—, 1960—61: The Shape of New England Mountains, Appalachia, v. 33, no. 2, pp. 145—159; v. 33, no. 3, pp. 316—335; v. 33, no. 4, pp. 458—478.

Troll, Carl, 1941: Studien zur Vergleichenden Geographie der Hochgebirge der Erde. Bonn: Bonner Universität Buchdr., Gebr. Scheur.

—, 1943—44: Strukturboden, Solifluction und Frostklimate der Erde. Geologische Rundschau, Band 34, Heft 7 und 8, pp. 545—694. Translated in 1958 for the U. S. Army Engineers, Snow, Ice, and Permafrost Research Establishment, Wilmette, Ill.

Wahrhaftig, C. and Cox, A., 1959: Rock Glaciers in the Alaska Range, Bull. Geol. Soc. Amer., v. 70, pp. 383—436.

Williams, Joseph E., 1949: Chemical Weathering at Low Temperatures, Geog. Rev., v. 39, no. 1.

Willis, Bailey, 1903: Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range, U. S. Geol. Surv. Prof. Paper 19, pp. 41—101.

A PRELIMINARY REGIONAL DYNAMIC CLIMATOLOGY OF THE ANTARCTIC CONTINENT[1])

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With 14 Figures, 5 Tables

Zusammenfassung: Eine vorläufige regionale dynamische Klimatologie des antarktischen Kontinentes.

Die vorliegende Arbeit versucht trotz der, infolge der Kürze der Beobachtungszeit und der geringen Zahl von Beobachtungsstationen bestehenden Beschränkungen, eine vorläufige Basis für eine regionale dynamische Klimatologie von Antarktika zu geben. Zunächst wird eine grundsätzliche Differenzierung zwischen dem Klima des hohen ostantarktischen Plateaus und dem der Küstengebiete getroffen; das Klima des niedereren westantarktischen Plateaus gehört, obwohl es Übergangscharakter zeigt, dennoch in höherem Grad dem Klima der Küstengebiete an. Über diese grundsätzliche Zweiteilung hinaus, werden gut ausgeprägte Klimagebiete innerhalb des Gebietes mit Küstenklima identifiziert.

Die ausgeprägten regionalen Klimacharakteristika sind hauptsächlich ein Ergebnis des Perturbationselementes. In den mittleren Breiten entstehen zahlreiche Störungen, die spiralenförmig in das Innere des Kontinentes vordringen. Sie werden, hauptsächlich durch antizyklonale Sperrung, auf bevorzugte Gebiete hingesteuert, wobei sie sowohl Strecken des Küstensaumes als auch das niederere westantarktische Plateau klimatisch stark beeinflussen, während sie nur ganz selten in das hohe innere Ostplateau vordringen.

Während der Jahreszeit niederen Sonnenstandes besteht eine größere Häufigkeit von Störungen, und daraus ergibt sich, daß zu dieser Jahreszeit die Variationen aller klimatischen Elemente ein Maximum erreichen. Temperatur- und Luftdruckabläufe sind sowohl in Oberflächennähe als auch in der Troposphäre durch große unperiodische Schwankungen charakterisiert, von denen die ausgeprägtesten sich über weiteste Gebiete erstrecken und durch mächtige Luftschichten der Atmosphäre hindurch gleichzeitig vonstatten gehen. Diese Hauptschwankungen sind eine Art Singularitäten und können mit großräumigen Wetterlagen in Zusammenhang gebracht werden.

Während des größten Teiles des Jahres ist das Innere des Kontinentes von einer Schicht kalter Luft überzogen. Diese „Oberflächenhaut" von Kaltluft, die ungefähr 200 bis 300 m mächtig und durch ausgeprägte Inversionen und katabatische Luftströmungen charakterisiert ist, bildet zu der darüberliegenden Atmosphäre eine Diskontinuität. Störungen in bestimmten Wetterlagen und die Auswirkungen einer Wolkendecke auf die Strahlung zerstören die Inversionsschicht im entfernten Inneren nur äußerst selten, an der Küste jedoch wesentlich häufiger. Das Bestehen einer Diskontinuität zwischen der Oberflächen-Inversionsschicht und der Atmosphäre darüber und der Konflikt zwischen auf Isolierung hinzielende Kontrolle mit den Perturbationselementen sind die hauptsächlichen Determinanten des antarktischen Wetters und Klimas.

Die Aussichten für zukünftige Forschungsarbeiten zur Klimatologie von Antarktika sind nun besser als je zuvor. Mit der Weiterführung des Programmes des I. G. J. und der Wahrscheinlichkeit, daß antarktische Beobachtungsstationen vergleichbare Werte über eine Periode von fünf oder mehr Jahren zur Verfügung stellen werden, werden zweifellos neue Erklärungen für klimatische Charakterzüge von Antarktika entwickelt werden, wobei viele der hier entwickelten Erklärungen entweder ihre Bestätigung oder Widerlegung finden werden.

The specific objectives of this paper are to describe and explain the regional and seasonal variations of climate over a large part of the Antarctic continent. The analysis is based almost entirely on 1958 data collected during the International Geophysical Year (IGY) at 7 United States Antarctic stations (fig. 1). Although some twenty international stations operated during the IGY, data from only the 7 U. S. stations were available in a form useful for this study. Although the few stations and their short period of record impose a serious handicap, this is compensated for

[1]) This paper is a summary of a doctoral dissertation of the same title submitted to the Department of Geography, University of Wisconsin, in August 1961. The research, which included 6 months field work, was made possible by funds provided by the National Science Foundation through the United States Antarctic Research Program.

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The term 'regional dynamic climatology' is employed in this paper to mean explanations of areal differences in climate. 'Dynamic climatology' is therefore considered as simply explanatory climatology. The term has however been defined in a variety of ways, generally conflicting, by both geographers and meteorologists. (See F. K. Hare, "The dynamic aspects of climatology", Geografiska Annaler, XXXIX, 4 (1957), p. 90, and Glossary of Meteorology, ed., R. E. Huschle, American Meterological Society [Boston, 1959], p. 184).

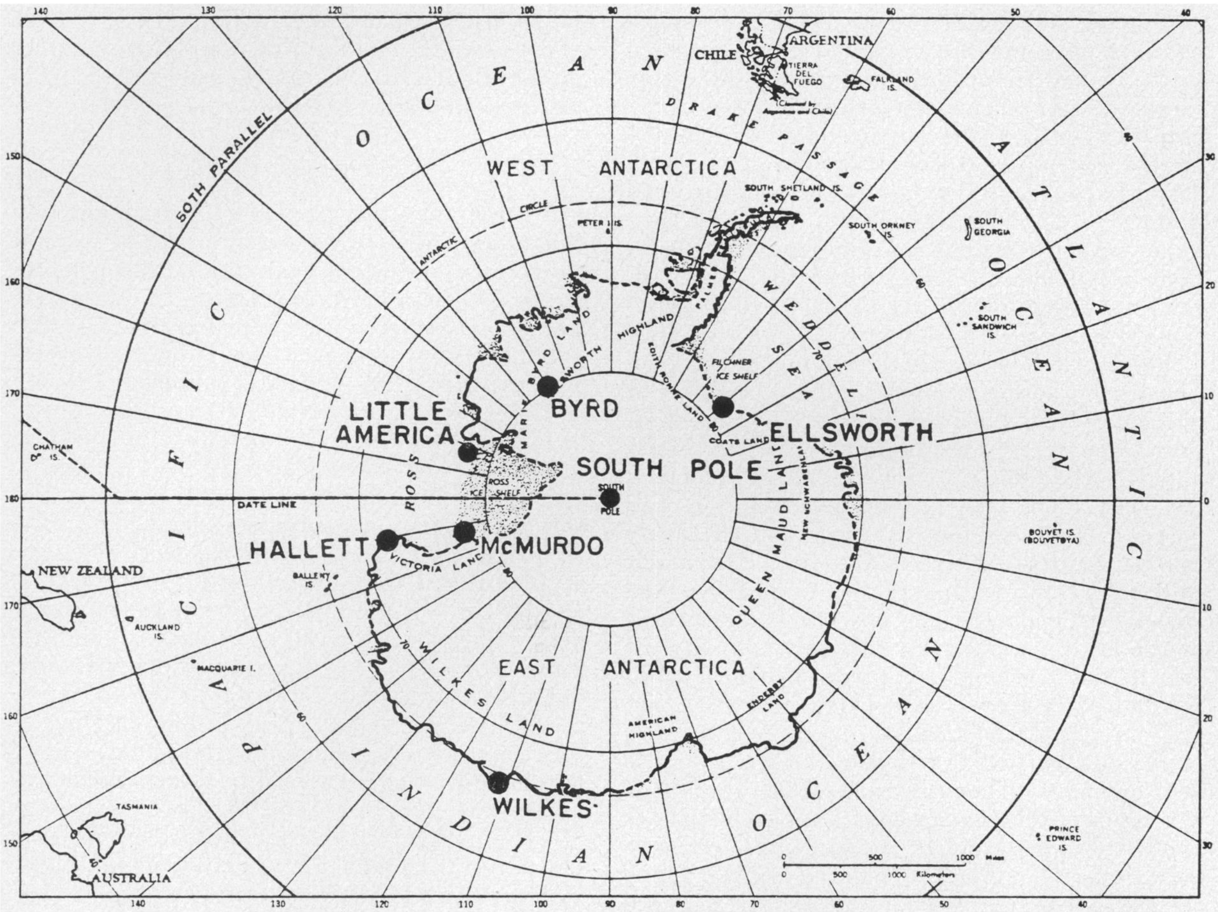

Fig. 1 : Location of US Antarctic stations

in a measure by the fact that these observations, taken simultaneously over a vast area, have a homogeneous quality which permits of their being treated in a rigorous statistical manner thereby providing the basis for a quantitative analysis of the dynamic climatology of Antarctica. It will, moreover, be some years before all of the IGY data become available for research.

Nature of the Data

The 7 U. S. stations which provided the data are located as follows (fig 1): Little America (78°11'S, 162°10'W, elevation 5 meters), Hallett (72°18'S, 170°18'E, elevation 15 meters), McMurdo (77°51'S, 166°37'E, elevation 27 meters), Ellsworth (77°43'S, 41°08'W, elevation 43 meters), Wilkes (66°16'S, 110°34'E, elevation 12 meters), Byrd (79°59'S, 120°01'W, elevation 1515 meters), and South Pole (90°S, elevation 2800 meters). The first five are coastal whereas the last two are interior stations. Of the coastal stations, three are located in the Ross Sea area (Little America, Hallett, McMurdo), one in the Weddell Sea area (Ellsworth), and one on the coast of east Antarctica (Wilkes). Of the two interior stations, Byrd is situated on the plateau of west Antarctica and the South Pole is on the high plateau of east Antarctica. Hence the stations are distributed geographically so that they represent a variety of regions, both plateau and coastal, in both east and west Antarctica. A certain amount of station bias naturally exists as far as the distribution is concerned, but local effects are not strongly prevalent at any station and each station is probably representative of the climate over a relatively large area.[2])

[2]) The author was able to visit 5 of the stations and thereby determine the consistency, reliability and representativeness of the data.

