SEASONAL VARIATIONS OF THE ANTARCTIC TROPOPAUSE

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ABSTRACT

Computations of radiative cooling are made, and the conclusion is reached that the rate of cooling in the antarctic atmosphere is more than sufficient for the observed minimum temperatures to be attained in the lower stratosphere. In addition, the vertical distribution of radiative cooling is such as to give a positive lapse rate in the stratosphere and, ultimately, the disappearance of the tropopause. Synoptic data indicate that there may exist a tendency for a somewhat weaker meridional exchange of air in the winter season in the high latitudes of the southern hemisphere, as compared to the analogous exchange in the northern hemisphere. Insofar as a weaker meridional exchange will allow radiative cooling to operate more effectively in the antarctic, Court's explanation for the disappearance of the tropopause is accepted.

1. Introduction

As a result of a series of 190 radiosonde ascents made in the antarctic at Little America (78°28′ S, 164°55′ W) during the period from 24 April 1940 to 15 January 1941, Court [1] called attention to the existence of several noteworthy temperature distributions in the stratosphere. Most striking anomalies are the large drop of temperature with height in the stratosphere, with the resulting disappearance of the tropopause in late winter, and the large seasonal variation in the temperature of the lower stratosphere. These phenomena, as well as the coldness of the antarctic troposphere at all seasons and the general low pressure, were thought by Court to result from a lack of circulation between the antarctic and the rest of the southern hemisphere.

Using direct comparisons between antarctic and arctic soundings, Court plausibly discussed the possibility of such obvious differences being due to basically dissimilar polar circulations. But it is only recently that enough empirical data have been available to permit the preparation of a quantitative estimate of the actual exchange of air between the antarctic and the rest of the hemisphere, and thereby to evaluate Court's theory. None of these data, unfortunately, are contemporary with the Little America soundings, and some are not even contemporary with each other. However, such an evaluation is thought to be necessary if a complete and realistic description of the hemispheric and planetary circulations is to be attained.

2. Radiation as a determining factor for stratospheric temperatures

Discussion of data and methods.—As a first approximation in attempting to explain the low wintertime stratospheric temperatures over Little America, Court's suggestion of a weak circulation was accepted. Computations of radiative cooling were expected to determine the validity of such an assumption, insofar as they would indicate to what extent cooling by radiation could account for the observed decrease in temperature within the time-limit of one winter season.

Since it is assumed that the antarctic upper-air temperatures would be similar to those of the arctic, were there the same exchange of air in the two polar regions, the monthly mean soundings from Arctic Bay (73°16′ N, 84°17′ W) [2] were examined. During the winter season, this station is located just to the west of a pronounced mean upper-level trough extending to at least the 300-mb level [2]. Also, the mean wintertime temperatures at all levels are lower than those for any other northern Canadian station. Coral Harbor (64°11′ N, 83°21′ W), which appears to be the next-coldest station, has mean wintertime temperatures at upper levels from 1 to 3C higher than Arctic Bay. Soundings at Yakutsk in Siberia (62°01′ N, 129°43′ E), which compares in latitude with Coral Harbor and which is also located to the west of a pronounced upper-level trough, show temperatures about as low as those at Arctic Bay above the 700-mb level, but colder below. From this it may be inferred that temperatures of the order from 1 to 3C lower are found north of Yakutsk, at a latitude comparable to that of Arctic Bay. Mean wintertime temperatures of this

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order still do not approach those at Little America above the 300-mb level.

In fig. 1 are shown the mean monthly soundings for Little America and Arctic Bay, for the summer months of January and July and the winter months of July and January, respectively. The notable features in the summer soundings are the warmth of the stratosphere over Little America, and the increasing difference in temperature with height. In the winter sounding, the levels above about 5 km at Little America become increasingly colder and no definite tropopause can be found. This last phenomenon is not merely a statistical oddity. Analysis of the individual soundings indicates the extent to which the tropopause becomes diffuse and disappears in the late winter. The criterion used in determining the existence of the tropopause was a change of lapse rate to less than 2C per 1000 m, with the temperature at the top of the sounding not more than 10C colder than at the base of the inversion. On this basis, the mean height of the tropopause of the individual soundings changed from 9000 m in May to 10,000 m in July, disappeared completely in August when the height of the maximum sounding was 14,680 m, and reappeared at 12,000 m in September. Furthermore, from a study of the upper-air data from the antarctic station at Maudheim (71°03′ S, 10°54′ W), Schmitt [3] finds that:

> The disappearance of the tropopause on many days during the Antarctic winter, suggested by Court and others, has become a well-established fact. . . . No minimum of temperature, or at least no distinct increase of more than 1C, has been found in the higher levels on 16 out of 20 days in August 1950, on 14 out of 16 days in July 1951, and on 10 out of 13 days in August 1951.

