CYCLOGENESIS AND EFFECT OF TURBULENCE ON FRONTS IN THE NORTHERN GREAT PLAINS

PART I

CYCLOGENESIS IN THE NORTHERN GREAT PLAINS

by

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PART II

TURBULENCE IN THE FRONTOGENETICAL FIELD

by

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TABLE OF CONTENTS

PART I

A Study of Cyclogenesis in the Northern Great Plains Region.

PART II

Turbulence in the Frontogenetical Field.

TABLE OF CONTENTS

PART II

(Cont.)

PART I

A STUDY OF CYCLOGENESIS IN THE NORTHERN GREAT PLAINS REGION

Introduction

The aim of this paper is to classify certain types of weather developments that arise in the region east of the Rocky Mountains in Southern Canada, Montana, Wyoming, and Colorado, and to correlate their frequency and intensity with various factors which seem most important in their development.

After discussing briefly the importance of the Rocky Mountain chain as an air mass boundary, synoptic situations most favorable for fronto- and cyclogenesis are illustrated. The variation of these favorable situations with season is then compared with the frequency of occurrence of the several types of developments which they produce.

The dates of initial eastward movement of secondary cyclone developments are correlated with dates of peaks in 14,000-foot pressure over the region. The influence of such wave developments on the buildup and dissipation of the Polar Canadian (Pc) high is studied.

Finally, a table of departure from normal temperatures is given for certain East Slope stations, during foehn wind frontogenesis.

The Importance of the Rocky Mountains as an Air Mass Boundary.

The Rocky Mountains provide a natural barrier for the air masses taking part in the circulation over this region. Pacific air entering from the west is forced to ascend the mountains; if the air to the east of the divide is sufficiently cold and stable in the lower levels, the Pacific air will pass aloft over it. Such a condition of cold and stable air persists through the winter season when a snow cover is present and pressure is fairly high over the Alaskan and Canadian portion of the east slope, except when an intense Pc outbreak to the south or a marked influx of Pacific air aloft has lowered pressures markedly. The same condition exists for that portion of the United States only during and for a while after a southward movement of Pc air over the northern Plains states has taken place.

The southern boundary of the region from which Pacific air is excluded at the surface, then, depends on the synoptic situation, but its mean position is displaced northward with the approach of spring, and is at high latitudes during the summer months when the air over the interior may be even warmer than that reaching it from the Pacific.

In a similar manner, the mountain barrier prevents flow of air westward over the divide; thus in winter when the factors responsible for the formation of high pressure over Canada and southward are most active and the gradient between this high and the Aleutian low is most intense, the effect of the mountains in damming the stable Pc air is at times very pronounced. An extremely well developed high over Canada may enable air to flow through the passes and over the lower ranges to allow the frontal boundary to move south and west across the divide toward the West Coast. (Map Group 1). Especially is this true in British Columbia. Frequently, also, the Pc air enters the Great Basin from the south after making a long clockwise circuit through the middle west, but it is by that time greatly modified. Large amounts of Pc air flow westward in northern Alaska during such periods of high pressure over the interior, to be quickly modified into Pp air on the back side of the Aleutian low. However, the greater part of a Pc air mass after leaving its source region must flow southeastward and spread out over the region to the east of the Rockies.

These two influences of the Rockies act together to facilitate the development of the immense highs over Canada in winter, the first tending to prevent warm Pp air from reaching the surface, the second providing a barrier to outward flow of cold air toward the Pacific Coast.

The Process of Fronto- and Cyclogenesis.

Polar Pacific (Pp) air, heated dynamically through loss of moisture on ascent of the west slopes of the ranges, and occasionally Polar Basin (Pb) air, even warmer as a result of subsidence in the Great Basin anticyclone, arrives on the East Slope considerably warmer than Pc or even returning Pc air, except in summer. Thus the boundary, north and east of which the warm air has not removed the cold air and penetrated to the surface, is a region of frontogenesis, and frequently of cyclogenesis. The process of reaching the surface is one of turbulent mixing. It will proceed at a rate proportional to the amount of shear at the boundary, and inversely proportional to the stability or vertical lapse rate of potential temperature at the boundary as described in Part II. The surface will be reached first at higher altitudes and lower latitudes where the cold air is usually most shallow; also where the shear, or vertical velocity gradient between the air masses is greatest, that is, where turbulence is most active.

This surface front will move eastward away from the mountains when turbulence is positive and, as evacuation proceeds at an uneven rate along the front, it will take the shape of a wave. The slower moving portion of the wave to the northwest can be considered a cold front, the more rapidly moving portion to the southeast a warm front. Their junction will have the lowest pressure, partly because there the warm air is deepest. Further, the cyclonic component of rotation set up by the increase of cyclonic vorticity due to vertical divergence during descent from the mountain crest will add its effect to that produced by the thermal low to establish a cyclonic rotation.[1] More important than these is the cyclonic shear at the boundary surface due to the relative motion of the two air masses.

After the wave moves out of the stationary trough to the lee of the mountain, the energy for further development will arise from the kinetic energy of the westerly flow, from the temperature difference between the air masses and from any latent heat of condensation released from either the warm or cold mass, together with that supplied by the passage either aloft or at the surface, of a trough

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1. Fink, Hutchison, Hovde. A Study of Flow in the Free Atmosphere in the Neighborhood of a Topographic Barrier. (Thesis), New York University, 1939

or front. Because of the dryness of Pp and Pb air reaching surface levels east of the Rockies, as well as of the Pc air, little latent heat is available, so that only with extreme temperature contrasts can an intense development be expected in the absence of some such superimposed effect. But it is with large temperature contrasts that effects of turbulence are most limited by stability.

A lessening of the eastward motion of the warm air adjacent to the cold front sector of the wave would permit it to move southward and at the same time retard the warm front, thus allowing the wave to become unstable and occlude. When the rate of production of turbulence becomes zero before the wave becomes unstable, this may cause the wave to become stationary or even be forced back toward the mountains. On the other hand, with an increase of westerly flow, the warm front would be accelerated, and the occlusion process retarded or prevented. (Map Group 2). In general, as the frontal system moves eastward, the wave will move along it toward southeast, frequently become unstable and begin to occlude. It is with such cases that we are chiefly concerned in this paper.

Assuming that the magnitude of temperature contrast is not too small, frontogenesis will take place as described above so long as the combination of northerly flow of returning Pc air from an old Pc outbreak and a strong westerly flow maintains an active deformation field. A buildup of the Columbian high will intensify the westerly flow in British Columbia and Montana. Such a buildup is usually a dynamic effect of a deep Aleutian low. This combination is usually attended by frequent passage inland of occlusions across Washington and southern Canada which, as stated above, add impetus to the development and movement of the waves after crossing the mountains at the surface or aloft. This synoptic setup is of very frequent occurrence and has been designated Type-B by the meteorology staff at California Institute of Technology.

With few exceptions, an occluding wave is found to develop only with the passage inland of an occlusion, though many stable waves may form on the front separating the Pc air from the Pp or Pb air. If the old occlusion passes across the divide on the surface, it may overtake and become a part of the wave or follow behind it. Usually in winter an occlusion will go aloft near the coast, ~~the trough aloft,~~ and as it passes over the wave to the east, intensify it and facilitate its eastward motion. In this sense, the process may be considered a regeneration of an old system.

Examples of Fronto- and Cyclogenesis.

The following groups of maps illustrate a number of interesting variations of the manner in which cyclogenesis may occur under different circumstances; the first group illustrates the effect of the Rocky Mountains as a barrier to air mass movements. All of the groups are copied from the synoptic maps drawn by the staff of the meteorology department at the California Institute of Technology. According to the classification of weather types by the staff, Group 1 is Type-B-Polar, Groups 2, 3, 4, 5 and 7 are Type-B, and Group 6 is Type E.

Group 1. (Maps for January 15, 16, 17, 18, and 19, 1940.)

A stationary front is forced across the divide. A sequence in which a wave chain which had entered the coast in British Columbia, became a stationary boundary along the divide between a Pc and a Great Basin high, and was finally pushed back across the divide to the West Coast. The deformation field between the two highs was maintained fairly stationary by the mountains until an appreciable flow of Pc air began to cross the divide.

Group 2. (Maps for February 8, 9, 10, 1940.)

Strong westerly flow retards occlusion of wave. This example illustrates a rapid eastward movement of the warm front portion of a wave formed in advance of a deep occlusion entering British Columbia; the cold front portion remained in an East-West position, at no time being able to break south and displace the strong flow of Pp air maintained in advance of the lagging occlusion. Low pressure in Northern Canada and continued strong westerly flow account for the fairly rapid eastward movement of the warm front, with practically no movement of the cold front, thus not permitting occlusion to take place. The tendency for a second wave formation is noted on the 10th. This frequently occurs when the cold front becomes elongated.

Group 3. (Maps for November 8, 9, 10, 1939.)

Occlusion overtakes cyclone formed in advance of it. An example in which the warm front portion of a wave, formed in southern Alberta by very old warm Pp air in advance of a recently occluded system, is overtaken and occluded by the latter. As this occurred, the system deepened rapidly, drawing cold Pc air into the system behind a secondary cold front which in time overtook the occlusion. The greater temperature contrast and higher pressure in northern Canada in this case, as compared to that of Group 2, explain the deepening of the system and southward movement of Pc air into the strong westerly flow of the Pp current.

Group 4. (Maps for December 5, 6, 7, 1940.)

Occlusion remains in warm sector of cyclone formed in advance of it. An example of a long occlusion entering the coast in a strong westerly flow extending as far south as Colorado. The center of the wave which formed in advance of it deepened somewhat as the occlusion overtook it. The occlusion was carried along in the warm sector as the system moved rapidly eastward.

Group 5. (Maps for January 28, 29, 30, 31, 1940.)

An occlusion crosses the Divide and becomes a wave. An occlusion moved northeast from 30° Lat. around the back of a large Great Basin high so as to enter the coast of Canada in a NW-SE position. The effect of two occlusions preceding it along the same path in excavating most of the cold air, though they passed across aloft, aided its passage inland at the surface. After dropping into the stationary trough east of the Divide, it became an unstable wave and moved slowly southeast into the Lakes region as it occluded. The strong southerly flow of warm Pp air behind it, maintained by the approach of another occlusion, accounts for its breakdown into a wave. When this flow was cut off, the Pc air to the north could move southward and begin occlusion.

Group 6. (Maps for December 16, 17, 18, 19, 20, 1940.)

An occlusion crosses the divide and becomes a wave. An elongated occlusion broke down the high over the Great Basin and, after crossing the divide, began to form a wave in southern Canada under the influence of the increased westerly flow from the next occlusion. This example is similar to that of Group 5, except that the occlusion entered the coast much further south in this case. It illustrates an infrequent case of cyclogenesis occurring as far north as southern Canada during a Type E situation.

Group 7. (Maps for June 20, 21, 22, 1940.)

A cyclone not due to the approach of an occlusion. This group illustrates an infrequent case where a wave development occurs with apparently no occlusion involved. A stationary front had formed between a long Pc high east of the Rockies and a NE-SW high off the West Coast and over the Plateau. A deep low south of the Aleutians reinforced the Pacific high and forced it across the divide in Alberta, pushing the stationary front northeast behind the southern portion of the Pc high; the northern portion of the Pc high moved southward behind the cold front of the wave while the warm front was retarded by the southern portion, and occlusion resulted.

The following table shows certain features common to most of the above maps during periods when cyclogenesis was taking place. In most cases there was a strong westerly flow across the divide as a result of the position and intensity of the Aleutian low, and Pacific and Great Basin highs. Returning Pc air from a recent outbreak covered the East Slope, indicating a shallow layer of moderately cold air at the surface. Only a weak high, if any at all, existed over northern Canada until after cyclogenesis had taken place.