The year 1958, can, moreover, by considered a representative year in Antarctic climate. (See statement by THOMAS GRAY, head of IGY Weather Central at Little America, during discussion at session on circulation studies, in *Antarctic Meteorology*, proceedings of the symposium held in Melbourne, February 1959, ed L. J. DWYER, Commonwealth of Australia, Bureau of Meteorology, Pergamon Press (New York 1960), p. 312.

Most of the data employed in this study were obtained from punch cards and microfilms issued by the United States Weather Bureau at Asheville, North Carolina. The only synoptic charts available were those of the surface, 700, 500 and 300 millibar levels prepared daily at Weather Central, Little America, by a group of international analysts[3]). U. S. Weather Bureau standard techniques and instruments were employed at all stations and data were submitted to the U. S. W. B. center at Asheville for verification and distribution.

There are, however, serious observational deficiencies resulting from the precarious behavior of meteorological instruments in the extreme Antarctic climate. It is therefore necessary to briefly appraise the climatic data. No reliable method has been found to measure precipitation and measurements were inconsistent and often grossly unreliable from station to station. The major problem results from high winds and blowing snow which make the identification and recording of precipitation extremely difficult. Consequently, a detailed regional precipitation analysis is not possible. Cloud cover and cloud height are not easily ascertained because of extreme weather conditions, particularly during the winter night. Measurements of humidity are totally unreliable, as a result of the extreme cold, both at the surface and in the upper atmosphere. Surface temperature measurements in the very cold and stable layer of surface air can be grossly affected by the presence of the observer if the temperature is read from a thermometer in an instrument shelter, particularly if the thermometer is not ventilated. However, aspirated thermographs are used at most U. S. bases, and surface temperature errors are largely eliminated. Pressure observations are reliable and essentially unaffected by the environment except where pressures are reduced to isobaric levels below the surface. At the South Pole, for example, where the elevation is 2800 meters, and the surface pressure averages about 680 millibars, even a reduction to the 700 millibar level creates a somewhat artificial high pressure effect. This is due to the formula adopted in the pressure-height reduction, where surface temperatures are employed. These temperatures are unrepresentative of the free air aloft because of steep surface inversions, often of the order of 30 to 50 degrees of Fahrenheit[4]). Despite the frequent occurrence of severe weather, however, the operation of upper air soundings is carried out regularly and provides consistent and reliable results at all stations.

Climatic Regions

A study of atmospherc circulation, air-mass structure, regimes of temperature and pressure at the surface and throughout the troposphere together with weather types, frequency and movements of disturbances, and precipitation and cloudiness suggests that a regional pattern of climate exists over the Antarctic continent. It is not possible with the available data, however, to regionalize quantitatively in terms of all these climatic elements. Consequently, it was decided to use temperature as a basis for regionalization. Not only is temperature considered to be the most important climatic element in Antarctica, but the detailed fluctuations in the march of temperature also reflect to a considerable degree the nature of the weather and climate. In order to establish a quantitative basis for regionalization, therefore, the surface temperature regimes at the seven stations were correlated. Correlation coefficients between the 5 day temperature trends at the seven stations (figs. 4 to 10) reveal the following pattern of regional groupings (table 1).

i. The strongest correlation occurred in the Ross Sea (fig. 1) between the three stations Hallett, McMurdo and Little America. In this region Hallett and McMurdo in the same longitudinal zone are more highly correlated than McMurdo and Little America in the same latitudinal zone.

ii. Byrd, on the west Antarctic plateau, is more closely correlated with Little America in the Ross Sea than with the South Pole on the east Antarctic plateau.

iii. Wilkes on the coast of east Antarctica has the lowest correlation with the other stations.

Correlation coefficients

	Ellsworth	Little America	Byrd	Wilkes	McMurdo	Hallett	South Pole
Ellsworth	1	.67	.61	.60	.68	.68	.66
Little America	.67	1	.81	.65	.88	.83	.63
Byrd	.61	.81	1	.64	.80	.76	.64
Wilkes	.60	.65	.64	1	.66	.69	.64
McMurdo	.68	.88	.80	.66	1	.90	.66
Hallett	.68	.83	.76	.69	.90	1	.65
South Pole	.66	.63	.64	.64	.66	.65	1

Table 1
Correlations of surface temperature (1958)

[3]) These daily synoptic charts are based only on radio reports and are not considered adequate for synoptic analysis. A complete historical series of synoptic charts based on all the available IGY data is now being prepared by the weather bureau in Pretoria, South Africa. A recent correspondence with Harry van Loon, the analyst working on these charts, indicates that they will probably not be completed before the end of 1963.

[4]) Throughout the paper temperature is given in degrees Fahrenheit.

iv. The South Pole has a relatively uniformly low correlation with all stations.

v. Ellsworth in the Weddell Sea is not highly correlated with any other station but is related closest to the Ross Sea group.

This correlation grouping forms a quantitative basis for a regional division which can be supplemented by a variety of climatic characteristics in each region. The same grouping pattern also occurs when correlating the 5-day surface pressure at the 7 stations (figs. 4—10, table 2). Moreover, the same pattern occurs again on the basis of temperature correlations throughout the lower troposphere up to 300 mbs. as well as for correlations of heights of upper air pressure surfaces.

Correlation coefficients

	Ellsworth	Little America	Byrd	Wilkes	McMurdo	Hallett	South Pole
Ellsworth	1	.45	.62	.59	.55	.59	.57
Little America	.45	1	.81	.52	.94	.90	.43
Byrd	.62	.81	1	.58	.76	.72	.75
Wilkes	.59	.52	.58	1	.63	.62	.41
McMurdo	.55	.94	.76	.63	1	.95	.52
Hallett	.59	.90	.72	.62	.95	1	.47
South Pole	.57	.43	.75	.41	.52	.47	1

Table 2
Correlations of surface pressure (1958)

However, the basis for regionalization is of lesser importance than the characterization of the actual climate of each region. The lines separating each region should be considered as transition zones where the climate changes from one regime to another. Using the correlation of surface temperature regimes as a guide, therefore, the Antarctic continent is divided into regions so as to provide a framework from which to examine differences in climate. In the regionalization presented here, two major divisions are recognized and these in turn are subdivided into nine secondary divisions. For four of the subregions station data are lacking so that any quantitative characterization of their climates is not possible.

On the map purporting to show climatic differentiation in Antarctica (fig. 2), all of the boundary lines for the subregions are chosen subjectively and consequently are shown as dashed lines on the map. The two major climatic regions are the Interior (I), which is shaded on the map, and the Marginal (M). Each is then subdivided, the Interior region into a core region and a transitional zone, and the Marginal region into 7 secondary regions, 3 in east Antarctica and 4 in west Antarctica. The subdivisions and their respective stations are as follows:

Interior Climatic Region

- cI – Interior core subregion (South Pole station)
- tI – Interior transitional subregion (no station)

Marginal Climatic Region

- eM^W – eastern Marginal Wilkes Land subregion (Wilkes station)
- eM^E – eastern Marginal Enderby Land subregion (no station)
- eM^Q – eastern Marginal Queen Maud Land subregion (no station)
- wM^B – western Marginal Byrd Land subregion (Byrd station)
- wM^R – western Marginal Ross Sea subregion (McMurdo, Hallet and Little America stations)
- wM^W – western Marginal Weddell Sea subregion (Ellsworth station)
- wM^P – western Marginal Palmer Peninsula subregion (no station).

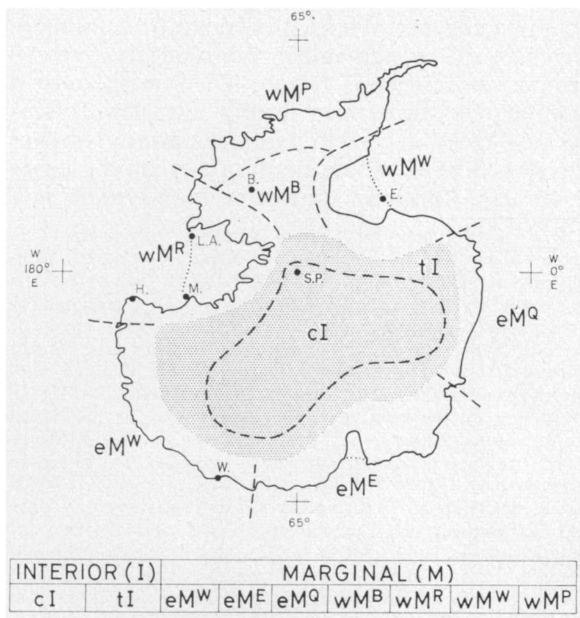

Fig. 2: Climatic Regions

The Climate of the Interior

The Interior region occupies the high central dome of the continent, centered around the Pole of Inaccessibility which is situated at the center of gravity of Antarctica (82°S and 55°E) at an elevation of over 4000 meters. The boundary line demarcating the Interior region is chosen to coincide fairly closely with the high plateau of eastern Antarctica approximately following the 2500 meter elevation contour, so that the region is asymmetrically located relative to the South Pole, which is at an altitude of 2800 meters and lies near the 'western' edge of the region (fig. 2). Two major factors, interior location as well as altitude, in addition to latitude, therefore, are mainly responsible for the climatic qualities of this region, the outstanding of which are the virtual absence of precipitation and the extremely low temperatures.

By far the most important climatic element of the Antarctic Interior is temperature. From 80 to 90 % of the incident radiation is reflected by the ice surface and for 9 to 10 months of the year the surface suffers a net radiation loss[5]). As a result temperatures are extremely low with the -40° annual isotherm closely following the outer boundary of the region. Moreover, in summer most of the Interior has an average temperature which is lower than the winter temperature along parts of the coast.

The annual march of temperature at the South Pole as represented by the month to month average (fig. 3) reveals a strong kernlose trend, that is, a curve with a broad flat winter minimum. From April to September the monthly average temperature remains below -70°F with only a few degrees fluctuation during this period. This coreless trend in the temperature pattern is better developed at the Pole than at any of the other American Antarctic stations[6]). However, it is a phenomenon only of the mean monthly temperature trend and is not in evidence on the detailed annual march of temperature (fig. 4).