To illustrate further the difference in the two polar temperature regimes, tables 1 and 2 give the change in monthly mean temperature at several fixed heights, respectively, over Little America during May through December and over Arctic Bay for comparable pressure levels and months. In fig. 2, the curves of the absolute minimum and maximum temperatures of all the soundings made at the two places are also seen to be different. In the central portion of the figure are given the mean monthly soundings for Little America during April and for Arctic Bay during December, which month is actually two months later in the winter season than is the former. April in the antarctic corresponds to October, not December, in the arctic. Except for the lower 3 km, the soundings are very similar. Since there were no upper-air humidity determinations made at Little America, and because of their close correspondence with respect to tempera-

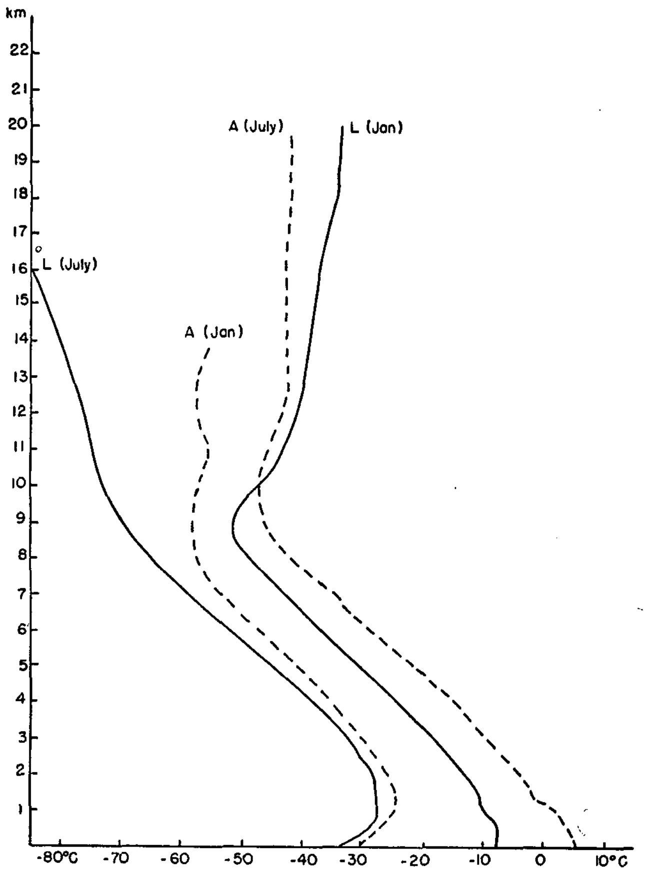

FIG. 1. Mean monthly temperature soundings at Arctic Bay (A) and Little America (L) for January and July.

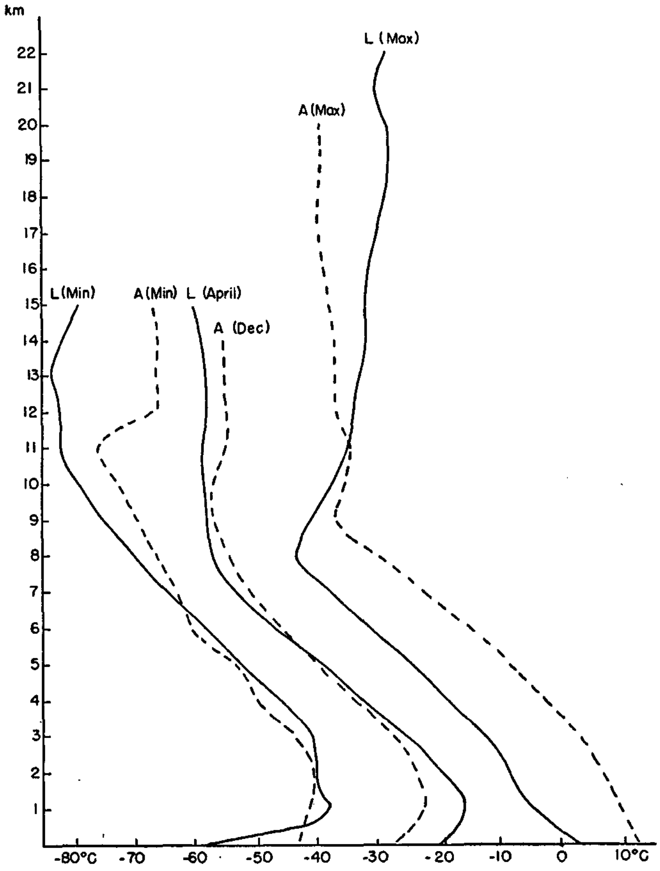

FIG. 2. Absolute minimum and maximum temperatures observed in free atmosphere over Arctic Bay (A) and Little America (L). Mean monthly temperature soundings at Arctic Bay for December and Little America for April.

ture, the Arctic Bay temperature and humidity distribution for December was substituted for that of Little America in computing radiative cooling rates in the polar regions.

