Technical Report No. 24

AIRMASSES, STREAMLINES,

AND THE BOREAL FOREST

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(with appendix: Non-linear
Parameter Estimation for the
Partial Collective Model of
Airmass Analysis by
Donald R. Johnson)

University of Wisconsin
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Contents

ABSTRACT

The analysis of July airmass frequency distribution
over Canada is analyzed by daily computation of trajectories
from grid intersections back to source regions. A zone of
rapid transition from Arctic Air dominance to Pacific Air
dominance is found to lie along the northern border of the
boreal forest, suggesting that the summer airmass distri-
bution might be an important causal factor for the distri-
bution of forest versus tundra.

An independent analysis of July airmass frequency
distribution by resolution of the daily maximum temperature
frequency distribution into partial collectives (component
normal distributions) yields results very similar to the
trajectory analysis but with more detail. This analysis
suggests that airmass dominance might be of importance to
other biotic regions as well as the boreal forest and tundra.

A final analysis using monthly resultant wind stream-
lines near the surface indicates that mean airstreams and
confluences between airstreams define climatic regions with
a distinctive annual march of airstream (and in the mean,
airmass) dominance. These regions show a clear congruence
with several major biotic regions. These analyses strongly
suggest that the boreal forest occupies the region between
the mean (or modal) southern boundary of Arctic Air in
winter and the mean southern boundary of Arctic Air in
summer.

According to Hare (1951), ecological climatology is
based on the concept that "vegetation and soils are mirrors
of the normal climate" and that "soil and vegetation maps
divided into regions ought therefore to give us a useful
method of defining rational climatic regions". As he pointed
out, this is the basis for the familiar climatic classifi-
cations of Köppen and Thornthwaite. In the same article, he
discussed the attempts to find climatic values of the tem-
perature which would correspond to the tundra-Boreal forest
border, but concluded that the attempts were "hit-and-miss
affairs with no rational basis".

Certain aspects of this approach leave the student of
climates unsatisfied, and with unanswered questions. Even
if "climate is the ultimate ecological control" (Hare, op.
cit. p.953), is it only the temperature climate that is
causative to the variety of distinctive biota of the north?
This implies that certain temperature combinations alone
result in certain plant communities, holding site and sub-
strate constant. How does one relate a dichotomized biotic
distribution to a temperature continuum? Or is there really
a natural regionalization of climatic complexes which re-
sults ultimately in biotic regions? It is towards the answer
of this last question that the present study is directed.

For many years the meteorologist has recognized the
existence of naturally occurring atmospheric complexes, sub-
sumed under the concept of the airmass. Arctic airmasses,
for example, have a certain temperature range in each place
and season, and characteristic moisture, turbidity, and
structure as well. It is the distinctive combination of
these elements into a recognizable complex that is at the
heart of airmass analysis. He has also recognized the

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natural, more or less sharp, boundaries between these com-
plexes as the well-known "front" or "frontal zone". If it
can be shown that these fronts have distinguishable mean
locations, which change with the seasons so as to create
more-or-less homogeneous regions which differ from each
other in airmass regimen, then we will have obtained a
discontinuous pattern of climatic complexes <u>independent</u>
<u>of the biological data</u> which can be compared with the biotic
distributions. If, then, there is seen to be a correspon-
dence of patterns and one assumes that climate <u>is</u> the ultimate
ecological control, perhaps our insight into the climatic-
biotic relationship will have been deepened.

This study has been under way for at least ten years,
yet cannot be considered complete. Too many questions and
uncertainties remain; but the results summarized here are
sufficiently encouraging to justify entering into the enor-
mous task of data processing and analysis that will be re-
quired to expand the techniques and explore other regions
and possibilities. In the already considerable effort the
author has been aided by students and colleagues too numer-
ous to list, but two in particular must be mentioned because
of their special contributions: Prof. Lyle H. Horn, who did
one of the first trajectory analyses described herein, and
Prof. Ernest Sabbagh, who actually wrote a first draft of
chapter 2. Their help, and that of the many others, is
most gratefully acknowledged.

AIRMASSES, STREAMLINES, AND THE BOREAL FOREST

1. INTRODUCTION

In the course of field investigation of the climate and climatically related terrain parameters in north central Canada, it has been observed that in mid-summer the northern forest border is frequently the site of more disturbed weather than the region either to the north or to the south. In-flight observations of wind changes across this disturbed area strongly suggest the frequent presence of a front near the forest border. Many days of ground observation from just north of the forest border at Ennadai Aeradio Station (61° 08' N, 100° 51' W) also included notice of maximum cloud development over the boreal forest to the south.

That fronts and wave cyclones are more common in the general vicinity of tree line than over either the tundra or boreal forest proper is rather easy to demonstrate through the examination of synoptic charts, though the wide spacing of weather stations makes precise location difficult (Reed 1959). In turn this implies that the dominance of a particular air mass over the tundra and a different air mass over the boreal forest may be of more than casual interest to the scholar concerned with the possible causal relationship between climate and biotic communities in the north. It is the purpose of this paper to explore the sources and distribution of air masses in order to add to the synoptic evidence that the tree line is indeed related to the mean (or perhaps modal) frontal zone. In addition, we shall consider whether the southern edge of the boreal forest is also a meteorologically defined boundary, and suggest some other climatic-biotic relationships. In this study the paucity of weather stations, and the near non-existence of aerological observations in the

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northern area, require the use of rather non-standard ana-
lytical techniques. Fortunately the area of concern is
relatively simple geographically--low surface of slight
relief, homogeneous, continental interior, with only a few
major biotic regions.

One approach to the study of air mass frequencies
is that of Brunnschweiler (1952) who applied to the North
American continent the technique he had used earlier in the
analysis of European air mass distributions. Though the
technique of utilizing the air mass identification placed
on the synoptic chart by the analyst may be applicable in
Europe, it is of doubtful validity in the identification of
any but maritime tropical air in North America. The manu-
script maps from which Brunnschweiler's frequencies were
determined reflected little thoughtful or objective dis-
crimination between the colder varieties of air. The
typical American analyst of a decade or two ago was likely
to class all cold air coming from Canada as cP with little
consideration of true source, and apply even less discrimi-
nation to the air masses of northern Canada. We shall,
therefore, reject the frequencies found by Brunnschweiler
ab initio as showing much too great a predominance of cP
air in southern Canada and the northern United States.

Penner (1955) recognized four main air masses
over North America (mT, mP, mA, and cA). Canadian analysis
generally identifies three fronts in winter: the polar front
which separates mT and mP air, the maritime arctic front
which separates mP and mA air, and the continental arctic
front which separates mA from cA air. In summer, only two
fronts are distinguished since there is no source for conti-
nental arctic air. Reed (1959 op. cit.) verifies the exis-
tence of this frontal scheme but emphasizes the impermanency
of the fronts.

2. AIRMASS FREQUENCY ANALYSIS BY THE TRAJECTORY METHOD

Since every air mass (in the classical sense)
must have a source, tracing the air trajectory back to
this source serves to eliminate some of the uncertainty
of terminology which arises when one must decide how a
particular column of air acquired its characteristics.
For our present purpose, the trajectories were followed
back only to the borders of Canada. On this basis four
external sources were defined: Arctic, Pacific, Atlantic,
and United States. Only for the U. S. border did this
lead to uncertainty, for air of both Pacific and Gulf
origin crosses the Canadian border east of the Rocky Moun-
tains, but for our purposes the admixture will be neglected.
A fifth, but rather unimportant, source was found from
those trajectories which showed a long residence time in
an anti-cyclone located over Hudson Bay. For July this
truly Canadian source was uncommon.

On the basis of the trajectories, frequency of
occurrence of the various air masses was plotted for each
five degree latitude and longitude grid segment for the ten
months of July from the years 1945-51 and 1954-56. The
geostrophic trajectories from twelve-hourly surface synoptic
charts were used.

As expected, air originating over the Arctic
Ocean occurs with the highest frequency over the Arctic
Archipelago.(Figure 1) The southward decrease in the fre-
quency of occurrence of Arctic air is fairly rapid. At 70°N
latitude Arctic air prevails with a frequency of 90 percent
or more, while at 60°N latitude the frequency of occurrence
varies from less than 10 percent at 140°W longitude on the
west coast to 50 percent in the vicinity of Hudson Bay, de-
creasing again east of the Bay to 30 percent along the east
coast in the vicinity of northern Labrador, at 60°W longitude.
The isolines dip southeast over the Hudson Bay area, portray-
ing a tongue of high frequency of Arctic air spreading south-
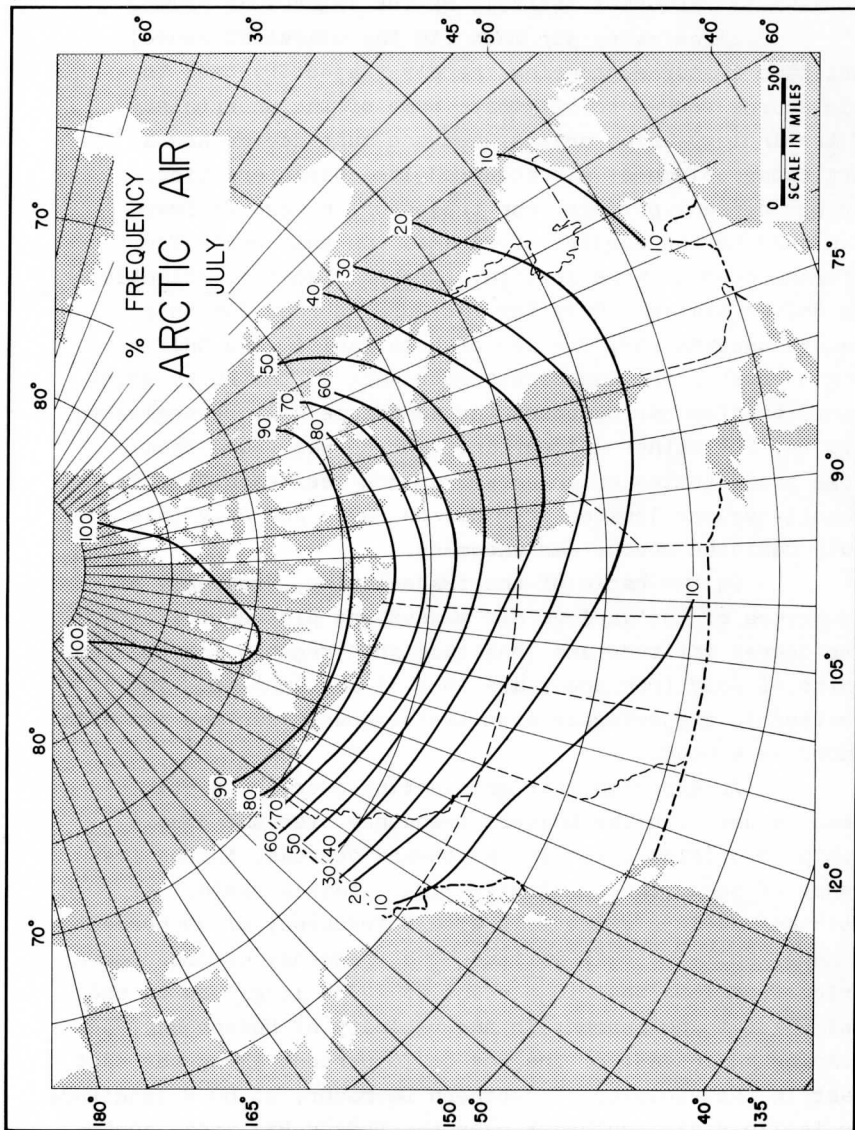ward over the Bay. Hudson Bay appears as a cold region in

Figure 1. Isopleths of the percentage frequency of occurrence of Arctic air over Canada in July, determined by computing trajectories back to the source from each grid intersection for each July day in the period 1945-51, 1954-56.

the pattern of July daily temperature mean isotherms, the
pattern being particularly pronounced in the case of the July
daily maximum temperature (Thomas 1953).

Throughout British Columbia Arctic air is rare,
penetrating west of the cordillera on less than 5 percent
of the days in July. Over the central part of the continent
the frequency of modified Arctic air reaching the United
States is only about 10 percent.

The distribution pattern of Pacific air shows a
close relationship to the mean atmospheric circulation.
(Figure 2) The core area of over 90 percent frequency of
Pacific air occurs in proximity to the source region west
of the cordillera. The eastward spread of Pacific air is
strongest in the region of the main stream of westerly
wind in July at about 50° to 55°N latitude. From west to
east the occurrence of Pacific air decreases generally,
the gradient being strongest in the Prairie Provinces and
weakest east of Hudson Bay. The westerly flow carries
Pacific air deep into the continent so that, despite the
mountain barriers obstructing the eastward flow of air,
Churchill, Manitoba, located more than 1000 miles from the
source region, experiences air from the Pacific one-third
of the time, a frequency almost equal to that of Arctic air
and many times the frequency of Atlantic air.

From the core region for Pacific air a much
stronger gradient occurs in a northeasterly direction towards
the region dominated by Arctic air. The pattern of occur-
rence of Pacific air, therefore, is one that reveals a change
from almost 100 percent frequency on the coast of British
Columbia to 10 percent frequency on the Newfoundland coast,
to less than 5 percent in the Canadian Archipelago. On the
other hand, the atmospheric circulation does not favor the
deep continental penetration of Atlantic air. Air of Atlan-
tic origin occurs with a frequency of generally less than
50 percent along the Atlantic east coast littoral (Figure 3).
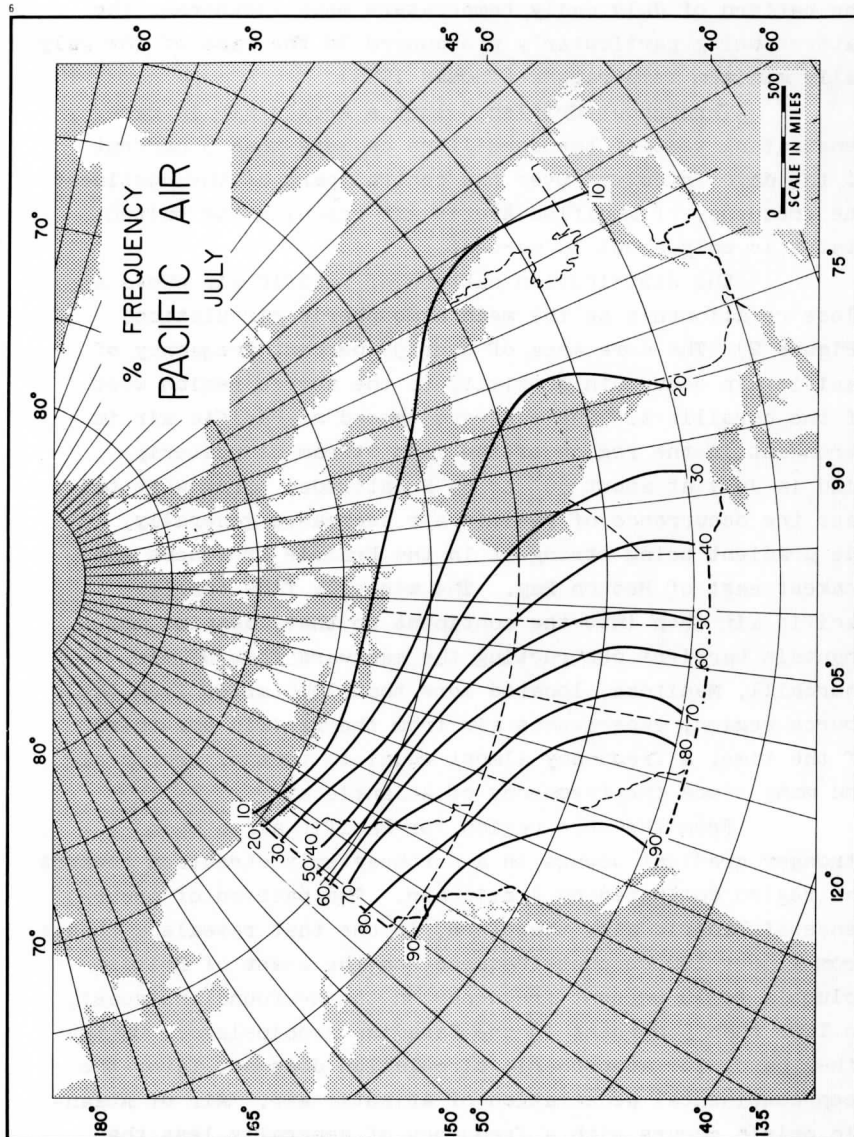The westward decrease in occurrence is rapid, so much so

% FREQUENCY
PACIFIC AIR
JULY

Figure 2. Isopleths of the percentage frequency of occurrence of Pacific air over Canada in July, determined by the trajectory method.

% FREQUENCY

ATLANTIC AIR
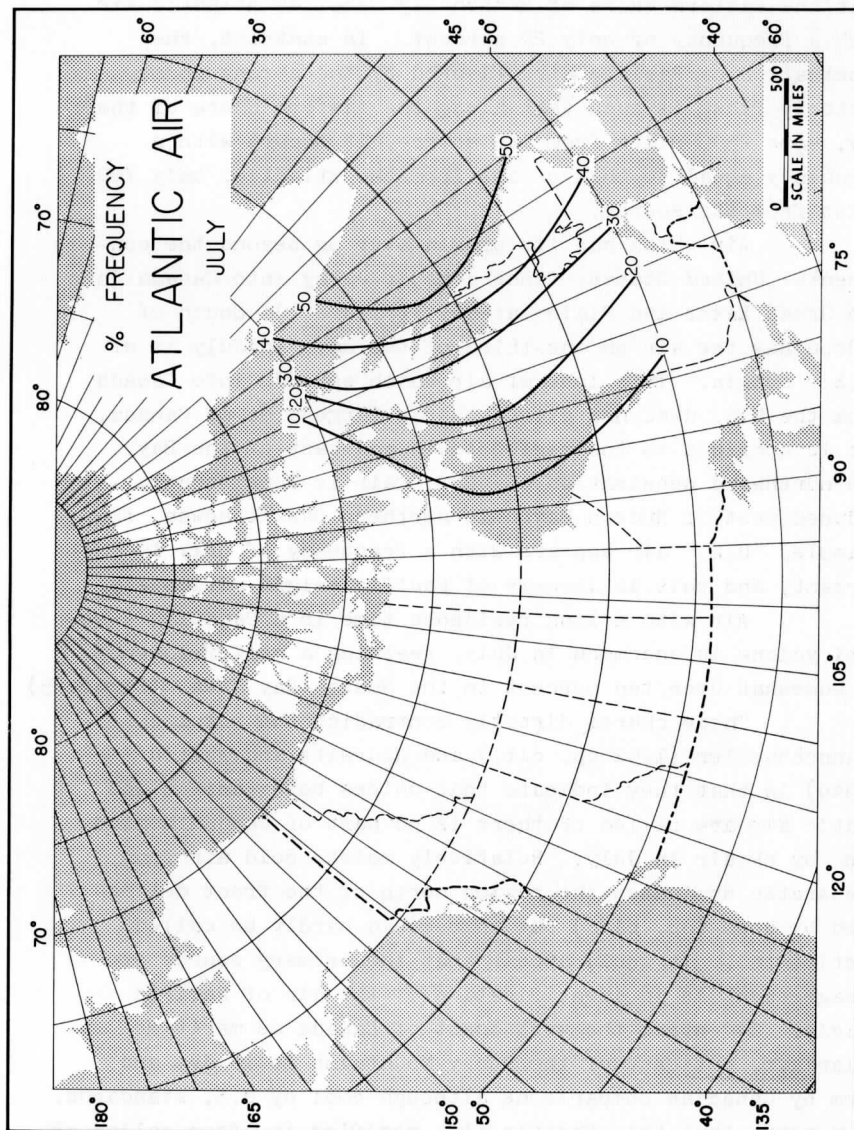
JULY

SCALE IN MILES

0   500

Figure 3. Isopleths of the percentage frequency of occurrence of Atlantic air over Canada in July, determined by the trajectory method.

that the eastern shore of Hudson Bay receives Atlantic air
with a frequency of only 20 percent. In contrast, the
penetration of Pacific air, favored by the strong zonal
westerly flow, is such that along the eastern shore of the
Bay, some 2500 miles from its source, it occurs with a
frequency equal to that of air from the Atlantic, only 700
miles from its source.

Air which has its origin over or beyond the con-
tinental United States, finds a major entry into Canada in
the Great Lakes and Plains areas. (Figure 4) South of
Hudson Bay the air on one-third of the days in July is of
"U.S." origin. This lobe of air which spreads into Canada
from the U.S. does not extend over a large area of Canada,
but is confined to the region south and east of the Bay.
The northward penetration of "U.S." air is considerably
reduced west of Hudson Bay. In northern Saskatchewan, for
example, "U.S." air appears with a frequency of only 10
percent, and this is largely of Pacific origin ultimately.