Temperature differences between the old Pp air in advance of the occlusions entering the coast near 50° Lat., and the RPc air are around 20° to 25°F, except in summer when there is practically no difference. Group 1, in contrast, shows a temperature difference of 60°F between the coast and the interior. Moderate rains on the coast indicate that the air is being dynamically heated on descending the east slope. The small amount of precipitation east of the divide is further evidence that the Pp air is not overrunning a deep Pc mass. All of these features are characteristic of a Type B situation. The rate of movement of the warm front is noted to be greatest when the cold air is shallow, the temperature difference across the front is small, and the component of wind in the direction of

TABLE I

Group	1	2	3	4	5	6	7
Synopsis	Stationary front is forced west across divide	Westerly flow retards occlusion of wave	Occlusion overtakes cyclone formed by its approach	Long occlusion remains in warm sector of cyclone	Occlusion crosses divide and becomes a wave	Similar to 5 but at lower latitude	Cyclone not due to occlusion
Dates	Jan.15-19, 1940	Feb.8-10, 1940	Nov.8-9, 1939	Dec.5-7, 1940	Jan.28-31, 1940	Dec.16-20,1940	June 20-22, 1940
Average westerly wind velocity across divide in m.p.h.	30 to North 25	35	35	40	40	35	35
Orientation of wave chains in Pacific	NE-SW	E-W	E-W	E-W	NE-SW	E-W	NE-SW
Days between approach of occlusion to coast	--	3	1 1/2	1 1/2	1 1/2	1 1/2	--
Their latitude of approach	--	50°	50°	50°	55°	30° to 50°	--
Position of Aleutian low	50° Lat. 165°W.L.	58° Lat. 147°W.Long.	52° Lat. 170°W.Long.	48° Lat. 160°W.Long.	N-S at 140°W.Long.	50°Lat. 150°W.Long.	None
Position of Pacific high	On shore	35° Lat. 135°W.Long.	37° Lat. 135°W.Long.	30° Lat. 135°W.Long.	None	20°Lat. 130°W.Long	N-S at 130°W.Long.
Pressure difference between low and high (mb.)	--	45	30	45	--	45	--
Strength of Great Basin high	Mdt. to weak	High	High	Mdt.	High	High to weak	Mdt.
Strength of Canadian high	Very high	Weak	Mdt. NE	Weak	Weak (high over Alaska)	Weak	Mdt.
Days since and intensity of last Pc outbreak	--	2 Mdt.	2 Mdt.	2 Weak	7 Strong	3 Mdt.	4 Weak
Pressure over eastern United States	Mdt. to high	Mdt.	High	Mdt.	Mdt.	High	High
Type of air over middle west	Pc	RPc*	RPc	RPc	RPc_{o}	RPc	RPc
Type of air crossing divide	--	$_{o}Pp2$	$_{o}Pp_{o}$	$_{o}Pp_{1}$	$_{4}Pp_{1}$	$_{2}Tp_{1}$ to $_{6}Pp_{1}$	RPp
Temperature difference between coast and Canada °F	60	30	35	40	35	40	0
Temperature difference across warm front °F	--	20	25	25	30	25	0
Intensity of precip. on coast	None	Heavy	Mdt.	Mdt.	Heavy	Mdt.	Lgt.
Intensity of precip. east of divide	Mdt.	Lgt.	None	None	None	None	Lgt.
Number of cyclones formed	--	1	1	1	1	1	1
Their rate of movement	--	Mdt.	Fast	Fast	Mdt.	Fast	Slow

* R indicates returning air. Subscripts to left are days out of source region over water; to right, days over land. o means old or long out of source region.

motion is large. This will be brought out clearly in Part II.

Seasonal Variations in Intensity of Fronto- and Cyclogenesis.

The great seasonal variations in temperature over the continent, and in intensity of the westerly flow of Pacific air over the divide should be reflected in the activity of the field of fronto- and cyclogenesis east of the Rockies. A study was made of maps for the three year period 1938-1940, with the purpose of noting seasonal trends, particularly as regards cyclogenesis.

The classifications given in the table below seemed the most definite into which systems passing inland from the Pacific, and the resulting cyclonic developments, might be divided. A few individual cases are open to question as to classification, as they are the writer's interpretation of the analyses made by the meteorology staff of the California Institute of Technology for the 7:30 A.M. and P.M. synoptic data. However, the excellent continuity of analyses adds much weight to the general accuracy of the figures.

A wide variance was noted in results for a given month from year to year, and from one month to the next. This is to be expected in view of the tendency of a given

TABLE II

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Winter	Spring	Summer	Fall
1.	Occlusions or cold fronts aloft	16	17	18	13	16	8	7	8	26	25	17	27	60	47	23	68
2.	Stationary fronts	5	8	5	4	5	10	7	6	4	4	3	4	17	14	23	11
3.	Cyclones due to occlusions	10	9	8	7	11	4	7	13	11	5	11	13	34	26	24	27
4.	Cyclones not due to occlusions	0	0	1	0	0	1	1	1	2	1	0	3	3	1	3	3
5.	Occlusions becoming waves	2	1	3	5	3	7	2	5	2	4	9	4	7	11	14	15

type of weather sequence to persist for a period of time, to be followed by another type, and to a shift in the streamline pattern from year to year. However, seasonal trends suggested by the figures should be indicative.

1. The count of Pacific occlusions and cold fronts aloft includes only those which appeared active as such after crossing the Plateau states. These were fewest in summer when the number of occlusions reaching the coast was a minimum.

2. Stationary fronts include only those forming a fairly stationary boundary along the mountains between Pc and Pp air. They are fronts which have collected there because of this favorable location for the axes of deformation. Those on which a significant wave development occurred are not included. Though fewer in number in winter compared to summer, they are of longer duration and separate masses of far greater contrast in temperature and moisture content. The position of the Polar Front in summer favors their formation.

3. Cyclones due to occlusions are those which form on the line of frontogenesis east of the divide as the warm air in advance of an occlusion approaching the coast bulges the front eastward into a wave, this wave

later occluding as it is carried eastward in the general circulation. This group is of particular interest as a measure of cyclogenesis in the region. Nearly all occur in a Type-B or B-Polar situation.

It was expected that this type would show a maximum in fall and spring, a minimum in winter and summer. The minimum in winter was expected for these reasons: The greater stability of the Pc air in winter and the persistence of a Pc high over Canada should increase the amount of turbulence required for formation of a wave. With the entrance of occlusions on the coast at a more southerly latitude, the greater distance from the coast to the divide should allow greater modification of the warm Pp air in advance of the occlusion by radiational cooling and a decrease in the intensity of the system in lower levels.

The number of occluding waves formed as far south as Colorado were very few, but many occlusions entered the coast far enough north to induce a few more waves in Southern Canada and Montana during winter than occurred in other seasons, most of them relatively intense.

During summer the decrease in intensity of the zonal circulation and number of occlusions in the Pacific, along with high temperatures in the interior of Canada would seem to lessen both the intensity and number of wave developments in this season. However, the northerly latitude of approach of Pacific occlusions to the coast, a Type-B characteristic, and some small temperature contrast in northern Canada seem to allow frequent development of weak waves in summer.

The small difference in temperature between Pc and Pp air at upper levels limits these cyclones to the lower levels. This is not as true when Pb air is involved, since its warmth extends to higher levels. Their shallow character, as well as the small amount of moisture involved, explains the fact that so many were noted to die out before reaching the Lakes region.[2]

4. As mentioned above, there were few cases of a cyclonic development when there was no occlusion on the coast to aid in its formation. Even in some of the cases listed, there is the possibility of some upper system not evident at the surface, facilitating their development. None of this group were very intense, though examples have been noted where intense cyclogenesis has taken place without the presence of any such superimposed effect.[2]

5. Occlusions which regenerate into cyclones are

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2. Irving P. Krick. Foehn Wind Cyclogenesis, Gerlands Beitrage Geophysics, p. 56, 1934.

noticed usually in connection with a long occluded front which parallels the coast and passes across the divide at the surface, later becoming an unstable wave under the influence of a strong westerly flow behind a portion of the front. (Groups 5 and 6). This type appears to be a minimum in winter when the low temperature and extreme stability of the Pc air and persistence of high pressure in northwest Canada and Alaska during the season, as well as the more southerly approach of occlusions to the coast, tend to limit such a development.

In summary, we note many weak stationary fronts along the divide in summer, but more prolonged and well-defined ones in winter; very little seasonal trend in number of cyclones formed at the approach of an occlusion, but those in summer are the least active, those in early winter most intense; fewer occlusions regenerating into cyclones in winter and spring, and comparatively few in all seasons; and very few cyclones formed without an occlusion entering the coast.

It is obvious that the persistence of a favorable weather type is far more important in determining the activity of this field of cyclogenesis than seasonal changes, except in so far as such types are more prevalent in one season than another.

A Relation between Time of Movement of Cyclones and Position of Migratory Wedges.

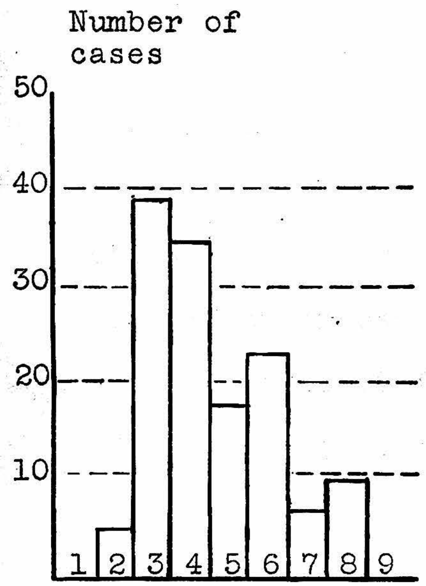
In studying the formation and movement of cyclones east of the Continental Divide, the position of migratory anticyclones or wedges separating successive chains of Pacific waves was suspected to be important in determining when the cyclones would move from their source region. It was noticed that they began to move eastward frequently just as these migratory wedges were entering the coast behind the last one of a series of occlusions in the preceding wave chain.

With the assumption that such wedges are associated with the West-East movement of waves along the tropopause, and thus extend to high levels, it was thought that their movement could be studied more easily by noting daily changes in the 14,000-foot pressure field, where the effects of low level systems would not make the moving wedges obscure, as is frequently true at the surface.

The 14,000-foot pressure field over the Northwest was studied for portions of the years 1938-1940 for which data were available. From this data, dates were obtained on which peaks of pressure prevailed over the region centered along the 115th meridian, which roughly parallels the Continental Divide in Montana and Southern Canada.

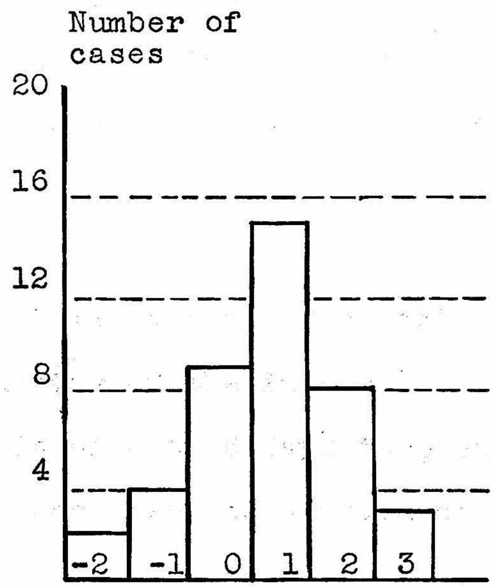
The number of days between these crests were grouped to see if any periodicity exists in these pressure waves. Table III below indicates that a three and four day period is most frequent. A secondary maximum is noted for six days.

Table III



Length of period (in days) of 14,000 ft. pressure waves.

Table IV



Number of days that peak in 14,000 ft. pressure follows initial movement of cyclone.

The dates of the crests of pressure were then compared with dates on which a cyclone forming east of the Rockies began its eastward motion. Since, as mentioned above, such movement was noted to occur frequently just before a wedge of pressure at the ground began to cross the divide, at 14,000 feet the pressure peak should be reached over the divide about a day afterward. A lee-way of 12 hours for the time chosen for the initial movement of the cyclone should be allowed.

Thus a maximum for 14,000-foot pressure peaks centered around one day after initial movement of the cyclone is to be expected. Table IV indicates that, in general, such is the case. It was noted that particularly in fall and early winter when cyclogenesis was most active, recurrence of cyclones was common at two or three-day intervals when periods of four to six days were occurring in 14,000-foot pressure waves. This accounts for most of the cases in Table IV falling outside of the interval 0, 1, and 2 days, since with periods of 4 to 6 days in pressure peaks a cyclone occurring between two peaks would be outside of that interval.

The above correlation apparently has no forecasting significance, however, since the 14,000-foot pressure peak lags behind the time of initial movement of the cyclone; further, the length of period of the pressure waves seems too erratic to be forecast and shows no relation to frequency of cyclogenesis.

No attempt has been made with the above data to correlate time at which cyclogenesis begins to occur.

This can be done more easily with surface data in light of earlier discussion on the process of cyclogenesis.

Effect of Wave Formations on Pc Outbreaks.

A study of Polar outbreaks was made to determine the role played by waves formed east of the Rockies in setting off a Pc outbreak. It was to be expected that the stage of development of the Canadian High is the most important factor in determining the intensity of a Pc outbreak in conjunction with a particular type of weather situation; moreover, that if the high develops to such an extent that stability of the southern boundary cannot be maintained by horizontal divergence, the boundary will break down and allow an immense outflow of cold air.

Polar outbreaks were divided as to immediate cause into six groups or combinations of these. These were subdivided as to intensity, defined arbitrarily in terms of amount of continental area covered by the outbreak and length of time it prevailed over the area. The following table gives the results of this classification for November through March for the three winters 1937-1940.

TABLE V

Cause	Number of Pc Outbreaks Weak	Mod.	Strong
1. Cyclone forms east of Rockies as occlusion approaches coast	8	3	0
2. An occlusion crosses Rockies and becomes a wave	1	1	0
3. A Pp occlusion passes eastward as such; no other development	2	3	0
4. An E-W front, formed in north-central U.S. between a Pc high and a Pp_o or Pc_o high over south U.S., moves southward	3	7	0
5. Low forms in central or south U.S. between Pp and Tg, or Pp and Pc_o.	9	10	4
6. Breakdown of Pc boundary	0	8	1
Combinations: 1 and 3	0	1	0
1 and 6	0	4	2
3 and 6	0	1	1
4 and 6	0	3	3
5 and 6	0	2	6
Totals:	23	42	17
	% of Total		
4, 5, 6, 4 and 6, 5 and 6:	57	78	87
1 and 2:	43	11	0
Combinations with 1 and 2:	0	11	13

It is noted that Groups 4, 5, 6, and combinations of the three account for over three-fourths of the moderate and strong outbreaks, whereas Groups 1 and 2 account for only weak outbreaks, most of them extending over only the northeastern states. This is reasonable in view of the necessity for strong East-West circulation for their formation, which does not usually accompany intense meridional interchange. Further, the condition of relatively low pressure over southern Canada necessary for wave formations, as well as their tendency to form just after a previous outbreak has taken place and returning Pc air is flowing northward east of the divide, is not compatible with the occurrence of an intense outbreak.

