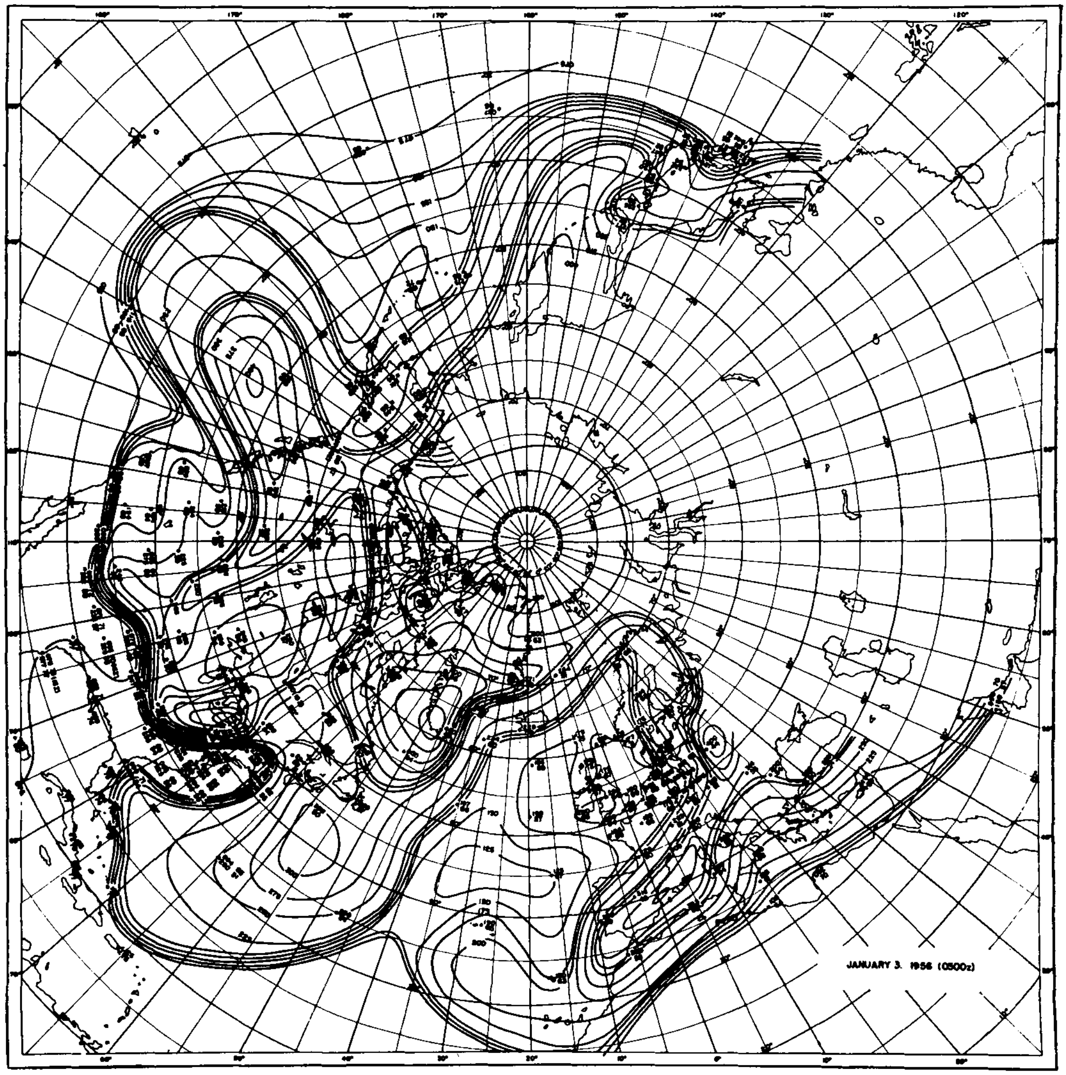


Fig. 3. Hemispheric tropopause map January 3, 1956 (0300 Z). For each station tropopause height in mb (3 figure) and tropopause temperature in °C (2 figures, minus sign omitted). In case of double tropopause levels both values are plotted. When the tropopause was not well defined no values are given. The breaklines in tropopause height are indicated by the concentration of the isolines.

the characteristic features in the upper troposphere, the height of the tropopause or the typical temperature distribution in the stratosphere. This is precisely the reason why such a selection is possible and just this feature characterises the different types in the total vertical structure of atmospheric soundings. In the lower tropospheric levels the vertical temperature distribution of the mean sounding for each separate day may differ somewhat from the means of other days. However, this change disappears completely when taking the mean for seven days, as the number of soundings in each area becomes great (about 250 in each area).

I. Tropopause maps for the period January 1 to January 7, 1956

Fig. 1 to 7 present a hemispheric analysis of the tropopause height for each day of the period January 1 to 7, 1956, 0300 Z. In all these analyses a rather marked distinction can