Air with a long residence time in a Canadian
anticyclone is uncommon in July, reaching a peak frequency
of somewhat over ten percent in the Hudson Bay area. (Figure 5)

These charts directly contradict the results of
Brunnschweiler (1952 op. cit.) and Haurwitz and Austin
(1944) in that they indicate that unless both Pacific and
Arctic air are called cP there is no part of Canada domina-
ted by cP air in July. Relatively moist, cold air from
the Arctic dominates the region north of the front deline-
ated by Reed (op. cit.) but this could hardly be called
continental. It would appear that the primary source of
disagreement is in identification of the air of Pacific
origin. It enters the west coast of Canada as maritime
Polar air, but east of the Rocky Mountains it is dry and
warm by Canadian comparisons although cool by U.S. standards.
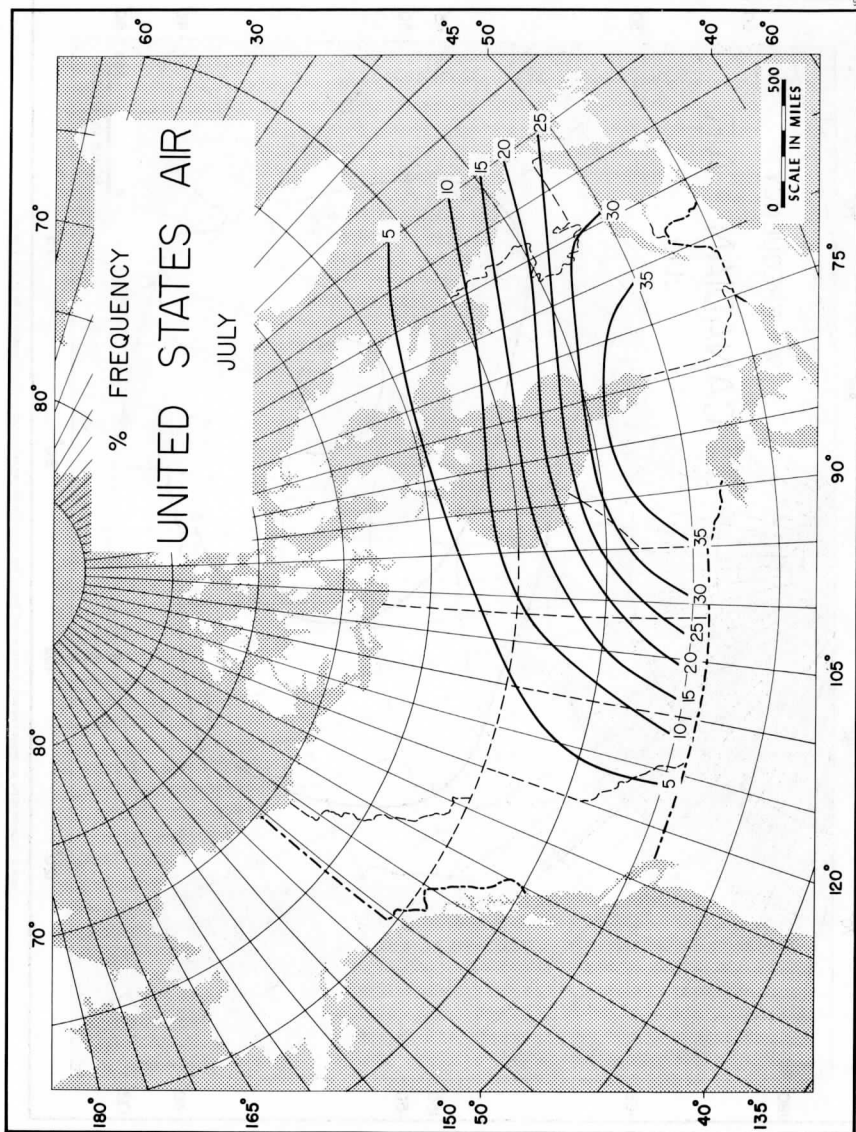It appears that this Pacific air, modified, is often called cP.

% FREQUENCY

UNITED STATES AIR

JULY

SCALE IN MILES

0   500

Figure 4. Isopleths of the percentage frequency of occurrence of air which entered Canada from south of the Canada–United States border in July, determined by the trajectory method.

% FREQUENCY

CANADIAN AIR

JULY

5

2

8

5

2

SCALE IN MILES

0   500

60°

30°

45°
50°

40°
60°

70°

80°

75°

80°

90°

80°

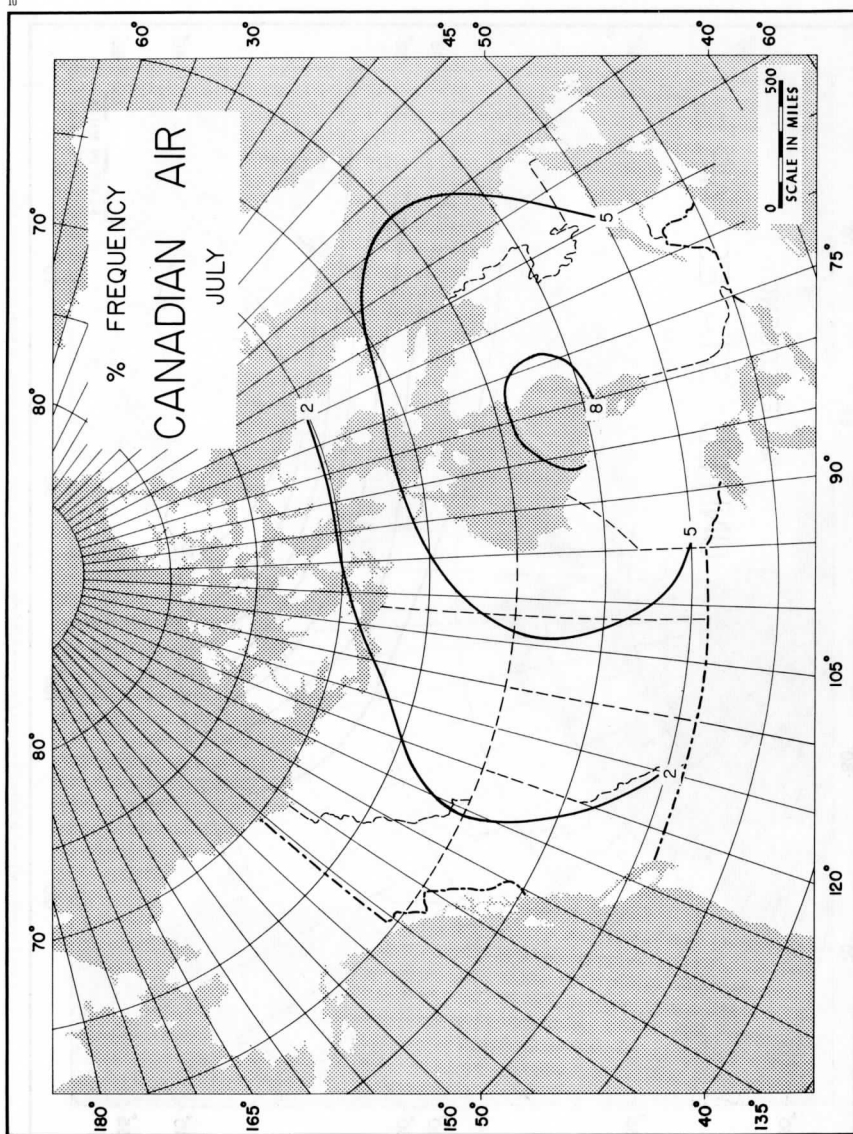105°

70°

120°

180°

165°

150°
50°

40°
135°

Figure 5. Isopleths of the percentage frequency of occurrence of Hudson Bay or true Canadian air over Canada in July, determined by the trajectory method.

This is an acceptable convention as long as there is no
implication of a true anticyclonic source region and long
residence time over the continental interior. In this study
it shall be called Pacific air.

        Examination of figures 1-5 reveals that in north-
central Canada there are basically two airmasses present
in July, Arctic and Pacific. If the region of equal fre-
quency of these two airmasses is regarded as the modal
position of the front between Arctic and Pacific air, one
finds that this frontal zone coincides quite closely with
the forest border and with the frontal position given by
Reed (op. cit.). The northern forest border in central
Canada is also the modal position of the front between
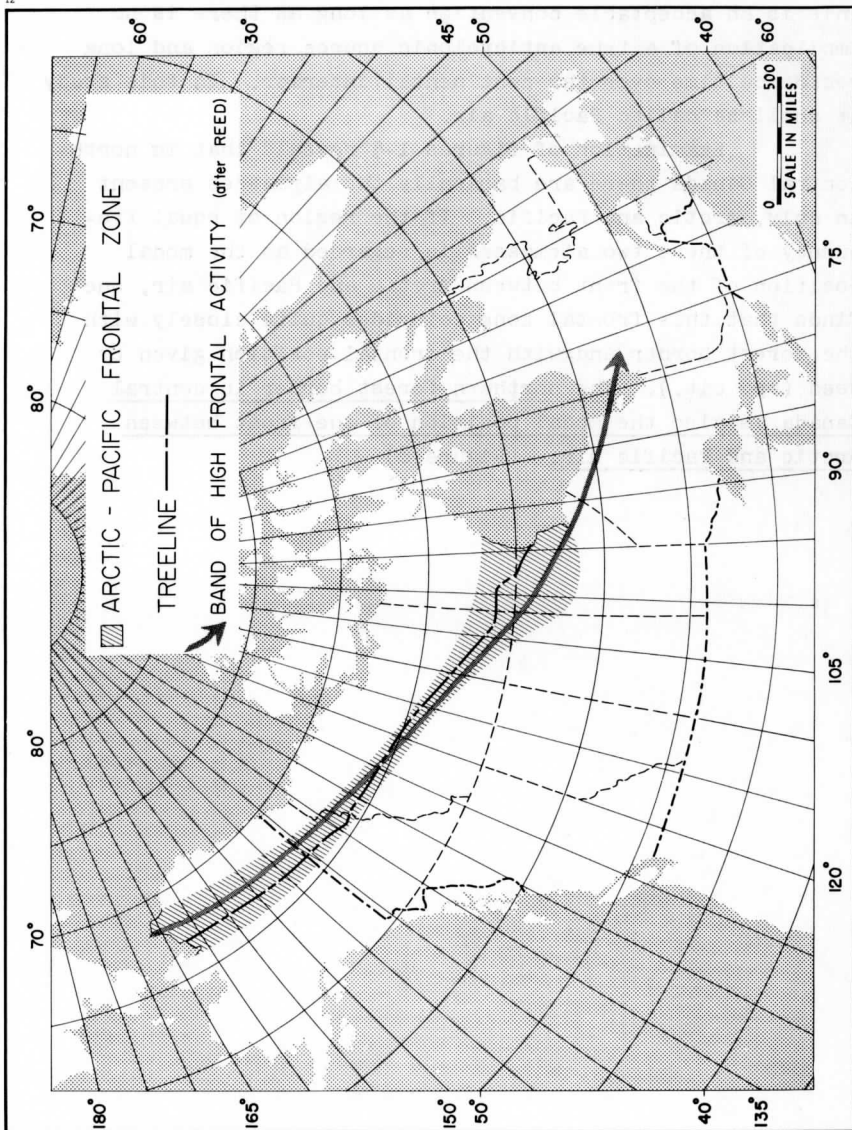Arctic and Pacific Air. (Figure 6)

Figure 6. Comparison of the modal frontal zone in July, derived from trajectory analysis of air masses, with the position of the forest border and the summer frontal position given by Reed (1959).

3. AIRMASS FREQUENCY ANALYSIS BY THE PARTIAL COLLECTIVE
   METHOD

   3.1 Multimodal Distributions and Partial Collectives

   It is implicit in the air mass concept that dif-
ferent sources produce air of different mean characteris-
tics, with relatively small scatter about these means.
Without this assumption the air-mass concept breaks down
and air-mass classification becomes arbitrary. Essenwanger
(1954) has demonstrated that the frequency distribution of
surface temperatures may be decomposed into partial collec-
tives (constituent distributions) which represent individual
air masses. An abbreviated version of his method was applied
to the frequency distributions of July daily maximum temper-
atures at about 120 Canadian and U. S. stations for the ten
year period 1948 through 1957. Maximum temperatures were
taken as being fairly representative of an air mass (Pet-
terssen 1940). The number of stations provided an adequate
sample to test the validity and usefulness of the method,
and the time period coincides fairly closely with the 10
year period of trajectory analysis so as to provide a basis
for comparison of the results of the two methods. For each
station, the percentage frequency of occurrence of tempera-
tures within 2-degree categories were calculated. The data
was subsequently subjected to a filter function of the form
$b' = 0.25a + 0.50b + 0.25c$ and then plotted in the form of
frequency curves. The filter function was decided upon sub-
jectively by experimentation with the data. Winter curves
were found to be generally much more complicated than summer
curves. For summer in Canada a period of 5 years would prob-
ably be adequate for this kind of analysis.

   3.2 Reduction to Partial Collectives

   The frequency curves so constructed appear to be
comprised of a series of normal curves. The method employed
here for their analysis is a modification and simplification

of that used by Essenwanger.*

The analysis proceeds as follows. First it is
assumed that the frequency curve is made up of a series of
normal curves. The approximate validity of this assumption
has been checked by constructing the frequency distribution
of maximum temperature for single airmasses identified by
the trajectory method. To separate the normal curves, the
first step is to inspect the frequency curve and select the
most prominent peaks to which a normal curve might be fitted.

To fit a normal curve to selected peaks, an attempt
is made to find peaks whose adjoining partial collectives do
not overlap the central section or end peaks which are more
than half uncontaminated by the next partial collective
(Figure 7). A half uncontaminated end collective may be
simply folded along the median ordinate, the resulting
symmetrical curve subtracted from the total distribution,
and then the analysis continued on the residue. An uncon-
taminated central portion of a collective will be symmet-
rical about the mode. Comparison of the ordinates one
unit above and below the mode with the modal ordinate and
reference to a table of normal ordinates will yield an
estimated standard deviation and reconstruction of the part-
ial collective can follow. A second check on the standard
deviation often can be made using the ordinate two units
away from the mode on the least contaminated side.

Once the partial collectives have been determined,
the percentage of the total represented by each may be de-
termined by planimetering.

A second method for reducing the frequency distri-
bution to partial collectives first involves drawing families

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* A machine method has been developed for least squares
fitting of a series of normal distributions to the total
frequency distribution (see Appendix). This method was not
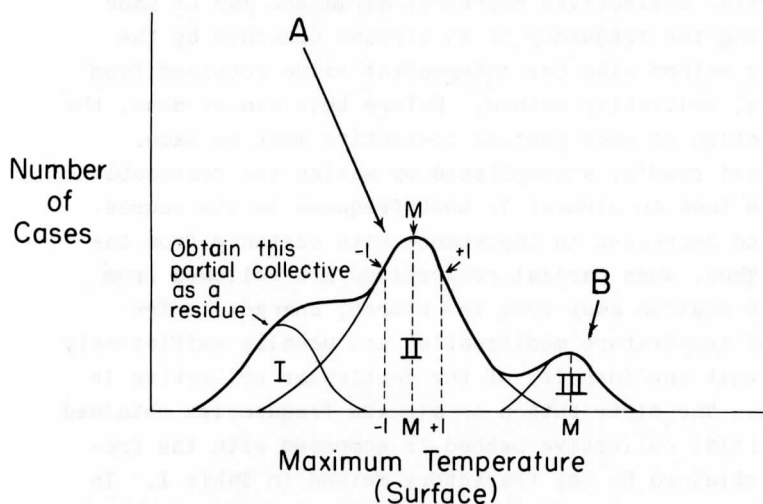available at the time the research for this paper was done.

Figure 7. Schematic multimodal distribution illustrating two approximate methods for resolution into partial collectives. The heavy line indicates the total distribution, the light lines indicate reconstructed partial collectives.

Method A – Observe median ordinate, express ordinates one unit above and below the median as a fraction of the median, calculate the standard deviation from tables and reconstruct the partial collective.

Method B – For end collectives, fold the distribution along the median ordinate and subtract from total distribution.

of normal distributions of many different standard deviations and modal ordinates. The appropriate curve may then be selected by superposing the frequency distribution plot over the normal curve families on a light table. Neither method is absolutely accurate, nor as precise as the original Essenwanger method (op. cit.) but probably give magnitudes within a few percent of the true value.

3.3 The Validity of the Partial Collective Analysis

A test of the validity of the assumption that these partial collectives represent airmasses may be made by comparing the frequency of an airmass obtained by the trajectory method with the independent value obtained from the partial collective method. Before this can be done, the identification of each partial collective must be made. This is most readily accomplished by making the reasonable assumption that an airmass is most frequent in its source region, and decreases in importance with distance from the source. Thus, when partial collectives are followed from station to station away from the source, changes in frequency and temperature modification are usually sufficiently small so that the identity of the particular collective is preserved. The distribution of airmass frequencies obtained by the partial collective method is compared with the frequencies obtained by the trajectory method in Table I. In general the values obtained by the two methods are in agreement, though some large discrepancies are evident. One would not expect perfect agreement, however, for the periods of time considered are not identical - four years out of ten not being common to the two analyses. Another source of discrepancy lies in the fact that trajectories were computed for 5° X 5° latitude-longitude "squares" and rather smooth isopleth patterns drawn, from which the station values for Table I were interpolated. In regions of strong air mass frequency gradient these interpolated values may be in error by 30%. The trajectory method is sufficiently accurate to

TABLE I

Comparison of airmass frequencies obtained by the
partial collective method with those obtained by
the trajectory method

Station	Arctic		Pacific		Atlantic		U.S.	
	PC	Traj.	PC	Traj.	PC	Traj.	PC	Traj.
Mould Bay, N.W.T.	94	95	5	~5	0	0	0	0
Cambridge, N.W.T.	78	80	23	15	0	0	0	0
Baker Lake, N.W.T.	65	60	34	25	0	<5	0	5
Calgary, Alta.	2	<5	83	83	0	0	13	7
Island Falls, Sask.	32	25	59	50	0	<5	8	15
Kapuskasing, Ont.	25	10+	48	25	0	<5	22	>35
Knob Lake, Labr.	35	20	32	15	24	35	7	20
Regina, Sask.	3	<10	71	60	0	0	26	23
Maniwaki, Que.	9	<10	51	15	3	<10	36	>35

	Pacific & U.S.		Arctic & Atlantic	
	PC	Traj.	PC	Traj.
Calgary	96	90	2	<5
Regina	97	83	3	<10
Maniwaki	87	>50	12	<20
Island Falls	68	65	32	30
Kapuskasing	60	>60	25	15
Knob Lake	39	35	59	55
Baker Lake	34	30	65	65
Cambridge	22	15	78	80
Mould Bay	5	5	94	95

provide a reasonably certain identification of the general airmass distribution pattern, and the partial collective method is sufficiently sensitive to give details.*

Some features of analysis by this method are illustrated by several profiles which extend from source regions into areas of considerable airmass heterogeneity.

Maritime tropical air entering the Gulf Coast of the United States is quite homogeneous and in places like Brownsville, Texas and Burrwood, Louisiana where the winds are onshore nearly all summer it should be present nearly 100% of the time. Thus one partial collective should be present with a modal temperature characteristic of mT air and a magnitude of about 100%. Farther inland (northward) various other varieties of air should become increasingly important and the magnitude of the mT collective should decline. This change in relative importance is quite clear in the array of collectives versus temperature shown in Figure 8. In this figure the modal temperature of each collective is arrayed on the abscissa and the latitude on the ordinate. The percentage of the total for each partial collective is given at its modal temperature.

At Brownsville, Texas, only one collective is present, and it represents the maritime Tropical air which is present throughout July. Moving farther north, Houston, Texas, has other than typical mT air present 11% of the time, but mT air continues to dominate and exists at about the same temperature as at Brownsville. Tropical air appears to be less common at Little Rock, Arkansas (70%) but it is warmer in mid-day than on the coast. It would appear that

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* A check on the validity of the graphical analysis of the frequency distributions may be made by comparing the results with those obtained by least squares computer fitting of a series of normal distributions (see Appendix).
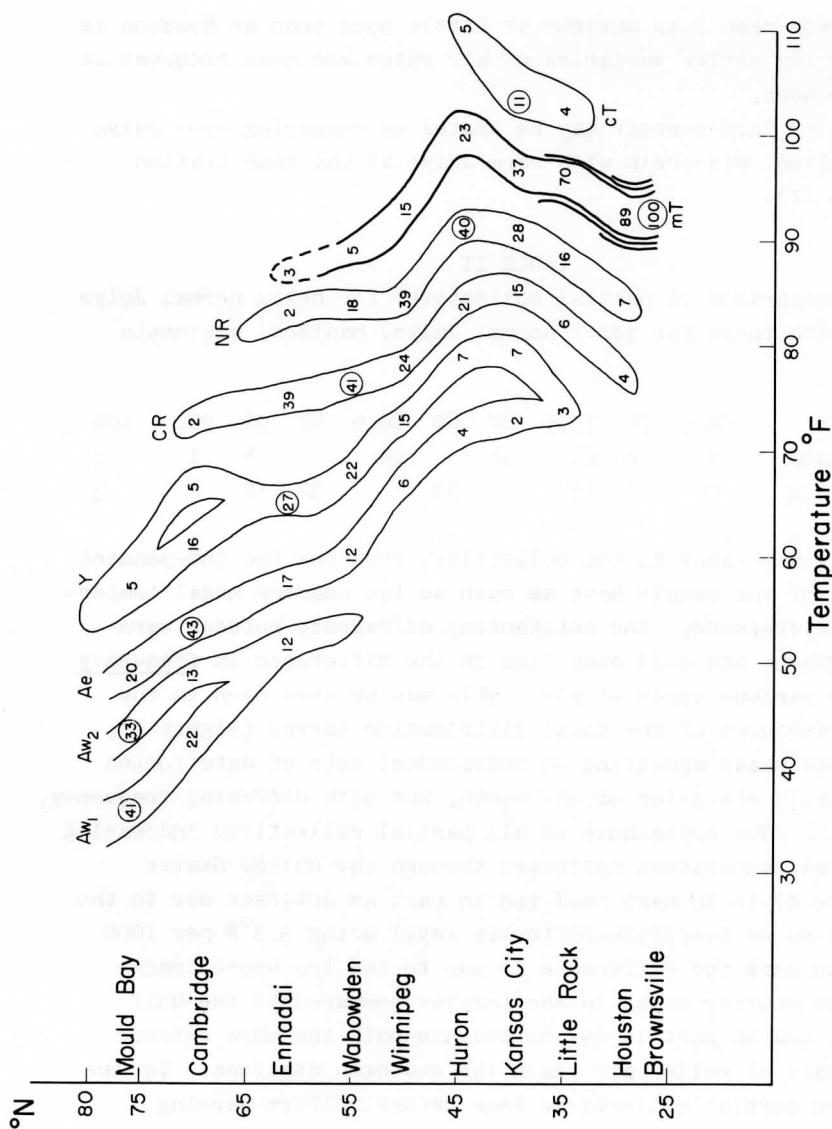
Figure 8. Relative frequency of occurrence of July air masses along a profile from the Gulf of Mexico to the Arctic determined by the partial collective method. The ordinate is latitude; the abscissa, temperature (°F) reduced to sea level. The magnitude of each partial collective is plotted at the corresponding modal maximum temperature value. Air mass identification symbols are defined in Table III. Maximum frequency for each collective is circled.

the lower mean July maximum at Little Rock than at Houston is
due to the cooler varieties of air which are more frequent at
Little Rock.

This concept may be tested by comparing cool Julys
at Madison, Wisconsin with warm Julys at the same station
(Table II).