In general, we conclude that wave formations east of the Rockies play little part in bringing about Pc outbreaks, except to release a small part of a high while it is not yet well developed, and thus delay a more intense outbreak. This conclusion is not in agreement with that of Taylor who states that many major Pc outbreaks are the sequel of a wave development in southern Canada of the type under discussion.[3]

Temperature Abnormalities during Foehn Wind Frontogenesis.

The warm dry winds in the warm sector of a wave formed east of the Rockies by influx of Pp and Pb air at the surface have been the subject of many papers, most of them calling attention to extreme temperature rises recorded as the warm air reached the surface. As a tool in forecasting temperature anomalies on the East Slope,

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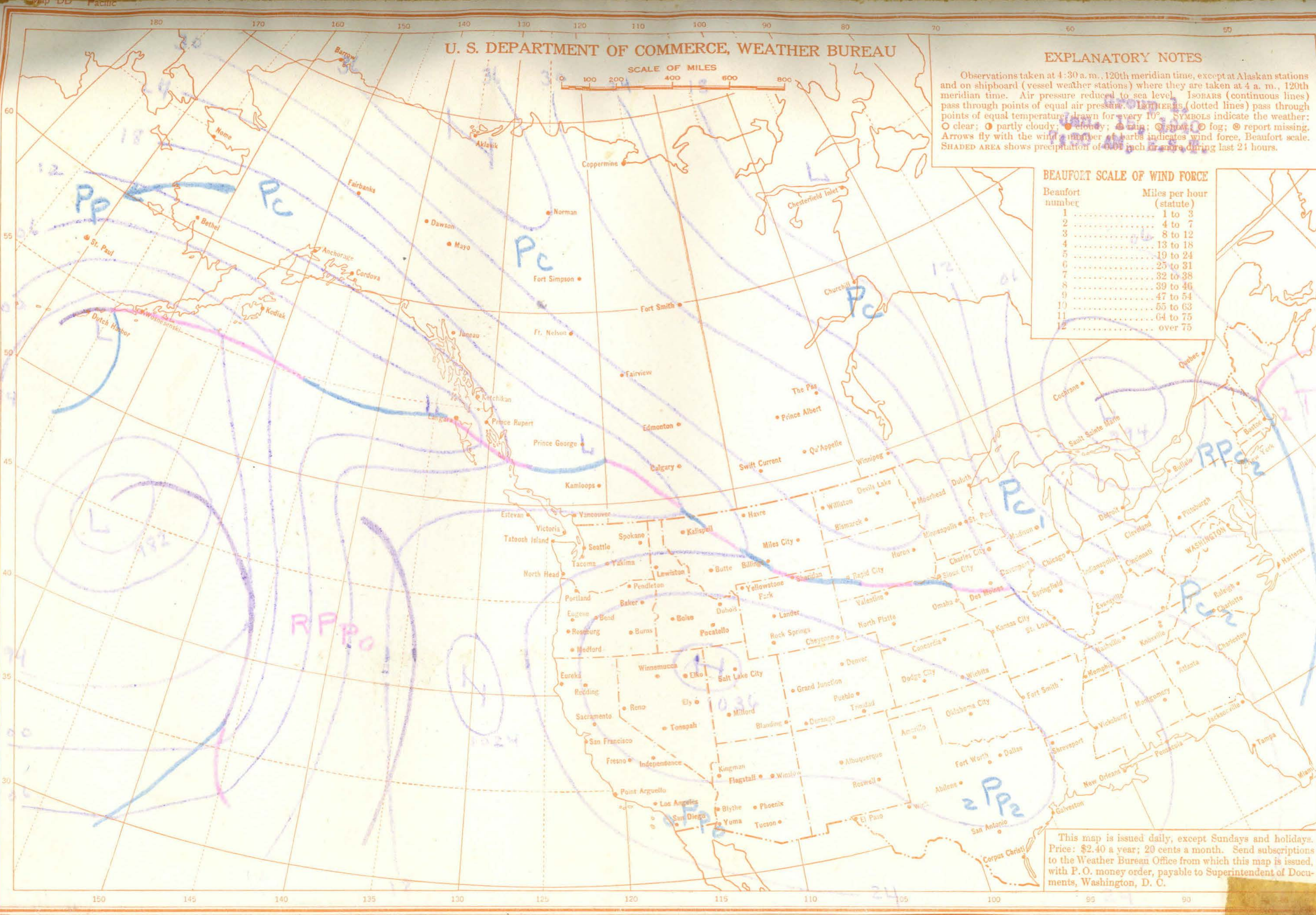
3. George F. Taylor. Aeronautical Meteorology, p. 231

average departures from normal maxima and minima at certain stations during December and January were obtained from data compiled from a large number of situations where the stations were in the warm sector. These departures are shown below.

TABLE VI

Station	Average departure from normal of Maximum	Minimum
Havre, Mont.	20°F	27°F
Miles City, Mont.	16	19
Billings, Mont.	15	23
Sheridan, Wyo.	14	16
Casper, Wyo.	8	16
Cheyenne, Wyo.	9	16
Denver, Colo.	8	14
Pueblo, Colo.	9	13

Large positive departures are noted, especially at the more northerly stations. Minimum departure is in all cases greater than maximum departure, mainly due to the fact that turbulence does not allow early morning inversions to develop.



EXPLANATORY NOTES

Observations taken at 4:30 a.m., 120th meridian time, except at Alaskan stations and on shipboard (vessel weather stations) where they are taken at 4 a. m., 120th meridian time. Air pressure reduced to sea level. ISOBARS (continuous lines) pass through points of equal air pressure. ISOTHERMS (dotted lines) pass through points of equal temperature; drawn for every 10°. SYMBOLS indicate the weather: ○ clear; ◑ partly cloudy; ● cloudy; Ⓡ rain; Ⓢ snow; Ⓕ fog; ⊗ report missing. Arrows fly with the wind; number of barbs indicates wind force, Beaufort scale. SHADED AREA shows precipitation of 0.01 inch or more during last 24 hours.

BEAUFORT SCALE OF WIND FORCE

Beaufort number	Miles per hour (statute)
1	1 to 3
2	4 to 7
3	8 to 12
4	13 to 18
5	19 to 24
6	25 to 31
7	32 to 38
8	39 to 46
9	47 to 54
10	55 to 63
11	64 to 75
12	over 75

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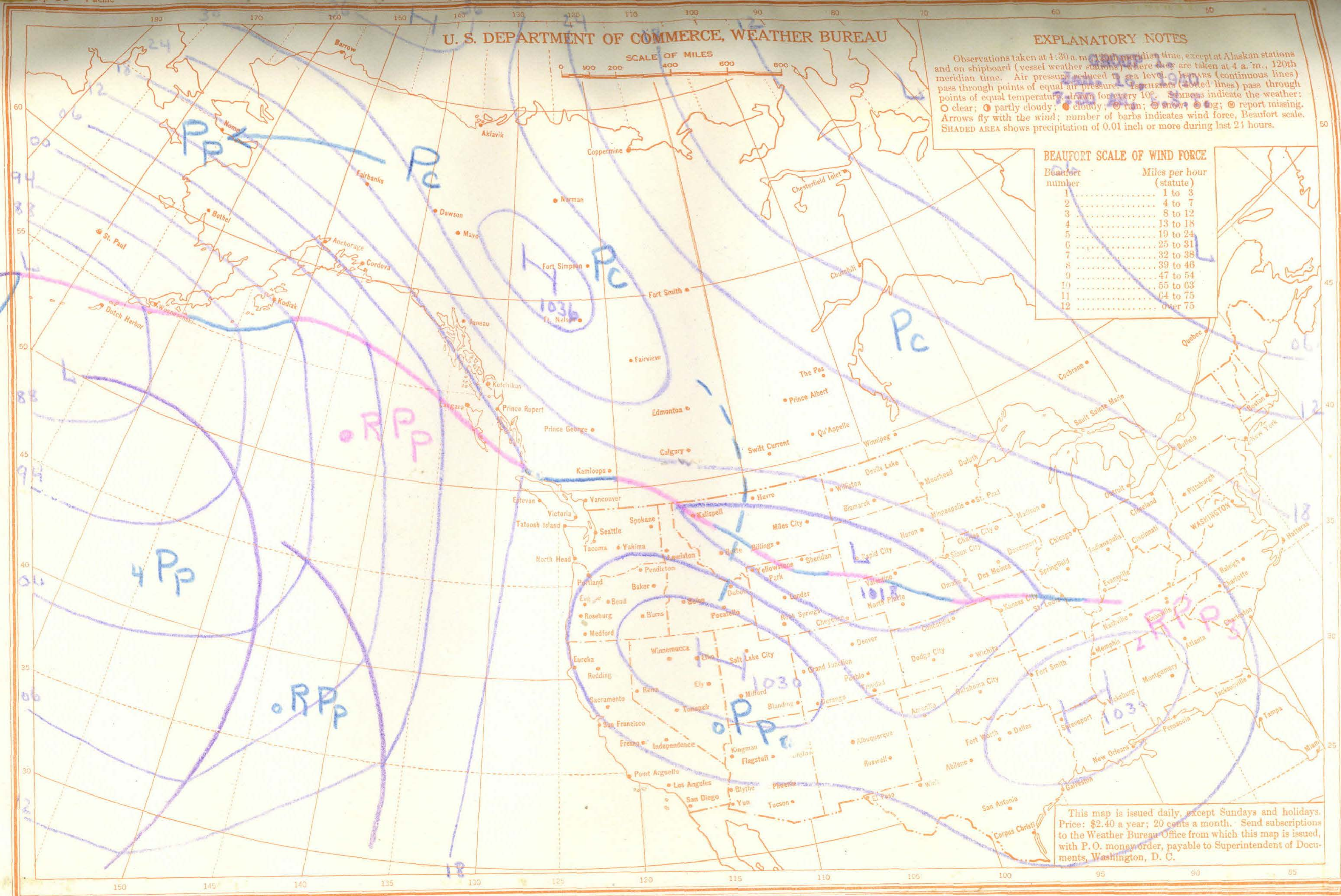
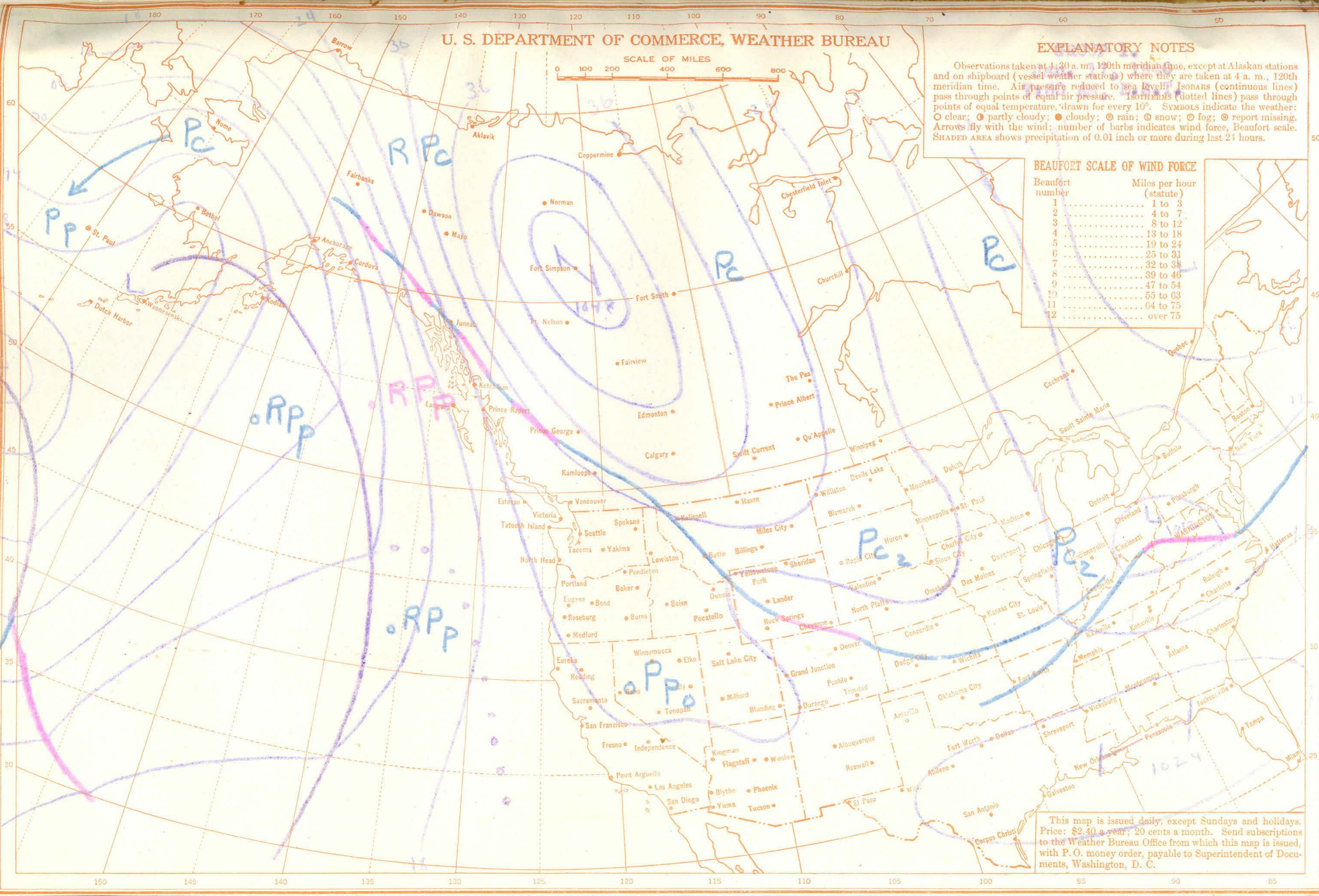
GROUP 7. GROUP 6. GROUP 5. GROUP 4. GROUP 3. GROUP 2. GROUP 1.