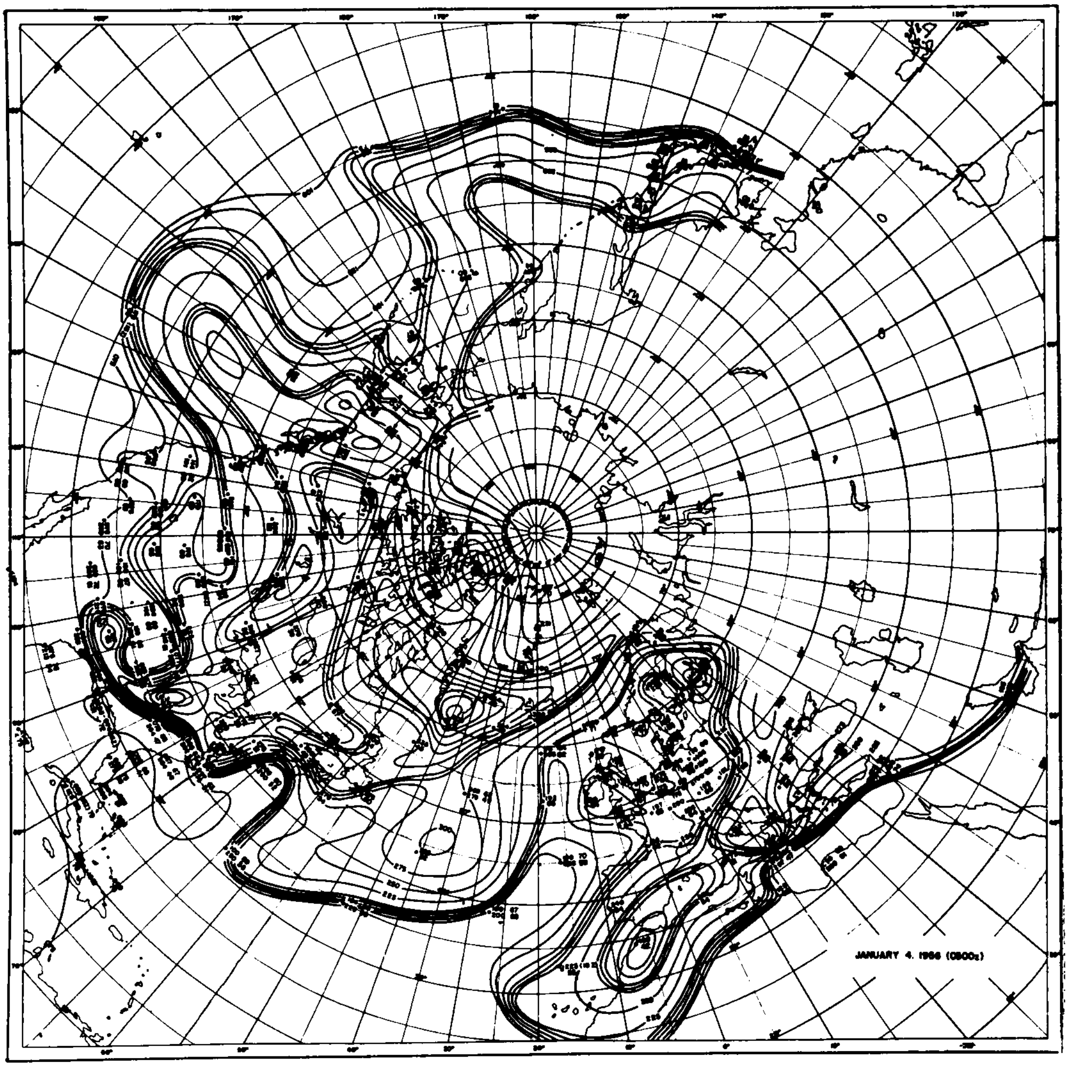


Fig. 4. Hemispheric tropopause map Januar 4, 1956 (0300 Z). For each station tropopause height in mb (3 figures) and tropopause temperature in °C (2 figures, minus sign omitted). In case of double tropopause levels both values are plotted. When the tropopause was not well defined no values are given. The breaklines in tropopause height are indicated by the concentration of the isolines.

be made between the tropopause breakline connected with the polar front jet and the one connected with the subtropical jet.

a) *Subtropical impulses in the Atlantic and European sector.*

We will first discuss the southern breakline. On January 1 (Fig. 1) this breakline situated near the latitude 30° N, shows a more zonal distribution in most parts of the northern hemisphere. This is true for the whole Pacific and the North American continent as well as North Africa. But over the North Atlantic it is displaced northward and crosses even the 60° parallel in the region south of Iceland. From there on it can be followed across England and France and down to the western part of North Africa. There seems to be no possibility of placing this breakline over the North Atlantic along 30° N. This rather surprising fact that the subtropical jet meanders so far

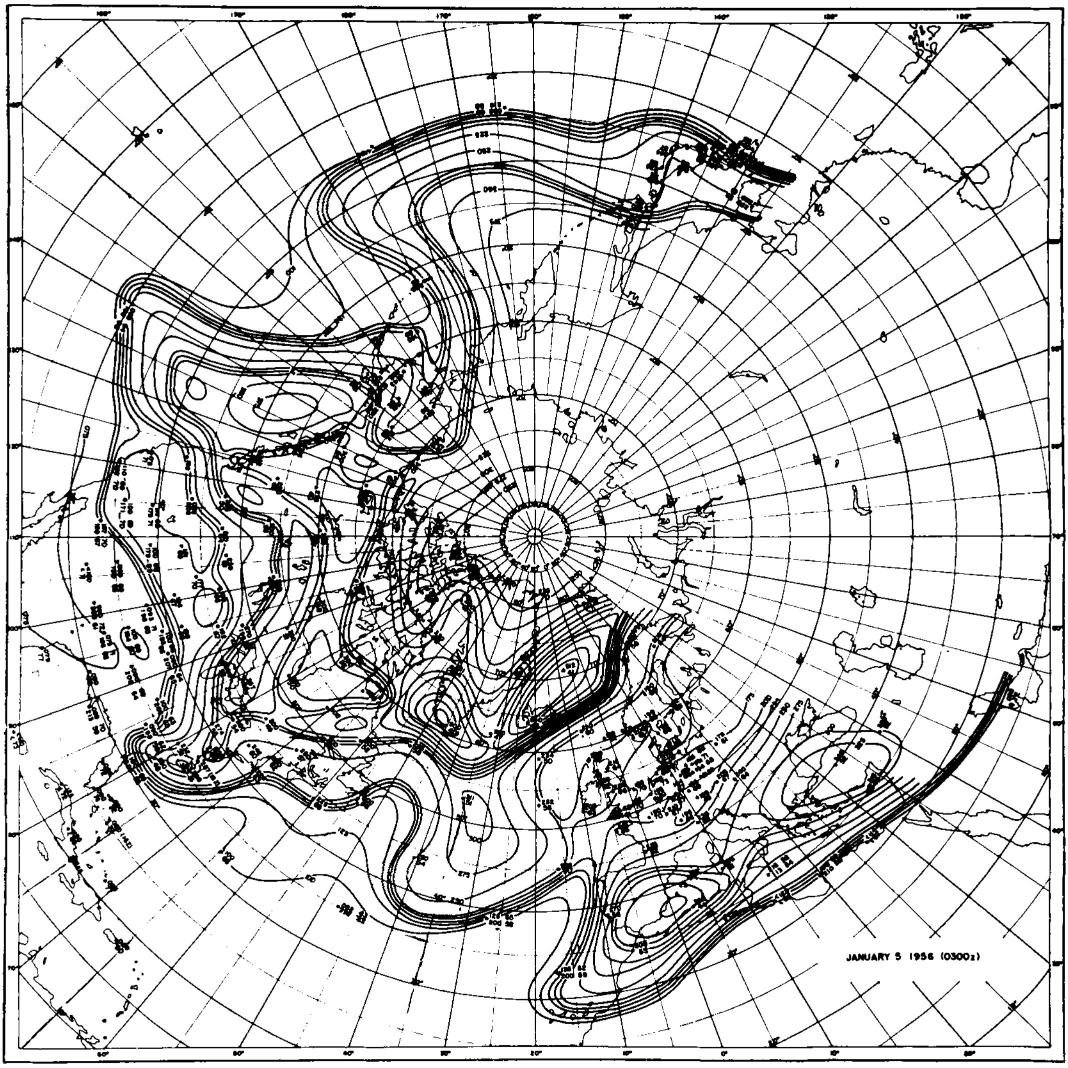


Fig. 5. Hemispheric tropopause map January 5, 1956 (0300 Z). For each station tropopause height in mb (3 figure) and tropopause temperature in °C (2 figures, minus sign omitted). In case of double tropopause levels both values are plotted. When the tropopause was not well defined no values are given. The breaklines in tropopause height are indicated by the concentration of the isolines.

to the north has not been mentioned to our knowledge in literature before. In a later paper (DEFANT, TABA, 1957) we shall present a definite proof that in this case a double jet exists over the British Isles and a sharp distinction must be made between the polarfront jet and the subtropical one. The northern breakline connected with the polarfront jet is well separated from the one discussed before.

Strong trough formation can be seen over the American East Coast. On its eastern side the two breaklines come closer together and in the region of Southern Greenland and Iceland no clear distinction between them can be made.