On the polar plateau, the prolonged period of net outward radiation gives rise to a steep low level inversion so that the surface is enveloped in a layer of cold air. This layer of cold air, characterized by steep temperature inversions averaging over 30°F in the 300-meter surface layer at the Pole in winter, prevails on over 90 % of the days during the ten month heat loss period[7]). It is during the 2 month 'summer' period of net radiation gain at the surface that the inversion is weakest and temperatures rise. As a result of these differences in seasonal behavior of the surface layer of air a range of 65°F occurs between the warmest and coldest month at the Pole.

For the year as a whole a surface inversion prevails on over 80 % of the days at the Pole and a discontinuity develops between the 300 meter layer of cold air and the atmosphere above. Atmospheric disturbances and radiation processes produce interactions between the surface skin and the air above which are generally reflected in temperature changes at the surface. Back long-wave radiation from clouds can heat the surface sufficiently within a period of 24 hours or less to produce temperature increases of the order of 20 degrees and on occasion completely destroys the surface inversion. Atmospheric disturbances in the form of frontal or non-frontal low pressure systems do penetrate the Interior troposhere,

[5]) R. J. HANSON, "Radiation Measurements on the Antarctic Snowffeld, a Preliminary Report", Jnl. of Geophysical Research, LXV, 3 (19605, p, 940.
The relative climatic significance of the presence of an ice cover can be examined quantitatively in terms of surface temperatures. At the South Pole where the albedo is over 80 %, sufficient net radiation loss is incurred during the year to maintain a temperature of below —140° F. However, during two years the temperature at the South Pole dropped below —90° F on only ten occasions. Moreover, the lowest temperature ever recorded anywhere in Antarctica is —127° F at Vostok, a Russian station at 78° S at an elevation of 3420 meters. Radiation, therefore, does not account for all of the heat transfer and the thermal balance of the continent is maintained by horizontal and vertical heat transfer through air circulation. Yet it is mostly because of the ice surface that Antarctica is so much colder than any other region on the globe. Outside of Antarctica the absolute lowest temperature ever recorded is —95° F in northeast Siberia while at Vostok the average temperature for the month of August 1958 was —97° F.

[6]) See H. WEXLER, "The 'Kernlose' Winter in Antarctica", Geophysica Helsinki, 6 (3/4) (1958) pp. 577—595.
This coreless broad flat winter minimum mean monthly curve is also well defined at Little America, Ellsworth and McMurdo, while it is least in evidence at Hallett and Wilkes. Explanations offered for this phenomenon in Greenland and in the Arctic, based on conduction of heat through the sea ice, seem to be inapplicable in Antarctica, since the effect is strongest at the Pole which is well in the continental interior and removed from coastal influences. It appears that in Antarctica the kernlose phenomenon is generally associated with the surface 'skin' of cold air. During the long winter period of minimum month to month temperature change, the inversion skin is strongest and generally present, while it is often absent or weak during summer at which time the substantial rise and fall in temperature take place. At Little America, for example, from one month before to one month after the March-September coreless winter period, surface inversions prevailed on over 70 % of the days, as against less than 50 % occurrence during the summer months. Moreover, at the Pole where the surface inversion skin is most effective, occurring with over a 90 % frequency during winter, the flat bottomed winter curve is also most marked. However, at the two stations where the broad flat winter curve is least evident, Hallett and Wilkes, surface inversions occurred with a frequency of only 24 % and 28 % respectively for the year as a whole. These stations, moreover, each had only two months with more than 50 % frequency of surface inversions. It seems likely therefore, that during the low sun period, from April to September, the presence of a surface inversion skin of stable cold air contributes towards the relatively flat monthly mean temperature curve.

[7]) The surface inversion though generally confined to a 300 meter layer, is often steepest in the veneer of cold air immediately adjacent to the surface. On the occasion of the lowest temperature on record at the South Pole, on September 18, 1959, the temperature at 2 meters was —102.1° F, at 5 meters —101.2° F and at 10 meters —79.6° F; an inversion of over 20 degrees occurring therefore within a layer 5 meters deep.

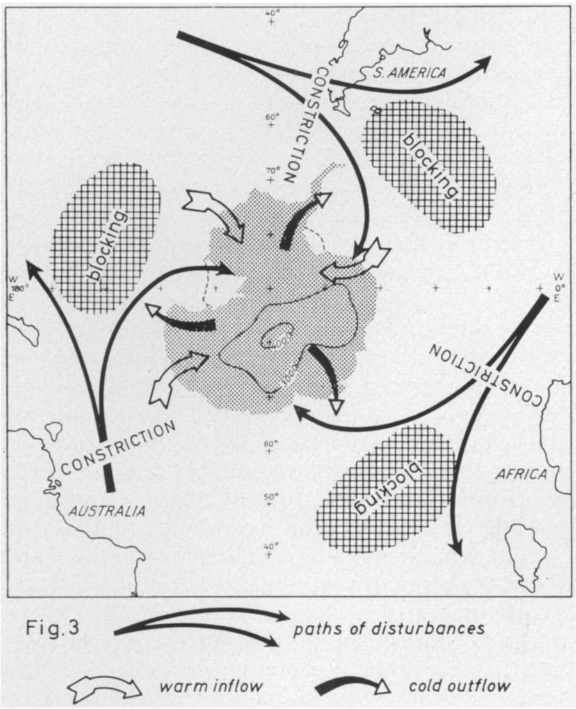

Fig. 3

though frontal disturbances are extremely rare at the surface in the deep interior of the continent[8]).

[8]) On the 28th and 29th of June, 1958, the passage of a warm and cold frontal system at the South Pole first raised the surface temperature by 43 degrees then lowered the temperature by 23 degrees, destroying the surface inversion.

As a result of the effect of both radiation and dynamic processes on the surface layer the intramonthly variability of surface temperature at the Pole is considerable, with a magnitude five times that at 500 mbs., only a few thousand meters above the surface. A number of variance measures show that there is clearly a much greater variety of weather conditions during the low sun season than during the high sun season. The difference between monthly maximum and minimum temperature increases from 5 degress in summer to three times that amount in winter, while the standard deviation of monthly maximum and minimum temperature increases from 5 and 4 degrees in January to 13 and 18 degrees in August respectively. At all levels in the troposphere, the variance of both temperature and pressure is strongest during the low sun season and it is during this season that the atmosphere is most active all over the Antarctic with greater frequencies of disturbances.

Details of the march of temperature at the surface at the Pole can be seen from the 5-day temperature profile (fig. 4). It is immediately apparent that the simple flat k e r n l o s e curve derived from monthly means is really a composite of a series of aperiodic fluctuations. As is to be expected, these fluctuations are not as strong at the Pole as at some of the coastal stations. Since dis-

Instances of distinctive fronts crossing the high east Antarctic plateau were rarely in evidence on the 1958 synoptic charts.

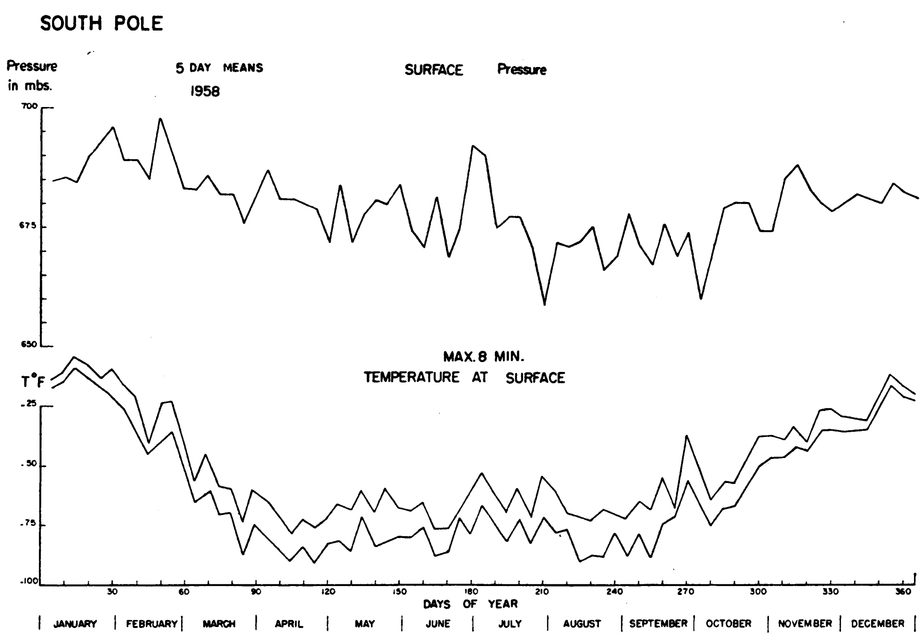

Fig. 4

turbances are rare at the surface in the Interior region, fluctuations in surface temperature are relatively modest resulting mainly from the radiation effect of clouds or from weaker systems aloft.

Some idea of the persistancy of anticyclonic weather in the Interior can be gained from an air mass analysis at the Pole (table 3)[9]). Typical 'anticyclonic' weather conditions, evidenced by a steep inversion in the first few hundred meters with low-velocity gravity winds blowing out from the Interior, prevail on most days at the Pole. A simple air mass structure with a steep inversion of about 20°F in the lower few hundred meters, and a stable lapse rate up to the height of the tropopause, occurred on 83 % of the days at the Pole, while upper air inversions, which generally reflect perturbation activity, appeared on less than 10 % of the days.

	Number of types (totalled over 12 months)	% frequency of each type					
		Surface inversion	Surface & upper inversion	Upper inversion only	More than one upper inversion	Instability	Stable, no inversions
McMurdo	46	6	22	25	15	9	22
Hallett	46	9	15	35	14	16	9
Little America	41	30	38	14	1	5	5
Ellsworth	44	29	30	16	6	6	2
Wilkes	41	14	11	37	4	18	6
Byrd	32	49	21	9	—	9	3
South Pole	18	83	2	5	—	2	—

Table 3

Classification *) of soundings, annual summary (1958)

*) See footnote 9.

[9]) A classification of vertical atmospheric structure at the seven Antarctic stations was made by examining the 1958 radiosondes. The twice daily soundings for every month for each of the seven stations were described in terms of five significant characteristics. The following differentiating characteristics were used in the description.

a. the existence or non-existence of an inversion.
b. the height of the inversion.
c. the number of inversions.
d. the depth and intensity of the inversion.
e. the occurrence or non-occurrence of instability.