GROUP 7. GROUP 6. GROUP 5. GROUP 4. GROUP 3. GROUP 2.


U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU
SCALE OF MILES
0 100 200 400 600 800
EXPLANATORY NOTES
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BEAUFORT SCALE OF WIND FORCE
Beaufort number / Miles per hour (statute)
1 ... 1 to 3
2 ... 4 to 7
3 ... 8 to 12
4 ... 13 to 18
5 ... 19 to 24
6 ... 25 to 31
7 ... 32 to 38
8 ... 39 to 46
9 ... 47 to 54
10 ... 55 to 63
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GROUP 6.
GROUP 5.
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U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU

EXPLANATORY NOTES

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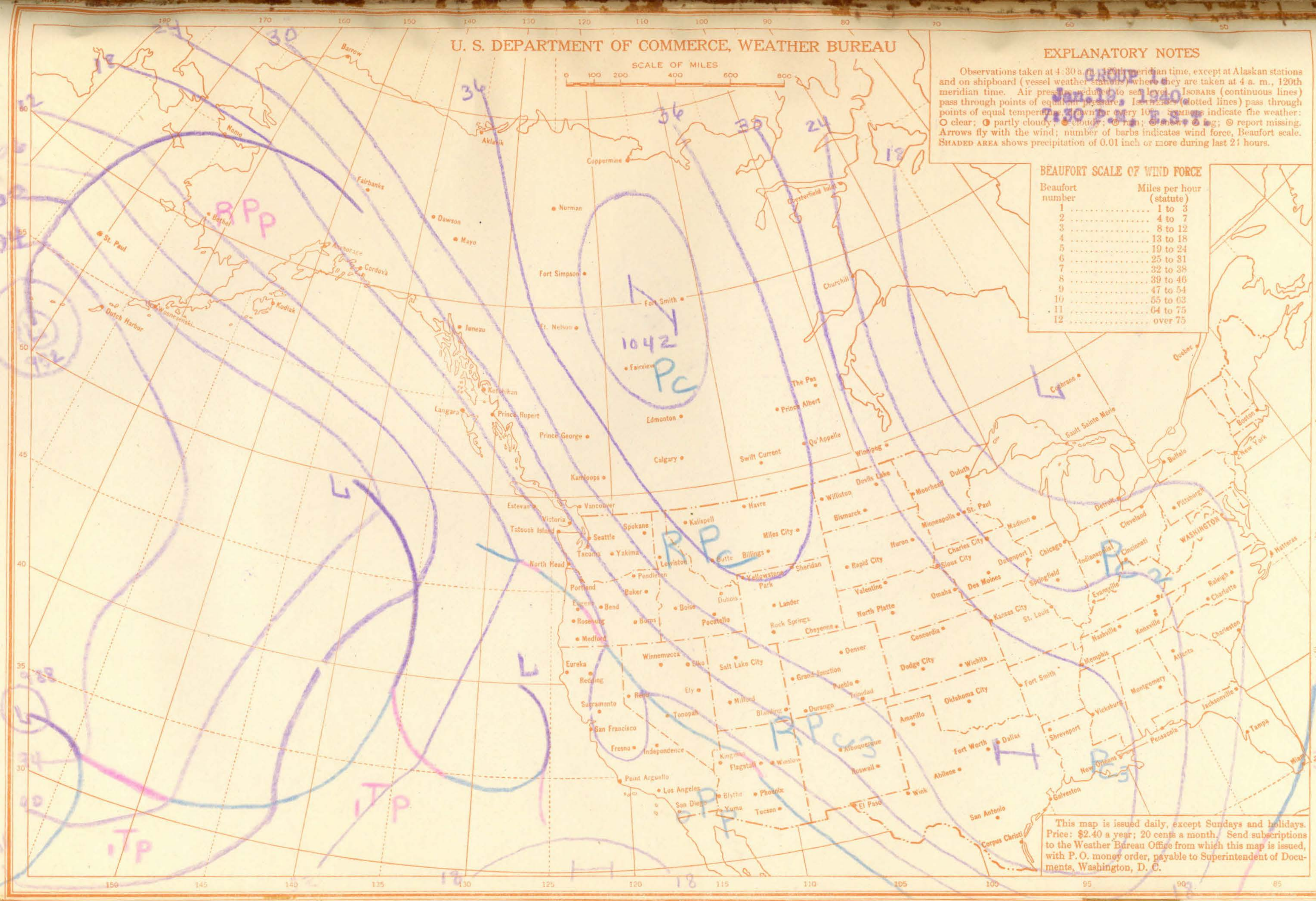
GROUP 7. GROUP 6. GROUP 5. GROUP 4. GROUP 3. GROUP 2

U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU

GROUP 1.
Jan. 19, 1940.
7:30 P.M., E.S.T.



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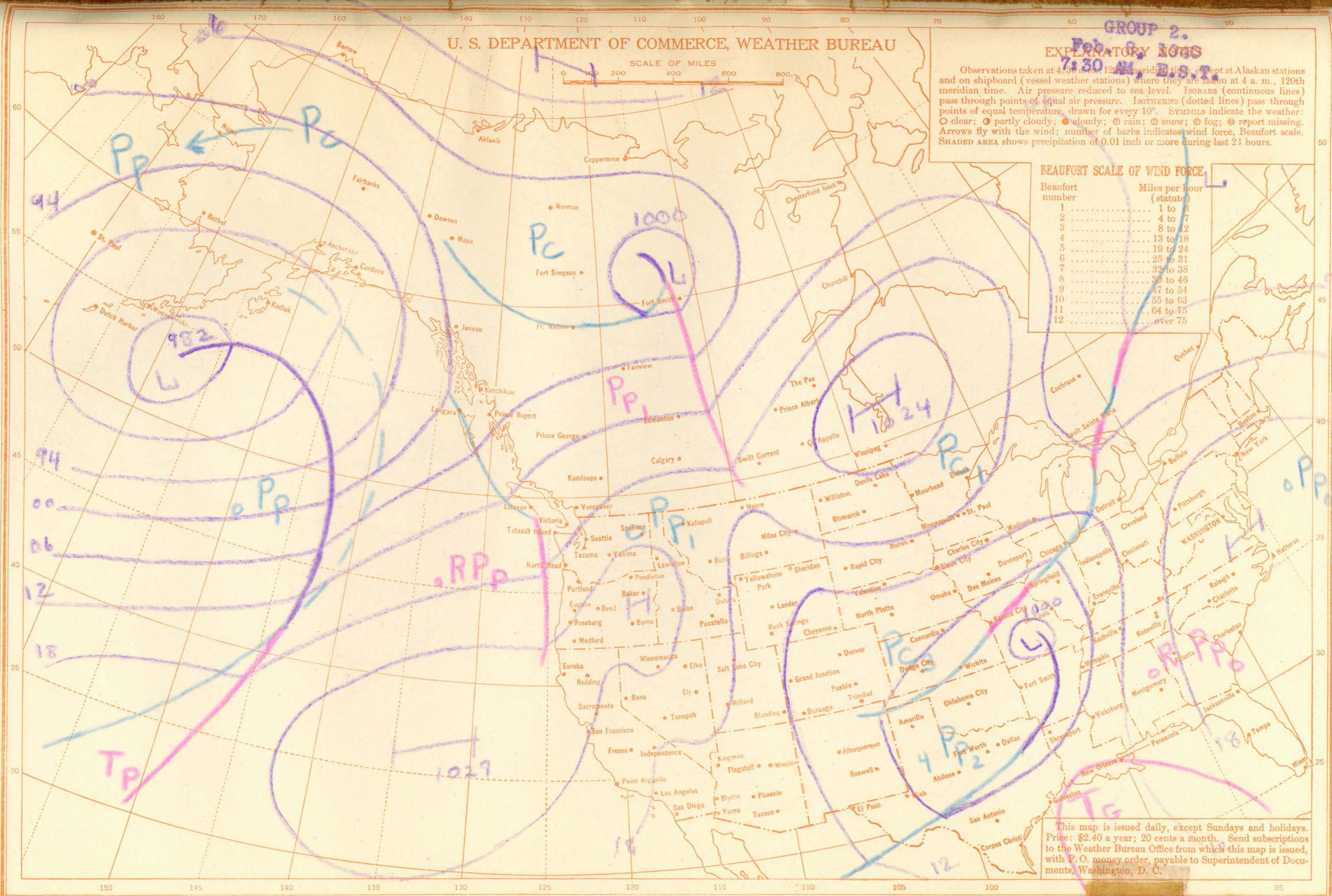
GROUP 7. GROUP 6. GROUP 5. GROUP 4. GROUP 3. GROUP 2.

U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU

GROUP 2.
Feb. 8, 19[illegible]
7:30 AM, E.S.T.



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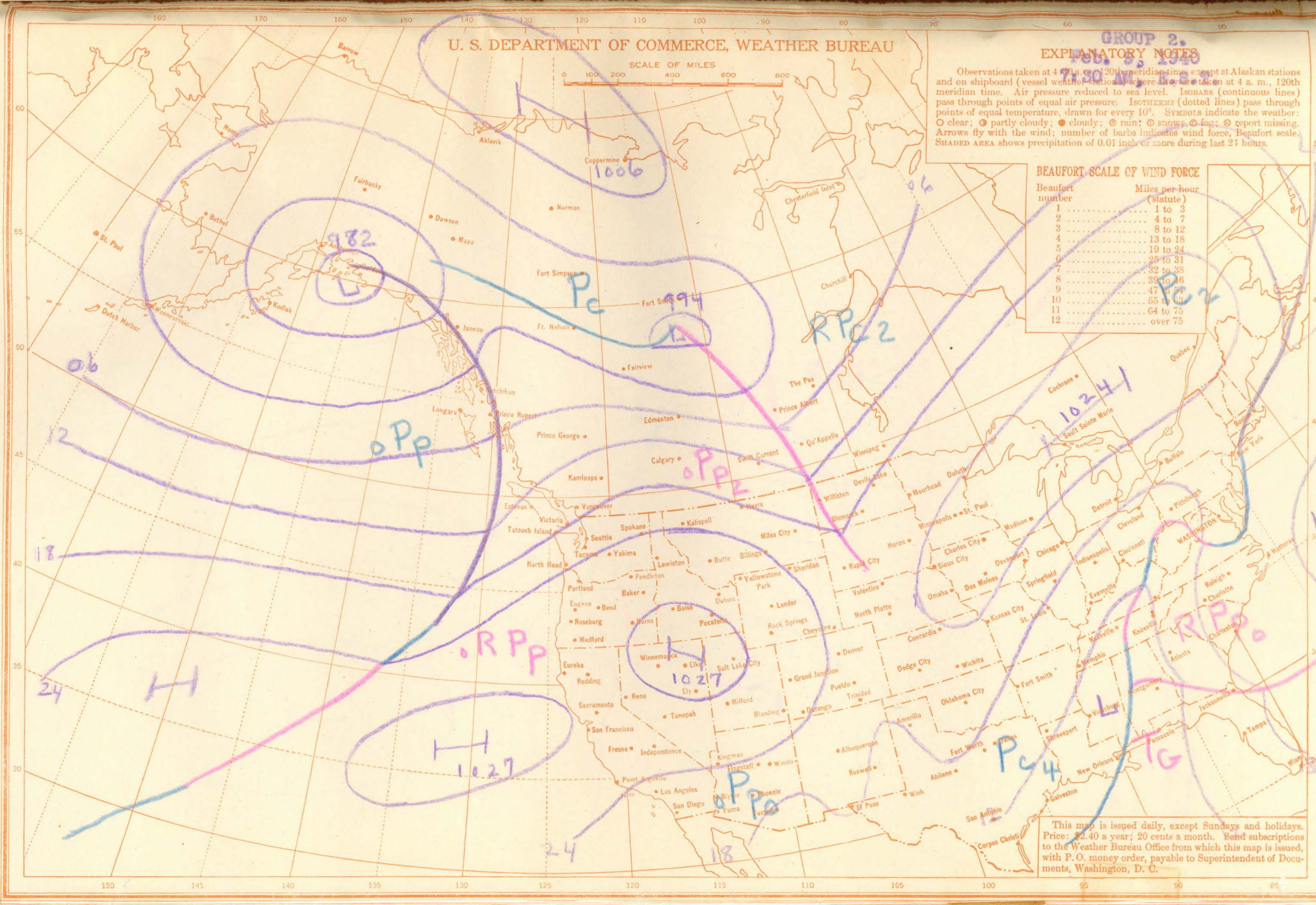