The surface cyclone situated just to the east of Iceland, on January 1 developed rather rapidly and an outflow of cold polar air occurred during the following night. It is worthwhile to mention that the approach of the two breaklines of the tropopause height seems to be closely related to this rapid out-

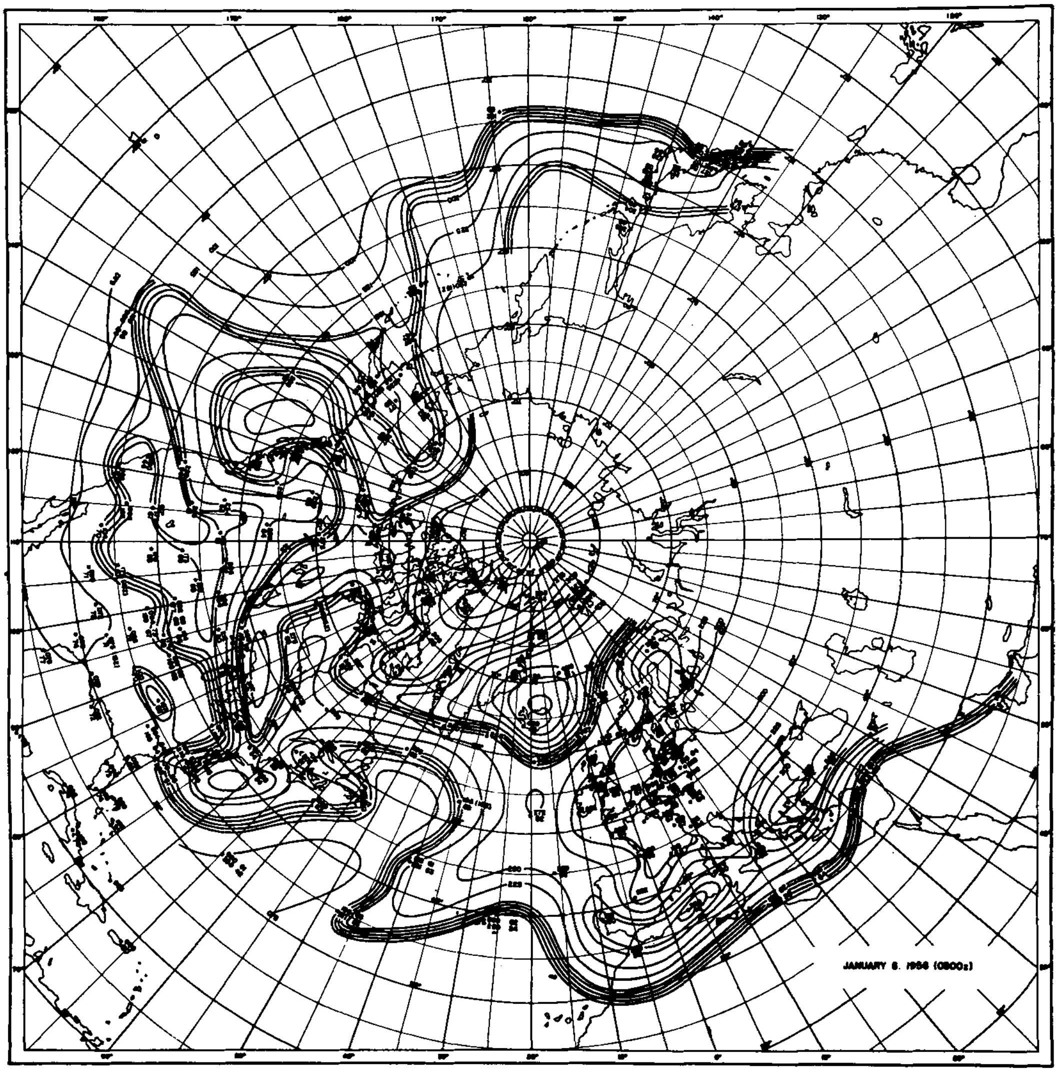


Fig. 6. Hemispheric tropopause map January 6, 1956 (0300 Z). For each station tropopause height in mb (3 figures) and tropopause temperature in °C (2 figures, minus sign omitted). In case of double tropopause levels both values are plotted. When the tropopause was not well defined no values are given. The breaklines in tropopause height are indicated by the concentration of the isolines.

break of polar air directed towards Central Europe.

The tropopause map of January 2 (Fig. 2) shows over Central Europe an area of low tropopause height connected with this cold outbreak of polar air. The more interesting feature is that the southern breakline still continued its movement towards the north-east and even approached Southern Scandinavia. The strong trough formation over the East Coast of North America is still present, but especially over its southern part the height of the tropopause rises.

On January 3 (Fig. 3) the development over Europe continues and it can be seen that this subtropical intrusion covered all of Western and Northern Europe. A branch of the subtropical jet surrounds this large area, inside of which the soundings have typical subtropical temperature structure. The tropopause is everywhere above the 200 mb level (mostly near 175 mb) with a tropopause temperature