The soundings described in terms of these criteria fall into six classes.

1. A surface inversion only. (Type S)
2. A surface inversion and an upper air (tropospheric) inversion. (Type SU)
3. An upper air inversion only. (Type U)
4. More than one upper air inversion and no surface inversion. (Type UU)
5. No inversion but a stable atmosphere. (Type A)
6. Instability occurring, with or without inversions. (Type I)

Except for the last class, instability, the groups are mutually exclusive. The soundings are classified for each month, and any type that occurred on more than 10 % of the soundings during the month is recorded as a class for that month. Practically every sounding falls into one of the six classes, there being no doubt that it belongs to one group rather than to another. In table 2, the annual summary is presented, showing the annual frequency of each type and also the summation of classes over 12 months.

Although the surface inversion is of a permanent nature it varies both in steepness and amount. Some idea of the amount of variation can be gained by considering the range of daily surtace temperatures[10]). In August daily maximum and minimum surface temperatures at the Pole occur over a range from −100°F to −50°F and in January from −30°F to +10°F.

On the mean monthly surface pressure charts[11]), the Pole appears to be on the edge of a shallow surface anticyclone for 10 months with a weak trough prevailing during the short summer period. At 500 mbs. however, about two thousand meters above the surface, the anticyclone appears only during July, a trough prevailing at the Pole for the remainder of the year. The surface profile of the continent is partly responsible for the development of anticyclonic surface weather conditions over the Interior region. The center of the anticyclone occurs at the Pole of Inaccessibility which is the highest part of the east Antarctic dome. Radiating out from here a shallow layer of gravity winds drains downslope over the ice-clad surface. Subsiding air replaces this constant outflow thereby possibly strengthening the shallow surface anticyclonic circulation[12]).

Downslope or katabatic winds, remarkably consistent in direction, dominate the wind field at the Pole. Consequently, over 90 % of the surface winds blow from the direction of higher ground, 0° to 90°E longitude, while almost no winds blow from the direction 50°W to 150°W longitude, the area of low elevation. Katabatic winds are best developed and most consistent during winter, when tle low level inversion is strongest, since gravity drainage is best produced under conditions of a cold stable surface layer. During winter at the Pole, wind shear between the surface and 150 meters is considerable and the katabatic wind is confined to this 150 meter layer. Wind shear is somewhat less during summer when

[10]) The frequency of daily maximum and minimum temperatures occurring in intervals of 10 degrees Fahrenheit were determined and frequency diagrams constructed. The range over which temperatures occur gives some indication of the variation of the bottom of the surface inversion.

[11]) J. Alt, P. Astapenko and N. J. Ropar, "Some Aspects of the Antarctic Atmospheric Circulation in 1958." IGY General Report Series Number 4 (Washington D. C., 1959).

[12]) Although the general outflow of air at the surface and the replenishment of air from above creates a subsidence effect in the surface layers, it is likely that without this constant drainage of cold air, a very cold, strong, deep anticyclone would build up over the continent with frequent surges of cold air taking place from the interior. The katabatic drainage acts to offset these probable surges, and may partly account for the fact that the Southern Hemisphere lacks the strong blasts of cold air that occur in the high northern latitudes.

although the katabatic layer is deeper, from 200 to 300 meters, katabatic winds are less prevalent[13]). Variability in both wind speed and direction increases above the surface at all stations and the inversion skin apparently affords some protection to the lower layers.

Precipitation occurs infrequently and in small amounts in the Interior region. The extreme stability of the air and the rare occurrence of upslope winds inhibit precipitation. Moreover, the intensely cold atmosphere can never hold more than a few tenths of an inch of moisture, and almost no evaporation takes place from the ice surface. Because of the difficulty of measuring and observing precipitation an accurate regional and seasonal analysis of precipitation cannot at present be undertaken. The Antarctic continent as a whole receives on the average less than 4 ins. of water equivalent during the year, the total accumulation in the Interior being less than 2 ins. and that at the coast about 5 ins. Precipitation is recorded at only 4 of the 7 U. S. stations and it is possible to discern only a very general pattern of the seasonal and regional distribution of precipitation from these observations. Table 4 shows for Ellsworth, South Pole, Byrd and Little America for each month the frequency of: a) all days on which precipitation of any kind was observed, b) days on which measurable precipitation, that is amount of 0.01 ins. of water equivalent or greater, were recorded, c) days with blowing snow, and d) total amount of precipitation[14]).

	South Pole				Little America				Byrd				Ellsworth		
	Days with precipitation	Days with blowing snow	Days with measurable ppt.	Amount of precipitation Water equivalent	Days with precipitation	Days with blowing snow	Days with measurable ppt.	Amount of precipitation Water equivalent	Days with precipitation	Days with blowing snow	Days with measurable ppt.	Amount of precipitation Water equivalent	Days with precipitation	Days with measurable ppt.	Amount of precipitation Water equivalent
	No.	No.	No.	Ins.	No.	No.	No.	Ins.	No.	No.	No.	Ins.	No.	No.	Ins.
Jan.	26	10	6	0.17	26	2	12	0.43	12	8	4	0.43	6	0	Trace
Feb.	20	9	8	0.23	21	8	9	0.17	11	11	0	Trace	11	3	0.06
Mar.	12	14	1	.01	21	16	13	0.55	22	8	3	0.08	11	2	0.08
Apr.	11	6	0	Trace	23	18	16	0.55	14	18	7	0.29	8	6	0.26
May	26	16	0	Trace	19	21	8	0.24	16	20	8	0.21	8	4	0.27
June	25	13	0	Trace	24	18	5	0.06	21	4	1	0.01	11	7	0.61
July	31	22	0	Trace	26	14	4	0.07	23	12	2	0.05	10	6	0.40
Aug.	31	9	0	Trace	25	15	9	0.42	17	14	0	Trace	13	5	0.11
Sep.	17	12	0	Trace	24	19	10	0.19	12	15	0	Trace	17	4	0.13
Oct.	24	19	2	0.04	29	14	11	0.23	17	13	2	0.03	15	13	0.48
Nov.	20	9	0	Trace	23	7	10	0.20	10	11	0	Trace	11	5	0.21
Dec.	15	4	0	Trace	16	9	7	0.22	19	15	6	0.67	11	6	0.26
Total	248	141	17	0.48	277	161	112	3.33	194	149	33	1.77	130	61	2.87

Table 4
Number of days with precipitation, blowing snow, measurable precipitation (more than 0.01 ins.) and amount of precipitation by months (1958)

Total precipitation amount, and days on which measurable precipitation was recorded, are the most reliable precipitation measurements. At the Pole during 1958 measurable precipitation was recorded on only 17 days and the total for the year amounted to only 0.48 ins. of water equivalent, making the high polar plateau the region of least precipitation. Moreover, the Interior region

[13]) Comparison between the wind fields at the surface, 150 meters and 300 meters above the surface, show the katabatic effect to be well developed in a shallow layer during winter and strongest at those stations (Pole, Byrd, Little America and Ellsworth) where surface inversions were most predominant.

[14]) These observations show that at all stations precipitation was observed on most days of the year, with particularly high frequencies at Little America (277 days) and South Pole (248 days). The totals are, however, not very meaningful by themselves without supplementary data of days with measurable precipitation, blowing snow and cloudiness. At the South Pole, for example, in July and August precipitation was recorded on every day, yet the tables indicate that there was no measurable precipitation during the whole of the low sun season. Moreover, table 5 shows that skies were clear on half the days during July and August. This apparent contradiction results from the fact that condensed ice crystals, suspended in the atmosphere, appear regularly with clear skies all year but particularly in winter, and are recorded as precipitation.

The frequent occurrence of blowing snow further complicates the precipitation picture. Table 7 shows that blowing snow occurs on most of the days on which precipitation was recorded. Since there is as yet no method of separating out actual snow precipitation from blowing snow, precipitation therefore is known definitely to have fallen only on days when there was no blowing snow.

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Ellsworth												
Clear	10	8	9	12	15	12	12	9	4	11	7	10
Partly cloudy	8	9	6	8	11	9	12	11	8	6	4	8
Overcast	13	11	16	10	5	9	7	11	18	14	19	13
Little America												
Clear	8	2	5	3	10	8	11	12	4	2	1	6
Partly cloudy	6	5	7	4	8	10	10	6	14	12	10	8
Overcast	17	21	19	23	13	12	10	13	12	17	19	17
Byrd												
Clear	4	1	3	9	5	11	10	7	4	3	8	5
Partly cloudy	13	7	7	5	11	13	10	13	16	11	6	9
Overcast	14	20	21	16	15	6	11	11	10	17	16	17
South Pole												
Clear	9	8	11	25	22	20	14	18	9	6	8	16
Partly cloudy	10	7	11	4	8	7	10	7	9	11	9	6
Overcast	12	13	9	1	1	3	7	6	12	14	13	9

Table 5
Frequency of days with clear sky (0 to 3 tenths cloudy), partly cloudy sky (4 to 8 tenths cloudy) and overcast sky (more than 8 tenths cloudy) (1958)

has more sunshine and less cloud than any other area of Antarctica, with an annual total of 165 clear days and only 100 overcast days at the Pole in 1958.

The extensive Interior region is subdivided into a continental Interior core region (cI) and a transitional subregion (tI), on a somewhat subjective basis, since there is no station within the transitional subregion (tI). The core region is separated out as a remote area with a severely cold climate bounded by the –60°F annual isotherm and the 3000 meter elevation contour. This deep interior region is effectively outside of the influence of oceanic disturbances, and is consequently almost permanently covered by an inversion skin of cold air. The transitional Interior subregion (tI), on the other hand, is occasionally subject to weather disturbances, thereby experiencing more oceanic influences. Perturbations moving along the Ross-Weddell trough on rare occasions do affect the transitional subregion (tI), while some of the more vigorous disturbances that follow a meridional path into the continent occasionally penetrate the high plateau and exert some influence at the surface in the interior peripheral zone (tI)[15]. This peripheral zone, therefore, forms a transition between the remote high Interior and the margins of the continent, and as compared with the former is presumed to have a greater variety of weather conditions, with stronger, more numerous temperature variations and probably a slight increase in precipitation.

[15]) In January of 1958 a cyclonic storm accompanied by high winds raised the surface temperature at the South Pole above 0° F for the first time in the station's history.

Climate of the Marginal Region

The Marginal region occupies the areas of the continent that are below about 2500 meters in elevation, including, therefore, the entire coastal margins and the relatively low Byrd Land plateau of West Antarctica (figs. 1, 2).