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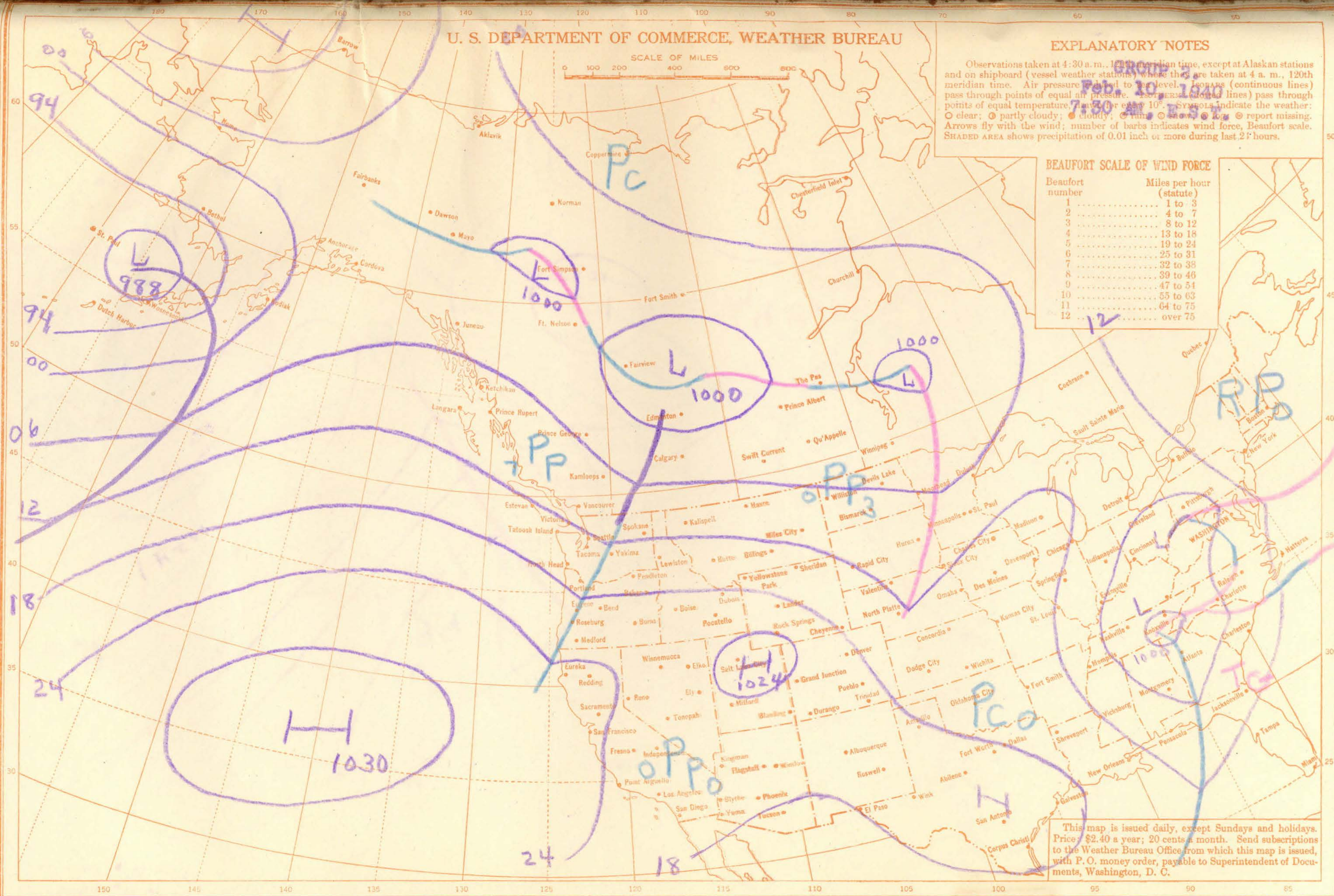
U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU



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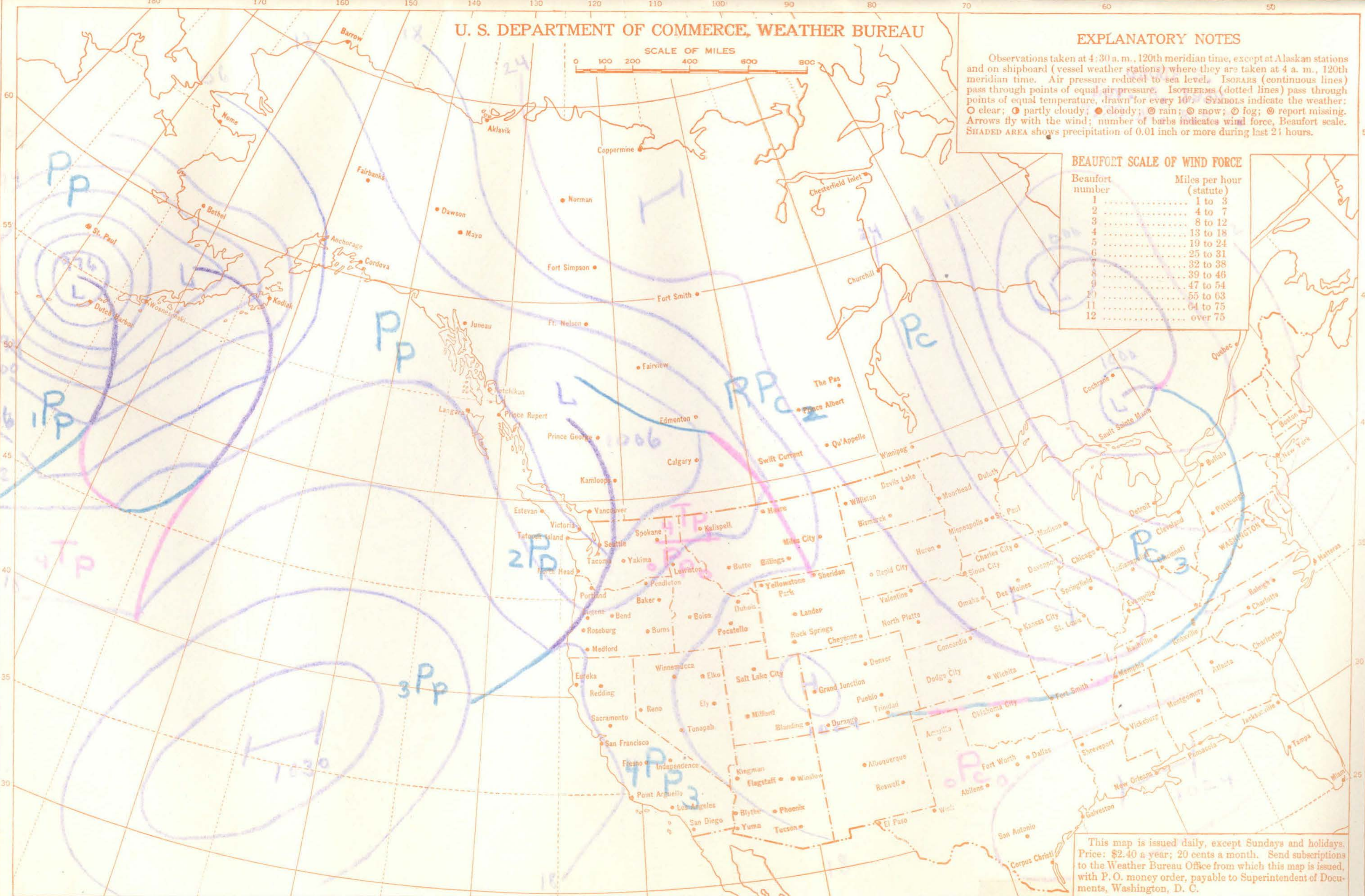
U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU

SCALE OF MILES



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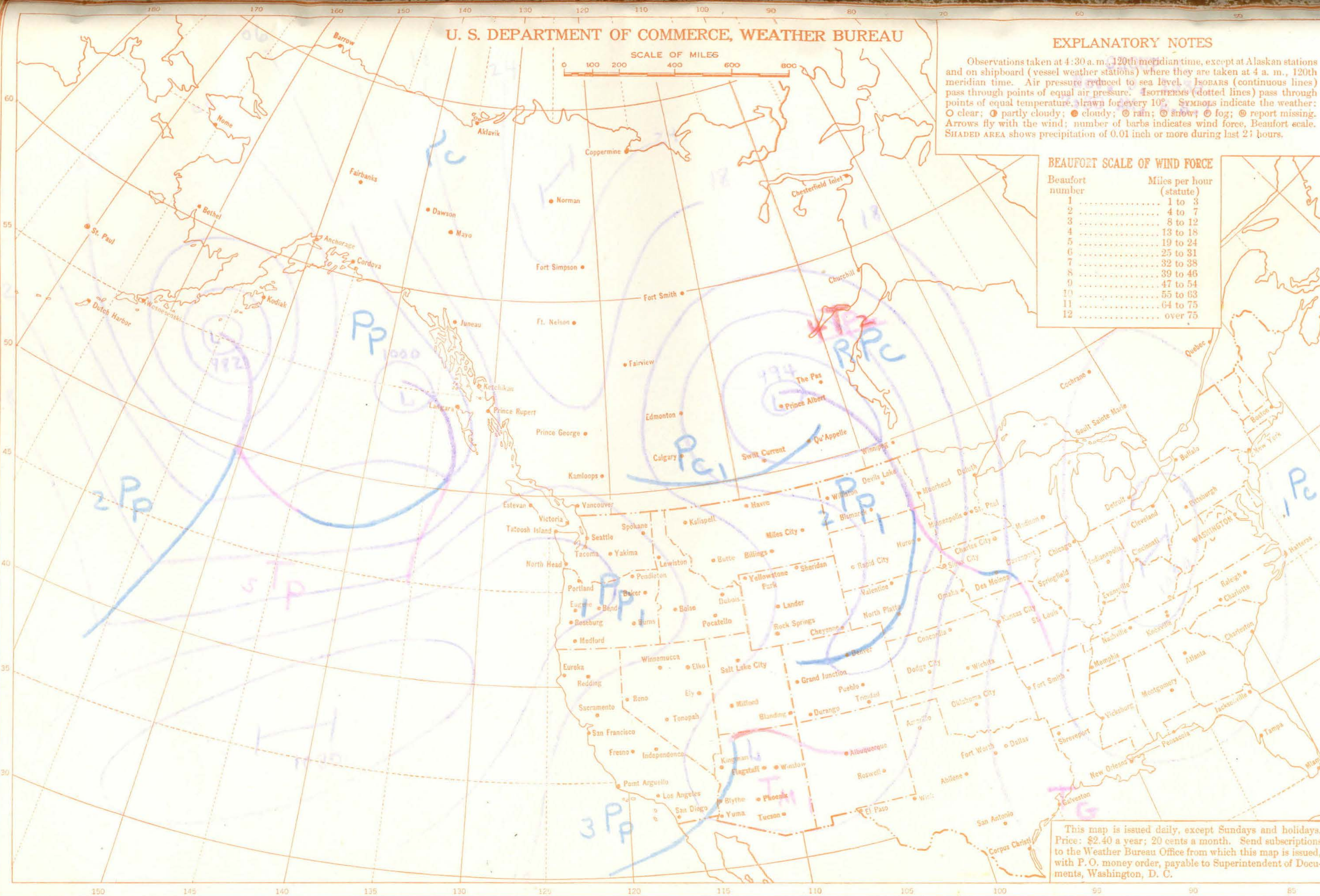
U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU



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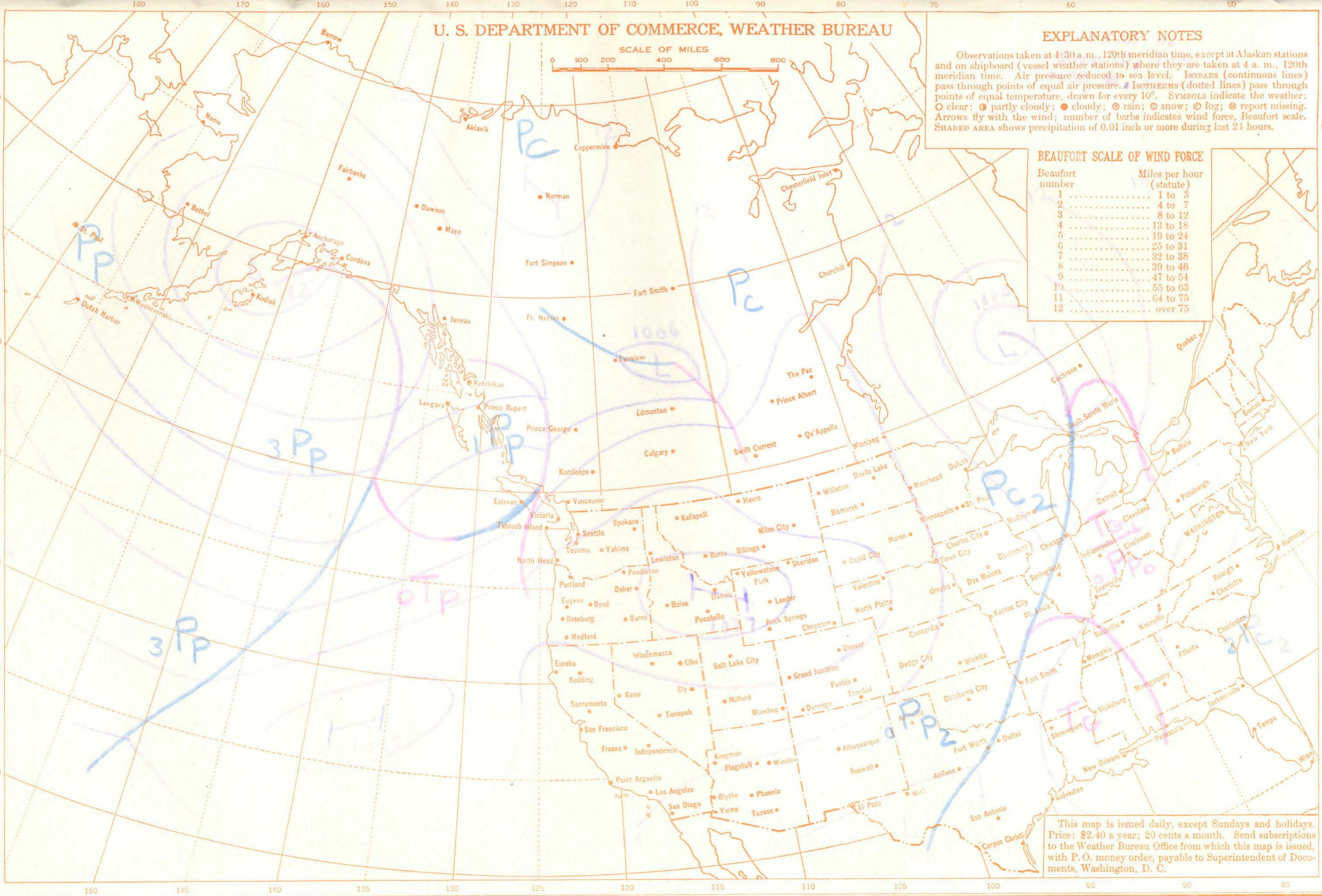