TABLE II

Comparison of partial collectives for below normal Julys
with those for above normal Julys, Madison, Wisconsin

Modal Temp $^\circ$F	64.5	70	75.5	80	82	86.5	87	92	95.5	100
% in Cold	2	8	21	34		29		4	1	1
% in Warm	0	0	15		32		31	12	6	3

In only two cases do the collectives from the two independent
halves of the sample have as much as two degrees modal temper-
ature difference.   The outstanding difference between warm
July months and cold ones lies in the difference in frequency
of the various types of air.   This may be seen even in the
gross features of the total distribution curves (Figure 9),
the same peaks appearing on independent sets of data sorted
by overall character of the month, but with differing frequency.

The appearance of all partial collectives increasing
in modal temperature northward through the United States
(Figure 8) is in part real and in part an artifact due to the
reduction of temperatures to sea level using 3.3°F per 1000
ft.   In part the difference is due to the two hours longer
day and shorter night in the Dakotas compared to the Gulf
Coast, and in part it may be because only the more extreme
outbreaks of colder air reach the southern stations.   In Can-
ada the partial collectives show rather uniform warming
southward.

Moving from south to north, one sees that types of
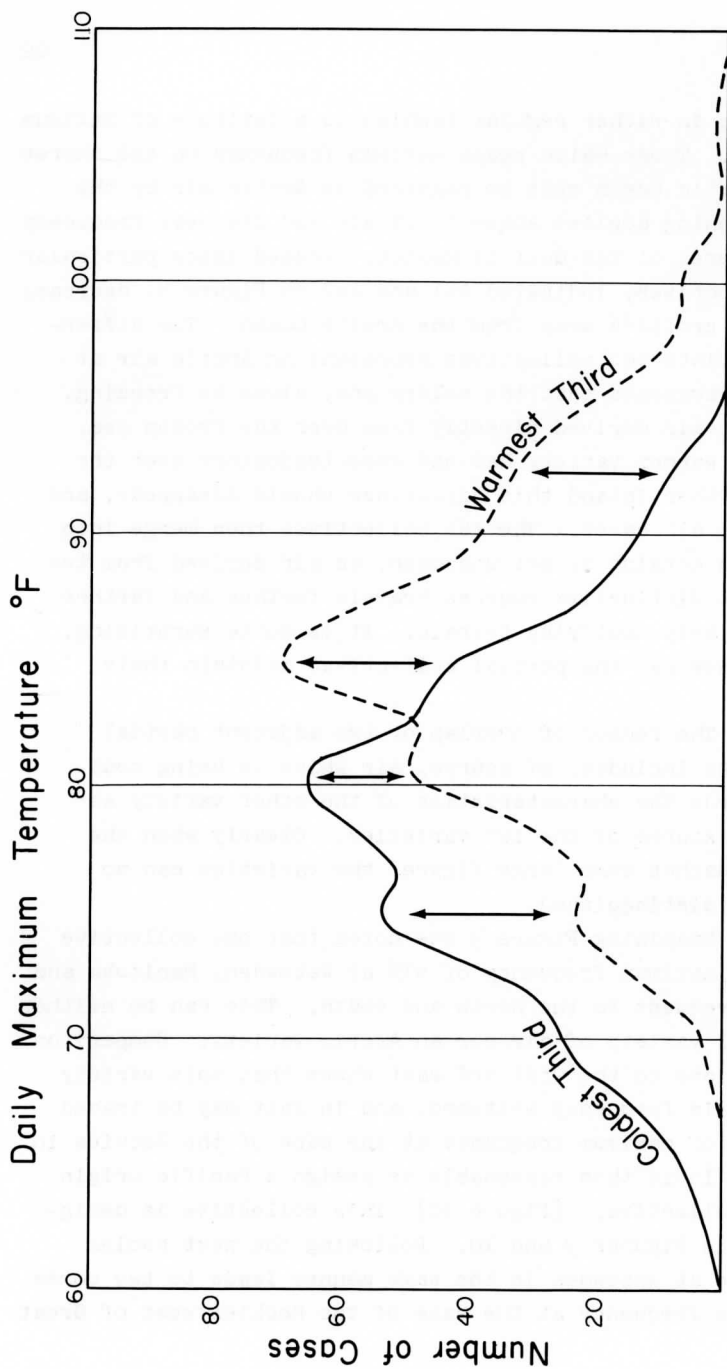air other than maritime Tropical appear and increase in

Figure 9. Frequency distributions of daily maximum temperature at Madison, Wisconsin in Julys with mean monthly temperature in warmest third of all cases on record and in coldest third. The same peaks appear in the two completely independent sets of data.

importance in rather regular fashion to a latitude of maximum
frequency. Those which reach maximum frequency on the shores
of the Arctic Ocean must be regarded as Arctic air by the
same reasoning applied above to mT air and its peak frequency
on the shores of the Gulf of Mexico. Indeed these particular
cold collectives, indicated Aw1 and Aw2 in Figure 8, decrease
along all profiles away from the Arctic Ocean. The differ-
entiation into two collectives representing Arctic air at
Mould Bay suggests that the colder one, close to freezing,
represents air derived directly from over the frozen sea,
while the warmer variety has had some trajectory over the
land. Farther inland this difference should disappear, and
it does in all cases. The two collectives then merge into
one. Such merging is not uncommon, as air derived from two
nearby but distinctive sources travels farther and farther
over similarly modifying terrain. It is quite surprising,
in fact, how far the partial collectives maintain their
identity.

The region of overlap of two adjacent partial
collectives includes, of course, air which is being modi-
fied towards the characteristics of the other variety as
well as mixtures of the two varieties. Clearly when the
overlap reaches some large figure, the varieties can no
longer be distinguished.

Examining Figure 9 one notes that one collective
reaches a maximum frequency of 41% at Wabowden, Manitoba and
is less frequent to the north and south. This can be neither
a tropical variety of air nor an Arctic variety. Comparison
with stations to the west and east shows that this variety
increases in frequency westward, and in fact may be traced
to a core of maximum frequency at the base of the Rockies in
Alberta. It is thus reasonable to assign a Pacific origin
to this collective. (Figure 10) This collective is desig-
nated CR in Figures 9 and 10. Following the next cooler
collective at Wabowden in the same manner leads to two cores
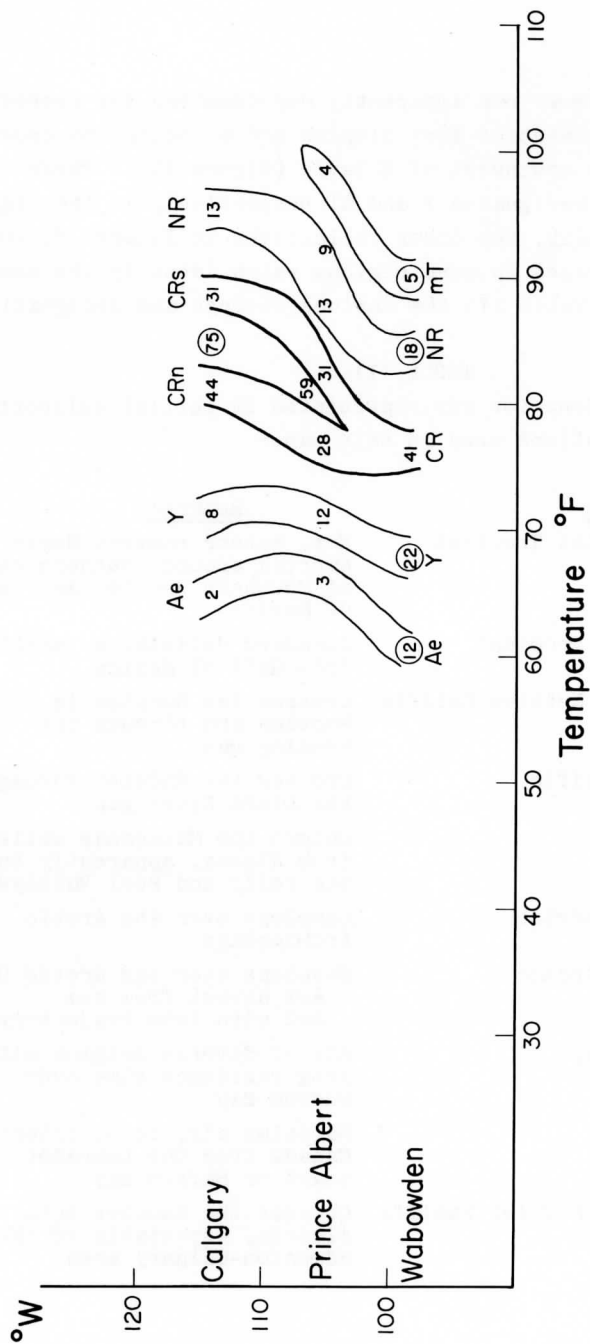of maximum frequency at the base of the Rockies west of Great

Figure 10. Relative frequency of occurrence of July air masses at Wabowden, Manitoba, Prince Albert, Saskatchewan, and Calgary, Alberta. Conventions as in figure 8. Bold figures between the two CR collectives give the combined frequency of the two sub-types.

Slave Lake, a warmer one apparently representing air crossing
the Rockies southwest of Fort Simpson and a cooler one cross-
ing the Rockies southwest of Aklavik (Figure 11). These
collectives are designated Y and Al respectively in the figures.

Similarly, the other collectives in Figures 8, 10
and 11 can be traced to core regions which identify the source
of the air. In Table III the various sources and designations
are summarized.

<div align="center">TABLE III</div>

Source regions for air represented by partial collectives -
and designations used in this paper

| Abbr.	Name	Remarks
cT	continental Tropical	Hot, enters eastern North America around southern end of Southern Rockies and out of Mexico
mT	maritime Tropical	Standard definition, mostly from Gulf of Mexico
NR	Northern Rockies Pacific	Crosses the Rockies in Montana and through the Wyoming gap
Y	Yukon Pacific	Crosses the Rockies through the Liard River gap
Al	Alaskan	Enters the Mackenzie Valley from Alaska, apparently through the Pelly and Peel Valleys
Ae	Eastern Arctic	Develops over the Arctic Archipelago
Aw	Western Arctic	Develops over the Arctic Ocean Aw1 direct from sea Aw2 with land trajectory
HB	Hudson Bay	Air of diverse origins with long residence time over Hudson Bay
Atl	Atlantic	Maritime air, cold, entering Canada from the Labrador coast or Baffin Bay
CR	Canadian Rockies Pacific	Crosses the Rockies into Alberta, especially in the Edmonton-Calgary area
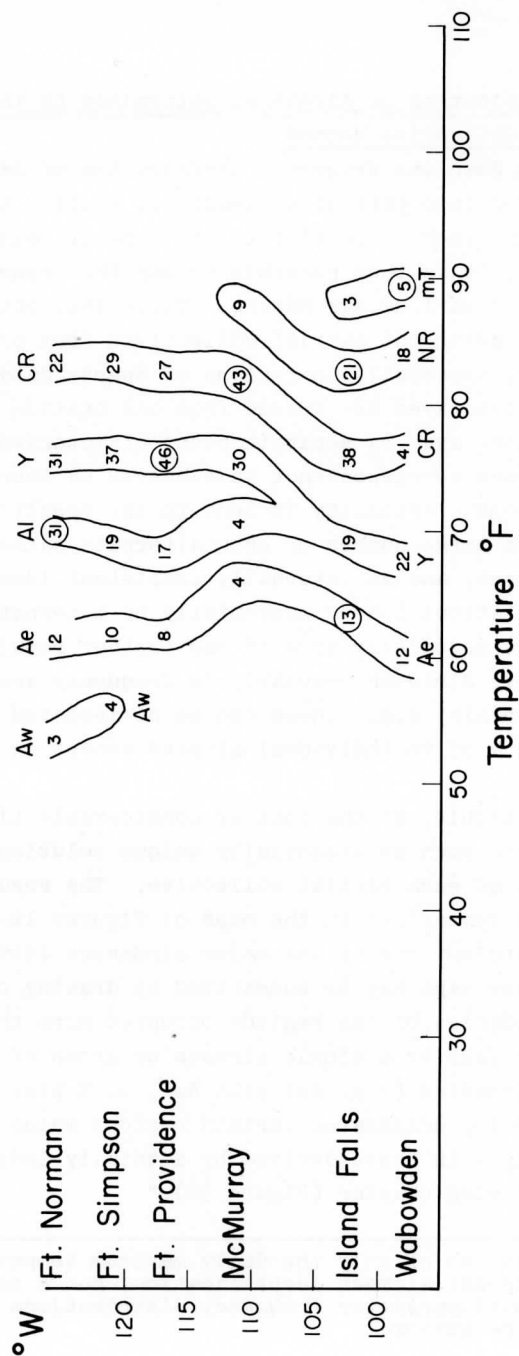
Figure 11. Relative frequency of occurrence of July air masses along a profile northwestward from Wobowden, Manitoba. Conventions as in figure 8.

3.4 The Distribution of Airmasses determined by the Partial Collective Method

Breaking down the frequency distribution of daily maximum temperatures into partial collectives, station by station, and tracing each collective to its core of maximum frequency (origin), it is then possible to map the frequency of occurrence of the various air masses. There are, obviously, many pitfalls in tracing the partial collectives from one station to another, especially in regions of sparse data. However, if the collectives are traced from one station to another some distance away by separate paths of intervening stations and the same correspondence is achieved by these alternate paths, some credibility is lent to the results. Clearly there are a large number of such alternate paths in a continental network, and an internally consistent identification for all stations leaves essentially no alternate solutions. This is especially true if one further requires that each collective diminish regularly in frequency away from its assumed origin, e.g., there can be no isolated maximum of frequency of an individual airmass except in its region of origin.

It is possible, at the cost of considerable time and care, to achieve such an essentially unique solution to the identification of each partial collective. The results of my analysis are summarized in the maps of Figures 12-19, which give the distributions of the major airmasses listed in Table III. These maps may be summarized by drawing on one chart the boundaries of the regions occupied more than 50% of the time in July by a single airmass or group of closely related airmasses (e.g. Aw1 plus Aw2, or Y plus Al). This chart, Figure 19, delineates certain regions which should be compared closely with those derived by a totally independent method in the following chapter (Figure 32).*