The coastal margins are comprised of a variety of rugged ranges, precipitous declines, and smooth sloping ice surfaces. The Victoria coast range stretches along the entire length of the western shore of the Ross Sea along 165°E) and meets the Queen Maud Range west of the Pole continuing to the eastern Weddell Sea coast (along 30°W). This continuous horst is from 20 to 150 miles wide, reaching heights of 2000 to 4000 meters within 50 miles of the coastline. Further west along the coast from the Ross Sea, the coastal sector between 150°E and 100°E is characterized by fairly gradual slopes and the absence of mountain ranges. The adjacent stretch of coastline from 100°E to 10°E is rugged but westwards from here to the Weddell Sea the slope is again gradual and the coastline is characterized by numerous indentations. The coast of West Antarctica includes the fjord-like mountainous Palmer Peninsula, the remainder of the coast being fringed by ranges reaching up to 2000 meters in elevation.

The Marginal climatic region stands out in strong contrast to the climate of the Interior not only in terms of the major climatic elements of temperature, wind and precipitation, but also because of basic differences in air mass, pressure trends and atmospheric disturbances. While the Interior suffers a net radiation loss for 10 months of the year, developing, as a result, a cold air mass all year, the coast on the other hand, experiences a net radiation gain throughout the high sun season and is, therefore, relatively warm in summer at some sections (the northern part of the Palmer Peninsula and the Wilkes Coast littoral qualify as 'tundra' (ET) climates in the Köppen classification with one month averaging above 0° C.)

The Interior develops its own air mass and low level circulation system, while the Margin is subject to rapid changes in weather, and consequently in all climatic elements, as a result of the relatively frequent penetration of oceanic disturbances. These disturbances, which largely control the Marginal climate but rarely invade the Interior, originate in the region of the strong temperature gradient of the mid-latitude atmospheric convergence zone which fluctuates around 45°S latitude. After cyclogenesis the systems move with the westerly stream following three general patterns of movement: zonal, spiral, or meridional (fig. 3). When the westerly flow is strong and unobstructed the tendency is for disturbances to move zonally until they either lose their identity or encounter an obstruction and as a result change direction. Generally, however, the westerly flow is interrupted and consequently disturbances follow a spiral or meridional path. Interruption of flow is provided by orographic barriers or circulation obstructions, such as blocking anticyclones. The southern Andes and the Palmer Peninsula provide the only real orographic barriers to the westerly flow, although the Australian and African land masses could cause sufficient lateral constriction of the flow to change the vorticity of the air, thereby causing disturbances to follow a spiral path. The obstruction of air flow by the Andes and the Palmer Peninsula, makes the area east of the Palmer Peninsula a corridor for the exchange of mid-latitude and polar air. Not only is the convergence zone further south here, but the north-south pressure gradient (zonal index) for the southern westerlies is weaker and more variable in this region than in the remainder of the southern oceans.

The meridional movement of disturbances southward into the Antarctic from the mid-latitudes results mainly from anticyclonic blocking activity. Blocking action takes place southeast of the continents of Africa, South America and Australia, bifurcating the westerly flow and deflecting disturbances towards preferred areas on the Antarctic continent. Figure 3 shows the general location of blocking activity, the bifurcation of the westerly stream, and the resulting movement of lows into the continent. The three main regions of entry are the eastern Ross Sea, the eastern Weddell Sea and eastern Enderby Land (70°E longitude) so that the major concentration of coastal disturbances is therefore at these three areas. Moreover, on the mean monthly 700 mb. pressure charts a low pressure system appeared on every month at each of these three regions. Whereas over the high plateau of east Antarctica the strong surface anticyclone is only rarely disrupted by disturbances, the lower plateau of west Antarctica, on the other band, is frequently traversed by perturbations. Systems moving into the eastern Ross Sea, along one of the major paths of entry, find relatively easy access across west Antarctica. This may account for the fact that west Antarctica has twice as much precipitation as east Antarctica, a feature which in turn may explain why west Antarctica appears to be a growing ice cap while the east Antarctic ice cap is diminishing [16]).

Important climatic effects result from the interaction of the secondary circulation and the strong surface inversion 'skin' that cloaks the greater part of the Antarctic continent for most of the year. Surface disturbances penetrating the continent destroy the low surface inversion and consequently the frequency of intrusions of disturbances is, therefore, roughly proportional to the breakdown of the surface inversion. Significantly, at the Pole where disturbances are rare, a steep surface inversion (type S) prevails on over 80 % of the days, while at the coast, where disturbances are numerous, the steep surface inversion occurred on less than 30 % of the days [17]). Consequently, the simple anticyclonic type of airmass structure of a steep surface inversion (type S) and a stable atmosphere above which is so prevalent in the Interior, is replaced at the coast by a more complex airmass structure.

A second climatic manifestation of the oceanic disturbances are the strong aperiodic temperature fluctuations. These aperiodic fluctuations which characterize the temperature trends at the coast can be traced not only over vast areas but also

[16]) C. R. Bentley and N. A. Ostenso, "Glacial and subglacial topography of West Antarctica", Jnl. of Glaciology, III, No. 29 (1961), 882—913.

[17]) The perturbation element is probably responsible for some of the dramatic Antarctic weather changes. In May of 1957 at Little America, both the highest and lowest temperatures for the year were recorded. The warmest temperature on record for that station occurred on May 11, 30.2° F, followed ten days later by the coldest temperature for the year, —63.4° F. During the following May, a frontal system brought about rapid temperature changes, first an increase from —36° F to 25° F then a decrease to —26° F within 24 hours. On September 18, 1957, while the South Pole experienced the all-time minimum temperature ever recorded, —101.2° F, at Little America, 600 miles away, the temperature was 32° F. On May 10 the South Pole recorded a temperature minimum of —99.4° F, while at Byrd, also on the plateau, the temperature was 19.4° F.

through deep layers of the atmosphere. Small surface temperature fluctuations may result from radiation effect of clouds, but most of the large changes are caused by circulation effects. In order to identify these major fluctuations, changes that exceeded 30°F in a 5 or 10 day period are identified as 'climatic events' (fig. 11)[18]). It is immediately apparent from figure 11 that there is almost an absence of climatic events involving temperature changes of more than 30°F during the high sun period. This is a consequence of the fact that during summer well-developed cyclonic systems advecting warm oceanic air into the continent occur less frequently than in winter.

A further consequence of the high frequency of coastal disturbances is that in the Marginal region clouds are twice as frequent and, in some areas, precipitation is five times as great as in the Interior.

The wind field at the coast is largely determined by the nature of the topography, more so in some parts than in others. Along the coast the katabatic wind effect varies from one section to another, depending on the conditions of slope, surface covering, exposure and barometric gradient. Whereas rough terrain is not favorable for the formation of downslope gravity winds, the smooth, sloping sections of the coast assist the development of strong and persistent katabatic winds. In areas where the general barometric gradient is in harmony with the direction of katabatic flow strong winds result; when the pressure gradient force is opposed to the direction of katabatic flow, the katabatic wind is considerably reduced in velocity, but can overcome the gradient force provided the slope is sufficiently steep. At Cape Dennison on the Adelie Coast (142°E) the strong and persistent katabatic flow has caused this area to be named 'Pole of Winds', with wind speed for the year as a whole averaging 40 miles per hour. Here, conditions are exceptionally favorable for the development of high velocity winds: an off-shore low pressure system and a surface anticyclone on the plateau create a barometric gradient which is in harmony with the direction of katabatic flow; the slope of the continental surface is long and smooth, the surface is ice clad and there are no orographic barriers to obstruct the katabatic flow.

The strength and effectiveness of the katabatic wind decreases with distance away from the escarpment. The winds are strongest about two-thirds of the way down the slope where the plateau drops off to the coast. At the foot of the slope the wind still retains most of its force, but at the coastline itself the katabatic effect is weak, and is almost lost a few miles out on the ice shelf. The long downslope passage dehumidifies the air and creates a predominance of clear coastal weather along particular parts of the coast, with bands of clouds appearing some distance out to sea where the katabatic effect is lost.

Marginal Subregions

Within the Marginal region 7 climatic subdivisions are identified. Four of the subregions can be quantitatively regionalized, as shown earlier, on the basis of temperature and pressure regimes both at the surface (tables 1, 2) and in the troposphere. For these 4 subregions (Byrd Land wM^B), Byrd Station; the Ross Sea wM^R, McMurdo, Hallett and Little America; the Weddell Sea wM^W, Ellsworth; and Wilkes Land eM^W, Wilkes Station) a fairly detailed description of the climate is presented below. Three other subregions (fig. 2) for which no station analysis was possible are also delimited, mainly on the basis of characteristics of the atmospheric circulation, allowing therefore only a very general description of the climate. Altogether there are, therefore, 7 subregions represented by only 6 stations so that all boundary lines are necessarily tentative. However, the division does provide a basis for investigating regional climatic differences and the causes for these differences.

Byrd Land wM^B. The Byrd Land plateau from about 1000 to 2000 meters in elevation, is more closely related to the coastal climate than to the Interior, since it is subject to frequent disturbances and consequently, like the coast, experiences large fluctuations in all climatic elements. Weather disturbances frequently cross the west Antarctic plateau producing a climatic regime at Byrd that is similar to that of the coastal regions, particularly the eastern Ross Sea area. As a result of frequent intrusions of warm oceanic air, Byrd Land is considerably warmer than the high eastern plateau, particularly in winter when the deep interior is effectively isolated from warm intrusions, while at Byrd major temperature fluctuations occur as manifested by a series of warming trends. (Compare the average

[18]) For the purposes of this study a rapid and substantial change in temperature is referred to as a 'climatic event'. Many such large changes appear concurrently at more than one station, and are, therefore, in the nature of singularities. Since, however, only one years' data is examined the recurrence of these changes over a period of years cannot be investigated. In order, therefore, to avoid confusion with the use of the term 'singularity' as it is employed in the literature, where it generally denotes a recurrent feature, the large fluctuations in temperature are defined here as 'climatic events'.