Brooks' [4] tabular method of computing the rate of temperature change in the free atmosphere due to infra-red radiation was used. This method gives the cooling rate at a fixed level rather than for a layer, and is simpler and less time-consuming than graphical methods. The results obtained are comparable with those of other methods, although Brooks' tables give somewhat larger values than Elsasser's method, for instance. It also now appears that Elsasser's values are too large at upper levels, because the use of the factor $(p/p_s)^{\frac{1}{2}}$ rather than a factor p/p_s overestimates stratospheric cooling. The factor $(p/p_s)^{\frac{1}{2}}$ gives a greater optical thickness of water vapor, and thus a greater absorption of long-wave radiation than does the factor p/p_s. Since there is a greater absorption in the one case, there will also be greater loss of radiation to space by each stratum. There are also overestimates in the cooling rate due to the use of standard pressure and temperature emissivities, but their magnitude cannot be determined as yet.

Another consideration was that of finding a representative distribution of water vapor at levels above 500 mb, at which level the Arctic Bay data, which were substituted for the Little America data, no longer contain humidity values. Unfortunately, little in the way of high-level humidity measurements, especially in the stratosphere, is available. Shellard [5], Dobson *et al* [6] and Barrett *et al* [7] have given some indication of moisture distributions in the stratosphere. On the basis of these data, and partly to determine the effect of high and low moisture content, three calculations of radiative cooling were made, using constant relative humidities of 10, 45 and 90 per cent at several levels above 500 mb. The results of the computations for levels from 500 to 150 mb are given in table 3. Using Elsasser's radiation chart, Penner [8] has computed the radiative cooling at Arctic Bay and seems to have obtained comparable values.

Inasmuch as Court's concept of an isolated antarctic atmosphere was tacitly accepted, and since the region from 300 to 100 mb is isothermal in April, it was assumed that the relative humidity at these levels could be constant. This is not equivalent to saying that the mixing ratio is constant, although this condition certainly does not exist to the top of the atmosphere. Since the transmission of the air above is also a factor in computing the loss of heat by radiation, it constitutes another source of error because the amount of water vapor above the 100-mb level is not known. This lack of a definite measure of the water-vapor content of the antarctic atmosphere is a serious obstacle when attempting to make accurate radiation calculations. The results are presented here, however, as a first approximation and in lieu of computations based upon actual observations of humidity.

A statistical study of diurnal variation of temperature in the lower stratosphere over England has been made by Kay [9]. From this work, it appears that the rate of cooling at the 150-mb level in the winter season is 1.6 C/day. This compares with the value of −1.1 C/day based upon the December Arctic Bay data at the 150-mb level, with assumed relative humidity of 10 per cent.

From the mean April and September soundings at Little America, the change in temperature was computed for levels above 500 mb. This temperature difference was assumed to be due to radiative cooling alone, as explained above. Table 4 gives the dates on which there is first observed less than 24 hr of continuous sunshine and when there is again 24 hr of continuous sunshine for several levels over Little America. At the beginning of the dark period, and again at the beginning of the light period, there may be some heating of the air due to direct solar radiation. Kay's work [9], however, shows that in the winter over England (50–60°N), where there is some possible sunshine on all days, no heating is observed at the 100- and 150-mb levels, and only 0.1 C rise in temperature during the daylight hours at the 80-mb level. From the computed cooling rates given in table 3, a calculation was made of the number of days necessary for such a temperature difference to be brought about. The results are combined with the cooling rates in table 3. In this instance, as with the cooling rates, no correction is made for the fact that the rate of cooling will be affected by the progressively lower temperatures that will prevail later in the winter.

For the purposes of this study, it is assumed that

Table 1. Change in monthly mean temperature at fixed heights over Little America.

Height (km)	Change in temperature (deg C) May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
16	−8	—	—	—	—	14	28	−1
14	−7	−6	−8	−1	3	10	27	0
12	−5	−5	−8	−1	2	6	23	3
10	−5	−3	−7	−1	2	3	18	3
8	−4	0	−5	1	2	1	9	4
6	−5	−1	−1	0	0	4	4	6
4	−6	2	−1	0	0	4	2	7

Table 2. Change in monthly mean temperature at fixed pressure levels over Arctic Bay.