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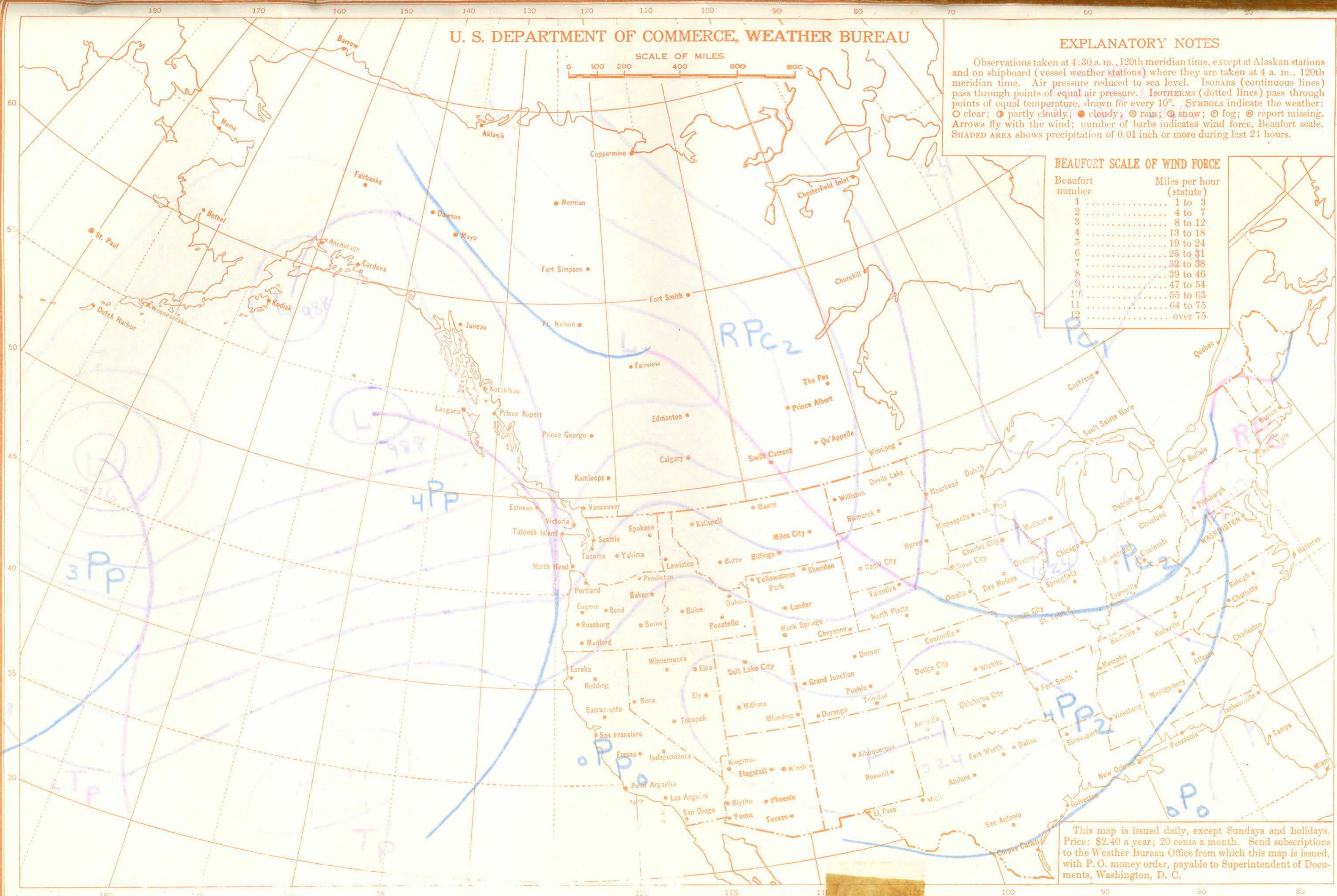

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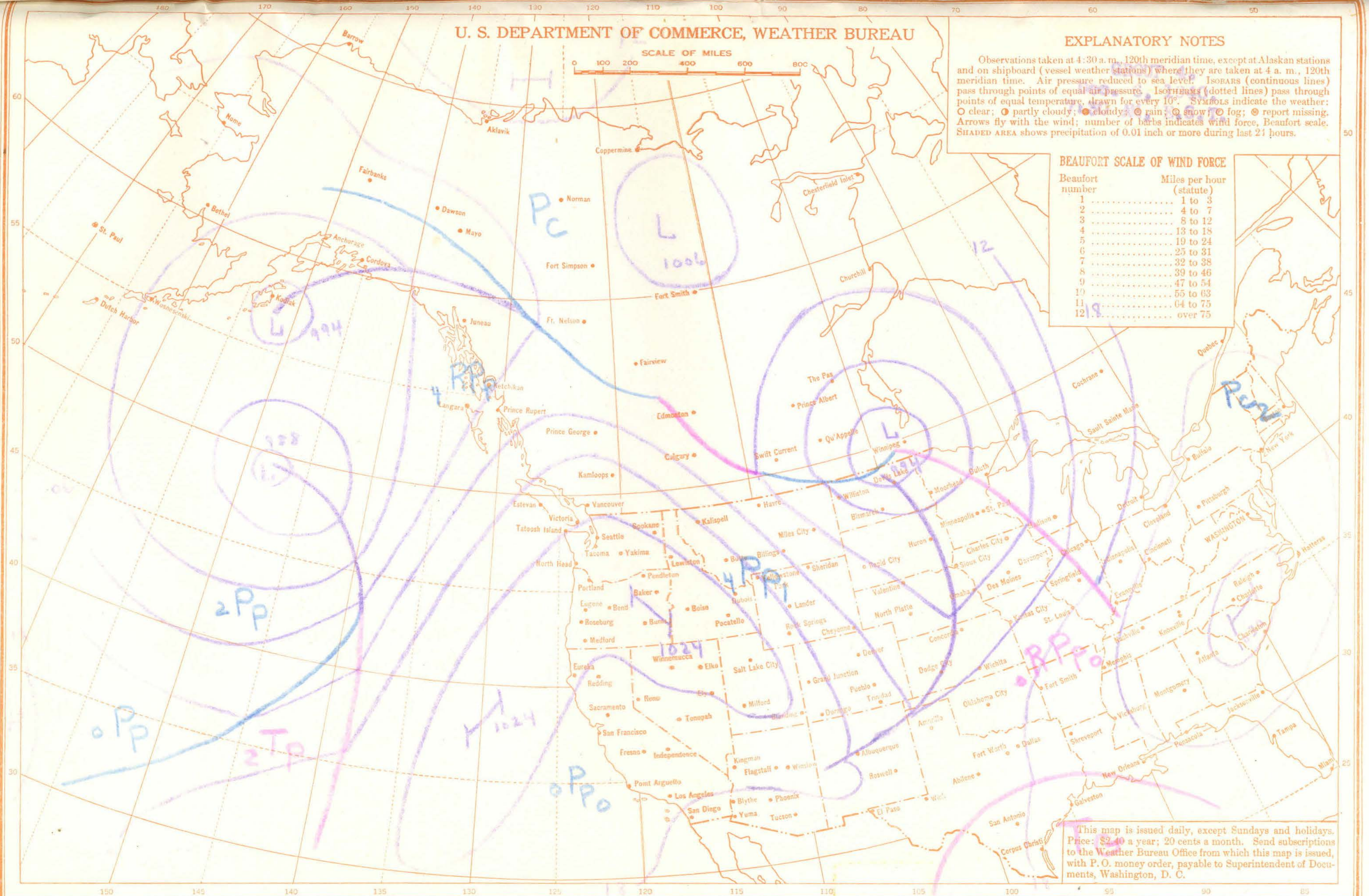

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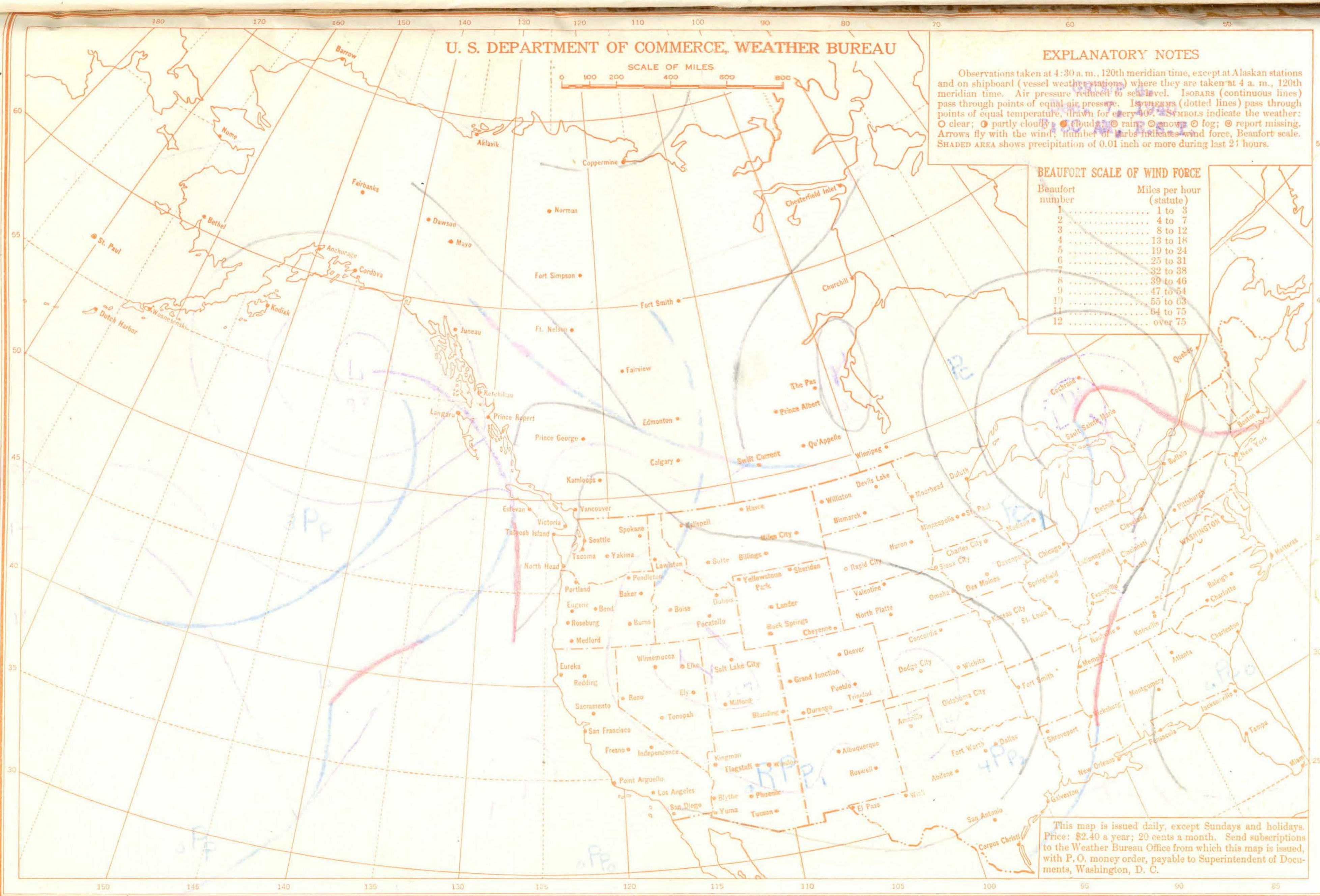