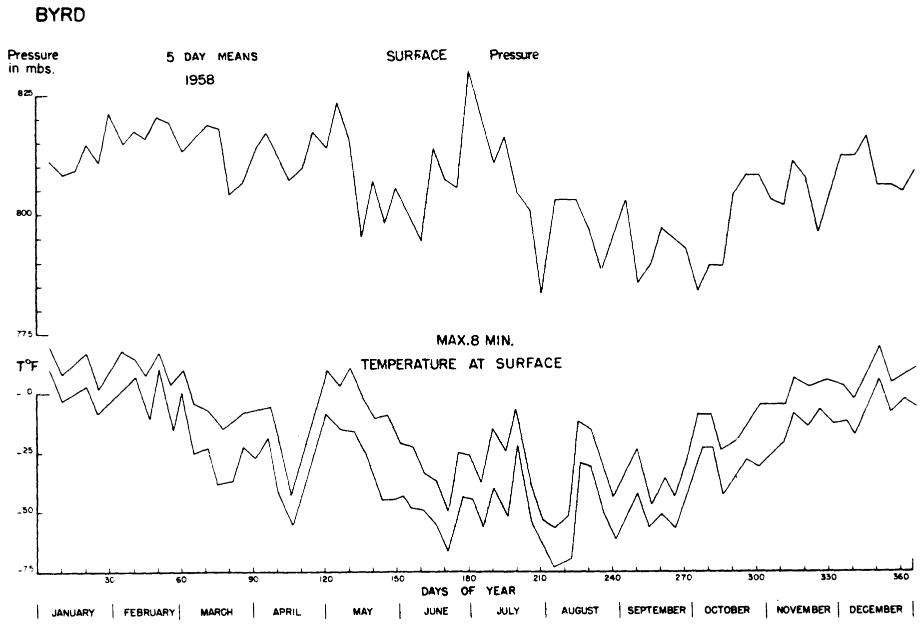

Fig. 5

August temperature of −97°F at the Interior Russian station, Vostok to −45°F at Byrd).

As in the case of all stations, the monthy curve appears to be relatively flat, although the kernlose quality of the curve at Byrd is disrupted by a large rise of the curve in fall. This rise results from a 'singularity' in late April caused by a warm inflow of air from about 40°S along a deep ridge extending into Byrd Land from the Pacific Ocean (fig. 12). The aperiodic character of the temperature curve is particularly strong at Byrd where the 5-day temperature profile (fig. 5) reveals six major climatic events (fig. 11) of temperature changes exceeding 30°F. Further evidence of the aperiodic fluctuating character of the march of temperature at Byrd can be found in intra-monthly ranges of maximum and minimum temperatures. The range between the mean maximum and mean minimum monthly temperature is considerably larger than at the Pole, increasing from 15 degrees in January to over 20 degrees in August. There is, moreover, a large monthly standard deviation of temperature at Byrd of both maximum and minimum temperatures and, as is the case with all other stations, the strongest variation occurs in winter. While in August the standard deviation of maximum and minimum temperature is 21 and 20 degrees respectively, it is only 6 and 7 degrees respectively in January. It is also during winter that all six climatic events occurred at Byrd (fig. 11). In winter the range of daily maximum and minimum temperatures is remarkably high, varying from −80°F to +10°F in August (compare this to the range at the Pole from −50°F to −100°F) compared to a range of −10°F to +30°F in summer.

In some respects the climate of Byrd Land is intermediate between that of the Interior and that of the coast. While Byrd does not experience the anticyclonic conditions of the Interior, it nevertheless is effected by only about half as many disturbances as at Little America on the coast. Moreover, the air mass structure at Byrd is more complex than that of the Interior, but less so than that at the coast, with 32 sounding types occurring at Byrd over a 12 month period, as against 18 at the Pole and 41 at Little America (table 3). Measurable precipitation was recorded on 33 days of the year at Byrd, which is twice as often as in the Interior and less than half as often at the coast, while total precipitation at Byrd (1.77 ins.) is four times that at the Pole and half that at Little America (table 4). In terms of cloudiness too, Byrd, with 174 overcast days is intermediate between the Pole with 100 days and Little America with 200 days (table 5).

As a result of similarities in air mass structure and general and secondary circulation Byrd Land has a climatic regime similar to that of the West Antarctic coast. Consequently almost all the temperature singularities at Byrd are associated synoptically with similar singularities at Little America and Ellsworth. There is little doubt that Byrd Land can be considered a Marginal rather than an Interior climate.

The Ross Sea wM[R]. The Ross Sea, particularly the eastern section, is an area that probably experiences more frequent disturbance activity than any other part of the Antarctic continent. As a consequence there are continuous weather changes, particularly during the low-sun season, and subsequent fluctuations in all climatic elements. Disturbances, which are most frequent and most vigorous during the low sun season, occur with a frequency of about 50 % during that season. The 5-day pressure trends (figs. 6, 7, 8) are characterized by aperiodic variations and reveal about 30 fluctuations, mostly in winter, almost all of which occur simultaneously at the three Ross Sea stations, McMurdo, Hallett and Little America. Moreover, the high frequency of disturbances is also evidenced both by the appearance of a Ross Sea low pressure system on every month of the year at the 700 mb. level and by the high frequency of upper-air inversions (table 3).

At the surface, fluctuations in climatic elements, particularly temperature, are not as strong in the western Ross Sea as they are in the eastern section. The western Ross Sea (Hallett and McMurdo) is protected from disturbances by the high Victoria Land mountain barrier and consequently experiences weather that is somewhat different from the eastern Ross Sea (Little America), which is exposed to the vigor of disturbances moving in from the northwest (fig. 3). Hence while there are numerous small temperature changes occurring simultaneously at all three stations, thus providing a high correlation in temperature regime, no major 'singularities' occur in the western sector, while the eastern sector experiences 7 temperature changes greater than 30°F, more climatic events than occur at any of the other six stations. The fluctuating character of the march of temperature at Little America (fig. 6) can be expressed by a variety of measurements. Mean monthly temperature curves show a range between maximum and minimum temperature at Little America of 12 degrees in summer and 24 degrees in winter, which is 5 degrees more in both seasons than the range at Hallett and McMurdo. Moreover, the monthly standard deviations of maximum and minimum temperature are 21 and 22 degrees respectively in August and 6 and 9 degrees in January at Little America which is twice as large as those at Hallett and McMurdo in both seasons, and also larger than the standard deviations at any of the other stations. As a result of these large variations, Little America experiences an extraordinary large range of temperatures, particularly in winter, from −70°F to +30°F in August and from −10°F to + 40°F in January. These high ranges are equalled only by Ellsworth in the Weddell Sea. At Hallett and McMurdo the range is considerably less, from −50°F to +20°F in August and from +10° F to +50°F in January. It is obvious that the kernlose curve, a feature of the mean monthly temperature trend at Little America, does not exist in the detailed temperature march as shown by the 5-day means.

Largely as a result of its ice-shelf location, Little America, with a mean January temperature of +20°F and a mean September temperature of −35°F, is 10 degrees colder than Hallett and McMurdo in summer and 20 degrees colder in winter. At the surface over the ice shelf a low level inversion occurs with a 70 % frequency [19]). This inversion encourages katabatic flow so that Little America experiences a strong katabatic component, with a high frequency of southerly winds, while Hallett and McMurdo experience very little katabatic effect with stronger westerly and easterly components respectively.

Precipitation measurements in the Ross Sea are available only at Little America but it is probable that precipitation and cloudiness occur more frequently in the eastern than in the western Ross Sea. At Little America in 1958, measurable precipitation was recorded on 112 days with the total precipitation for the year amounting to 3.3 ins. of water equivalent (table 4). More than half the days of the year were overcast (193 days) while there were only 72 clear days. This Ross Sea region experiences perhaps more precipitation, cloudiness and disturbed weather than any other part of the Antarctic continent.

The Weddell Sea wM[W]. The Weddell Sea, like the Ross Sea, is one of the main areas where disturbances enter the continent (fig. 3). However, since the routes of entry are different, weather changes at Ellsworth are not closely correlated in time with those at Little America. Ellsworth experiences disturbances along two main tracks, mainly from blocking activity southeast of the South American continent and probably to a lesser degree from a passage across the Ross-Wed-

[19]) The striking difference in soundings with surface inversions, 70 % at Little America compared to less than 30 % at McMurdo and Hallett, results mainly from the infrequent occurrence of surface inversions in summer at Hallett and McMurdo, and can be partially accounted for by the difference in the underlying surface during summer. Both Hallett and McMurdo are situated on a land surface, covered by a thin veneer of snow in winter but exposed in summer, while Little America is on the ice shelf. During the summer, therefore, when the snow covering is removed, the dark underlying surface can absorb much of the solar radiation, allowing the surface layers to heat up and thereby destroying the lowlevel inversion at Hallett and McMurdo. A similar situation occurs on the other side of the continent at Wilkes, the third station on land, where surface inversions occur also with a frequency of less than 30 %.