Press. (mb)	Change in temperature (deg C) Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
100	—	—	—	—	—	1	0	2
125	−3	−2	−1	—	—	0	1	1
175	−3	−2	−2	4	6	1	2	1
250	−3	−3	−1	1	4	4	2	1
350	−2	−2	−2	1	2	2	3	4
450	−3	−2	−1	1	1	1	5	5
600	−4	−2	−1	1	1	2	5	6

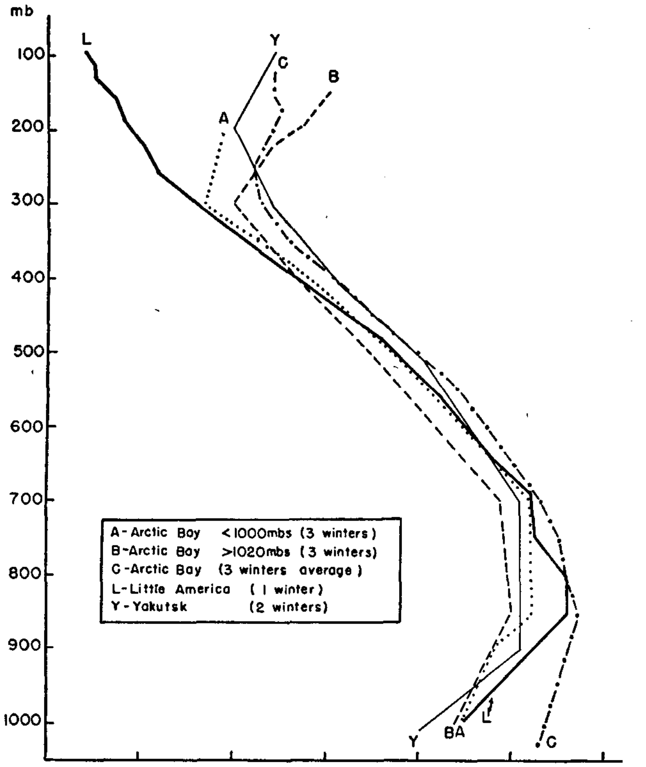

FIG. 3. Mean winter temperature soundings at Arctic Bay with surface pressure less than 1000 mb (A), Arctic Bay with surface pressure greater than 1020 mb (B), Arctic Bay three-winter mean (C), Little America one-winter mean (L), Yakutsk two-winter mean (Y).

the sun's radiation is constant with time and that only the varying distance of the earth from the sun in the course of the year is likely to cause significant differences in summertime insolation. During its summer the southern hemisphere is, of course, closer to the sun than is the northern hemisphere during its own summer. Milankovitch [10] has computed the daily insolation at the earth's surface in the absence of an atmosphere due to this difference in distance. The values of insolation at 70 and 80°N and S for several days in the year are given in table 5. Since it is assumed that there is no significant difference in the turbidity of the two polar atmospheres, the values are directly comparable.

Discussion of results.—Little America is situated at the edge of a perpetually ice-covered continent which extends southward to the pole. Arctic Bay is located amidst a group of broken land areas in an ice-covered sea which also extends to the pole. In the wintertime, the atmosphere over Arctic Bay is heated by the relatively warm ocean which lies below a comparatively thin layer of ice. Court quotes an estimate of Finn Malmgren of the amount of heat passing from sea water to the air. It is approximately 317,000 cal m^{-2} day^{-1} during the winter season. This is sufficient to raise the temperature of the lowest 150 m of air by 6C. This amount of heat, however, is utterly insufficient to account for a 15C warmer stratosphere at Arctic Bay than at Little America in the winter. Even such a seemingly different geographical location is not as important as it first appears. But Little America, too, is subject to the temporizing influence of the ocean. In the hourly observations of temperature and wind presented by Grimminger and Haines [11], there are cases of rises in surface temperature of more than 50F within 18 hr during the winter season. Such rises are associated with a change in wind direction from south or southwest to east.

In fig. 3, a comparison is made between Yakutsk and the two stations we have discussed. Up to the 600-mb level, Yakutsk has colder air than the mean for each of the other two stations, but above that level it is very similar to Arctic Bay. It does not seem appropriate, therefore, to ascribe the colder stratospheric temperatures at Little America to greatly different conditions of geographical location.