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* Tt is clear that use of only the daily maximum temperature cannot give unequivocal airmass identification, but a method for the analysis of multi-parameter frequency distributions is not yet known to the author.
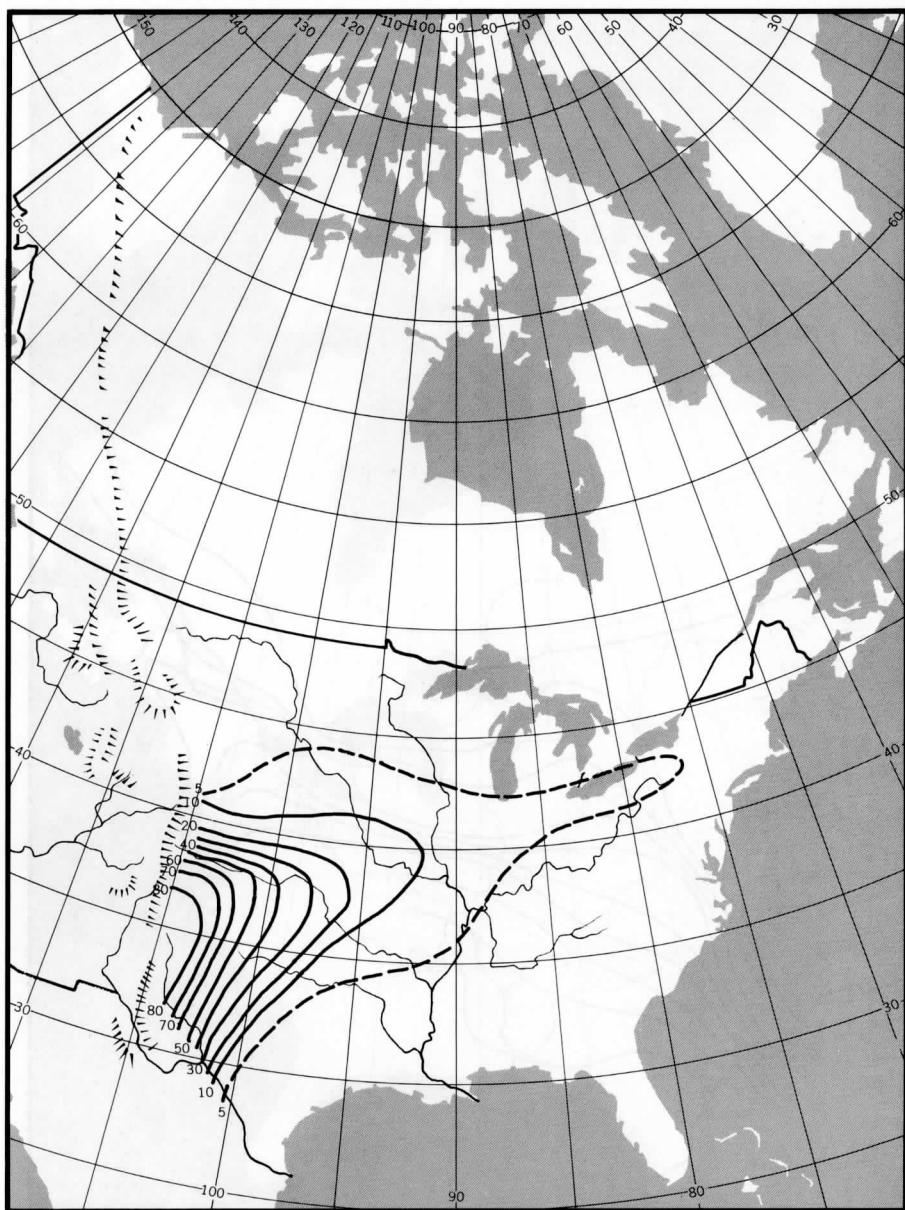
Figure 12. Frequency of occurrence of continental Tropical air east of the Rocky Mountains in July (%).
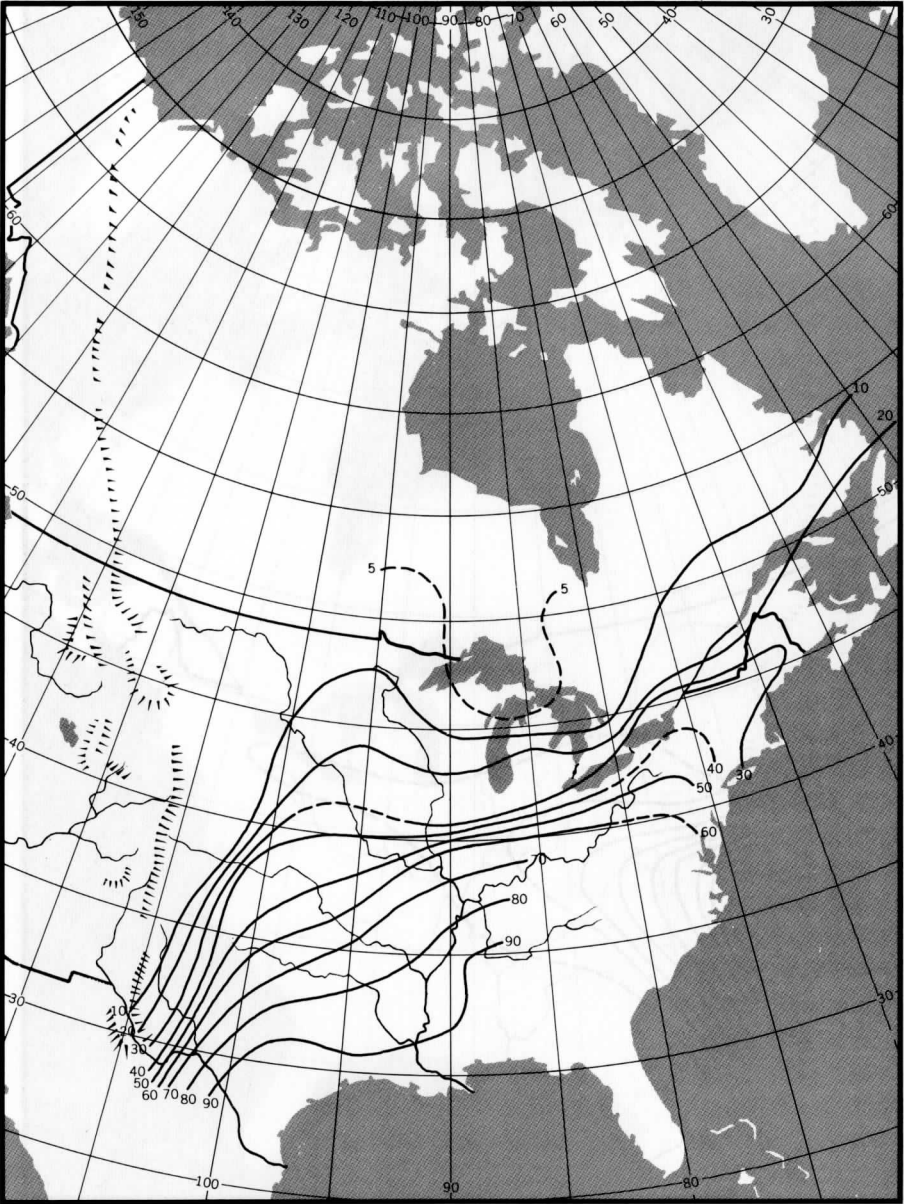
Figure 13. Frequency of occurrence of maritime tropical air east of the Rocky Mountains in July (%).
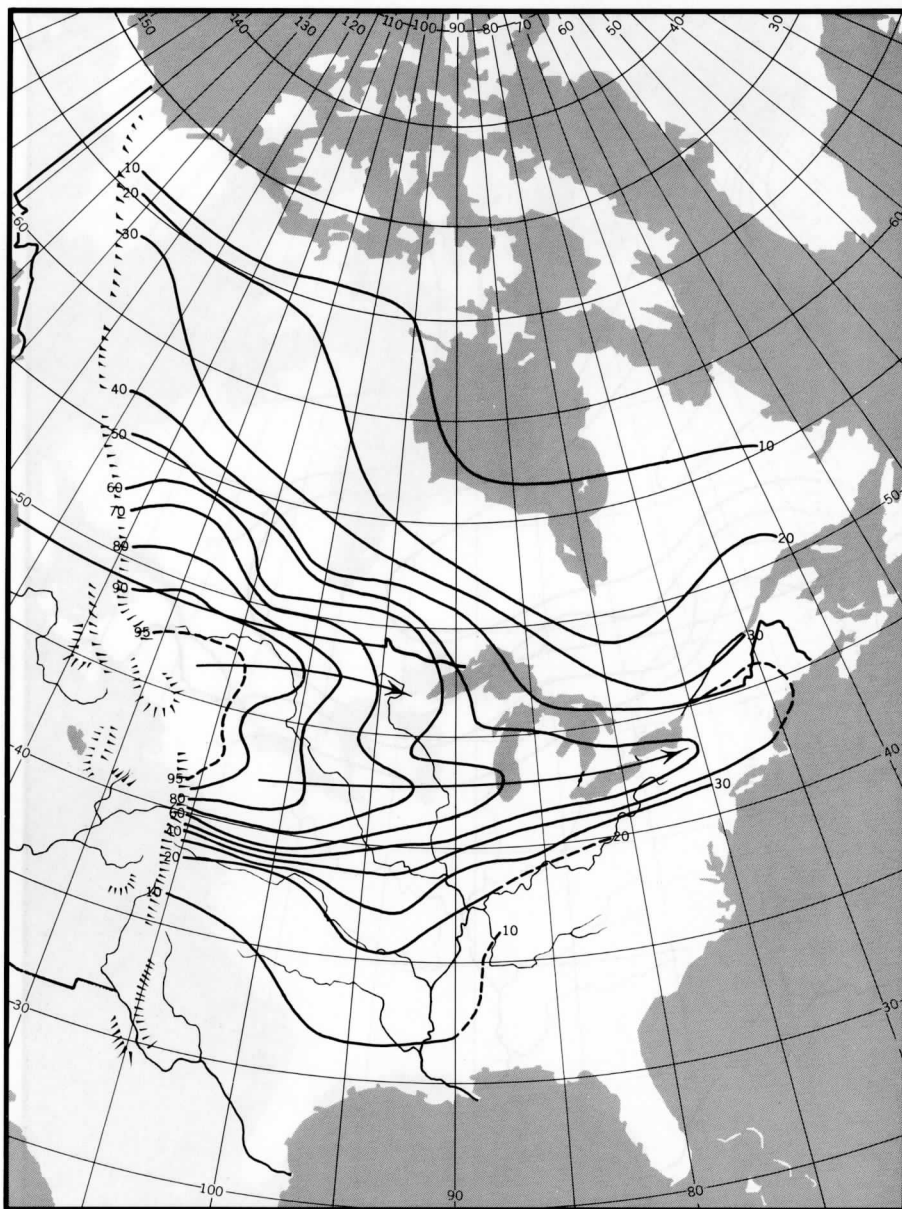
Figure 14. Frequency of occurrence of Pacific air entering the region east of the Rocky Mountains through Wyoming, Montana and Southern Alberta (CR and NR air masses of Table III) in July (%).
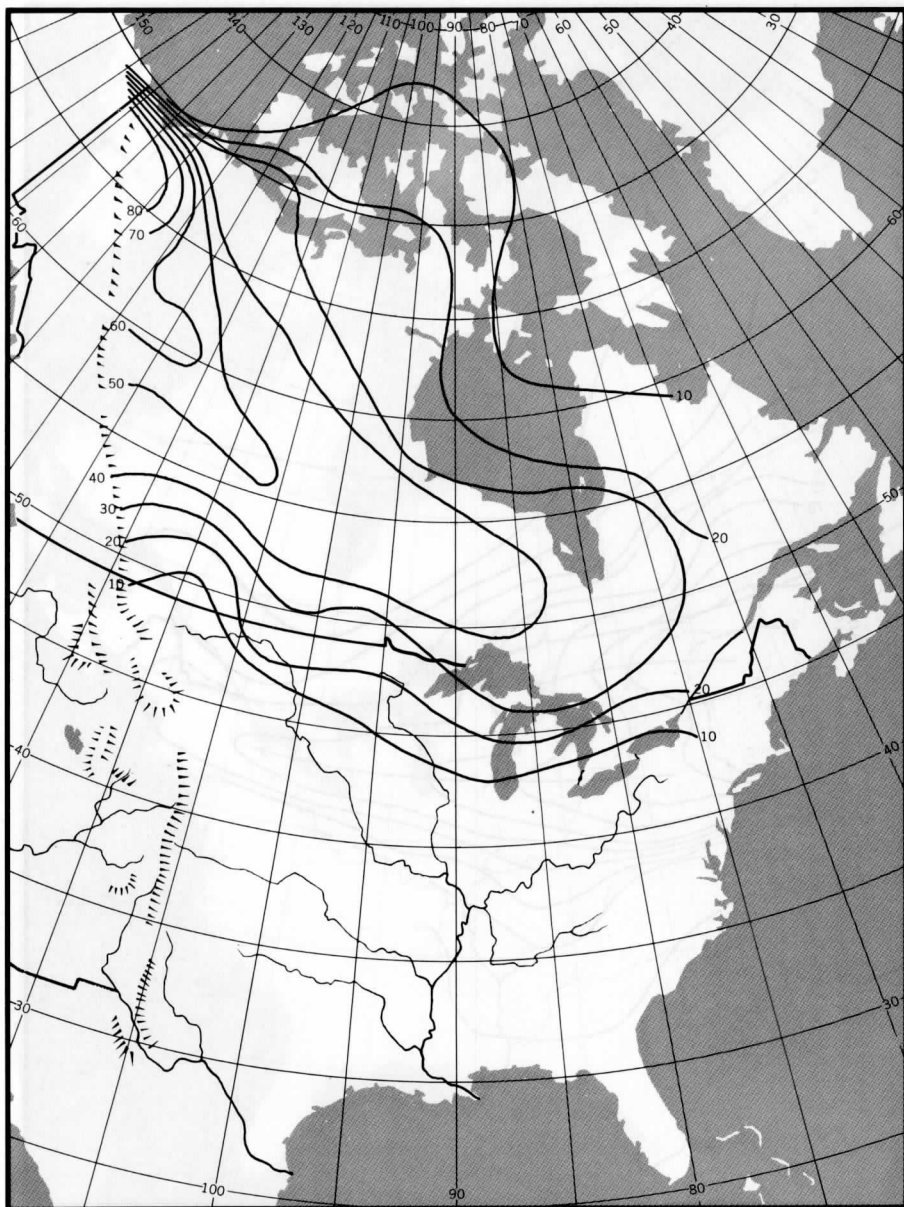
Figure 15. Frequency of occurrence of air which originates west of the Cordillera and enters the region east of the mountains from Alaska and the Yukon Territory (A1 and Y air masses of Table III) in July (%).
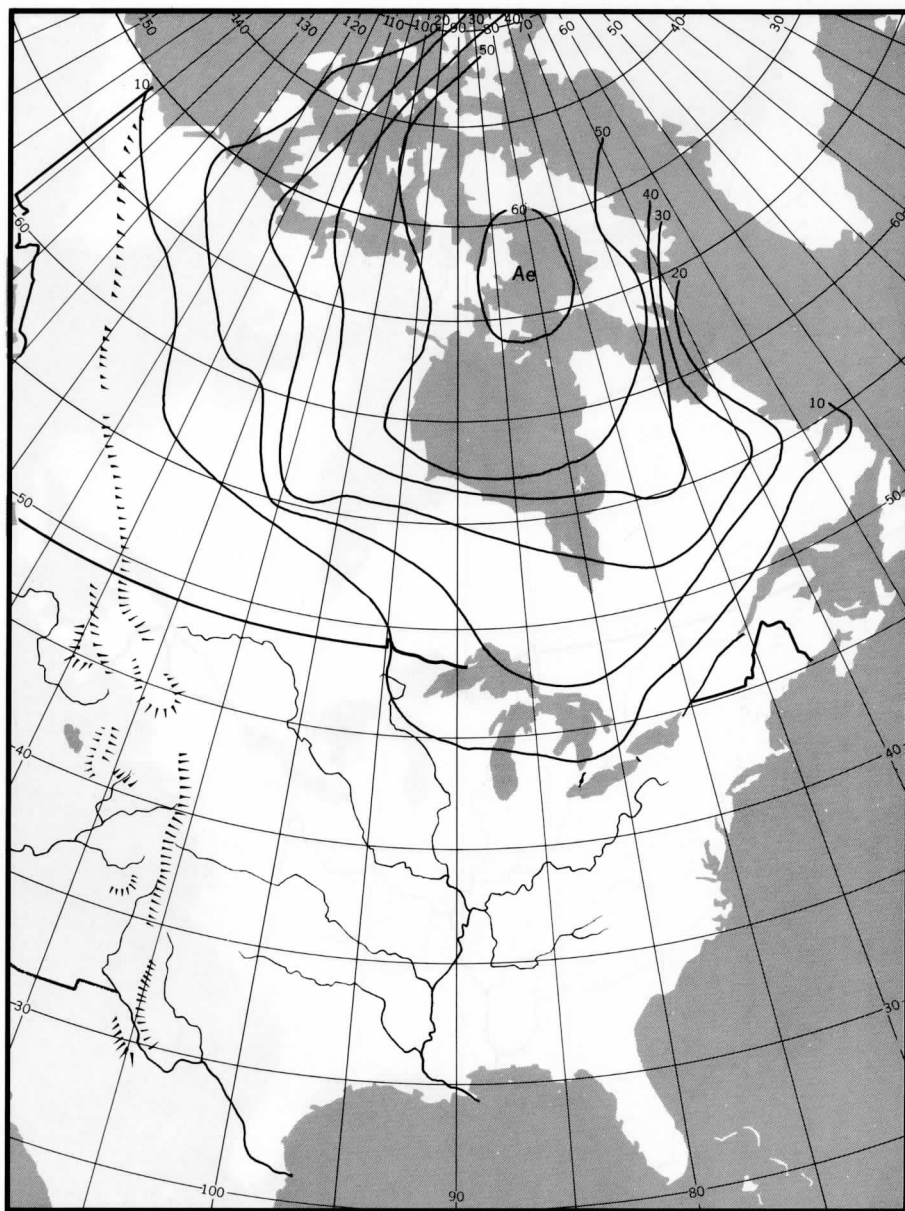
Figure 16. Frequency of occurrence of air masses originating over the Canadian Arctic Archipelago (Ae) in July (%).
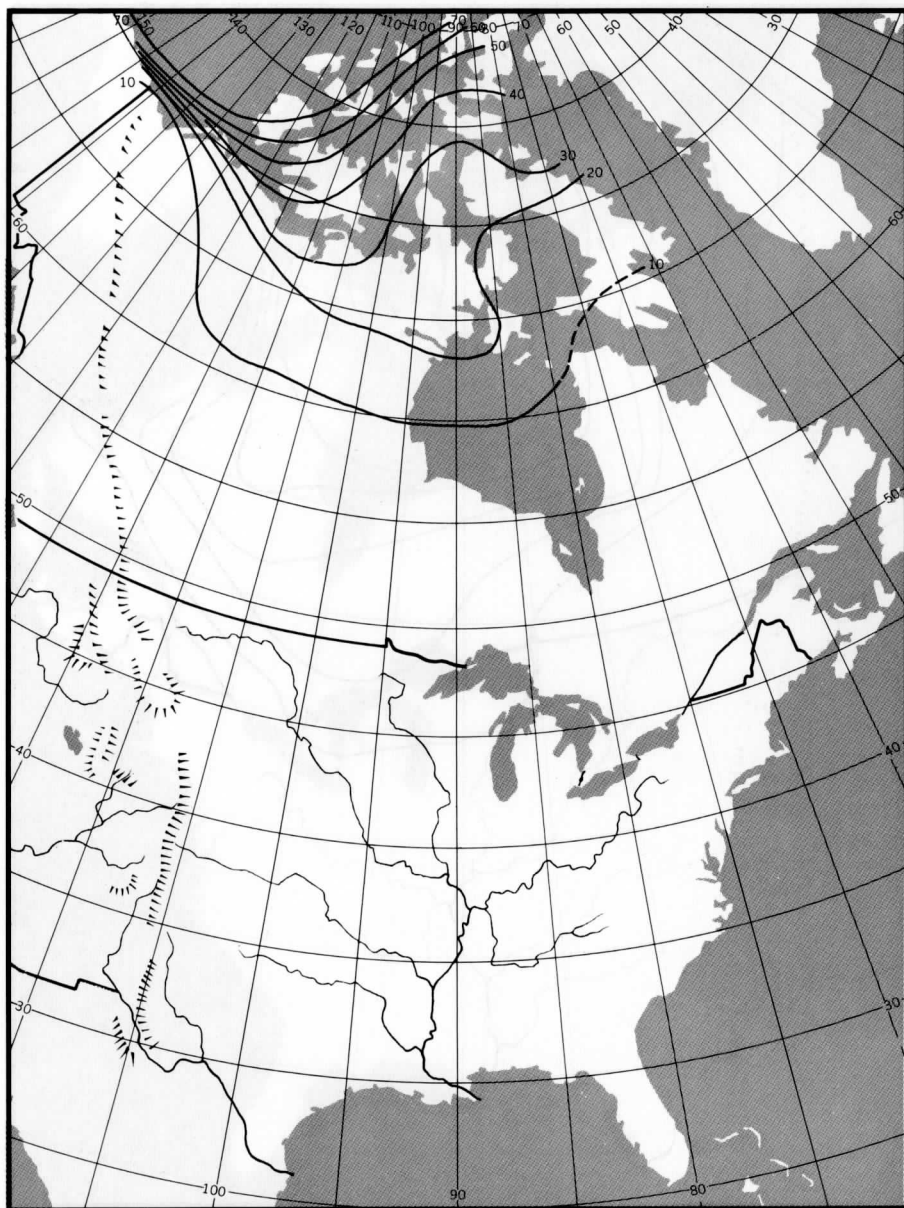
Figure 17. Frequency of occurrence of air masses originating over the Arctic Ocean (Aw) in July (%).
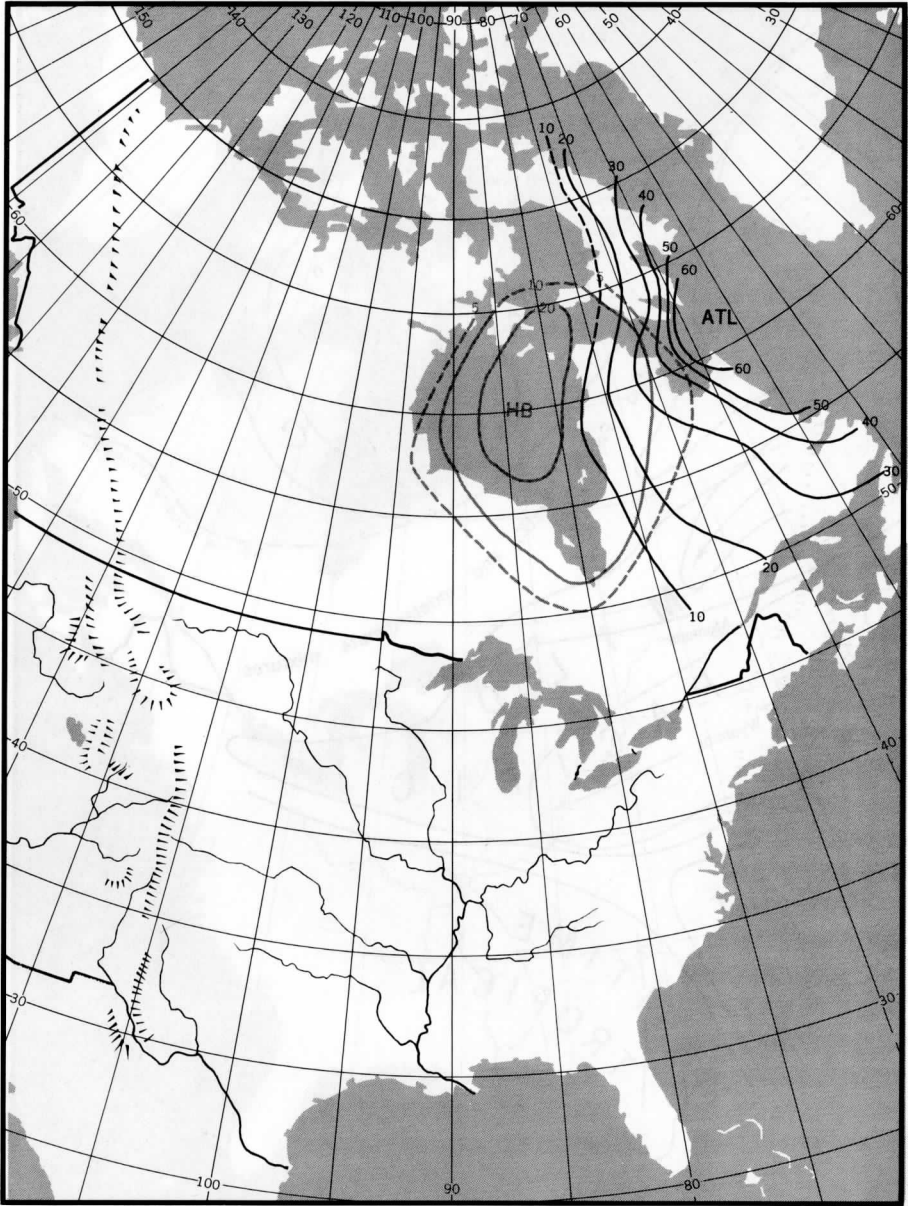
Figure 18. Frequence of occurrence of air masses originating over Hudson Bay (HB) and the North Atlantic (Atl) in July (%).
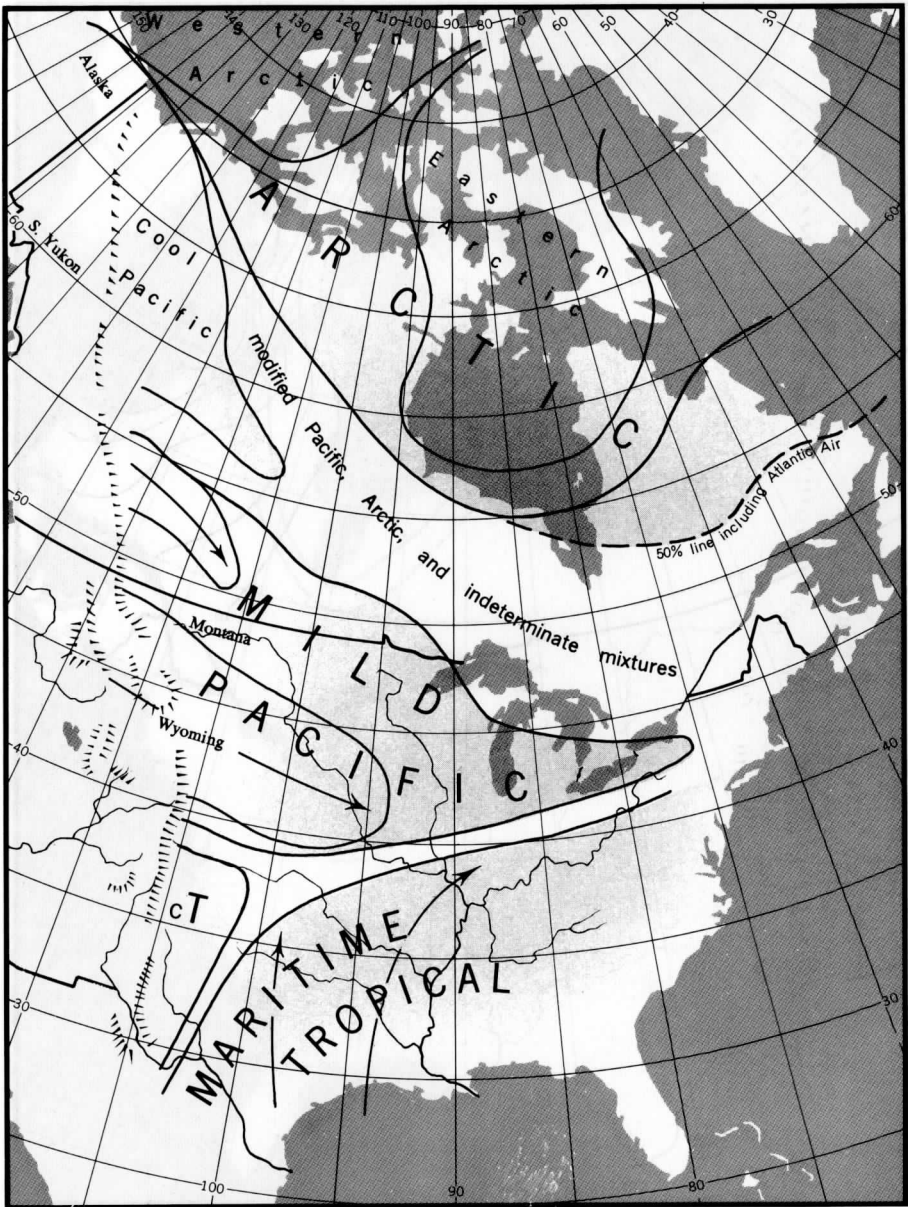
Figure 19. Composite chart of regions dominated by the various air mass types. The shaded regions are occupied more than 50% of the time by the indicated air masses.

3.5 Partial Collective Distribution and the Boreal Forest Boundaries

In the preceding chapter it was shown that the area occupied more than half the time by Arctic air in July (determined by trajectory) lies north of the tree line in Central Canada, and the area occupied by Pacific air on more than half the July days lies south of this biotic boundary. The same is found to be true on the chart derived by the partial collective method, which is based on independent data. This boundary should then be the modal position of the front that normally separates Arctic and Pacific air, or approximately the modal track of wave cyclones which move along that front (Reed, op. cit.). The agreement in position of the tree-line, the storm track, the airmass boundary derived from trajectories, and the airmass boundary derived from the partial collectives of daily maximum temperature is amazingly good. Once again it appears that the northern forest border is also the modal July position of the Arctic Front in Central Canada. The 50% isopleth for Arctic air passes between Fort Reliance and Artillery Lake at the eastern end of Great Slave Lake. The forest border is clearly defined in this region and crosses Artillery Lake about twenty miles from the position of the 50% isopleth. This same isopleth passes about 20 miles south of Ennadai Station in southwestern Keewatin, within five or ten miles of the true position of the forest border as seen in the field. The isopleth cannot reflect the detailed wanderings of the tree-line but approximates the forest border very well from Aklavik to the Atlantic.