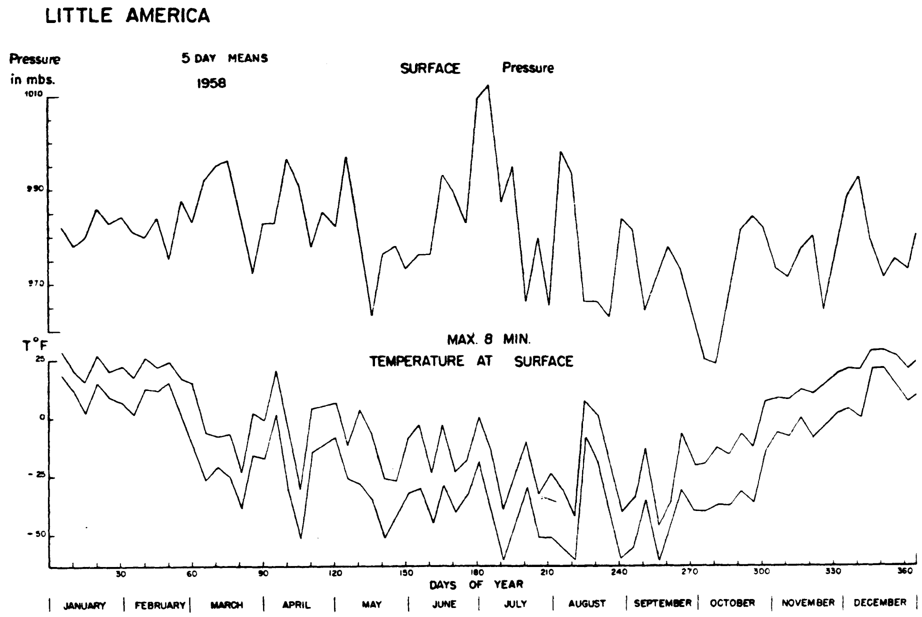

Fig. 6

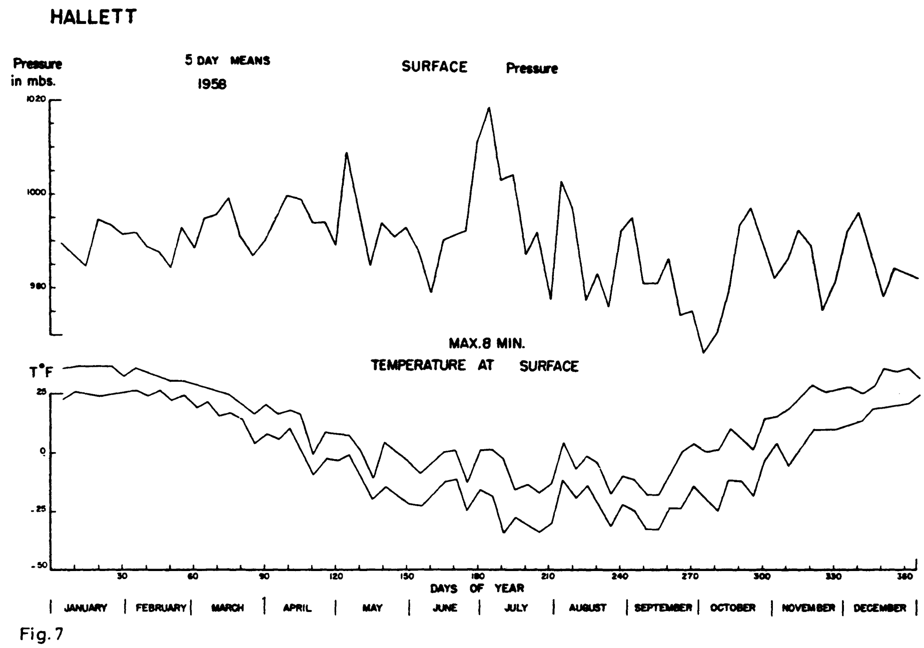

Fig. 7

dell graben[20]). As a result this region is second only to the eastern Ross Sea in disturbance activity and subsequently variations of all climatic elements are almost as strong at Ellsworth as at Little America.

[20]) In a recent correspondence (November 1961), Van Loon, who is at present assisting in the preparation of an historical series of IGY Antarctic synoptic charts, suggests that the Ross-Weddell graben is not an important path for disturbances.

The monthly temperature trend at Ellsworth ranges from ±15 in January to –30°F in August, displaying a k e r n l o s e curve similar to that at Little America, although here again the flat bottom of the winter curve does not appear in the detailed temperature trend (fig. 9). Temperature variations are high with a large monthly range between maximum and minimum temperatures, increasing from 15 degrees in summer to 20 degrees in winter and high monthly standard

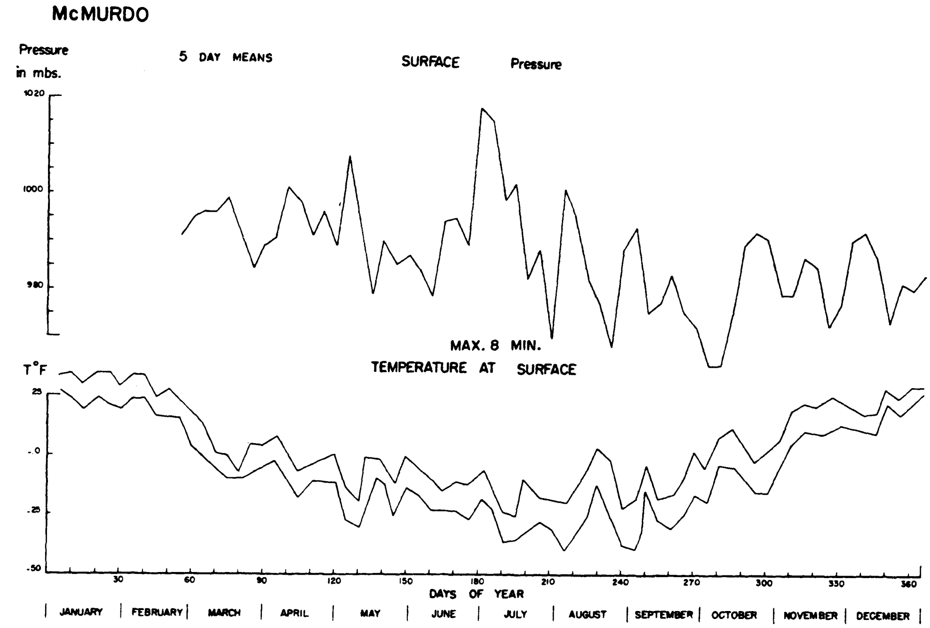

Fig. 8

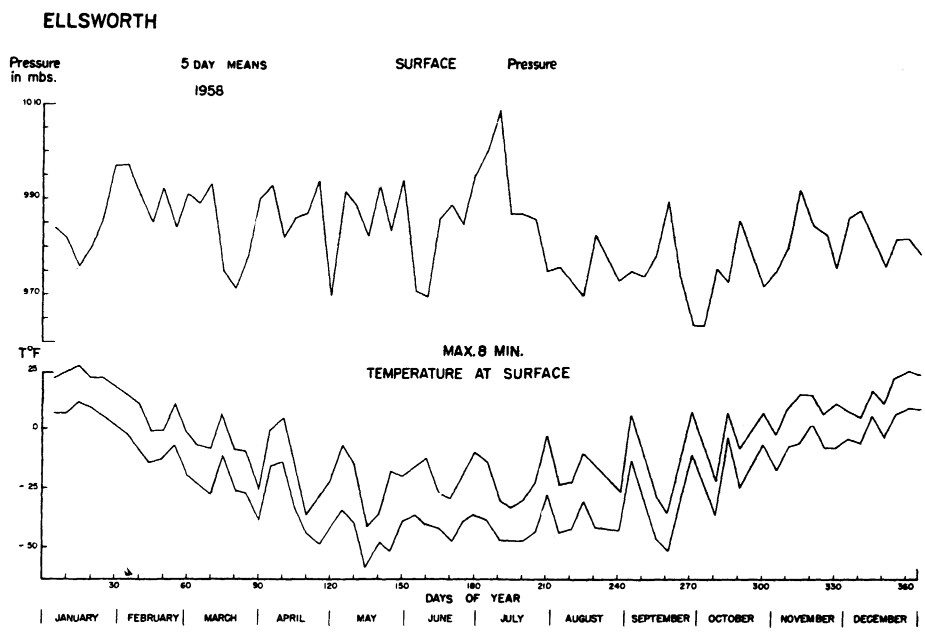

Fig. 9

deviations of maximum and minimum temperature, 10° and 11°F respectively in August and 5°F and 4°F respectively in January. Moreover, Ellsworth experienced six climatic events in 1958, just one less than occurred at Little America, while the range of daily temperatures, from –70°F to +30°F in August and from –10°F to +40°F in January, are the same as those at Little America for both seasons.

As is the case at Little America, the air mass structure at Ellsworth reveals a high frequency of over 50 % of upper air inversions, reflecting to some extent the high frequency of perturbations. Moreover, because of its ice-shelf location (see footnote 19) surface inversions occur on over 70 % of the days at Ellsworth. The surface inversion skin is agin, as at Little America, associated with katabatic winds blowing steadily over the ice shelf out of the interior from the south in the lower few hundred meters.

As is to be expected as a consequences of frequent disturbance activity, precipitation in the Weddell Sea is almost as great as that in the Ross Sea, 2.87 ins. of water equivalent for the year occurring at Ellsworth, which is only slightly less than that in the eastern Ross Sea (table 4). However, the 67 days with measurable precipitation at Ellsworth, are only about half the number at Little America. Accordingly, Ellsworth has a high proportion of clear days (119), which is 50 % more than at Little America, and only 146 overcast days compared to 119 at Little America.

Wilkes Land eM^W. Wilkes is the warmest of the seven stations with a monthly mean temperature of −5°F in August and 33°F in January and is therefore the only one of the American Antarctic stations that has a 'tundra' climate according to the KÖPPEN classification. Moreover, since Wilkes is not a region of preferential entry of cyclones into the continent, in contrast to the three marginal regions discussed previously, there is but little variation of all climatic elements in both seasons at Wilkes. The monthly range between mean maximum and mean minimum temperature is low, 10°F in summer and 12°F in winter, while the monthly standard deviation is only 2°F in January and 10°F in August. Moreover, the range of daily temperatures is less at Wilkes than at any other station, from 20°F to 50°F in January and from 0°F to 40°F in August. In August (winter), therefore, the complete range of temperatures at Wilkes is warmer than those at the Pole in January (summer).

Wilkes does, however, experience occasional large aperiodic temperature fluctuations with three climatic 'events' occurring during 1958 all of which were well defined in the lower troposphere (fig. 11). Although Wilkes is not generally in the major meridional path of disturbances, systems do affect the entire coastline and Wilkes occasionally falls under the influence of strong deep lows. It is the alternating influence of the strong continental anticyclone with outflow of cold air (fig. 13) and the occasional influx of warm oceanic air drawn into the continent through the mechanism of deep offshore lows (fig. 14) that produce these singularities at Wilkes.

Wilkes' location between these controls is reflected also in the surface and upper air wind directions. At the surface there is a high frequency of both southerly winds, as a result of outflow from the continental anticyclone, as well as easterly winds from the off-shore lows. The katabatic effect is not strong, mainly because of the particular location of the station with respect to topography and exposure. Other sections along the coastline of this region (eM^W) have, however, persistent katabatic winds, in some instances with extremely high velocities.