In table 1, it is seen that the overwhelming trend from April to September is for cooling at Little America at all levels from 4 to 16 km. The greater cooling seems to be above 8 km. Table 2, as well as figs. 1 and 2, shows that Arctic Bay has no corresponding rate of cooling. From table 3 we see that the temperature difference observed at Little America between April and September can be brought about by radiative cooling alone, if there is no meridional exchange of heat. Heating by the sun is negligible during this period. It is recognized that this is only a first approximation to the actual rate of cooling. The result, however, is encouraging.

The opposite phenomenon of very rapid warming of the higher levels, beginning in September, is forcefully pointed out in table 1. A similar, but lesser, trend is present at Arctic Bay beginning in February. It ap-

TABLE 3. Radiative cooling rates and time required to cool atmosphere over Little America, based upon April and September mean soundings and assumed relative humidities.

		Rel. hum.: 10 per cent		Rel. hum.: 45 per cent		Rel. hum.: 90 per cent	
Press. (mb)	ΔT (deg C)	$\partial T/\partial t$ (C/day)	Δt (days)	$\partial T/\partial t$ (C/day)	Δt (days)	$\partial T/\partial t$ (C/day)	ΔT (days)
150	−17.2	−1.10	15.5	—	—	−1.51	11.4
175	−15.4	—	—	−0.70	22.0	—	—
200	−13.2	−0.48	27.2	−0.60	22.0	−0.70	18.8
300	− 5.6	−0.14	41.0	−0.10	56.0	−0.01	560
400	− 4.2	−0.57	7.3	−0.32	13.1	−0.43	9.8
500	− 4.1	−0.23	17.8	−0.87	4.7	−0.86	4.8

TABLE 4. Dates of complete disappearance and reappearance of sun at latitude of Little America for various levels.

Height (km)	Sun disappears	Sun reappears
0	April 23	October 19
15	May 7	October 10
25	May 14	October 6

pears that the higher levels are warmed first and that the heating progresses downward in the later months at Little America. On a purely radiative basis, it indicates that the source of the heat is at levels above 4 km. It is tempting to locate this source in the ozone layer. We know, from table 5, that there is approximately 7 per cent more solar radiation received at 70 and 80°S in the summer than at corresponding northern latitudes. What such an increase of radiation could do at the ozone layer is a moot question. Nor do we know yet just what ozone distribution there is over Antarctica, neither with respect to seasons nor compared to Arctic Bay. As regards heating in the ozone layer, Craig [12] has the following comment to make:

> The sample calculation indicates that the lower, isothermal part of the ozone layer (10–30 km) should be heated. This heat may be transferred to the troposphere as a result of diffusion or subsidence. The computed values of heating or cooling have the same magnitude as possible temperature changes due to air motion, so that no part of the ozone layer is necessarily in radiative equilibrium.

The coincidence of the return of the sun in the spring (table 4) and the rapid warming of the high levels first (table 1), with a later warming at progressively lower levels over Little America, points out the possibility that the ozone layer is the source of the heat. The 7 per cent greater insolation may also be helpful in directly raising the temperature, although to what extent is not known. A weak meridional exchange of air, as postulated by Court, would not be at variance with the observed warming, since the confinement of the air over Antarctica will result in at least a temporary concentration of warm air aloft. Even if the assumption of a weak meridional circulation in summer is thought to be invalid, since the heating in the ozone layer due to solar radiation is said to be of the same magnitude as temperature changes due to air motion, a meridional exchange in summer should add to the effect. At this season, the atmosphere is everywhere being warmed.

TABLE 5. Daily insolation (cal cm^{-2} day^{-1}) at earth's surface in absence of atmosphere. (After Milankovitch.)

	Latitude			Latitude	
Date	70°N	80°N	Date	70°S	80°S
Mar. 31	316	160	Sept. 23	312	158
May 6	772	784	Nov. 8	802	814
June 22	1043	1093	Dec. 22	1114	1167
Aug. 8	765	777	Feb. 4	809	821

3. Dynamic and synoptic factors influencing stratospheric temperatures

Discussion of data and methods.—At the time Court first suggested that the disappearance of the tropopause is due to the lack of exchange between Antarctica and the lower latitudes, he was not able to present synoptic data to support the theory. It is only recently that a reliable continuing series of daily weather maps has been prepared for the southern hemisphere. The first complete series is for the year 1949, for which the circulation indices have been computed by the U. S. Weather Bureau — M.I.T. Extended Forecasting Project. The seasonal averages of meridional indices for both hemispheres at latitudes 45 and 60 deg are tabulated in table 6.

Sea-level meridional indices are indicative of cross-latitude flow at the surface and, perhaps, within the lower several kilometers of the atmosphere. To arrive at a reasonable representation of the general circulation, however, it is necessary that reliable wind observations be available at all levels. In the southern hemisphere, there is only one regularly reporting rawin station poleward of 50°S; consequently, no definite conclusions can be reached regarding upper-air exchange.