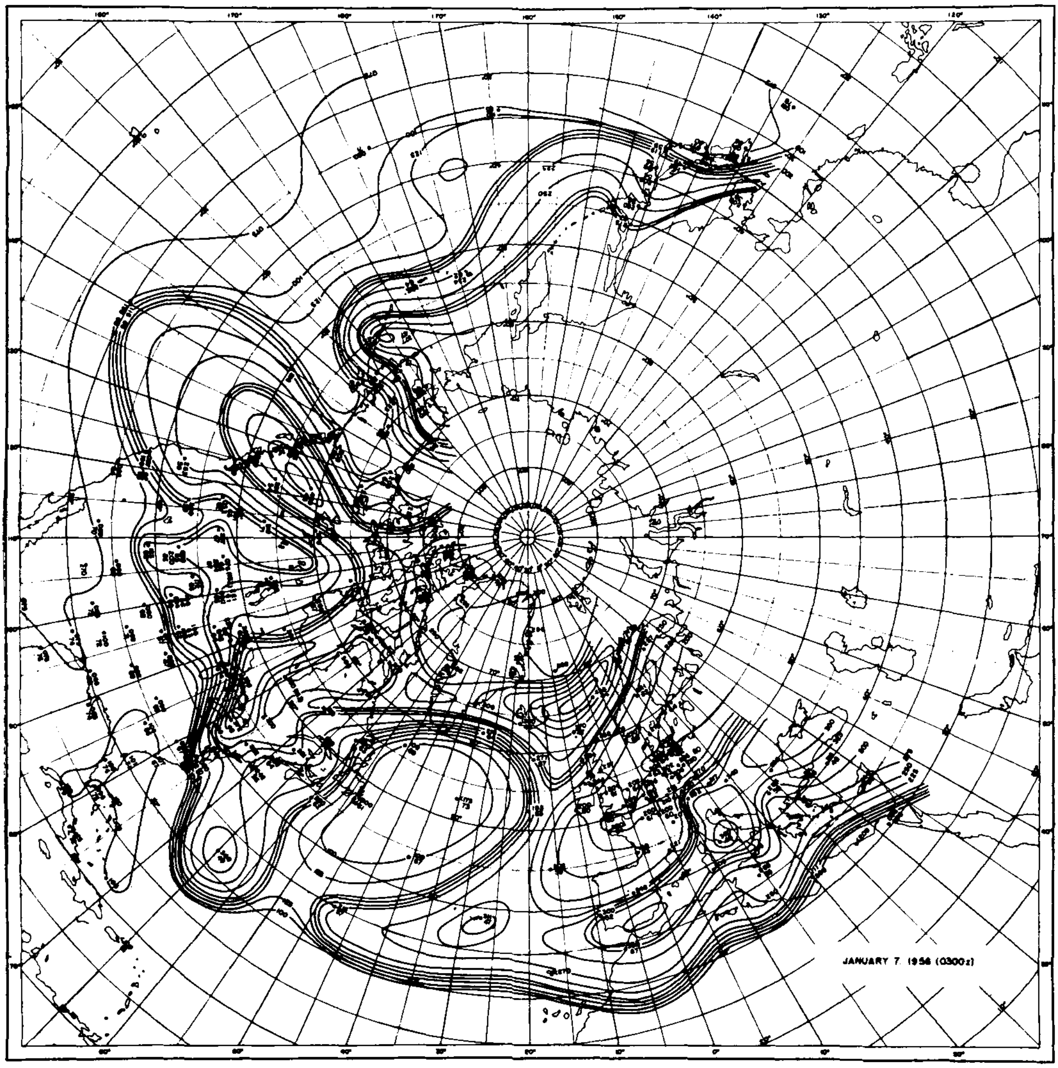


Fig. 7. Hemispheric tropopause map January 7, 1956 (0300 Z). For each station tropopause height in mb (3 figures) and tropopause temperature in °C (2 figures, minus sign omitted). In case of double tropopause levels both values are plotted. When the tropopause was not well defined no values are given. The breaklines in tropopause height are indicated by the concentration of the isolines.

between — 65 and — 72° C. This northward progression of a large part of the subtropical atmosphere over the Atlantic causes an extremely strong pressure rise at the surface and a formation of the well known blocking anticyclone takes place. One would expect that the advection of subtropical warm air should cause a pressure fall but as in the higher tropospheric layers and in the lower stratosphere extremely cold air is advected northward, a strong pressure rise at the surface is created. It is a well known rule in synoptic meteorology (ERTEL, 1930), (ERTEL, SJAN-ZSI-LI, 1935), (HAURWITZ, 1927), (ROSSBY, 1928), (SCHEDLER, 1917), (STEINER, 1926), (THOMAS, 1935), that advection of warm air in the lower troposphere in combination with strong pressure rise at the surface always tends towards the establishment of very persistent anticyclonic conditions. The over-compensating effect of cold advection in the very high troposphere and lower stratosphere was studied several years ago by H. THOMAS (1935).

We may further observe that after a separate high pressure cell has formed in northern latitudes the subtropical jet forms again along latitude 30° N. The trough over the Western Atlantic Ocean has weakened considerably and the northern tropopause breakline connected with the polarfront jet and the polar front appears in rather northerly latitudes over Southern Greenland and Northeastern Canada.

In the area north of Florida one can observe the start of a development similar to that just described. The subtropical breakline in that region shifts northward again and on January 4 (Fig. 4) it becomes quite obvious that a second intrusion from the subtropical region takes place which builds up more and more east of the American East Coast (Fig. 5, Fig. 6, and Fig. 7 on the 5th, 6th, and 7th). By this process the development of a second large anticyclonic block was expected on January 7 west of Newfoundland surrounded in the higher tropospheric layers by a branch of the subtropical jet. It is of the same type as that over Europe which extended in the meantime its influence far into the North Asiatic continent. This cannot be seen from the tropopause maps presented here as no data are available in Asia but the lower level charts point in this direction.

From the 4th to the 7th the rather high tropopause over Europe (considerably higher than 200 mb) remains unchanged. The subtropical structure of the soundings inside this first subtropical intrusion was conserved during four days and did not alter appreciably. In spite of the northward movement from 30° N to Central and Northern Europe and the four days time taken, the soundings in Central and Northern Europe do not indicate a temperature structure characteristic of soundings taken between the two breaklines (with a tropopause height around 240 mb). Therefore no doubt remains to which category they belong. This characteristic temperature persistence inside such a blocking anticyclone is well known.

b) *Subtropical impulses over Southern America and Pacific.*

Thus far only developments over the Atlantic and European sector of the maps have been discussed. We now proceed to explain the features of atmospheric developments in the North American sector and the Pacific. On January 1 the two tropopause breaklines in this part of the world are well separated. The polar line is located at rather high latitudes. Over the Japanese Islands, south of Alaska, over the Southern Rocky mountains and along the American East Coast trough formations can be noticed with low tropopause heights. This separation of the two breaklines continues on January 2. On the 3rd the subtropical jet starts to move northward over Southern California, similar to its behaviour over the Atlantic and European sectors. On January 3 and 4 the two breaklines of tropopause height come close together and a cold outbreak takes place over the Northern Rockies. This progresses rapidly southeastward towards Florida. The source region for this cold outbreak was the cold air mass south of Alaska. This outbreak of polar air was followed by a second one on the January 5 and 6 which even entered the Southern Atlantic Ocean. This can be seen from the tropopause maps of January 6 and 7 by a tongue of low tropopause height extending from Canada in south-easterly direction to the Atlantic area between Florida and Bermuda. This cold outbreak, directed towards the southwestern part of the Atlantic, has a close connection with the second subtropical impulse northward in the western Atlantic area described before. It suggests that such an outbreak of cold air directed from the continent across the American East Coast, moving out over the rather warm Gulf stream part of the Atlantic, may contribute to a northward displacement of the subtropical system farther to the east. Although this may not be the only cause of the development at the northern border of the tropical circulation cell (at about latitude 30° N), but it may favour its formation. Over Southern California a second impulse follows the first one on January 6 and advances very far northward towards Central Canada by January 7. Each of these intrusions caused cyclogenesis followed by outbreaks of polar cold air. A similar development can be noticed in the middle of the Pacific Ocean. Here the subtropical system even approached Alaska on the 5th and tropopause heights higher than

200 mb can be noticed over Alaska on January 6 and 7.