The southern edge of the boreal forest also follows quite well the 50% isopleth at the northern edge of the wedge of mild Pacific air which has crossed the Rockies in southern Alberta, Montana and Wyoming. However this reflects only a change in dominance of mild Pacific air versus a cooler variety of Pacific air. This seems to be physically too insignificant to be causally related to the boundary between prairie and spruce forest. This may be a fortuitous

coincidence, but the evidence to be presented in the next
chapter suggests that the summer position of the transition
in airmass dominance shown in Figure 19 is a reflection of
a more significant winter contrast.

4. SURFACE STREAMLINES AND MEAN CONFLUENCES OVER LOWLAND
    NORTH AMERICA

    4.1 Monthly Mean Surface Streamline Charts

            In the preceding chapters reference has been made
    to mean or modal frontal positions implied by narrow zones
    of transition between regions dominated by differing airmasses.
    In this chapter we shall try to corroborate the existence and
    location of these mean fronts by using still a third set of
    data.

            In chapter 2, trajectories were computed to estab-
    lish the distribution of airmass frequency, and in chapter 3
    the distribution of airmass frequencies was determined by
    analysis of the daily maximum temperature frequencies. Since
    distinctly different airmasses are normally separated by
    fronts, it would seem reasonable to look for mean convergences
    or at least mean confluences in the regions normally occupied
    by these fronts. On mean charts, mean streamlines are also
    mean trajectories, so one must expect that the region normally
    occupied by Arctic air, for example, should be a region of
    streamlines leading back to the Arctic source region, etc.

            If the mean confluences of the airstreams are as
    sharply defined as implied by the narrow zones of airmass
    frequency transition, then they should also be sharply defined
    on resultant wind streamline charts, more so in central Canada
    and the plains and less so in the east where the airmass anal-
    ysis is less definitive as the result of extensive modifica-
    tion before arrival.

            For our present purpose the resultant winds aloft
    are available for only a loose network, but over much of
    North America east of the Rockies there is little relief and
    the surface resultants should serve. Indeed if significantly
    pronounced confluences do exist they should be evident in
    surface winds.

            Unfortunately, a homogeneous set of surface result-
    ants for the same period of time as the airmass analyses does
    not exist. For the United States, resultant winds for the

surface level at pilot balloon stations were available for intervals of five to twenty or so years, mostly in the 1930 decade. For Canada, resultants were reconstructed from tables of wind speed and frequency by direction to eight points at anemometer level. As a check, ten year mean geostrophic winds were calculated at grid intersections over North America, corrected for cross-isobar deviation within the friction layer, and used wherever no other data was available. Resultant surface streamlines were then drawn for each month. These charts are reproduced as Figures 20-31.

The series of streamline charts starts with the pattern for November, for reasons that will soon be obvious (Figure 20). Distinct airstreams are clearly defined on the chart. There is an anticyclonic center located over Alabama and Georgia, the outflow from which flows northward across the south-central states, north-eastward along the Appalachians and eastward to the Atlantic. On the north this airstream meets the southern edge of an airstream flowing eastward from the base of the Rocky Mountains. The former represents a stagnant anticyclone, usually with modifying continental polar or maritime Polar air returning northward ("return Polar"), and the latter a stream of fresh Polar air of originally maritime (Pacific) origin, but modified by its passage across the Rockies. The boundary or confluence between these airstreams lies along a curve from Fort Collins, Colorado through northern Missouri, then through Southern Ontario to central Maine. This boundary we shall call the "Pacific front" rather than the "Polar front" because there is undoubtedly a front between the "return Polar" air in the southeast and the true maritime Tropical air to the south, beyond the data coverage on which the chart was based.

The western edge of the "return Polar" air meets air from the southwest, Pacific air which has skirted the southern end of the main mass of the Rockies, in west Texas. This "front" or confluence is recognized by the synoptician,
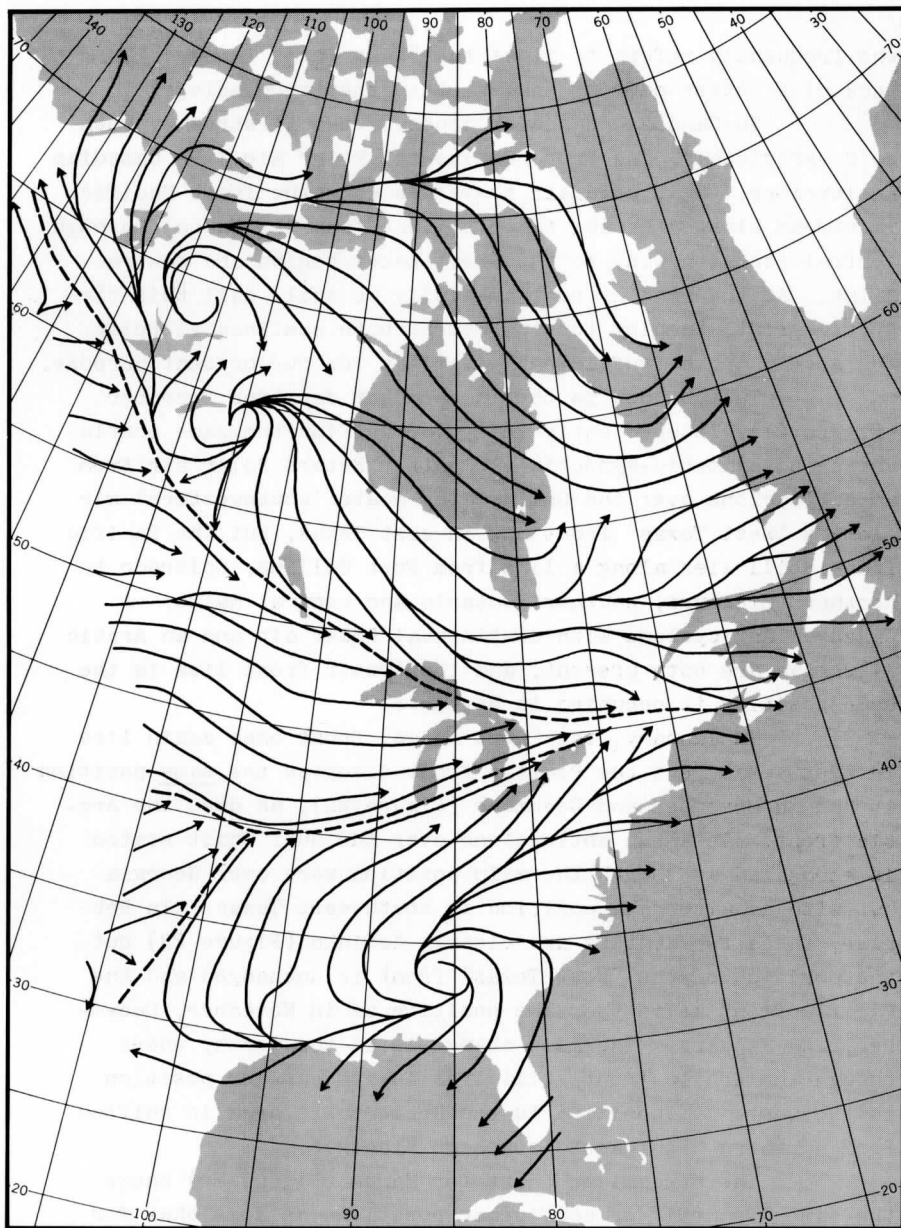
Figure 20. Streamlines of the surface resultant wind in November.

who frequently refers to it as the "West Texas front." For
lack of a better name we shall retain that terminology.

In Canada, we see evidence of two airstreams, both
cold--Arctic air, and true continental Polar air in a Canadian
Anticyclone. This cold air converges with the fresh Pacific
airstream along a broad, sweeping line from the Yukon, through
central Saskatchewan, to the Great Lakes region and central
Maine. At the risk of some ambiguity we shall call this the
Arctic front, lumping for the moment both continental Polar
and Arctic air as sufficiently similar for our present purpose.

Turning now to the independent data for December
(Figure 21), independently analyzed, we find the same conflu-
ences and climatic-synoptic elements. Return Polar air from
an anticyclone over the Gulf states meets "southwestern" air
along a "West Texas" front now in east Texas, but the Pacific
front still lies along a line from Fort Collins, Colorado to
northern Missouri, southern Ontario and central Maine. A
Canadian Anticyclone with continental Polar air and an Arctic
airstream are both present, and the Arctic front lies in the
same position it occupied in November.

In January, the "West Texas" front once again lies
in west Texas, but the Pacific front occupies the same position
it had in November and December (Figure 22), as does the Arc-
tic front. The mean anticyclone over the Gulf Coast states
is elongated as though the main position were over Georgia
but with an alternate position in south-east Texas. In Feb-
ruary these two centers are clearly defined (Figure 23) but
the position of the "West Texas" front is unchanged and the
Pacific front is in the same position as in November, Decem-
ber, and January. The main change is in the north, where
though the Arctic front still lies in its earlier position
in the west, its position in the Great Lakes area is shifted
from northern Michigan to southern Michigan.

The streamline chart for March (Figure 24) shows
the same "frontal" or confluence positions as does that for
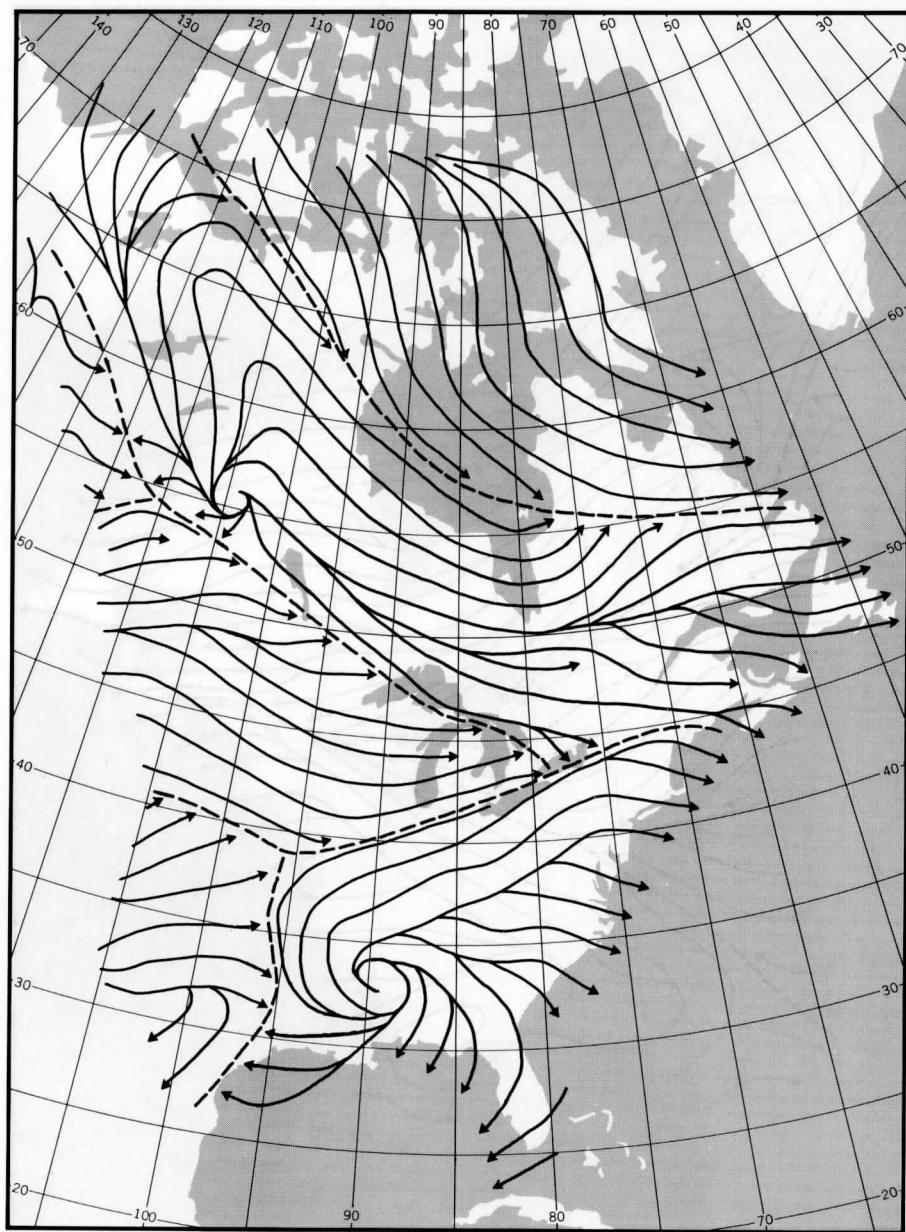February. The major difference is found in the disappearance

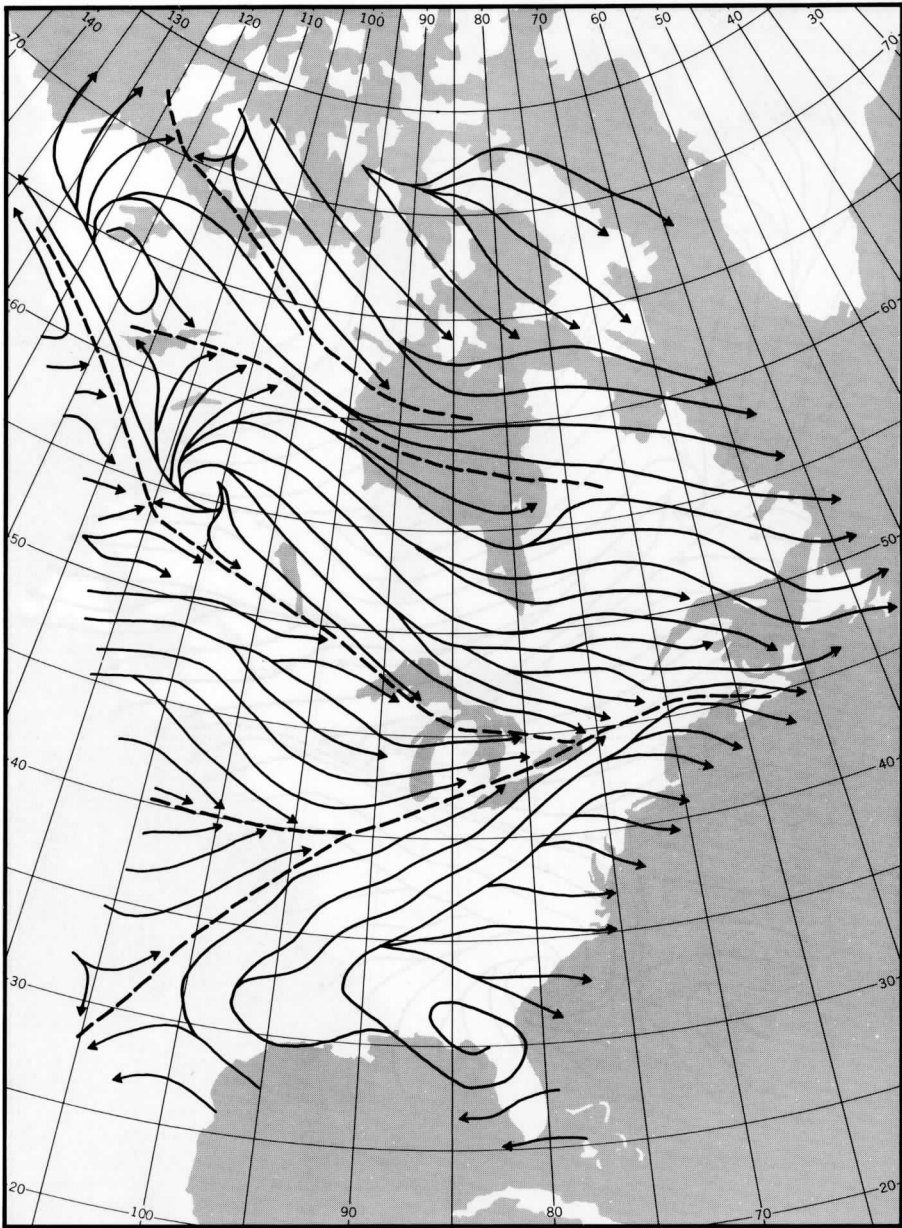Figure 21. Streamlines of the surface resultant wind in December.

Figure 22. Streamlines of the surface resultant wind in January.
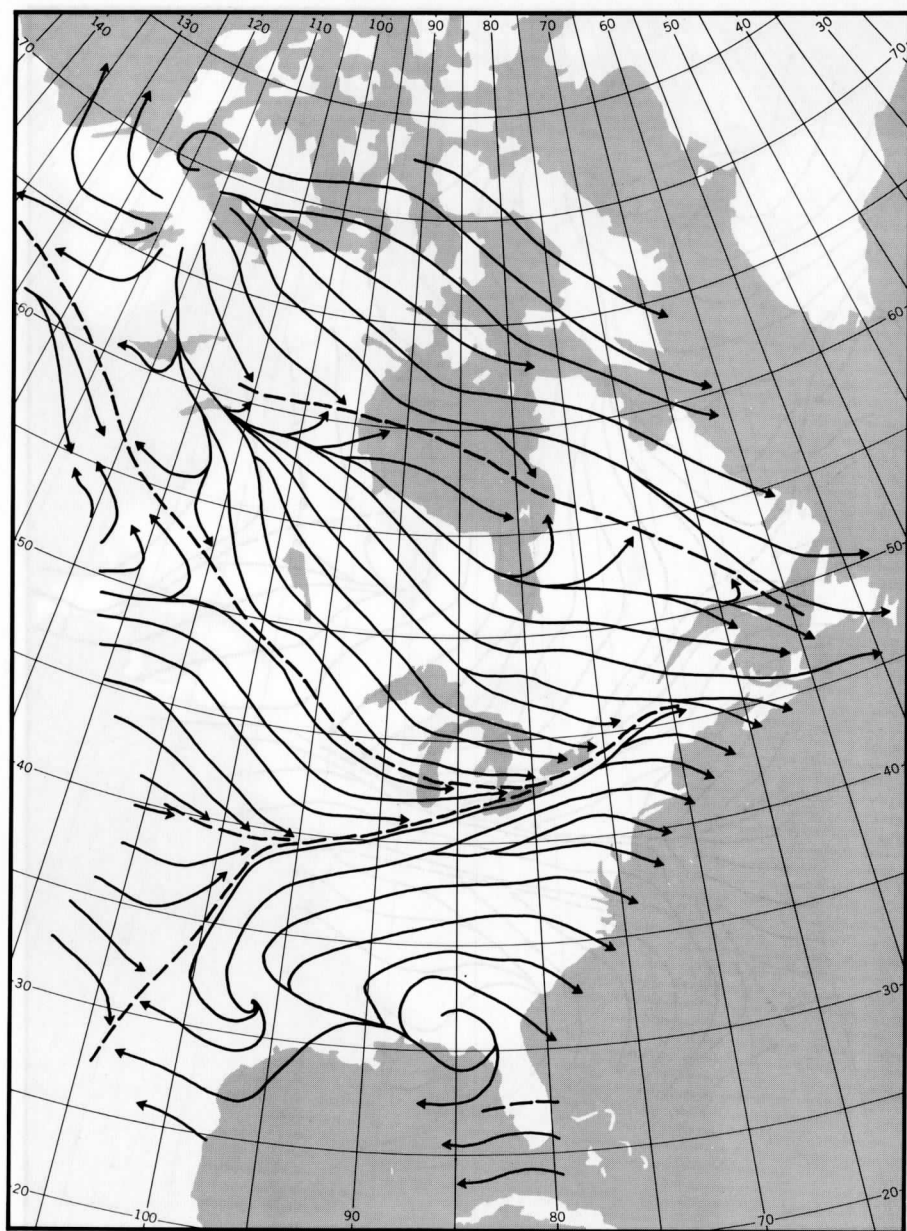
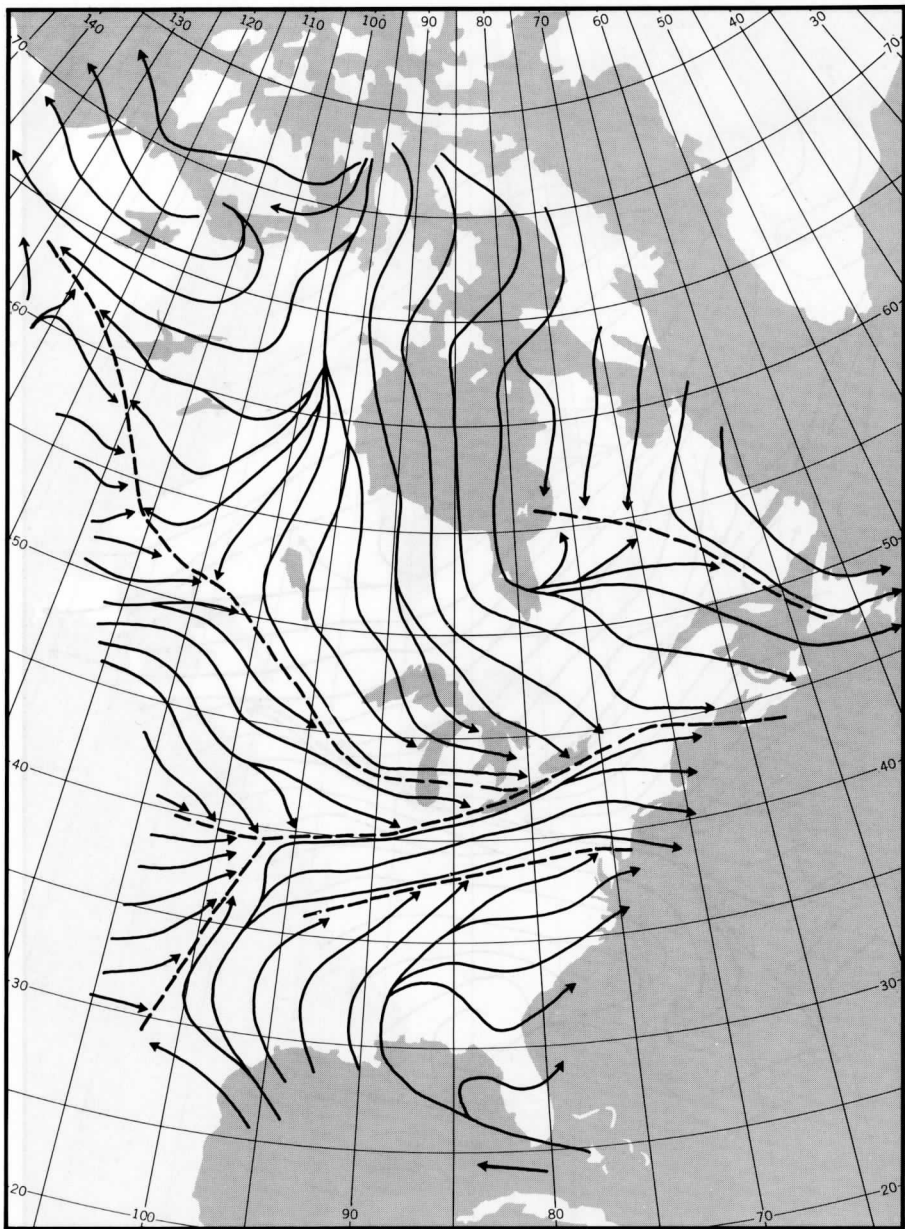Figure 23. Streamlines of the surface resultant wind in February.