It has been observed that a multiple or indeterminate tropopause is generally associated with low-pressure centers. Also, some well-developed high-level cyclones have, in addition to a tropopause at low levels, a very high and cold tropopause. Such observations lead one to question whether the difference in the tropopause heights at Arctic Bay in the winter, or any season, may not be related to the difference in surface pressure, since it appears that Little America must be strongly affected by cyclonic activity. The mean annual pressure at Little America, based upon three years of observation, is 983.9 mb. The mean annual pressure at Arctic Bay is 1011.1 mb. The mean seasonal pressures at the two stations are shown in table 7. To test this hypothesis, wintertime daily soundings from Arctic Bay were divided into two groups, one consisting of soundings with surface pressure lower than 1000 mb and the other with surface pressure higher than 1020 mb. The data are for the winter months of February 1949, January 1950, January 1951 and February 1951. These were the only months in the three winters studied when there were

TABLE 6. Seasonal averages of meridional indices (m/sec) for 1949.

Season	NMI-45*	SMI-45	NMI-60	SMI-60
Summer	4.35	5.21	4.62	6.53
Fall	5.65	6.45	6.52	6.88
Winter	7.13	6.56	7.32	7.17
Spring	6.28	5.81	5.86	7.14

* Northern-hemisphere meridional index at latitude 45 deg, *etc.*

soundings that fell within the set limits of pressure. Three of the curves in fig. 3 represent the mean soundings at Arctic Bay for (a) three winter seasons, (b) surface pressure lower than 1000 mb and (c) surface pressure higher than 1020 mb.

Flohn [13; 14], among others, has stated that soundings made at Yakutsk show a colder troposphere there than at Little America and an ill-defined tropopause at around 6 km. The Yakutsk data referred to by Flohn are monthly means for levels up to 6000 m only, and show no tropopause. To check further this opinion, a series of fifty soundings made at Yakutsk in the winters of 1949–1950 was averaged and a mean obtained. This curve is also shown in fig. 3. As regards the above, a number of the individual Yakutsk soundings still show a weak positive lapse rate from the 300-mb level up to the 200-mb level, at which point the soundings ended. However, whenever this type of sounding continued above the 200-mb level, there invariably was a tropopause. The positive lapse rate between 300 and 200 mb did not appear to be related to either a high or low surface-pressure exclusively.

In addition to the Yakutsk data, other arctic soundings [15; 16] were examined for indications of tropopause disappearance in the wintertime. None of the individual soundings from Barrow and Kotzebue in Alaska, or Kiruna and Abisko in Sweden, exhibited lapse rates at high levels that could be taken as evidence of a tropopause disappearance.

Discussion of results.—It has been previously stated that the differences in heat transfer from the surface to higher levels at Little America and Arctic Bay due to geographical location are not important, insofar as such heat transfer affects the temperature of the upper troposphere and lower stratosphere. However, it is incorrect to assume that the dynamic and synoptic factors are likewise not significantly different. Unfortunately, until such time as sufficient antarctic synoptic data are available, only an inference as to possible differences can be made.

At 45°N there is considerable cross-latitude exchange in the winter season, as evidenced by an index of 7.13 in table 6. The southern-hemisphere meridional index for the same latitude and season is 6.56. Since most strong outbreaks of polar air cross latitude 45 deg in the wintertime, it may be said that the southern-hemisphere circulation at 45 deg is less meridional. A similar condition also exists in the spring season. The opposite holds in the summer and fall. At latitude 60 deg, it is only in the winter season that the sea-level indices show that the southern hemisphere has a lesser meridional exchange. Such figures are not conclusive, but they show a tendency which is in accord with the hypothesis of a weaker meridional exchange. Insofar as the southern hemisphere has mainly an oceanic surface poleward of latitude 45 deg to the edge of the polar continent, the east-west gradients of temperature at most levels in the troposphere will be weak compared to the other hemisphere. It can be assumed, therefore, that the lower levels of the atmosphere will reflect the same condition of lesser austausch. Consequently, with increasing height the difference in austausch between the hemispheres will become even larger. That there is a weaker east-west gradient of temperature, and less variability from one season to another, is brought out by the small variation in the southern-hemisphere meridional indices. A study of the daily surface synoptic charts for the winter seasons of 1949 and 1950 reveals few strong outbreaks of polar air from Antarctica. The impression one has from the charts is mostly of a slow seeping out of polar air. The writer, however, does not wish to intimate that polar outbreaks are non-existent.