c) *Summary of the above discussion.*

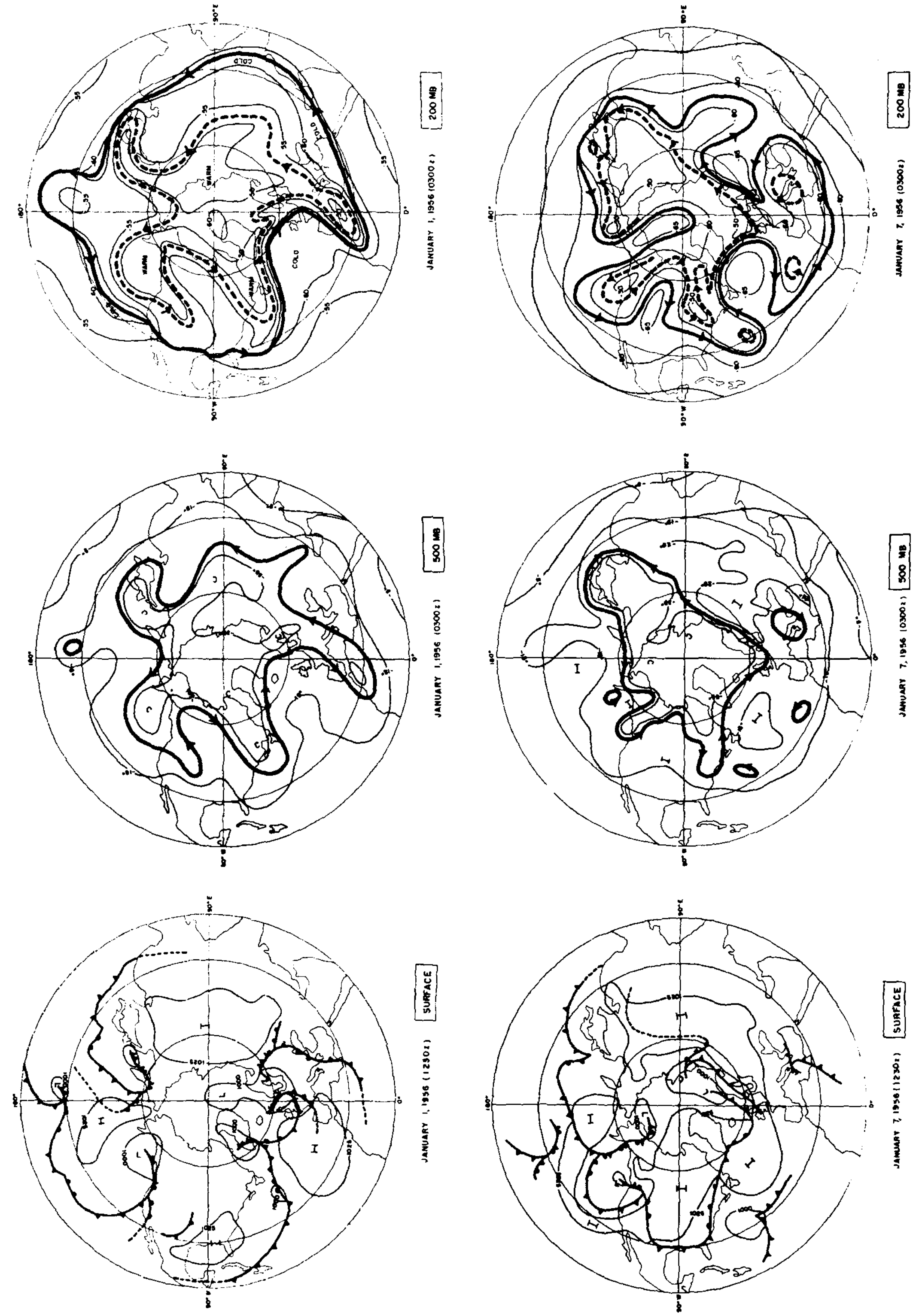
In summarizing the above discussion of large scale atmospheric developments which become very noticeable in the changes of the tropopause height, resp. in the latitudinal changes of the analysed tropopause breaklines, one may state that during the period January 1 to 7 the subtropical part of the atmosphere has been active. This was in the sense that the subtropical breakline of tropopause height in many parts of the earth shifted northward and part of the subtropical atmosphere seems to be displaced to rather northern latitudes. In the higher troposphere a deep inflow of extremely cold air occurs on top of rather warm air. By overcompensation large anticyclones are generated (blocking highs) over Europe and Northern Asia, over the Western North Atlantic, over the whole USA and Alaska. These large areas contain subtropical warm air and the structure of the soundings inside these intrusions was found to be typical for the subtropical group. They all possess a tropopause unusually high for these latitudes. The temperature at the tropopause is always between — 65° and — 72° C which are typical temperatures of the subtropical tropopause for stations south of 30° N. The northward shift of large parts of the subtropical atmosphere starts from preferred regions (mostly southwestern parts of oceans). However, this is not true in all cases. Such a development goes parallel with a strong meandering behaviour of the subtropical jet. The subtropical jet surrounds these large anticyclonic eddies. Finally a complete separation from the source region may be observed. The subtropical jet then forms again along latitude 30° N.

II. The principal distinction between meridional and zonal circulation type[1] at different levels

Fig. 8 presents in a schematic way the fundamental difference in atmospheric circulation patterns at the beginning (January 1) and the end (January 7) for surface, 500 and 200 mb. On the surface map of January 1 tracks of cyclones (cyclone families) are oriented in a more meridional direction separated by individual high pressure cells. No continuous subtropical high pressure belt exists. In 500 mb a meandering polar front jet with a number of long waves separates the polar air inside the jet (northern side) from the warmer air on its southern side. In this warm air the temperature increases gradually towards south. South of about 30° N we only observe 500 mb temperatures characteristic for real subtropical air. A clear distinction between the two types of warm air mentioned before is rather difficult at this level. However, in studying the complete vertical structure of the soundings and the height difference of the tropopause this difference will stand out clearly. Evidently the phenomenon of the subtropical jet is not visible at this level. It was already pointed out clearly by PALMÉN and BRADBURY (1953), when discussing the features of 500 mb analysis, that in addition to the temperature concentration of the polar front another but very much weaker temperature concentration could be noticed farther south. This is due to the difference between the middle and subtropical group of soundings discussed before and is closely related to the existence of a continuous hemispheric west wind belt in higher elevations (the subtropical jet). For the sake of clearness one should point out that the 500 mb analysis deals therefore only with the polarfront jet and the strong tropospheric temperature concentration related to the polar front. When the subtropical jet near the 200 mb level is well developed, one might observe some indications of high wind velocities at 500 mb which are in magnitude comparable with those of the polar front jet, but are widely different in latitude. One should be rather careful not to speak about a double polar front jet in these

1) Meridional and zonal with respect to a more meridional and zonal form of the polar front jet stream.

Fig. 8. *Principal differences in surface, 500 and 200 mb charts.* Upper pictures: Jan. 1, 1956; surface, 500 and 200 mb. *Meridional circulation type* (meridional type of polarfront jetstream, see 500 mb) (approximately zonal subtropical jetstream with exception of Atlantic Ocean, see 200 mb). Lower pictures: Jan. 7, 1956; surface, 500 and 200 mb. *Zonal circulation type* (zonal type of polarfront jetstream, see 500 mb; note its rather northern position, with exception of more permanent trough over Eastern Asia;) see 500 mb) (rather strongly meandering subtropical jetstream; see 200 mb).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WARM
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occasions (ALAKA ET AL., 1953). The analysis of moving jet maxima and minima along the jet axis on one and the same isobaric surface is quite erroneous due to the fact that the jets do not follow isobaric surfaces. Such deviations may be relatively smaller at 500 mb, but at 200 mb where the wind speed decreases sometimes rather rapidly with height when entering the stratosphere, winds at that level may widely differ in speed from one region of the map to the next although the jet may still be present very close to this level (ALAKA ET AL., 1953).