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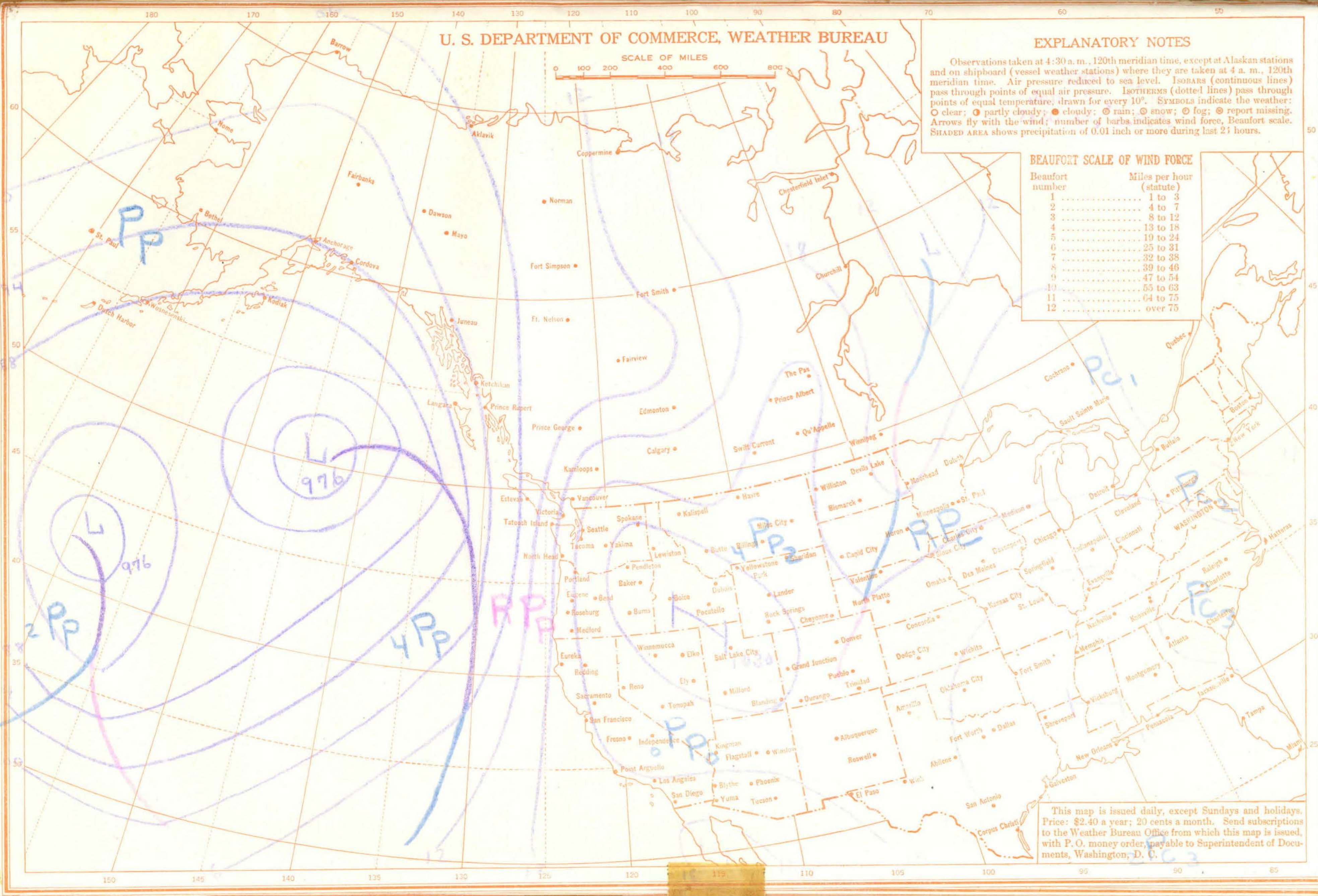
U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU



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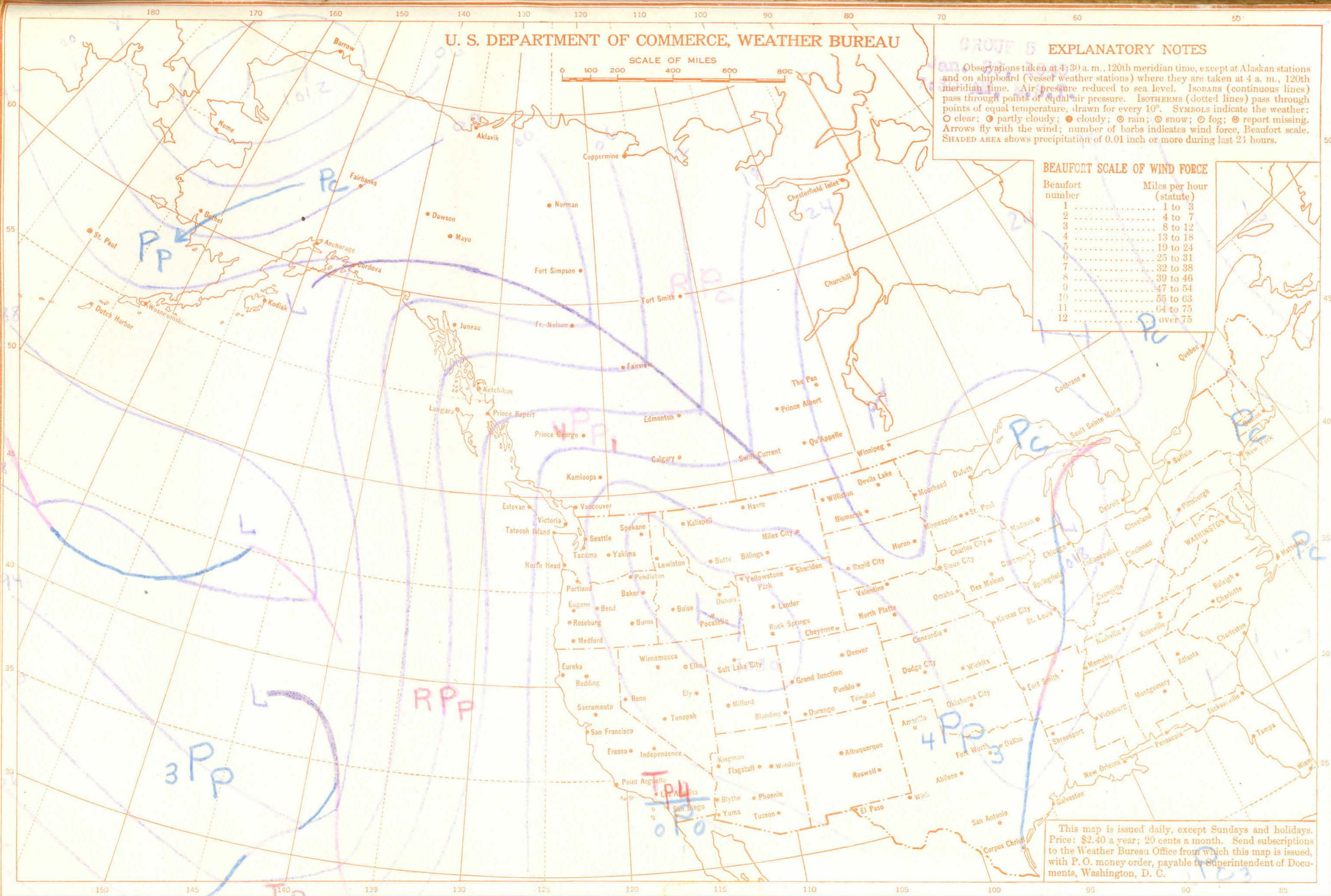

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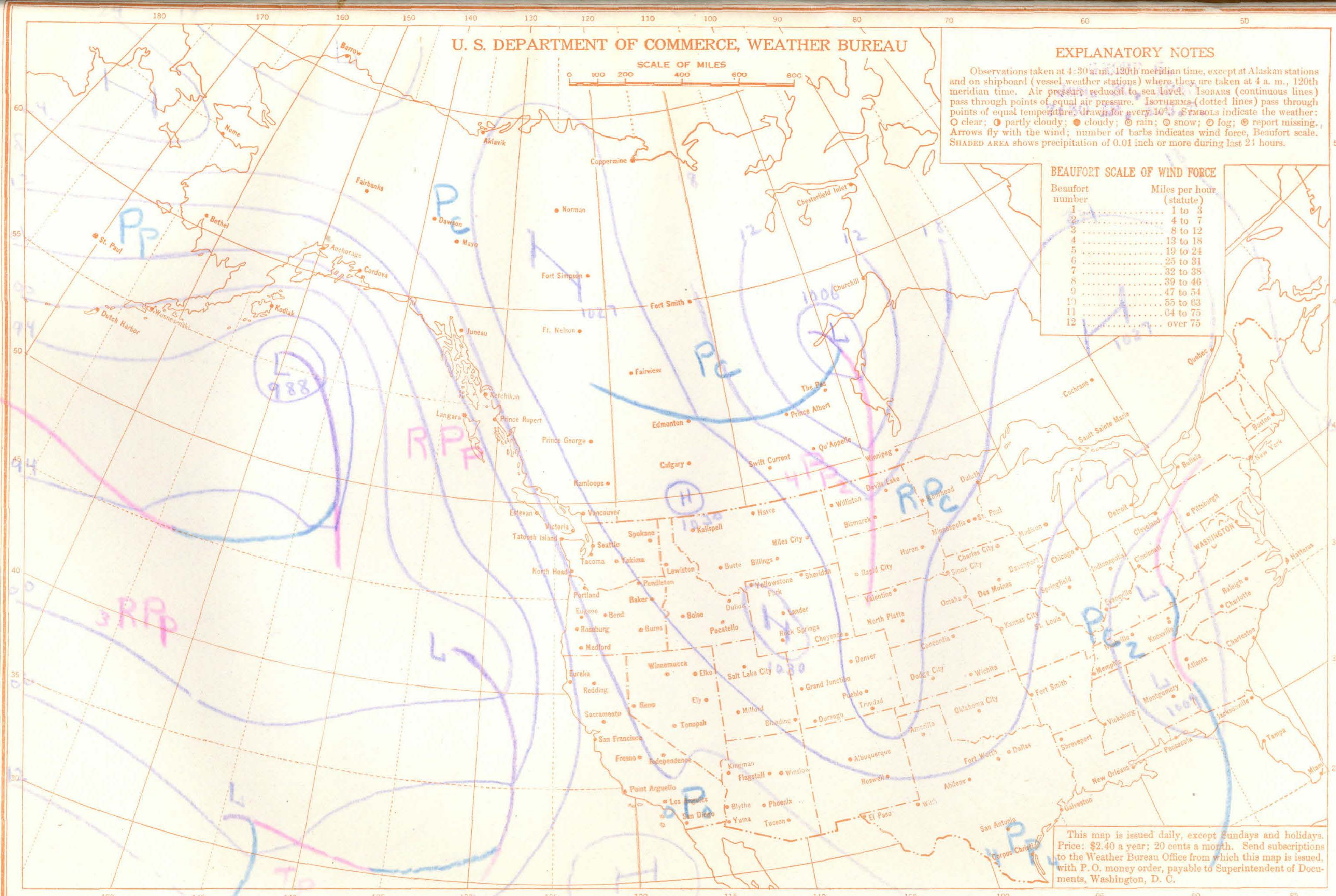

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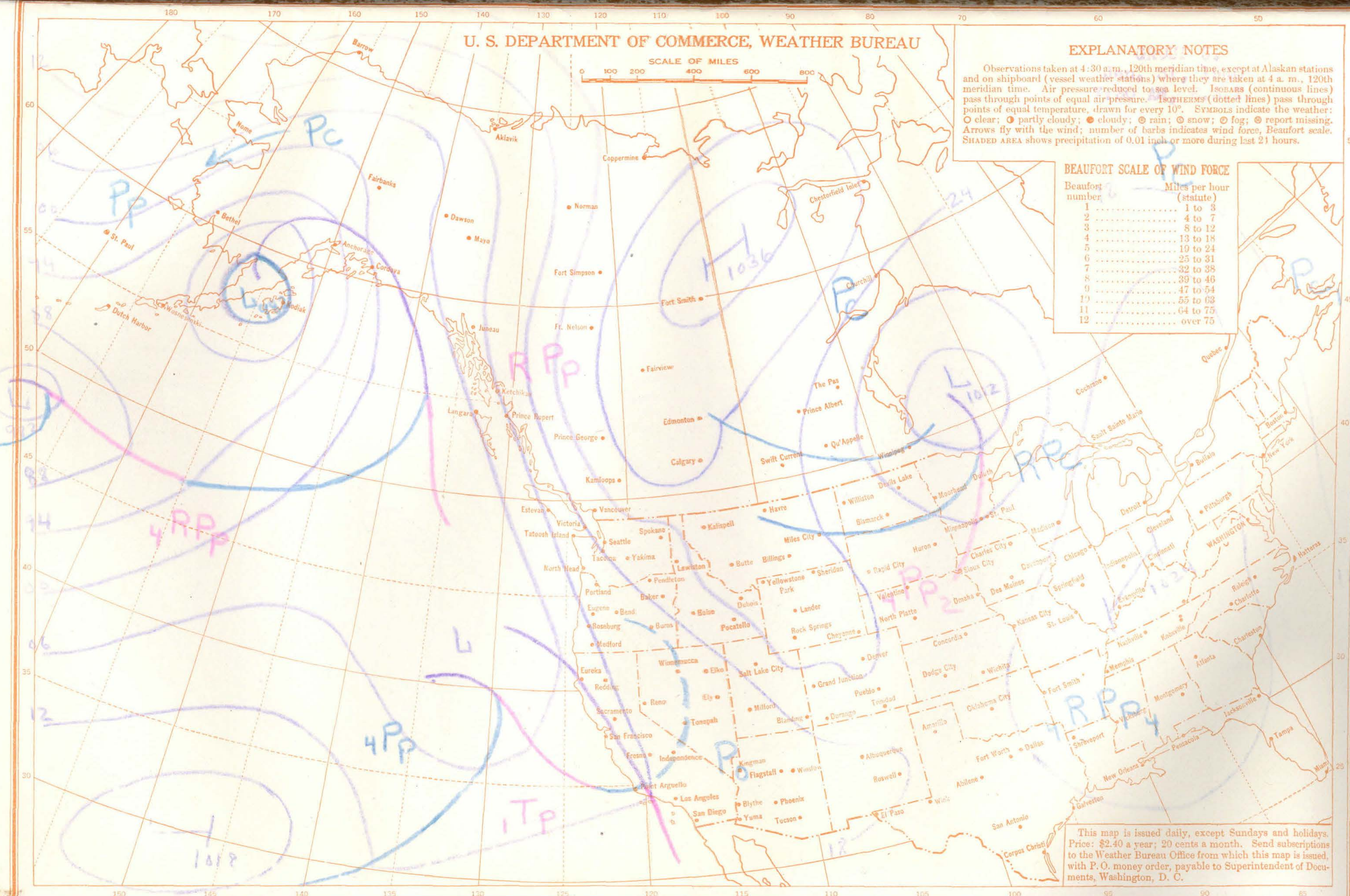