The seasonal trends of surface pressure at Little America and Arctic Bay, as presented in table 7, are exactly opposite. The means of the three years of observations at Little America reflect a continuous fall of pressure from the summertime maximum to the springtime minimum. Arctic Bay has its minimum in the summertime, with a slow rise to the springtime maximum. If the seasonal values of surface pressure at Little America can be taken as criteria, there is a marked decrease in mass from summer to spring. This suggests, if the idea of a separate antarctic circulation is to be accepted, that the change in surface pressure results from a redistribution of the mass of air already present in the region. The low temperatures reached in the atmosphere over Little America, and especially at levels above 8 km, should bring about a sinking of the isobaric surfaces and a strong meridional pressure-gradient. This results, of course, in a stronger circumpolar vortex. The strength of the vortex would tend to increase during the course of the winter, and by spring, with a weakening of the gradient, outflow due to the super-geostrophic winds may account for the minimum pressure. An analogous explanation, and the idea of polar air being trapped by strong upper-level westerlies, have been used by Namias [17]. In the summer season, although the lower atmosphere is still colder, Little America is warmer than Arctic Bay above 10 km. Such warming would tend to weaken the meridional pressure gradient and decrease the strength of the vortex and the outflow of air. This may be reflected, then, in the summertime pressure

TABLE 7. Mean seasonal and annual pressure (mb) at Little America (1929, 1934, 1940) and Arctic Bay.

Period	Little America	Arctic Bay
Summer	992.2	1008.6
Fall	985.6	1009.3
Winter	980.5	1011.8
Spring	977.4	1014.6
Year	983.9	1011.1

maximum. Other possibilities, which Namias also considered, are that (a) the height of the atmosphere may be lower over Little America than over Arctic Bay, and that (b) there may be regions above the limits of the soundings where the antarctic stratosphere is warmer than the arctic one. These explanations, especially the second, do not appear to be as reasonable as that of the increased circumpolar vortex to account for the seasonal variation in pressure.

That there may be more outflow of cold dry air and also less inflow of warm moist air in winter than in summer is borne out by the table of mean seasonal cloudiness presented by Grimminger [18] for the combined years 1929 and 1934. The values are as follows, in tenths of the sky covered: summer 6.8, fall 6.5, winter 5.1, spring 5.7, light season 6.7 and dark season 5.3.

The three temperature curves for Arctic Bay in fig. 3, as well as the lack of tropopause in the individual winter soundings, show that the disappearance of the tropopause at Little America is not primarily a multiple- or high-tropopause phenomenon, such as is often associated with low-pressure systems. The mean soundings for surface pressure lower than 1000 mb and higher than 1020 mb both have essentially the same slopes as the mean winter soundings, and all have a definite tropopause. The sounding at Yakutsk shows no similarity to the Little America sounding, insofar as tropopause disappearance or cold stratosphere are concerned. None of the soundings that were examined from Barrow or Kotzebue in Alaska, and Kiruna or Abisko in Sweden, exhibited lapse rates in the upper troposphere and lower stratosphere that were much different from any other arctic station.

4. Summary and conclusions

When the sun's rays no longer reach the polar regions, the effect is an immediate cooling of the atmosphere; but observations indicate that the greater cooling at Little America is in the region above 8 to 10 km during the winter. By late winter (August–September), the tropopause inversion weakens considerably and a lapse rate comparable to that of the middle troposphere prevails in the lower stratosphere. In the spring the sun returns first to the high levels, and a rapid rise of temperature which works its way downwards is observed. The warming at levels above 10 km from the winter minimum to the summer maximum is greater than at comparable arctic stations. The absolute minimum temperature is lower, and the absolute maximum is higher.

The course of the temperature in the free air above Little America seems to follow the annual pattern that should prevail if the changes were mainly due to radiational heating and cooling. During the first part of the winter, the levels below about 7 km cool rapidly and soon reach a state of relative equilibrium. The upper levels do not reach a state of equilibrium until late in the winter. Upon the return of the sun, the heating at all levels is rapid, but especially so at upper levels where ozone is concentrated and the days become longer sooner. The difference in summertime temperatures between the two polar regions grows greater above 10 km as higher levels are reached, becoming approximately 12C at 20 km. It is felt that the higher temperatures at these levels may be partly due to the earth's being closer to the sun during the southern-hemisphere summer.

Computed cooling rates of from -0.1 to -1.5 C/day at various levels are found to be higher than necessary for the arctic and antarctic atmosphere to cool to the low temperatures observed at Little America. The wintertime distribution of radiational cooling in the vertical is such that the lapse rate is increased in the lower stratosphere. The result agrees with the observed increase in height of the tropopause at Little America and its eventual disappearance. This phenomenon is not observed at any known arctic station, but has recently been found at another antarctic station during two consecutive winter seasons.