Figure 24. Streamlines of the surface resultant wind in March.

of evidence for a continental Polar airstream and anticyclone
distinct from the Arctic airstream, the latter sweeping directly
into the Great Lakes area. The anticyclone in the south also
shows some changes, apparently representing the transition from
a "return Polar" anticyclone to a sub-tropical anticyclone of
maritime Tropical air, agreeing with the rapid March increase
in frequency of thunderstorms in the central United States.
Another point of change worth noting is the appearance during
March of a secondary confluence paralleling the Pacific front
but lying through northern Arkansas, Kentucky and Maryland.
This may be associated with the late winter rainfall maximum
just south of that line (Horn and Bryson, 1960).

Reviewing the charts in Figures 20-24, one finds
very little change from month to month except for some oscil-
lation of the "west Texas" front and the February-March dip
of the Arctic front from the northern Great Lakes region to
the southern Great Lakes. April and May (Figures 25 and 26)
have streamline patterns very similar to each other which,
however, are quite different than those which prevail from
November through March. The wedge of fresh Pacific air which
crosses the plains to a maximum eastern extent in northern
Illinois in late winter (February-March) is pinched out in
April and May between a southward expansion of the Arctic
airstream and a northward expansion of the Tropical airstream.
These two airstreams of maximum contrast meet along the line
that was occupied all winter by the Pacific front, except in
the midwest, where the Arctic-Tropical mean convergence bulges
northward into southern Minnesota. It is not surprising, on
examination of these charts, that the midwest has violent
weather in April and May. Nor is it surprising that this is
a season of fine weather (though still very cold) in the cen-
tral Canadian sub-arctic, for the continental Polar-Arctic
confluence of winter is gone and a broad difluent stream of
Arctic air prevails.

June (Figure 27) differs from May primarily in that
the Tropical airstream bulges into the Dakotas, to Winnipeg
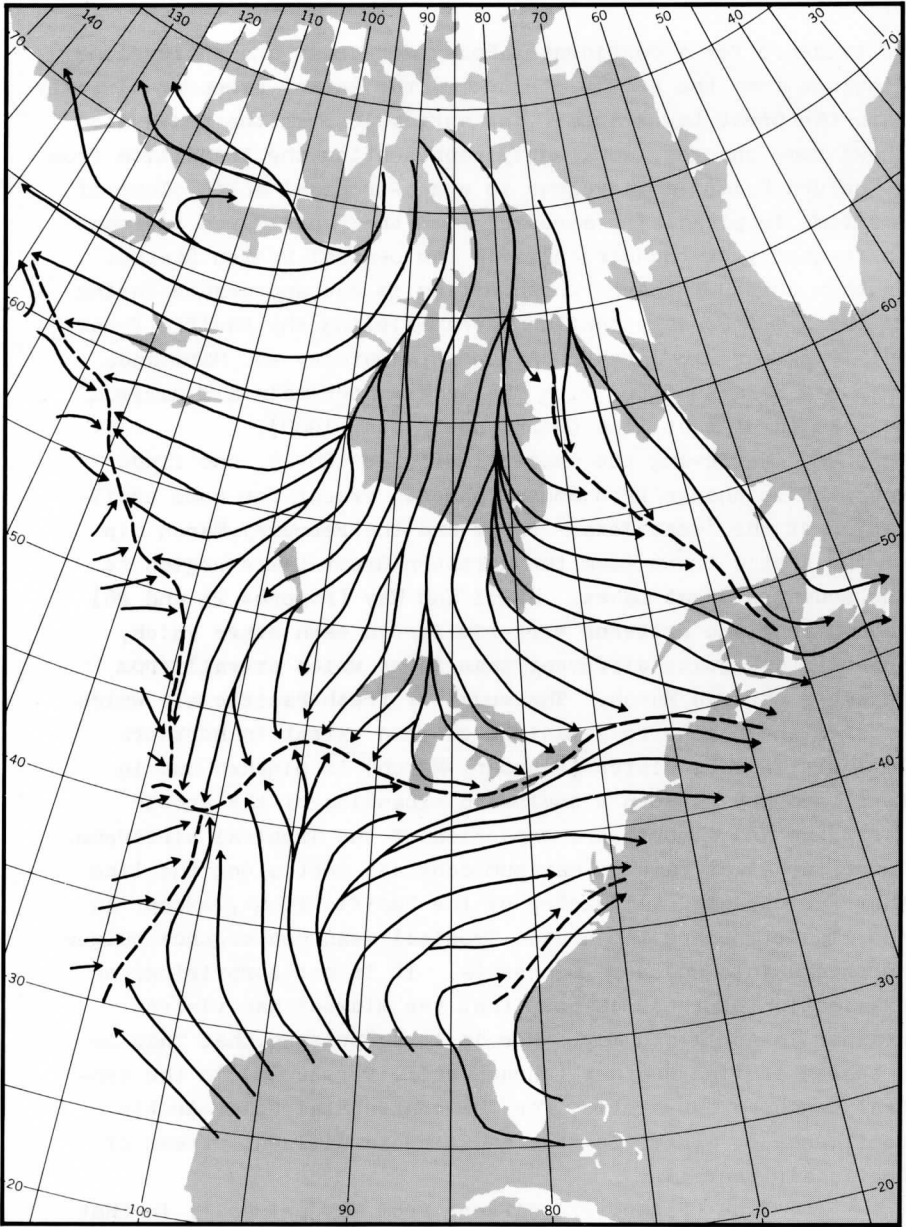
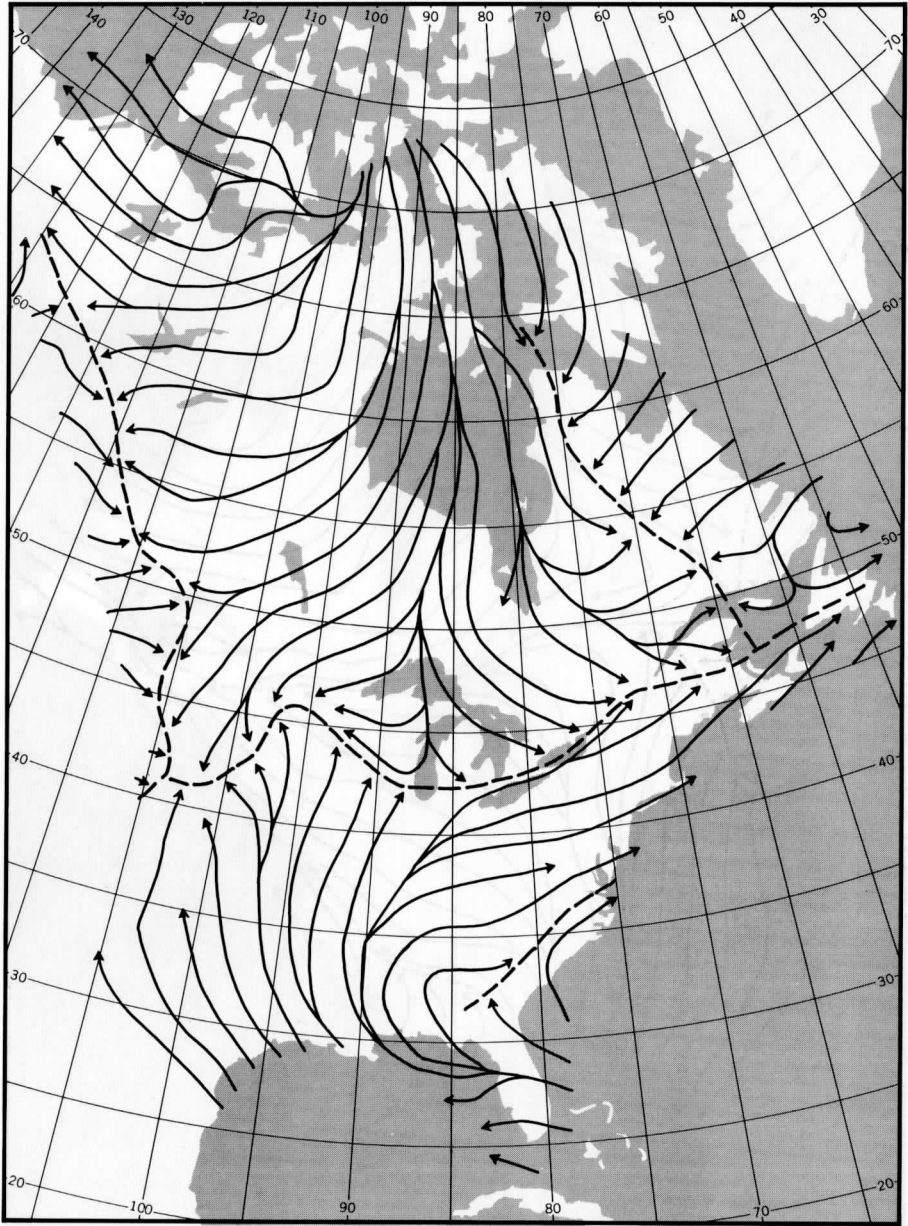Figure 25. Streamlines of the surface resultant wind in April.

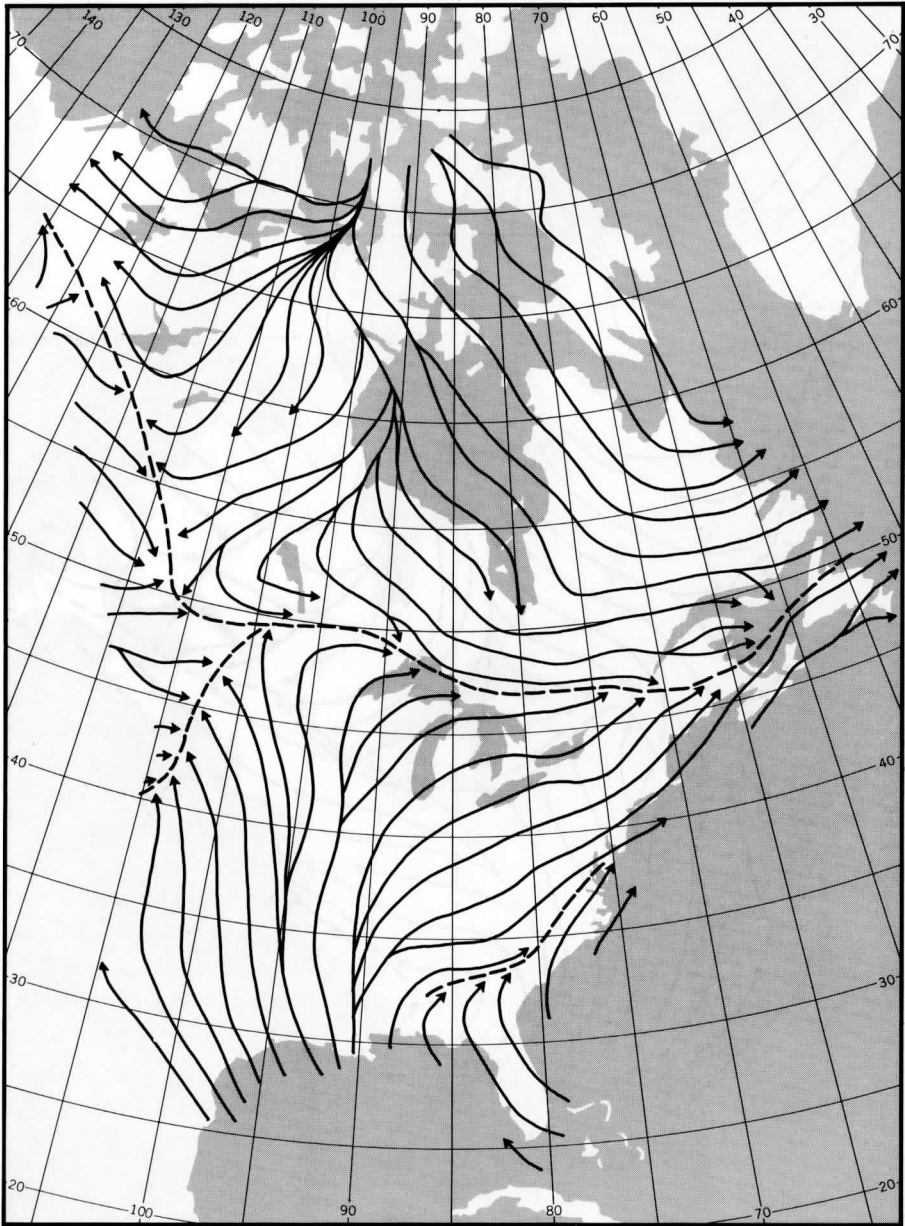Figure 26. Streamlines of the surface resultant wind in May.

Figure 27. Streamlines of the surface resultant wind in June.

and over the Great Lakes. The confluence at the northern
periphery of the Tropical airstream is still anchored near
Fort Collins, Colorado and passes through Maine for the eighth
consecutive mean month.

July and August (Figures 28 and 29) might as well
be treated as a single unit, for the flow patterns are very
similar indeed, yet quite different than April, May and June.
The Tropical airstream reaches to the same limit in the Da-
kotas as it did in June, but now extends also into southern
Quebec and Labrador.* The southern limit of Arctic air has
retreated to a line which sweeps from east of Aklavik in
Mackenzie Territory across Great Slave Lake to the southern
end of Hudson Bay and northern Quebec. The data are quite
far apart in this region, so that great precision cannot be
attained in fixing the location of the mean southern edge of
the Arctic air, but it clearly parallels and is near to the
forest border. A wedge of Pacific air once again extends
eastward south of the Arctic airstream. The boundary be-
tween the Tropical and Pacific airstreams is still anchored
near Fort Collins, Colorado. Examining the charts for May,
June and July, it would appear that June is a mixture of May
and July patterns.

September (Figure 30) differs from August in three
main respects: (1) the Arctic front appears to be a little
farther to the south, (2) the Pacific airstream once again
pushes across the Dakotas, and (3) the southeastern United
States is once again dominated by an anticyclone. The bound-
ary between the air spreading northward across the plains
from this anticyclone and the fresh Pacific airstream is still

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* One must remember, however, that this is the mean or
resultant flow and other varieties of air clearly are quite
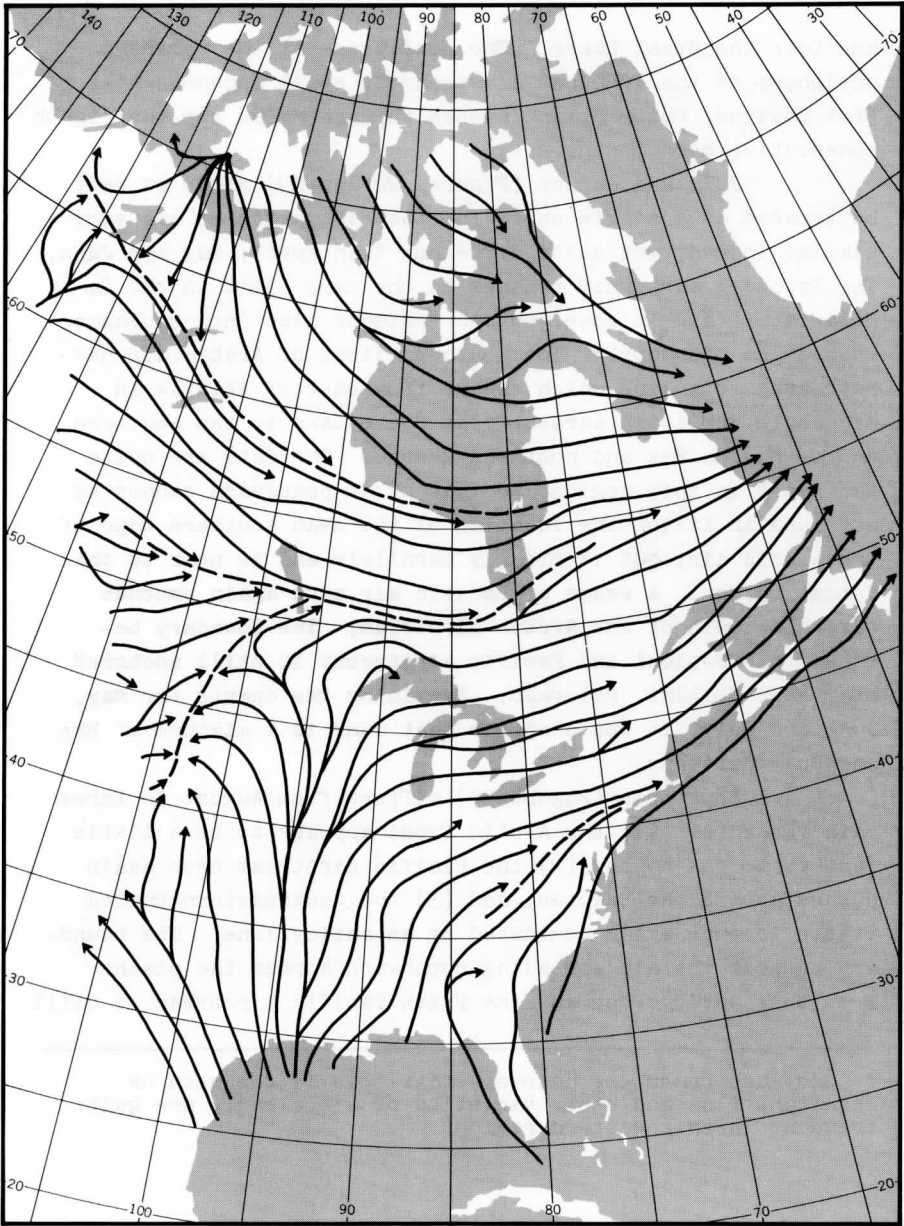frequent in this eastern region.

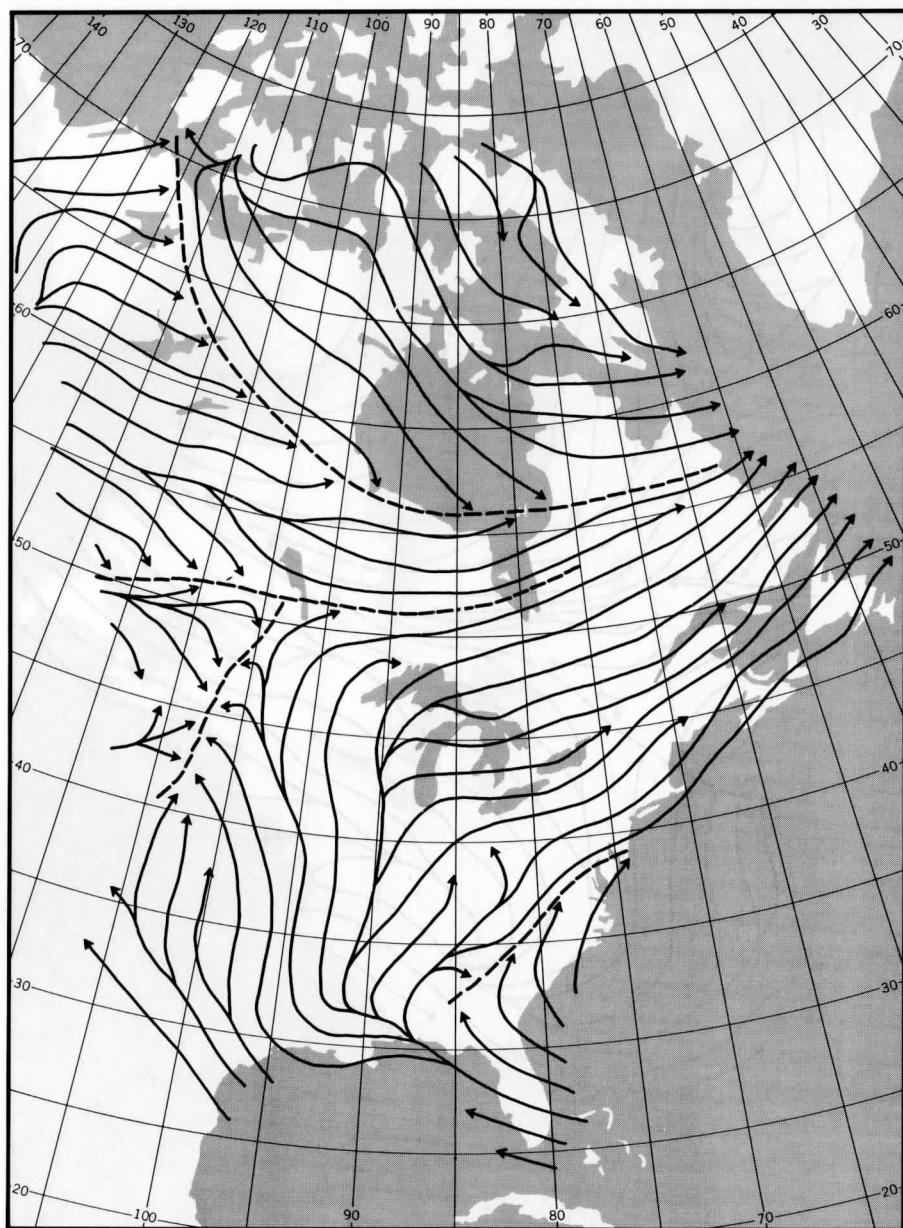Figure 28. Streamlines of the surface resultant wind in July.