At the 200 mb level inside the area surrounded by the upper part of polar front jet relatively warm stratospheric air is present. The subtropical jet on January 1, with the exception of the Atlantic area, appears near latitude circle 30° N. In most of the northern hemisphere its location is widely different in latitude from the polar jet. In the belt between the two jets the temperatures belong also to the stratosphere. But south of the subtropical jet they belong to the high subtropical troposphere. Here mostly very low temperatures are present in a band, where the tropopause intersects the 200 mb level (ALAKA ET AL., 1953). A strong temperature gradient appears to the north of the subtropical jet. This different vertical structure in surface, 500 mb and 200 mb, characterises the meridional type of circulation on January 1. The 300 mb analysis is the most difficult one with respect to the separation of the two jets. The polar front jet is strongest close to that level but also high wind speeds appear at 300 mb below the subtropical jet. A further difficulty is the weak temperature gradient in meridional direction.

Contrary to this state the zonal circulation of January 7 has quite another character. At the surface a more or less continuous high pressure belt is present quite north of latitude 30° N. The main polar front appears in the very northern latitudes. One should not mix up weak frontal systems connected with low pressure centres south of the main high pressure belt with the main polar front. These are minor frontal systems. At 500 mb a rather concentrated circulation appears and the polar front jet is present in very northern latitudes, specially over the Atlantic, Northern Europe and Northern Asia. One can observe strong anticyclonic cells over the Northern Atlantic, over Asia and in the Mid-Pacific as well as over the Southern United States. Inside these anticyclonic cells the temperature is usually high which indicates strongly that they belong principally to subtropical air. No subtropical jet phenomenon can be seen on January 7 in 500 mb, but in 200 mb the subtropical jet meanders extremely far to the north in many parts of the earth. Therefore the vertical temperature structure of such a subtropical intrusion is so that above the centers of the high pressure belt in the surface, rather warm anticyclonic cells are present at 500 mb. However, in the upper troposphere and lower stratosphere a deep cold layer near to the high tropopause exists. One gets the impression that the polar jet in principle has a zonal form and the subtropical jet meanders strongly. The large area between the two jets, present on January 1, has diminished, and in special regions of the map in very northern latitudes, polar front- and subtropical jet nearly superimpose each other.

The six schematic pictures of Fig. 8 contain therefore the essential differences between meridional and zonal circulation, with respect to the behaviour of the main west wind belts and with respect to the temperature field in different altitudes.

III. Interpretation of vertical temperature field and their means during the whole period January 1—7, 1956

The computation described in the previous paper (DEFANT, TABA, 1957) was carried out for the seven days period along the same lines. Stations were again selected according to their location with respect to the tropopause breaklines. For each day the mean vertical temperature for each of the three groups (polar, middle and subtropical group) has been computed. Fig. 9 shows the mean soundings for each group and for each separate day. The mean soundings in each group look rather similar. Only minor changes are present within each group. Therefore it is quite justified to state that the atmosphere in this seven days period can be divided in three typical parts each of which having a characteristic vertical temperature distribution in the upper troposphere and in the stratosphere, as well as a rather different tropopause height. We may clearly state that each of these means

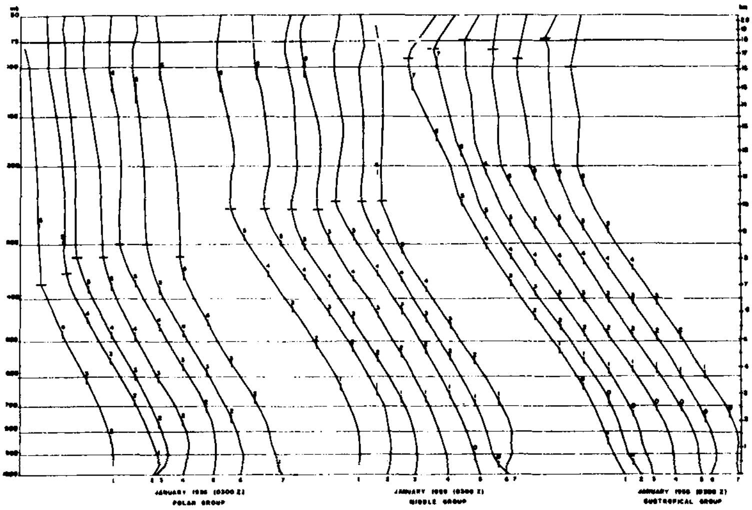

Fig. 9. Mean vertical temperature distribution for each day of the period January 1 to January 7, 1956 (0300 Z) and for the three different groups (polar, middle and subtropical group). The — 10, — 20, — 30° C a.s.o. are indicated by 1, 2, 3 etc.).

is made out of soundings distributed in widely different latitudes. It is therefore not the latitudinal location which characterises the type of sounding, but its position with respect to the main west wind belts. In looking at the temperature distribution in the upper troposphere in each of the three groups one can notice that the heights in which f.i. — 20°, — 30°, — 40°, — 50° C appear are almost constant during the whole period. So the temperature structure of the upper troposphere is almost conserved *in each group* with time, but it changes markedly from group to group. The temperature discontinuity in the troposphere between the polar and the middle group is more pronounced than that between the middle and subtropical group. The height of the tropopause seems to be the best indication to distinguish one type from the other. In the polar group the mean tropopause height remains between 300 and 370 mb. In this group the tropopause of each individual sounding is rather changeable, within the range 300—500 mb, but mostly between 300 and 400 mb. In the middle group the mean tropopause keeps almost a constant height (240—250 mb). Under no condition can these tropopause heights be mixed up with those of the polar group. The third group shows the very high subtropical tropopause (little above the 100 mb level). Only in the last four days there is a tendency for formation of a lower tropopause level at about 200 mb. This is due to the fact that all the soundings inside the strong latitudinal displacements of the subtropical atmosphere described above have been included in the subtropical group for making the mean. They really belong to this group. This, however, does not alter principle features of the subtropical group. If one would only select soundings south of 30° N and exclude those inside the subtropical northward displacements, one would certainly obtain means which would have the same vertical construction as the means for January 1, 2 and 3.

On January 1 three different areas with a markedly different character represented by the three means are present and therefore the polarfront jet and subtropical jet are far apart in most of the northern hemisphere, as was shown in Fig. 8. But on January 1 the approach of the two jets in most parts of the map has caused the middle part to disappear so that the temperature structure of polar mean has come side by side with the subtropical mean. The mean of the middle group on January 7 consists of very few soundings and its temperature structure is very similar to that of the subtropical group although there is no difficulty in identifying it.

The layers lower than 750 mb in all different groups are greatly affected in the individual soundings by different kinds of influences, so that the means show a rather weak temperature decrease with height, isothermal conditions or slight inversion. They should not be looked upon as representative means. After all in this study we are not very much interested in the behaviour of these layers. Therefore the above discussion refers to the levels from 700 mb upwards.