For the radiational cooling to be effective in the antarctic and not in the arctic, an assumption is made of weaker meridional exchange in the southern hemisphere. The synoptic and dynamic evidence at hand tends to give some support to this idea, but there is no definite evidence that such is actually the case. At no time, however, nor under any synoptic conditions, do any of the known northern-hemisphere soundings approximate the extremely low temperatures of the late wintertime soundings at Little America. Some factor, therefore, is operating to overcome the radiational cooling in the arctic. Condensation is ruled out as being of minor degree in a cold dry polar atmosphere, but the north-south exchange of air is thought to be greater in the arctic than in the antarctic. Due to the weaker east-west temperature gradients in the southern hemisphere, the austausch is thought to increase proportionately less with altitude. A smaller austausch at all levels would operate in the proper sense, to allow temperatures to fall to lower values by radiative cooling.

At the same time as the total north-south exchange in the southern hemisphere is decreasing, the net outflow from the polar regions may actually be increased, due to a strengthened circumpolar vortex. If such is the case, it must be that the inflow undergoes an even greater decrease in winter and the cooling of the atmosphere is thereby facilitated, although there can be some transport of warm air at times and even warming by subsidence to slow down the rate of cooling.

It is expected that the observations made recently at Adelie Land and Maudheim will throw more light upon this problem.

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REFERENCES

1. Court, A., 1942: Tropopause disappearance during the antarctic winter. *Bull. Amer. meteor. Soc.*, **23**, 220–238.
2. Henry, T. J. G., and G. R. Armstrong, 1949: *Aerological data for northern Canada.* Toronto, Dept. of Transport, pp. 132–145.
3. Schmitt, W., 1952: Terre Adelie. *Weather*, **7**, 288–289.
4. Brooks, D. L., 1950: A tabular method for the computation of temperature change by infra-red radiation in the free atmosphere. *J. Meteor.*, **7**, 313–321.
5. Shellard, H. C., 1949: Humidity of the lower stratosphere. *Meteor. Mag.*, **78**, 341–349.
6. Dobson, G. M. B., *et al.*, 1946: Meteorology of the lower stratosphere. *Proc. roy. Soc. London*, A, **185**, 144–175.
7. Barrett, E. W., *et al.*, 1950: Some measurements of the distribution of water vapor in the stratosphere. *Tellus*, **2**, 302–311.
8. Penner, C. M., 1948: Note on radiative cooling in the free atmosphere over Arctic Bay. *J. Meteor.*, **5**, 69–70.
9. Kay, R. H., 1951: The apparent diurnal temperature variation in the lower stratosphere. *Quart. J. r. meteor. Soc.*, **77**, 427–434.
10. Milankovitch, M., 1936: In *Handbuch der Klimatologie* (W. Köppen and R. Geiger, *eds.*), **1**, A, Berlin, Gebrüder Borntraeger, pp. 13–19.
11. Grimminger, G., and W. C. Haines, 1939: Meteorological results of the Byrd antarctic expeditions 1928–30, 1933–35: Tables. *Mon. Wea. Rev.*, Suppl. no. 41, pp. 276–330.
12. Craig, R. A., 1949: *Radiative heating and cooling of the ozone layer.* Cambridge, Harvard Univ., 39 pp.
13. Flohn, H., 1944: Zum Klima der freien Atmosphäre über Siberien, I. Temperatur und Luftdruck in der Troposphäre über Jakutsk. *Meteor. Z.*, **61**, 50–57.
14. ——, 1950: Grundzüge der allgemeinen atmosphärischen Zirkulation auf der Südhalbkugel (auf Grund der aerologischen Ergebnisse der Deutschen Antartischen Expedition "Schwabenland" 1938–39). *Archiv Meteor. Geophys. Bioklim.*, A, **2**, 17–64.
15. Maurice, H., 1913: L'Expédition Franco-suedoise de sondage aeriens à Kiruna. *Nova Acta Regiae Soc. Scient. Upsala*, Ser. IV, **3**, No. 7.
16. Rolf, B., 1932: Lancers de ballons-sondes à Abisko de 1921 à 1929. *Medd. fr. Stat. Met.-Hydr. Anstalt*, **5**, No. 5.
17. Namias, J., 1947: Characteristics of the general circulation over the northern hemisphere during the abnormal winter 1946–47. *Mon. Wea. Rev.*, **75**, 145–152.
18. Grimminger, G., 1941: Meteorological results of the Byrd antarctic expeditions 1928–30, 1933–35. Summaries of data. *Mon. Wea. Rev.*, Suppl. no. 42, p. 74.