Figure 29. Streamlines of the surface resultant wind in August.
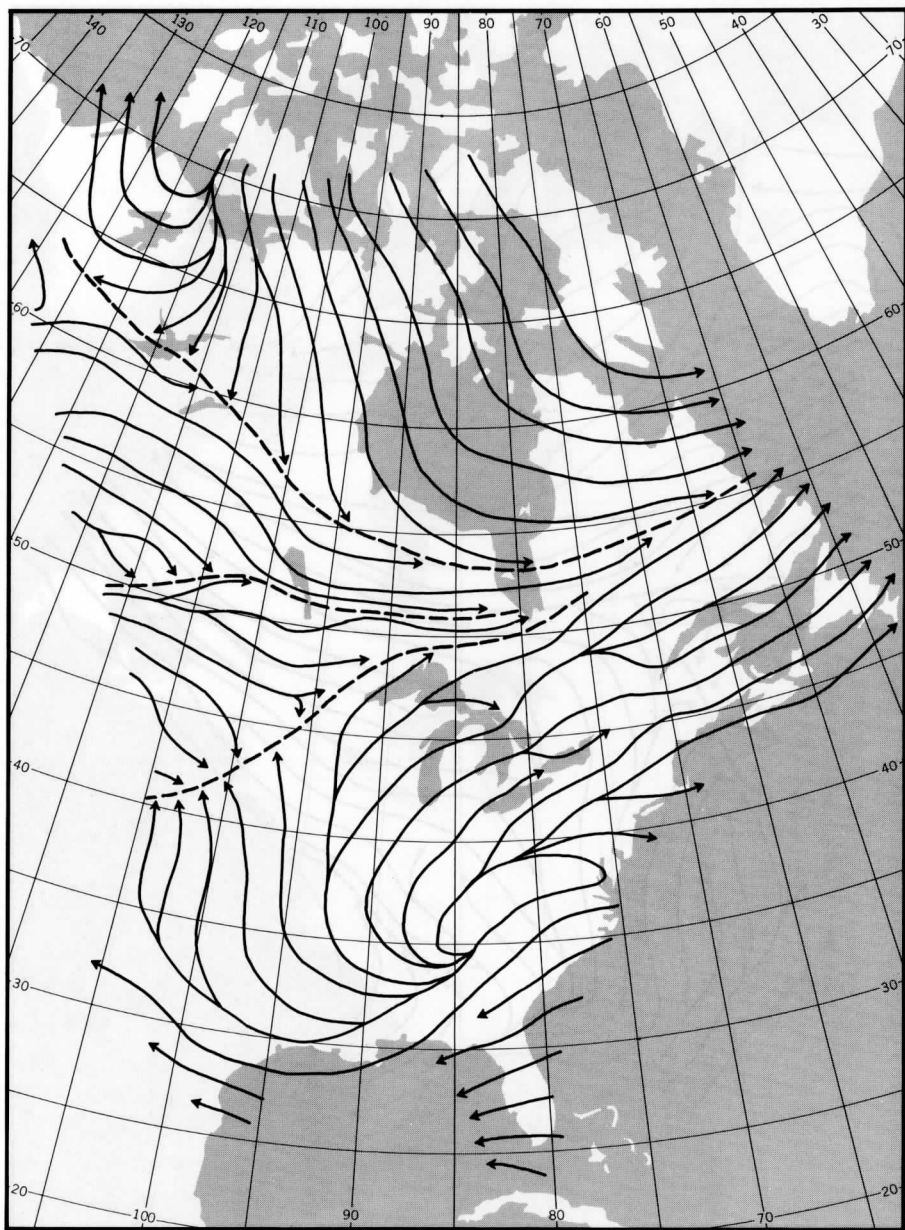
52

Figure 30. Streamlines of the surface resultant wind in September.

anchored in northern Colorado. October (Figure 31) is the
only month where this is not true. In other respects the
October pattern is very similar to that for September except
for the southward withdrawal of the air from the southeastern
anticyclone, its northern boundary being about the 46th
parallel.

Then the winter pattern begins in November with
the development and southward push of continental Polar air,
the southward shift of the fresh Pacific airstream, and the
reestablishment of the Pacific front in its winter position.

4.2 The Composite Airstream Pattern

In the preceding paragraphs the areas occupied by
the various airstreams and the positions of the monthly mean
confluences were discussed as they appear on the mean stream-
line charts. Hypothetically one could superimpose the charts
to obtain isochrones of the north-south annual march of the
mean confluences or "fronts." In practice this breaks down
for the "fronts" do not progress regularly north and south,
but stay in one position for several months (a meteorological
season) then move abruptly to a new seasonal position. This
is very clearly shown on a chart containing all the monthly
airstream boundaries (Figure 32). Distinct seasonal bound-
aries are quite localized in position. The areas, bounded
and delineated by these mean "frontal" positions are char-
acterized by a definite sequence of seasons each with its
particular dominating airstream. These are natural or genetic
climatic regions, defined entirely by meteorological param-
eters.

Consider as an example, the region occupied by
fresh Pacific air in winter (Nov.-Mar.), maritime Tropical
air in summer, and with an early spring burst of tropical air
in April and May. There is only one such area on Figure 32,
the diamond shaped area with apices near North Platte, Nebr.,
Redwood Falls, Minn., South Bend, Indiana, and north of
Springfield, Mo. This distinctive climatic region, derived
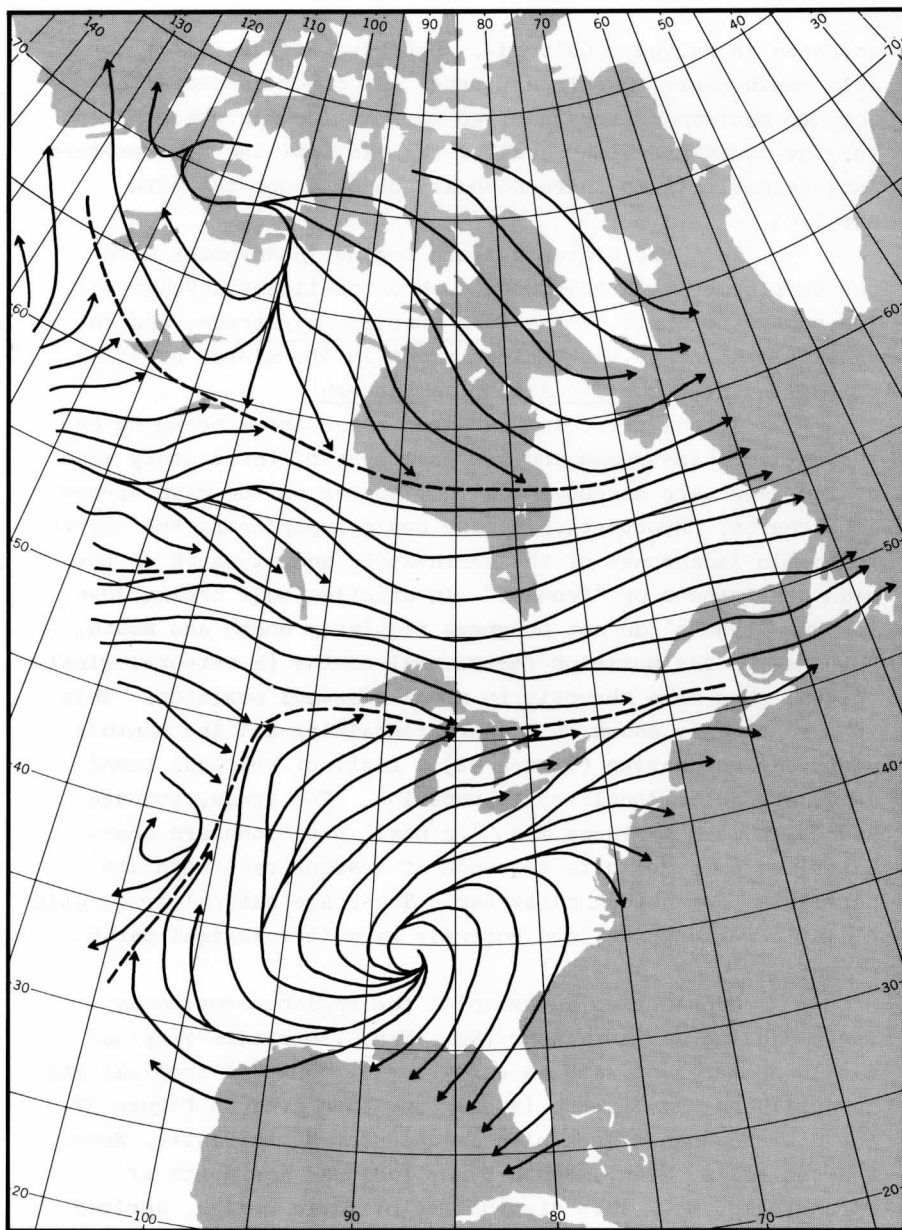from the airstream patterns and sequences coincides with the

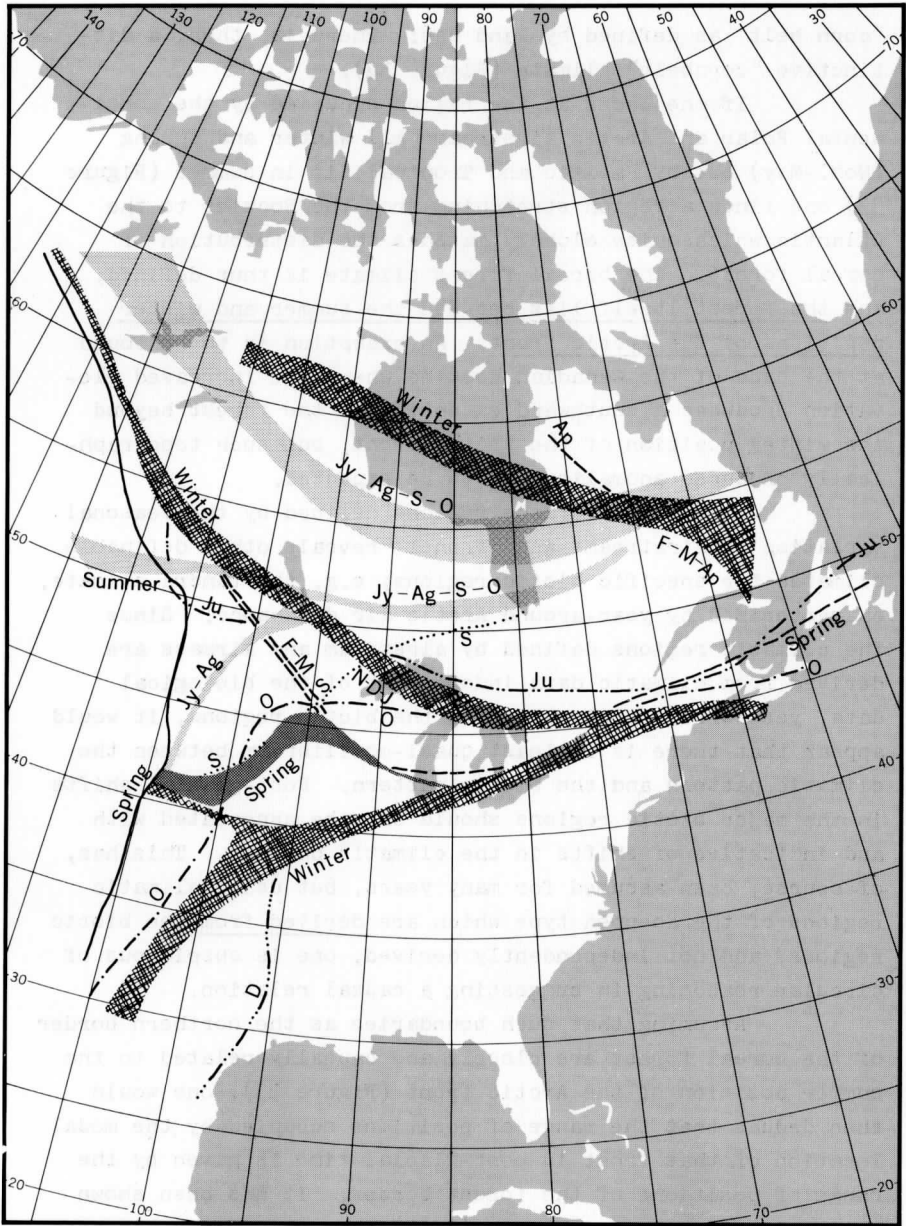Figure 31. Streamlines of the surface resultant wind in October.

Figure 32. Composite chart showing the seasonal positions of mean confluences between major airstreams, as determined from the monthly surface resultant streamline charts. The hatched bands give the total range of the monthly mean position of the major confluences during the seasons indicated.

"corn belt" as defined by land use! There is, then, a dis-
tinctive "cornbelt" climate (Figure 33).

If one looks at the region occupied by the conti-
nental Polar and Arctic airstreams all winter and spring
(Nov.-May) but by Pacific and Tropical air in summer (Figure
33) one finds a region stretching from the Rockies to the
Atlantic which quite closely matches the distribution of
boreal forest. The boreal forest climate is thus defined,
and the forest itself lies between the summer and winter
positions of the Arctic front. An exception is to be found
at the base of the Canadian Rockies where the increased ele-
vation produces a southward extension of the forest beyond
the winter position of the Arctic front, but such topograph-
ically produced anomalies are to be expected.

Examination of the regions defined by the seasonal
variation of airstreams and "fronts" reveals other definable
climates for specific biotic regions; e.g. the tundra climate,
characterized by year-around Arctic air dominance. Since
the climatic regions defined by airstream and airmass are
derived from climatic data independent of the biological
data, yet correlate closely with the biotic regions, it would
appear that there is at least quasi-equilibrium between the
climatic pattern and the biotic pattern. Post-glacial shifts
in the major biotic regions should then be associated with
and indicative of shifts in the climatic pattern. This has,
of course, been assumed for many years, but using climatic
regions of the Koeppen type which are derived from the biotic
regions, and not independently derived, one is suspicious of
circular reasoning in suggesting a causal relation.

Assuming that such boundaries as the northern border
of the boreal forest are closely and causally related to the
summer position of the Arctic front (Figure 33), one would
then deduce that the range of positions occupied by the modal
location of that front in post-glacial time is given by the
range of positions of the forest border. It has been shown
by Bryson, Irving, and Larsen (1965) that this range has been
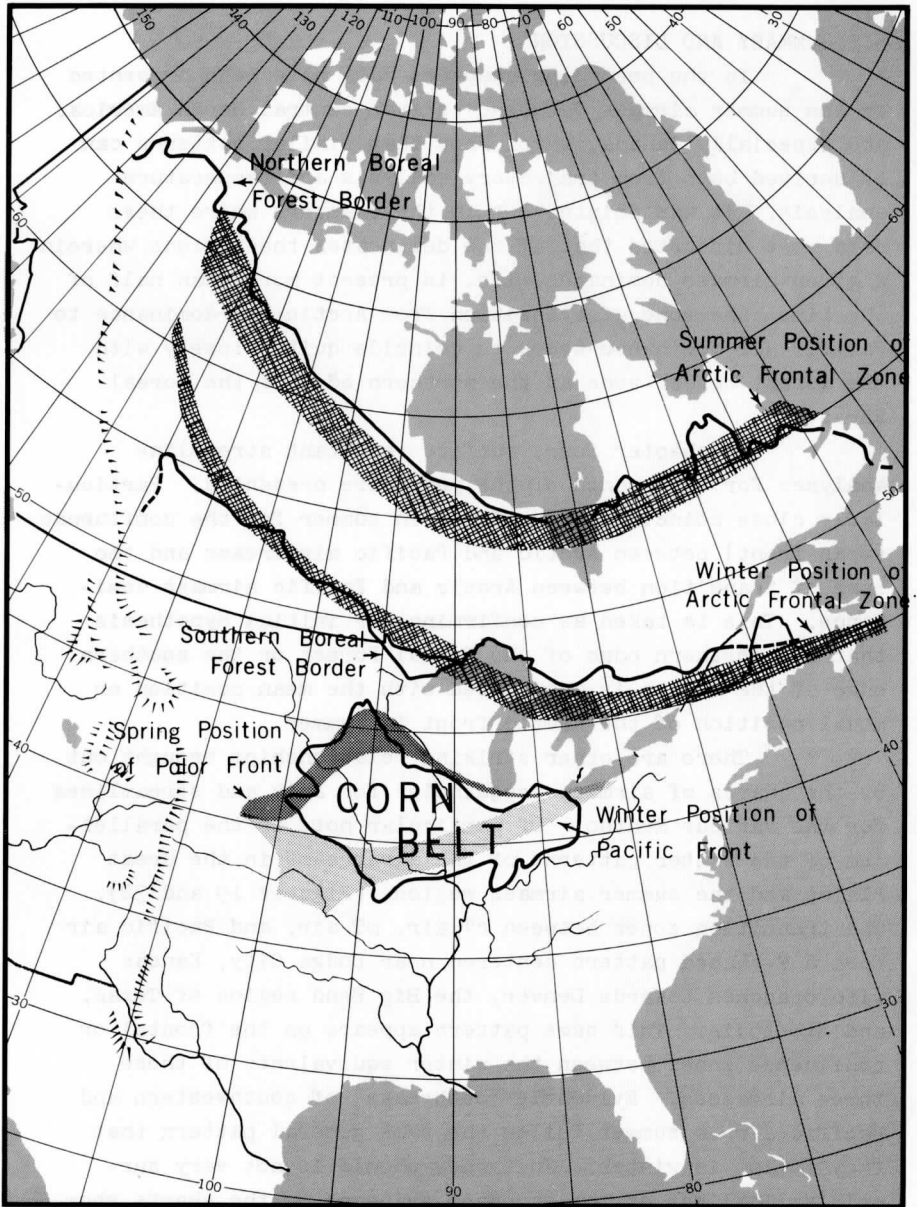on the order of 150 miles in the past 4000 years in Keewatin.

Figure 33. The coincidence of the "corn belt" and "boreal forest" biotic regions with meteorologically defined climatic (air mass) regions. Climatic regions are taken from figure 32, the "corn belt" from "Soils of the North Central Region of the United States" (1960), and the boreal forest generalized somewhat from Rowe (1959) and Larsen (1965).

5. SUMMARY AND DISCUSSION

     In the preceding chapters data have been presented
on the summer airmass frequencies over central North America,
and especially Canada, which show that similar patterns can
be derived both from trajectory analysis and temperature
analysis. It was pointed out in the chapters where these
data were discussed that if one delineates the regions wherein
a given airmass dominates, i.e. is present more than half of
the time, the zone of transition from Arctic air dominance to
Pacific air dominance seems to coincide quite closely with
the forest border zone at the northern edge of the Boreal
Forest.

     In chapter four, surface resultant streamline
analyses for each month of the year were presented. Particu-
larly close coincidence was found in summer for the confluence
(mean front) between Arctic and Pacific airstreams and the
zone of transition between Arctic and Pacific airmass domi-
nance. This is taken as confirming the initial hypothesis
that the northern edge of the Boreal Forest or the southern
edge of the Tundra is associated with the mean position or
modal position of the Arctic front in summer.

     There are other striking relationships brought out
by the charts of airmass frequencies for July and streamlines
for the various months. Of particular note is the parallel-
ism of the winter patterns of the airstreams in the Great
Plains and the summer airmass regions (Figures 19 and 32).
The transition zones between cT air, mT air, and Pacific air
form a Y-shaped pattern centered near Dodge City, Kansas
with branches towards Denver, the Big Bend region of Texas,
and St. Louis. This same pattern appears on the frontal or
confluence zones between the winter equivalents of these
three airmasses. Evidently "outbreaks" of southwestern and
Pacific air in summer follow the same general pattern that
they follow in winter. That they should is not very sur-
prising in light of the abundant evidence on the charts show-
ing the profound effect of topography on the airmass and

airstream patterns.

One indication of the topographic control of the
patterns may be seen by comparing the streamline chart for
July (Figure 28) with the composite airmass chart (Figure 19).
The streamlines at the base of the Rockies exhibit different
patterns spreading from specific locations along the mountain
front. These same regions can be identified as the core
regions of maximum frequency of the various varieties of
Pacific air discussed in chapter 3. The core region of the
Yukon variety of Pacific air (Y) is found in the difluent
region near 60-61°N, Canadian Rockies air (CR) is most fre-
quent in the difluent region of southern Alberta, and the
airmass labelled NR for the northern U. S. Rockies is most
frequent in the difluent region of eastern Wyoming. That the
northern and southern of these three regions represent gaps
in the cordillera through which the winds sweep Pacific air
into the continental interior is quite apparent. Why there
should be a maximum intrusion of Pacific air with distinctive
character into central Alberta is less apparent, though there
seems to be little question of its reality. Perhaps it is
due to the maximum trans-montane pressure gradient in this
region coupled with the lower elevations of the Coast Moun-
tains in southern British Columbia.

Another indication of topographic control is to be
found on the streamline charts of Figures 20 through 31. The
Arctic front seems to be topographically anchored at the
northern end of the Cordillera near Aklavik year-round, but
swings north and south with the seasons in the continental
interior where the terrain is relatively flat. Similarly
the confluence called the Pacific front in chapter 4 is an-
chored at the northern end of the southern Rockies for eleven
months of the year and swings north and south with the seasons
in the plains area. On the east coast the position of the
"Pacific front" is far less variable with the seasons than
in the interior, and the location suggests that oceanographic

conditions might be an important factor in that region.

Still a third example is to be found in the position of the "chinook front" between Pacific and Arctic air in spring. From the Yukon to Montana this boundary approximates the 2500 ft contour, suggesting a mean depth of the western edge of the Arctic airmass over which the Chinook air descending the high plains finally spreads (Figures 25-26).

Clearly, there is a need for extending the airmass analyses presented here to months other than July before the interpretations presented in this paper can be regarded as more than advanced working hypotheses. Also more detailed attention must be paid to the montane area, and to the southeast, especially in winter. These extensions, however, must await first the acquisition of better wind data for the southeast; second, the application of the objective computer method for reducing frequency distributions to partial collectives; and third, the development of a technique for examining the climates of the montane area. Enough progress has been made on the second of these requirements to know that the graphically obtained solutions are not much different than those obtained by least squares fitting of a series of normal distributions to the total frequency distribution. It would appear, however, that a genetic regionalization of climates, using synoptic climatology of the sort presented here, is possible.