There is still another interesting feature to be seen in Fig. 9. Looking at the polar means one can observe in the higher stratospheric layers deviations from a purely isothermal temperature distribution. On January 1 the temperature remains constant with height from the tropopause level up to about 175 mb. Going further up, a slight temperature decrease with height occurs which becomes stronger in the very high levels (above 100 mb). It seems that these high stratospheric deviations from an isothermal structure become stronger and stronger in time. On January 7 only a very shallow layer with constant temperature may be seen immediately above the polar tropopause and from there on a pronounced decrease of temperature continues upward. Therefore the upper stratosphere is cooled in very high altitudes at first and later on the lower stratospheric layers seem to be affected. It is remarkable that in these higher layers negative deviations of 10° to 12° C from the isothermal structure can be seen in the mean soundings. In the individual soundings this influence in the high stratospheric polar layers can amount to as much as 15 to 20° C. The magnitude of these temperature deviations suggests that they are not only due to outgoing radiation and this factor cannot be the sole reason although it might contribute. Furthermore cooling due to upward motion can hardly be the cause as pronounced vertical motions in these layers are unlikely to exist. Therefore it is justifiable to attribute this stratospheric cooling which becomes stronger and stronger during the time interval in question mainly to an advective inflow of cold air from the subtropical regions. This idea is supported by the fact that not only soundings situated in the very high latitudes show this kind of high level stratospheric cooling, but also soundings inside deep troughs situated over more southern latitudes. They also show this phenomenon whenever the subtropical system shifts northward and the trough is approached by the subtropical jet. This subject will be referred to in section IV.

The middle group shows in almost all soundings a similar further temperature decrease with height in the higher stratospheric layers. Only on rare occasions (strong northward shifting of the subtropical system) are the polar soundings affected. This points again in the direction that this upper cooling is mainly due to horizontal advection from southern latitudes.

For each of the three groups a total mean sounding for all the seven days has been computed. These means are shown in Fig. 10. Each of these means is made out of approximately 250 soundings. The three-fold difference is again very obvious. In the troposphere a strong baroclinicity can be seen between polar and middle group which amounts to about

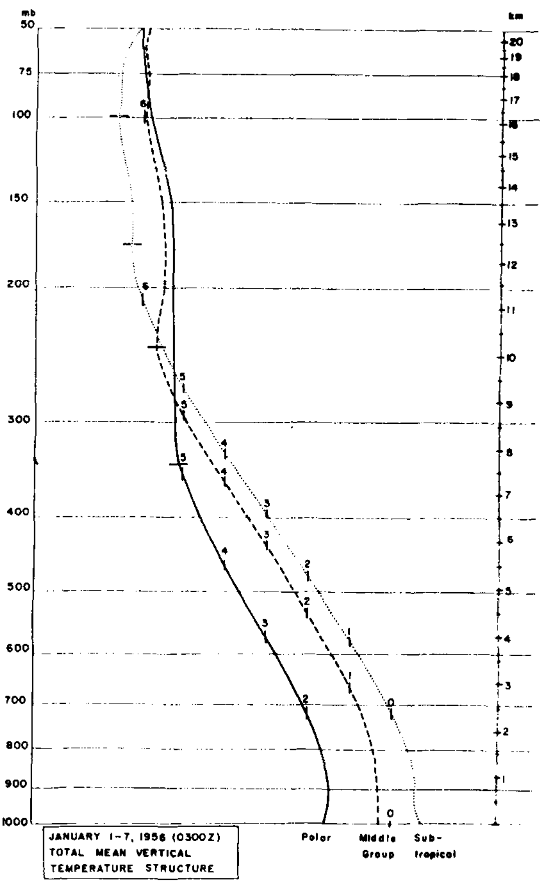

Fig. 10. The total mean vertical temperature distribution for the period January 1 to January 7, 1956 and for each different group (polar, middle and subtropical).

12° C between 700 and 400 mb. It is strongest near 500 mb (14° C). It becomes less between 400 and 280 mb and at 280 mb no meridional temperature difference is present. One could already see from Fig. 9 that inside each of both groups (polar and middle) the vertical temperature structure in all tropospheric layers above 700 mb was very much conservative, otherwise the temperatures — 20°, — 30° C, — 40° C would not appear in all the means at nearly the same height. So in both of these groups a quasi-barotropic state is present which is a well known feature in all synoptic meridional cross sections where the horizontal levels have to be drawn quasi-horizontally. This quasi-barotropic behaviour of upper troposphere in each of the two different groups of soundings which most of the time are separated by the polarfront is of special interest. It is this feature which allows us to treat the atmosphere in the mid- and upper troposphere as a quasi-barotropic one in numerical forecasting. As we deal most of the time only with these two groups of soundings and from 280 mb upward relatively little change can be seen in the stratospheric vertical temperature structure, very little influence or contribution may be expected from the stratosphere. Essentially only the baroclinicity at the polar front has to be dealt with. Fig. 10 shows furthermore that comparably little temperature contrast between middle and subtropical group appears in the troposphere from 700 to 230 mb. This contrast is strongest in the layers between 700 and 500 mb and gradually decreases upwards. But in the stratosphere between 230 up to 50 mb a marked reversed temperature contrast appears. In case of a strong northward displacement of the subtropical system and in cases where the middle soundings cover only a small part of the northern hemisphere (decrease in area) not only a stronger baroclinicity will be present in the troposphere and concentrated at the polar front surface (difference between polar and subtropical soundings), but in the stratosphere above the reversed temperature contrast between the two systems under consideration will be of great importance. Under these circumstances one might expect the presence of a state in which drastic changes in the general circulation might occur. In this case the underestimation of stratospheric contributions on tropospheric developments may be serious and may lead to severe failures in applying barotropic assumptions. In numerical forecasting the application of quasi-barotropic models not taking into account the stratospheric changes during such time intervals, may lead to failures. Under such conditions we observe extremely strong and rather surprising cyclone developments just in such locations where the above described interaction of tropo- and stratospheric temperature conditions were present. It will be left for a later investigation to show definitely that from these locations the rapid breakdown of the zonal circulation type of January 7 occurred, resulting in a meridional circulation type later on (DEFANT, 1957).

IV. A general outline of a possible mechanism of index change

The foregoing discussion dealing with a characteristic behaviour of the whole general circulation during a time interval of several days, during which the main features drastically changed, gives some clues which might possibly be tied together to a more orderly mechanism which acts in such a period of circulation change. According to the foregoing discussion it seems only possible to get some insight in this complicated process by considering the whole space of the atmosphere up to the very top (about 25 km). Such a possible mechanism we attempt to present here and we clearly state that it is not a definite and final presentation. We further must point out that this mechanism may only operate in such time intervals in which large interactions between the more permanent tropical-subtropical circulation cell and the mid-latitude circulation takes place (DEFANT, 1954), (DEFANT, 1954).