Other Marginal Subregions. In the subregions of Palmer Peninsula (wM^P), Queen Maud Land (eM^Q) and Enderby Land (eM^E) (fig. 2), there are no American stations and therefore no station analysis could be undertaken in

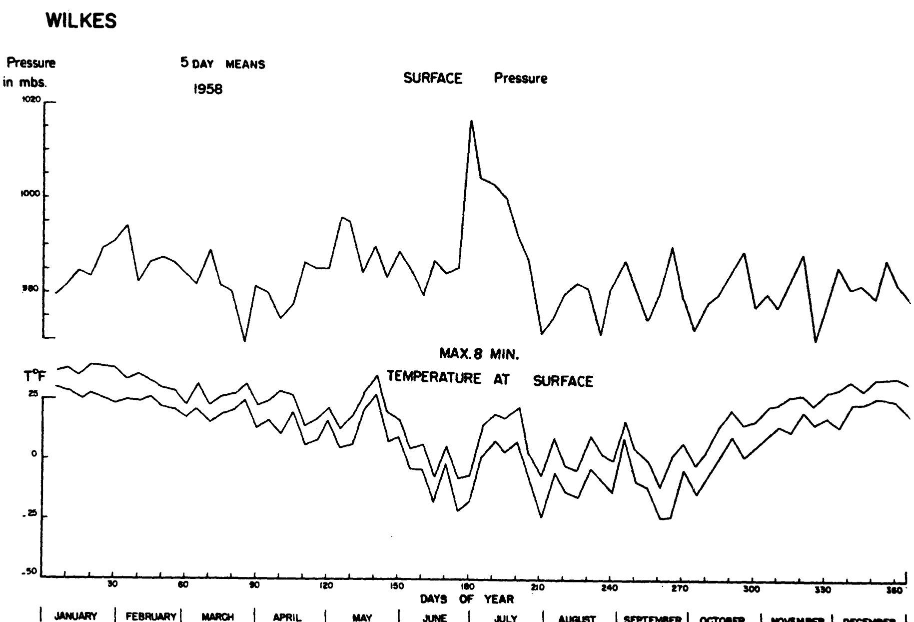

Fig. 10

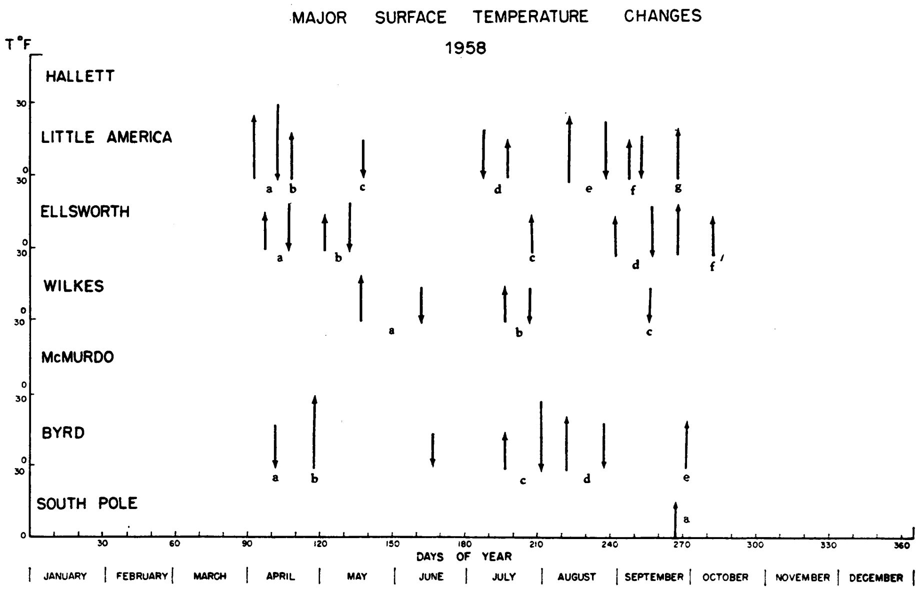

Fig. 11

this paper. Thus, while it was possible to examine regional differentiation of the four other marginal regions, wM^R, wM^W, wM^B and eM^W on the basis of correlation coefficients, these three Marginal subregions without American stations are subjectively delimited from the surrounding regions mainly on the basis of differences in atmospheric circulation. The Palmer Peninsula subregion (wM^P) lies between two regions of frequent disturbance activity, the Ross Sea (wM^R) and the

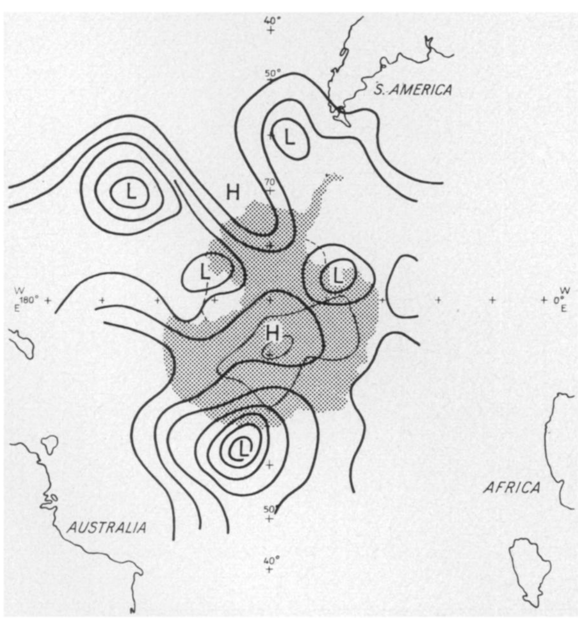

Fig. 12: Surface pressure pattern associated with temperature increase at Byrd during 120th period (April 25—30)

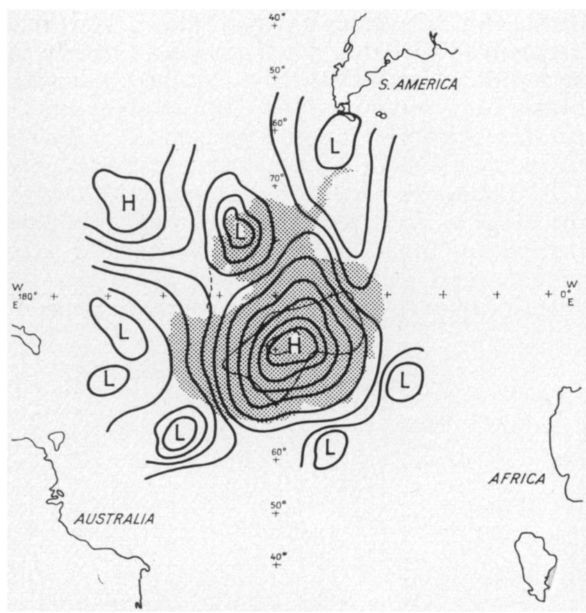

Fig. 13: Surface pressure pattern associated with temperature decrease at Wilkes during 165th period (June 9—14)

Weddell Sea (wM^W). The Peninsula section of this subregion is often under the influence of a ridge, while the rest of the coastal margin of the subregion, unlike the areas to either side, is not in the path of meridional entry of disturbances into the continent. Since the circulation has little disturbance activity, it is reasonable to assume that the climate of the Palmer Peninsula subregion (wM^P) will accordingly be different from that of the areas of frequent disturbances on either side.

The second region without a station, Enderby Land (eM^E), on the coast of east Antarctica, is delimited because of its high frequency of disturbances as opposed to the relatively low frequency of disturbances in the adjacent areas (fig. 3). This area is in the direct path of disturbances that enter the continent as a result of anticyclonic blocking east of South Africa. Moreover, the circulation at this same region stands out as one of the four main features in the Antarctic atmospheric circulation, in the form of a persistent low pressure that appears every month on the mean 700 mb. charts. It is assumed, therefore, that the circulation pattern of strong perturbations does create a distinctive climate with much weather activity at Enderby Land.

The third and last Marginal sub-region without a station is the Queen Maud Land region (eM^Q), which, like the Palmer Peninsula region (wM^P), lies between two regions of strong cyclonic activity, in this case Enderby Land (eM^E) and the Weddell Sea (wM^W). Queen Maud Land (eM^Q) itself, does not, however, experience a high frequency of disturbances and its climate is likely to differ accordingly from that of the regions to either side. Despite lack of data, therefore, it seems feasible to tentatively delimit seven Marginal climatic subregions.

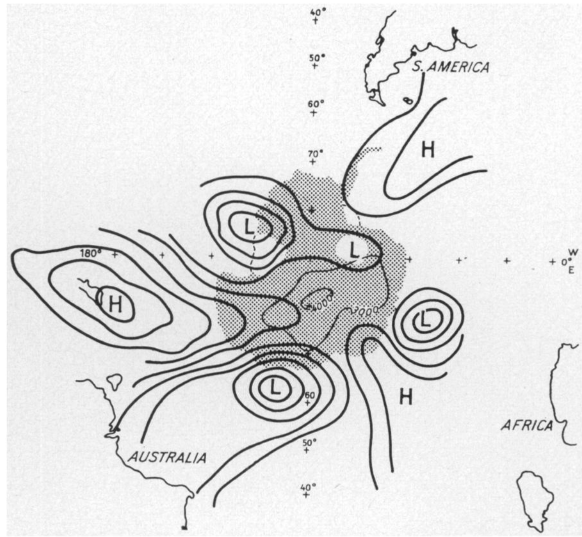

Fig. 14: Surface pressure pattern associated with temperature increase at Wilkes during 140th period (May 15—20)

SOME OBSERVATIONS ON DESICCATION IN NORTH-WESTERN NIGERIA

R. Mansell Prothero

With 4 Figures

Zusammenfassung: Einige Beobachtungen über Austrocknung im nordwestlichen Nigerien.
In den nördlichen Teilen Westafrikas sind die Niederschläge gering, veränderlich und unverläßlich. Die durchschnittliche Bevölkerungsdichte ist niedrig — weniger als acht Einwohner pro qkm. In einigen Gebieten hat jedoch die Kombination örtlich günstiger naturräumlicher Faktoren, besonders ausreichender Wasserversorgung, mit sozialen und historischen Einflüssen viel höhere Bevölkerungsdichten — bis über 80 Einwohner pro qkm — hervorgerufen. Eine charakteristische Erscheinung dieser Gebiete sind Bevölkerungsbewegungen. Es gibt kaum Anzeichen einer Klimaverschlechterung und eines Vordringens der Wüste nach Süden; menschliches Einwirken mag jedoch eine Verschlechterung der naturräumlichen Bedingungen hervorrufen. Anbaumethoden waren und sind nicht immer in ausreichender Weise auf die Bedürfnisse der zunehmenden Bevölkerung abgestimmt und mögen ein Abnehmen der Bodenfruchtbarkeit und Bodenzerstörung hervorrufen. Diese Fragen werden in dem vorliegenden Aufsatz für die Provinz Sokoto im nordwestlichen Nigerien untersucht.

Only in comparatively recent times has man come to modify the environment of West Africa significantly, and there is little evidence of human modifications of the environment to consider before the present century. Although the last sixty years are but a fraction of the ages through which the West African environment has passed the changes and modifications that have taken place in recent times are of the greatest importance. They have created many problems for which solutions are urgently required. Amongst these problems are those which result from increases in the numbers of people who, in turn, exert increasing pressure on resources to provide for their needs. In West Africa where the internal and external economies still depend very largely on farming it is obvious that increasing human needs will exercise very important modifying influences both directly and indirectly on the environment. More land is required for cultivation and for grazing and the demand for timber for fuel and other purposes increases. Depending on the man/land relationships in different areas changes may become necessary in agricultural practices. These are only the more important of the influences at work.

These influences are particularly significant, and the changes that result from them often all