REFERENCES

Brunnschweiler, D. H. 1952, "The Geographic Distribution of Airmasses in North America", Vierteljahrschr. Naturforsch. Ges. Zurich 97:43

Bryson, R. A., W. N. Irving, and J. A. Larsen 1965, "Radiocarbon and Soil Evidence of Former Forest in the Southern Canadian Tundra", Science 147:46-48

Essenwanger, O. 1954, "Neue Methode der Zerlegung von Häufigkeitsverteilungen in Gauss'sche Normal kurven und ihre Anwendung in der Meteorologie" Ber. d. Deutsch. Wetterdienstes No. 10, Badkissingen

Hare, F. Kenneth 1951, "Some Climatological Problems of the Arctic and Sub-Arctic" in Compendium of Meteorology, T. F. Malone, Ed., Boston, Amer. Meteorol. Soc.

Haurwitz, B. and J. Austin 1944, Climatology, New York, McGraw-Hill.

Horn, L. H. and R. A. Bryson 1960, "Harmonic Analysis of the Annual March of Precipitation over the United States" Annals Assn. Amer. Geogr. 50:157-171

Larsen, James A. 1965, Geographical Position of the Central Canadian Northern Forest Border, Mss. in preparation, University of Wisconsin.

Penner, C. M. 1955, "A three-front model for synoptic analyses", Quart. Jour. Roy. Meteorol. Soc. 81:89-91

Petterssen, S. 1940, Weather Analysis and Forecasting New York, McGraw-Hill, First Edition, p.9.

Reed, R. J. 1959, "Arctic Weather Analysis and Forecasting", Scientific Report No. 2, Dept. of Meteorol. and Climatol., Univ. of Washington, Occasional Rept. No. 11, AF Contract 19(604)-3063, January 1959.

Rowe, J. S. 1959, Forest Regions of Canada, Canada Department of Northern Affairs and National Resources, Forestry Branch, Bulletin 123, Ottawa.

Thomas, M. K. 1953, Climatological Atlas of Canada,
Ottawa, Meteorological Div., Dept. of
Transport, p. 27.

- - - - - 1960, "Soils of the North Central Region of
the United States", North Central Regional
Publication No. 76, Univ. of Wisconsin Agr.
Exp. Station Bulletin 544.

APPENDIX: NON-LINEAR PARAMETER ESTIMATION FOR THE PARTIAL
COLLECTIVE MODEL OF AIR MASS ANALYSIS

BY   Donald R. Johnson

Introduction

In this appendix, a technique of air mass analysis by
the partial collective method (Essenwanger, 1954) utilizing
least squares estimation is briefly presented. In the air
mass analysis by the partial collective method, the assumed
mathematical model to represent the multimodal distribution
of daily maximum temperatures is a family of normal distri-
butions, hereafter called the partial collective model.
The parameters of the partial collective model, the mean
temperature, the variance, and the percentage frequency of
occurrence for each normal distribution enter non-linearly
in the mathematical model. Thus, the parameter estimates
must be determined by non-linear least squares estimation.
The object of this development of numerical methods to
estimate the partial collective parameters is to facilitate
future climatic studies of air mass frequency distribution,
produce information concerning the precision of the para-
meter estimates and to investigate the adequacy of the
partial collective model.

The Partial Collective Model

In the basic paper (Bryson, 1966), the partial collec-
tive model is used to describe the monthly probability his-
togram of the daily maximum temperatures occurring at a
climatological observing station. Two "a priori" factors
suggest that the family of normal distributions is the
natural model to represent the maximum temperature histogram.
The first factor, noted by Essenwanger (1954), is the multi-
modal nature of the probability histogram. From air mass.

theory, one associates the coldest daily maximum tempera-
ture with a particular air mass, likewise milder maximum
temperatures with other air masses, until the hierarchy of
air masses is complete. In the probability histogram, the
individual modes can be associated with the different
characteristic air mass temperatures and the frequency of
air mass occurrence at the observing station. The second
factor, although possibly more subtle, indicates that the
normal distribution is the proper function to represent
the distribution of maximum temperatures for each air mass.
The spread of temperatures about one mode physically repre-
sents the temperature departures due to many air mass modi-
fication processes that occur along the different trajec-
tories from the air mass source region to the observing
station. Since many of the modification processes may be
described as "independent effects" according to the Central
Limit Theorem (Cramér 1946), the distribution of daily
maximum temperature for an air mass about one characteristic
temperature will tend to be the normal distribution.

In the analysis, separate probability histograms are
formed for each month from the daily maximum temperature
series extending for several years. The equal class inter-
vals of the probability histogram are

$$(T_\mathcal{L} - \delta/2) \leq T_\mathcal{L} < (T_\mathcal{L} - \delta/2) ; \quad (\mathcal{L} = 1, \cdots M) \tag{1}$$

where T_s is the mid-point temperature in whole degrees and
δ is the size of the equal class intervals. T_1 and $T_\mathcal{M}$ are
the lowest and highest mid-point temperatures whose class
intervals contain the lowest and highest observed tempera-
tures respectively. The ordinate height of each class
interval for the probability histogram is

$$f_\mathcal{L} = m_\mathcal{L} / N \tag{2}$$

where n_s is the number of daily maximum temperatures occuring within the s-th class interval and N is the total number of observations. The 1XM vector of observations, $\underset{\sim}{\mathscr{L}}$, contains the values of the ordinate heights of the M class intervals. The envelope of the probability histogram obtained by connecting the mid-point ordinate heights by a smooth curve represents the function to be estimated by the partial collective model.

The model consisting of the family of normal distributions is formed from the definition of the ordinate height of a normal distribution given by

$$p(y) = \frac{1}{\sqrt{2\pi}\,\sigma}\ exp\left\{-\frac{1}{2}\left(\frac{y-n}{\sigma}\right)^2\right\} \tag{3}$$

where n , the mean, and σ , the standard deviation, are the parameters for the distribution of the variate y. Following this definition, the true ordinate height component of the t-th ($t = 1,\cdots k$) air mass for the s-th class interval is

$$\mathscr{S}_{ts} = \frac{\nu_t}{\sqrt{2\pi}\,\sigma}\ exp\left\{-\frac{1}{2}\left(\frac{T_s-n_t}{\sigma_t}\right)^2\right\}\Big/z \tag{4}$$

where n_t, the true mean temperature, σ_t, the true standard deviation, and ν_t, the true percentage frequency of occurrence, are the parameters for the t-th air mass. z , the normalizing element given by summing over all air masses and all class intervals, is

$$z = \sum_{s=1}^{m} \sum_{t=1}^{k} \frac{\nu_t}{\sqrt{2\pi}\,\sigma_t}\ exp\left\{-\frac{1}{2}\left(\frac{T_s-n_t}{\sigma_t}\right)^2\right\} \tag{5}$$

The true total ordinate height representing all k air masses for the s-th class interval given by the summation of the k component heights is

$$\mathscr{S}_s = \sum_{t=1}^{k}\ \mathscr{S}_{ts} \tag{6}$$

$$\underset{\sim}{\mathcal{S}}_a = \sum_{t=1}^{k} \frac{\mathcal{V}_t}{\sqrt{2\pi}\,\sigma_t}\; exp\left\{-\tfrac{1}{2}\left(\frac{T_a - \eta_t}{\sigma_t}\right)^2\right\}\Bigg/ \underset{\sim}{Z} \qquad (7)$$

Equation 7 is the partial collective model which is used to represent the observed histograms. One notes that the total number of parameters, 3k, is three times the number of air masses which are present in the probability histogram. For convenience of notation, the partial model, equation 7, is expressed as

$$\underset{\sim}{\mathcal{S}} = g\left(\underset{\sim}{T} \mid \underset{\sim}{\eta}, \underset{\sim}{\sigma}, \underset{\sim}{\mathcal{V}}\right) \qquad (8)$$

where $\underset{\sim}{\mathcal{S}}$ is the MX1 vector of true ordinate heights, $\underset{\sim}{\eta}$, $\underset{\sim}{\sigma}$ and $\underset{\sim}{\mathcal{V}}$ are the kX1 vectors of true air mass parameters and $\underset{\sim}{T}$ is the MX1 vector of mid-point temperatures.

The partial collective parameters enter non-linearly into the mathematical model. Hence, the usual method of linear estimation (of the parameters) by least squares does not apply and a non-linear estimation technique is utilized. The non-linear technique of least squares estimation is based on the sums of square function given by

$$S(\underset{\sim}{\eta}, \underset{\sim}{\sigma}, \underset{\sim}{\mathcal{V}}) = \sum_{a=1}^{M}\left(f_a - \mathcal{S}_a\right)^2 \qquad (9)$$

$$= \sum_{a=1}^{M}\left(f_a - g(\underset{\sim}{T} \mid \underset{\sim}{\eta}, \underset{\sim}{\sigma}, \underset{\sim}{\mathcal{V}})\right)^2 \qquad (10)$$

The optimum parameter estimates $\hat{\underset{\sim}{\eta}}$, $\hat{\underset{\sim}{\sigma}}$ and $\hat{\underset{\sim}{\mathcal{V}}}$ of the true parameters are determined by selecting those values which makes S a minimum and are frequently referred to as least squares estimates. The minimization of S is accomplished by iteration and employs a subroutine from the Wisconsin Computing Center based on a method originally due to Gauss (1821) and applied by Meeter (1964).

Maximum Likelihood Properties of the Least Squares Estimates

Least square estimates by this technique are also
maximum likelihood estimates (Fisher, 1922) and possess cer-
tain desirable properties (Mood, 1950) if the following
three assumptions are satisfied:

The first, Assumption I, is that the errors, ϵ_i, defined
by

$$\epsilon_i = f_i - s_i$$

are independent of the errors ϵ_j for all $i \neq j$.

The second, Assumption II, is that the expected value
of the errors is zero (there is no systematic bias in the
errors, ϵ_i.

The third, Assumption III, is that the probability
distribution of the errors is the normal distribution with
variance, σ^2. Hereafter, the assumptions are referred to
by Roman Numeral.

In essence, Assumptions I and II require that any de-
partures of the observation from the true value of the ordin-
ate height be due entirely to random independent errors.
Since the ordinate heights of the probability density func-
tions are determined from daily values of temperatures, it
is essential that the error components of the daily maximum
temperature observations be random and independent, if these
two assumptions are to be satisfied. Such is usually the
case except for an observer's tendency to record even values
in preference to odd values, or the temperature sensor may
be biased. The former bias error may be eliminated by
setting δ, the class interval, equal to two degrees. If
the sensor bias error is present, the estimating procedure
is valid except the least squares parameter estimate of each
air mass mean temperature will be biased by the amount of
the calibration error of the thermometer.

There are two factors which indicate that Assumption III
is satisfied. The first is that the observational errors are
nearly normally distributed if the bias error is non-existent

(Margenau, 1950). Furthermore, the observational error com-
ponent of the ordinate height is a result of the sum of the
nearly normally distributed temperature observational errors,
thus the Central Limit Theorem dictates that error components
of the ordinate heights are random and normally distributed
(Cramér, 1946). In view of the valid physical evidence that
the three assumptions are satisfied, the least square esti-
mates of the partial collective parameters determined by the
minimization of S possess the desirable properties of maxi-
mum likelihood estimates.

Results

The preliminary results of the least squares estimation
of air mass parameters are very promising. Only one solution
is presented; however, it is indicative of the successful
estimation of ten cases. The initial input to the program
requires an estimate of the number of air masses present in
the histogram, the initial parameter estimates for the vectors
of $\underset{\sim}{\eta}$, $\underset{\sim}{\sigma}$, and $\underset{\sim}{\psi}$ as well as the daily maximum temperatures
used to form the probability histograms. From the probability
histogram, the ordinate height vector, $\underset{\sim}{f}$, and the vector of
mid-point temperatures, $\underset{\sim}{T}$, are determined and used in the
iteration subroutine to gain the maximum likelihood estimates
of the air mass parameters $\underset{\sim}{\hat{\eta}}$, $\underset{\sim}{\hat{\sigma}}$ and $\underset{\sim}{\hat{\psi}}$.

Figure 1 for Pittsburgh, Pennsylvania presents the ob-
served probability histogram and the results of the partial
collective model estimates from the initial input parameter
values. For this diagram Bryson's parameter estimates from
his objective analysis are used as the initial parameter
estimates of the partial collective model. The five normal
distributions representing five air masses and the total
envelope of the sum of the normal distribution ordinate
heights are represented by the smooth curves in the lower
half of the figure. The residual histogram is displayed in
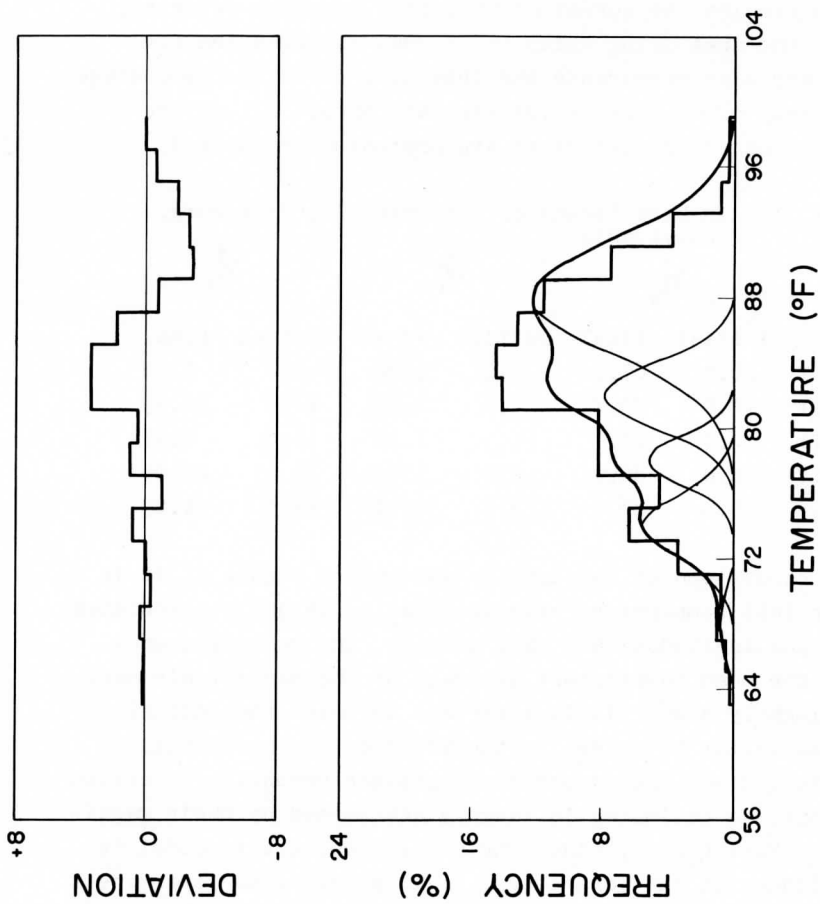the upper half of the figure and is given by the differences

Figure 1. Observed probability histogram and the results of the partial collective model graphical estimates for Pittsburgh, Pa.

of the ordinate heights of the observed histogram and the
initial ordinate heights of the partial collective model.
In this figure the area lying under both the observed
histogram and the normal distribution envelope is unity.
Thus, the area lying under the normal distribution for
each air mass represents the initially estimated percentage
frequency of occurrence for each air mass. All of the
initial parameter estimates are presented in Table I.

Table I: Air Mass Parameter Estimates for Pittsburg,
          Pennsylvania

	$\hat{n}_t$		$\hat{\sigma}_t$		$\hat{\chi}_t$	
	Initial	Final	Initial	Final	Initial	Final
I	68.0	67.8	2.0	1.88	2.0	2.42
II	74.0	73.7	2.0	1.53	14.0	12.39
III	78.0	77.7	1.5	1.18	10.0	9.97
IV	82.0	82.0	2.0	1.94	20.0	24.00
V	88.0	86.8	3.5	3.31	54.0	51.23

In a comparison of the tabular values and Figure 1, it is
clear that temperature estimates can be uniquely associated
with the individual air mass curves. The residuals show
that the mean temperature estimate of the warmest air mass
is slightly high. It is important to check the initial re-
sidual vector to determine the accuracy of the initial
guesses, since the number of iterations necessary to attain
the optimum estimates is largely determined by their magni-
tude. Furthermore, since the partial collective model is
non-linear in the parameters, it is possible to determine a
local minimum for the sums of squares function with physi-
cally unrealistic values for the air mass parameter estimates.
This possibility is enhanced by poor initial estimates for
the air mass parameters or by trying to determine a larger.
number of air masses than are present on the histogram.
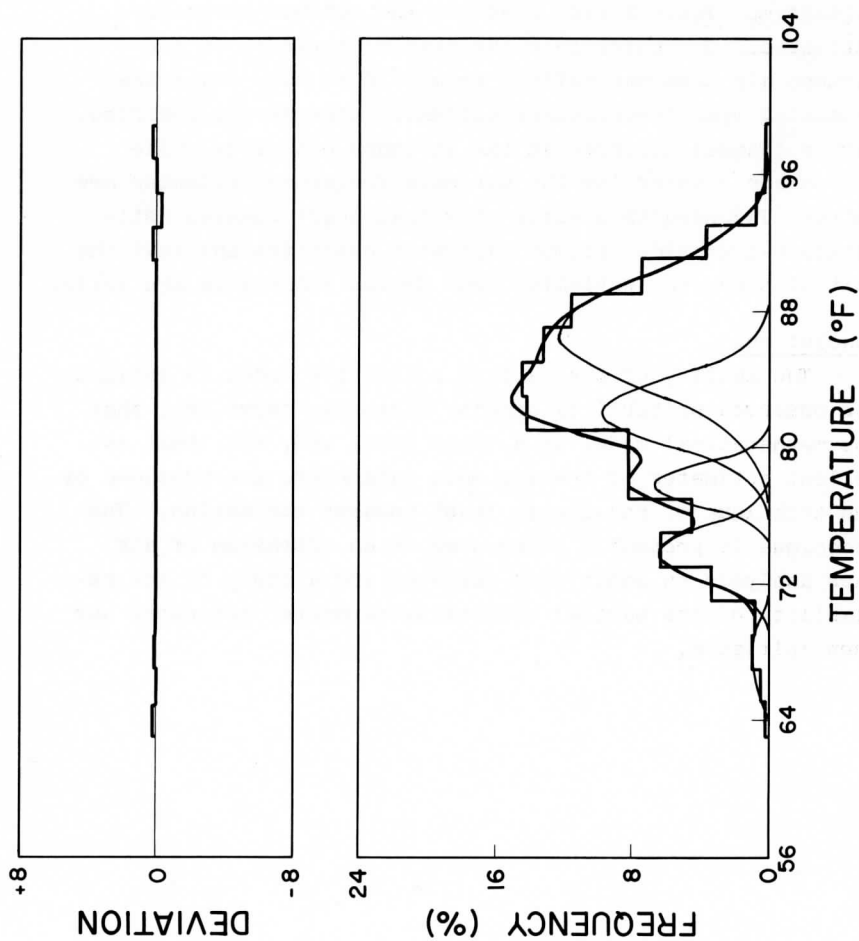   Figure 2 for Pittsburgh presents the excellent results

Figure 2. Least' squares estimates of the partial collective parameters for Pittsburgh, Pa.

from the least squares estimates of the partial collective parameters. The vector of residuals clearly portrays the nearly perfect fit of the model estimates to the observed histogram. Table I also presents the optimum parameter estimates. One notes that the mean temperature of the warmest air mass has shifted from 88.0 to 86.8 while the remaining mean temperatures estimates were hardly modified. Larger changes occurred in the variance estimates while only minor changes for the air mass frequency estimates are noted. The results clearly show that least squares estimation can provide optimum parameter estimates and that the initial parameter estimates from Bryson's analysis are valid.

Conclusions

The ability of the partial collective model to estimate the observed probability density histogram shows one, that the mathematical model is a valid model and, two, that excellent estimates of the air mass parameters are provided by the technique of non-linear least squares estimation. The technique is presently being used in an extension of air mass analysis to additional stations and a study of the reliability of the partial collective parameter estimates has been initiated.

REFERENCES

Bryson, R. A., 1966; "Airmasses, Streamlines, and the Boreal Forest," Technical Report No. 24, Department of Meteorology, University of Wisconsin, NR 387-022, Nonr 1202(07) & NSF GP-444.

Cramér, H., 1945; Mathematical Methods of Statistics, Princeton University Press, Princeton.

Essenwanger, O., 1954; "Neue Methode der Zerlegung von Haufegkeitswerteilungen in Gauss' sche Normalkurven und die Anwendung in der Meteorologie," Ber. d. Deutsch. Wetterdienstes No. 10, Badkissingen.

Fisher, R. A., 1922; "On the mathematical foundations of theoretical statistics," Philosophical Transactions of the Royal Society, Series A, Vol. 222.

Gauss, C. F., 1821; "Theory of least squares," English translation by Hale F. Trotter, Tech. Report No. 5, Statistical Tech. Res. Group, Princeton University, Princeton.

Margenau, H., 1950; The Nature of Physical Reality, McGraw Hill, New York.

Meeter, D. A., 1964; "Problems in the analysis of non-linear models by least squares," Ph.D. thesis, Department of Statistics, University of Wisconsin.

Mood, A. M., 1950; Introduction to the Theory of Statistics, McGraw Hill, New York.

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The analysis of July airmass frequency distribution over Canada is analyzed by daily computation of trajectories from grid intersections back to source regions. A zone of rapid transition from Arctic air dominance to Pacific air dominance is found to lie along the northern border of the boreal forest, suggesting that the summer airmass distribution might be an important causal factor for the distribution of forest versus tundra. (U)

An independent analysis of July airmass frequency distribution by resolution of the daily maximum temperature frequency distribution into partial collectives (component normal distributions) yields results very similar to the trajectory analysis but with more detail. This analysis suggests that airmass dominance might be of importance to other biotic regions as well as the boreal forest and tundra. (U)

A final analysis using monthly resultant wind streamlines near the surface indicates that mean airstreams and confluences between airstreams define climatic regions with a distinctive annual march of airstream (and in the mean, airmass) dominance. These regions show a clear congruence with several major biotic regions. These analyses strongly suggest that the boreal forest occupies the region between the mean (or model) southern boundary of Arctic air in winter and the mean southern boundary of Arctic air in summer. (U)

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