In the beginning one can think of a cyclic change where one can start at any instant and return later to the starting state. One mostly deals in the mid-latitude circulation with a meandering circulation type as we have described in Fig. 8. This type of circulation is characterised in the surface layers by individual cyclone tracks which are oriented more in a meridional direction and the subtropical high pressure belt is divided up in separate anticyclonic cells. In the middle troposphere a meandering polar jet with a certain number of long waves (mostly 5 or 6) around the northern hemisphere is present. The tropical circulation cell is restricted to about the latitude range between the equator and the 30° parallel, so that the subtropical jet near the 200 mb level is more zonal. The whole atmospheric temperature field can be divided up into three quite different parts. Each part has its typical tropopause height as well as its tropospheric and stratospheric temperature structure. Under these conditions one might expect in the region between two successive cyclone families a low level shallow outflow of polar air which penetrates even across latitude 30° N into the trade wind regions. (Breaks in a continuous polar front surface.) In addition one might expect cut-off processes of cold vortices towards the south due to instability in the long-wave pattern whereby cold vortices are excluded from their polar source region and penetrate into the tropical circulation. This doublefold process intensifies the tropical circulation. By these interactions not only the mean meridional circulation of the tropical cell, but also the turbulent transfer of angular momentum may increase. From the more recent works of the mean angular momentum balance of the tropical circulation PALMÉN (1955), PALMÉN and ALAKA (1952), RIEHL and YEH (1950), RIEHL (1954), a.o. it becomes likely that a stronger output of angular momentum northward in the high levels along the northern border of the tropical circulation may occur, because the angular momentum balance of the tropical circulation gets disturbed. In special regions along lat. 30° N in which in addition to the zonal components strong meridional northward components develop, the subtropical jet tends to take on a meandering form and shifts towards northern latitudes. These special preferred regions are mostly observed over the western parts of the Atlantic and the Pacific Ocean. The very favourable trough formations over Eastern Asia and over Eastern North America may favour such northward shifts of the tropical system over the western parts of the Oceans. Cold polar air flows out over the warm ocean areas (Gulf stream and Kuroshio) and strong heat will be given off to favour the displacement of the subtropical jet.

As a result of these processes the subtropical jet moves in several places far northward and therefore subtropical air is advected with it. This advection does not only take place in the lower and middle tropospheric layers (warm air advection), but especially in the higher troposphere and in the stratosphere (cold air advection). The advection of very cold high level subtropical air is even more pronounced due to the presence of higher wind velocities at these levels. Strong blocking highs develop in rather northern latitudes and the meandering polar front jet takes on a more zonal form. In certain areas polar front- and subtropical jet come very close together and form an extremely strong jet of a complicated vertical structure (double wind maxima or a single maximum of a broad vertical extent). On the surface a continuous high pressure belt forms around the earth which has on top in the high layers near the tropopause the very cold subtropical air. This situation we call then a zonal circulation type. This is characterized in the mid-troposphere by a more zonal polar front jet in northern latitudes. The polar front now separates the polar air north of it from the purely subtropical air to its south. But in the stratosphere the relatively warm stratospheric polar air stands next to the extreme cold high tropospheric tropical air separated by a tropopause with a very steep front-like slope.

Kinetic energy from the tropics has been transported into mid-latitude circulation by this process. A strong source of potential energy has been created in the vicinity of the polar front. Strong baroclinicity is present in the troposphere at the polar front, but a reverse strong baroclinicity appears in the higher levels of the atmosphere above the polar front. In this stage in our opinion half of the cycle has been performed. We need now to look for mechanisms to offset this critical stage.

There are several factors, which act simultaneously in this occasion. We have discussed before the apparent cooling of the very upper layers of polar stations just before we arrived at the critical stage. We have seen that this influence started at the very high stratospheric layers and could be noticed later on effecting the lower polar stratosphere. We also pointed out that this cooling of the polar stratospheric layers may be mainly due to an advection process of the subtropical air which slowly approached the polar cap from the south in very high stratospheric layers during the time interval before the zonal circulation was formed. Parallel with this process we noticed an increase of surface pressure in the polar cap which gradually increased from a value of 995 on January 1 to 1035 mb on January 8. By the establishment of a meridional pressure gradient (north—south) in the lower layers of the troposphere the conditions become favourable for easterly or northeasterly winds in the polar area. The air tends to break out towards more southern latitudes because of surface friction, especially in regions where the surface friction becomes large due to the topography of the earth's surface (east of Greenland, east of the Northern Rocky mountains and North-Eastern Siberia). This may be one factor to offset the critical stage. A second powerful factor may be instability of different kinds occurring in the regions, where the polar front has a steep slope and above a frontlike inclined tropopause with a counter slope exists. The upper wind field due to the superposition of the polar front jet and the subtropical jet branches becomes strong and there exists strong baroclinicity (strong positive vertical wind shear) in the inclined polarfront below the jet, but also an additional strong baroclinicity at the tropopause (strong negative vertical wind shear). In the upper parts of the polar-front and in the region between the jet core and the tropopause hydrodynamic instability may occur. This instability may destroy the equilibrium of the polar front. Strong cyclogenesis occurs and a new adjustment of mass distribution has to be made. The energy for such rapid cyclogenesis cannot be taken only from the horizontal temperature differences on both sides of the polar front within the troposphere but the very cold layers on top of the warm subtropical anticyclonic cells may act as a source in such a case. So not only the cold air tends to break out horizontally towards southern latitudes but it may get a continuous support from the upper cold air. Even if the upper cold air (with temp. of — 65 to — 70° C) has to descend during this process to the layers 300 or 400 mb and warm adiabatically, it will still be cold enough for these levels (— 40 to 45°). We may mention that a study of an extremely strong cyclogenesis of this type which took place south of Iceland on January 8 has guided us to these ideas. The result of an investigation of this cyclogenesis will be presented in a later paper (DEFANT, 1957). When this break-down has happened (and this does not necessarily happen only in one place of the northern hemisphere) the behaviour of the whole circulation changes drastically into a meridional type characterised by a meandering polar jet. There will be a strong outflow of polar cold air in different parts of the earth. The air inside such polar outbreaks gradually sinks and spreads out over a large area. This phenomenon has been clearly described by PALMÉN (1953, 1951). The blocking anticyclonic cells gradually shift westwards as a result of the strong polar outbreaks on their eastern sides. The cold layer on top of these anticyclones gradually disappears and the subtropical structure of the soundings gets destroyed. The soundings obtain a vertical temperature structure similar to the middle group in the sense of the foregoing discussion. In our opinion the cycle is completed and a meridional circulation pattern is being formed. Mid-latitude circulation only deals with polar and middle systems separated by the polar front. The subtropical system remains south of latitude of about 30° N and the subtropical jet takes on its normal zonal character near this latitude circle. We may clearly state that this life cycle during which a large index change happens is not always in action. Only when the subtropical system takes part in mid-latitude circulation, such remarkable index changes occur. There are cases when strong subtropical impulses of an unusual type develop and an extremely large blocking anticyclone is formed in high latitudes which remains stationary for a long time. A series of strong polar outbreaks may occur which are supported by the cold high tropospheric air on top of the large blocking anticyclone. We refer in this connection to the unusually long cold February 1956 in Europe, when such a development occurred.

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