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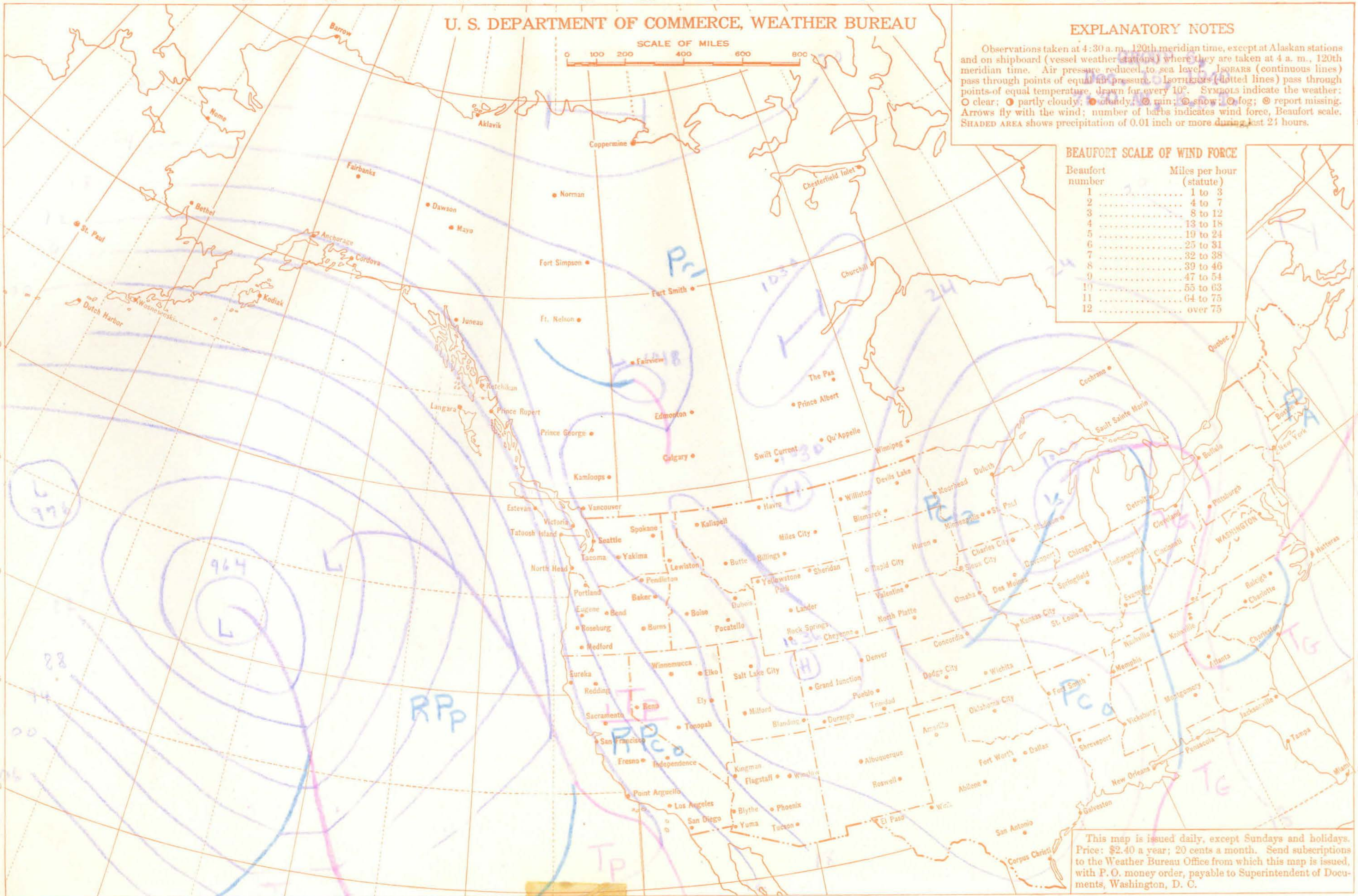

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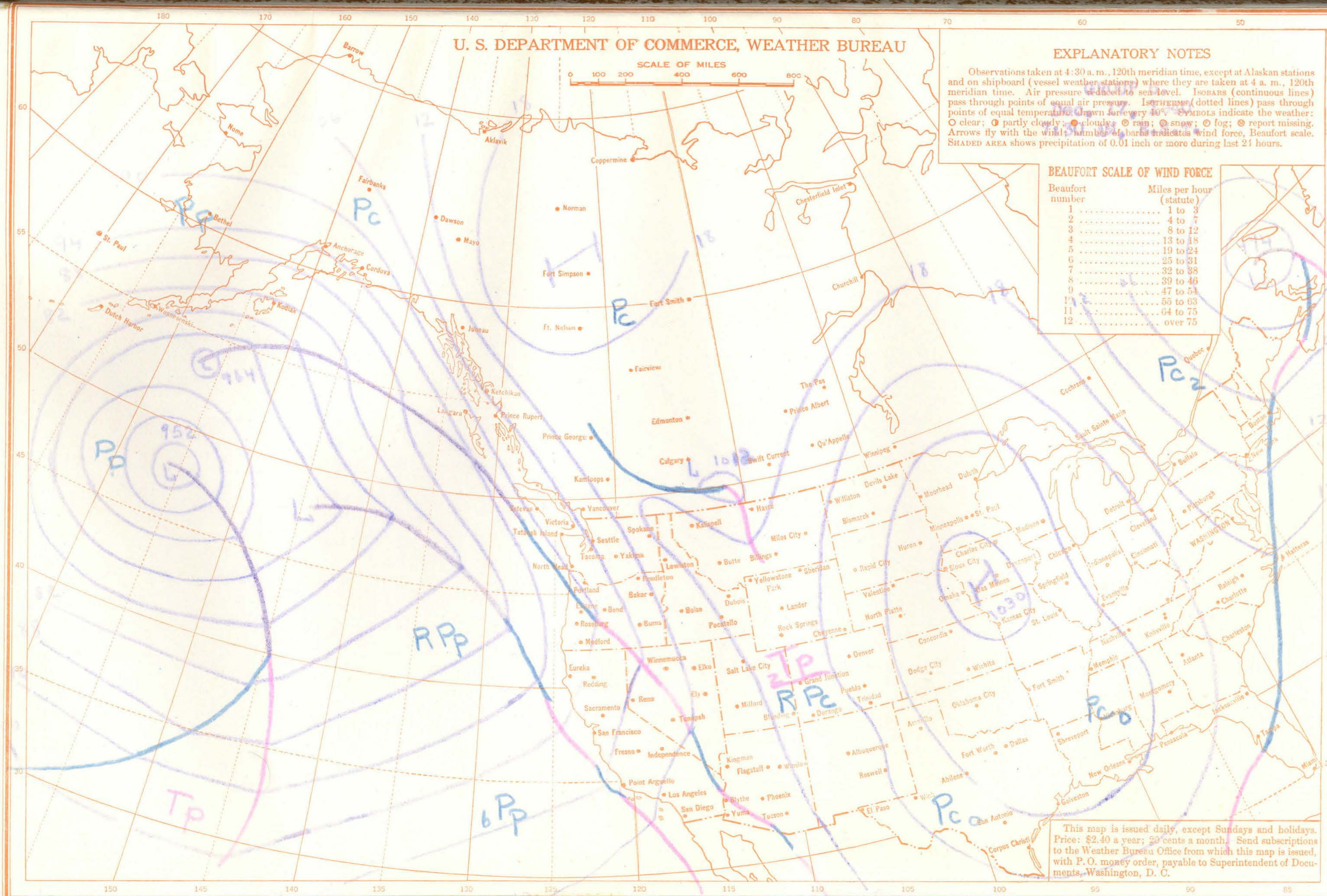

EXPLANATORY NOTES

Observations taken at 4:30 a. m., 120th meridian time, except at Alaskan stations and on shipboard (vessel weather stations) where they are taken at 4 a. m., 120th meridian time. Air pressure reduced to sea level. ISOBARS (continuous lines) pass through points of equal air pressure. ISOTHERMS (dotted lines) pass through points of equal temperature drawn for every 10°. SYMBOLS indicate the weather: ○ clear; ◑ partly cloudy; ● cloudy; ® rain; Ⓢ snow; Ⓕ fog; Ⓜ report missing. Arrows fly with the wind; number of barbs indicates wind force, Beaufort scale. SHADED AREA shows precipitation of 0.01 inch or more during last 24 hours.

BEAUFORT SCALE OF WIND FORCE

Beaufort number	Miles per hour (statute)
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3	8 to 12
4	13 to 18
5	19 to 24
6	25 to 31
7	32 to 38
8	39 to 46
9	47 to 54
10	55 to 63
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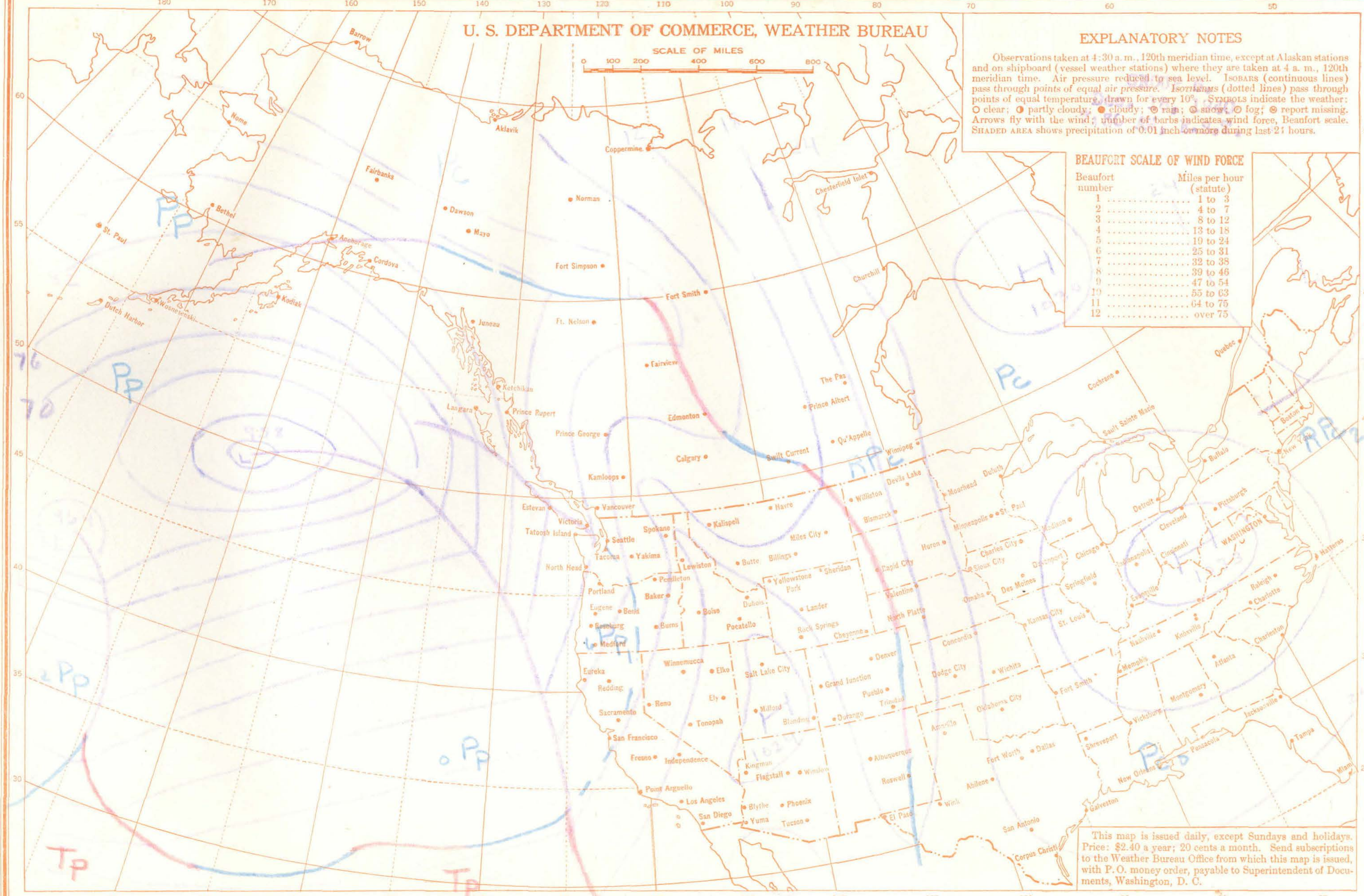

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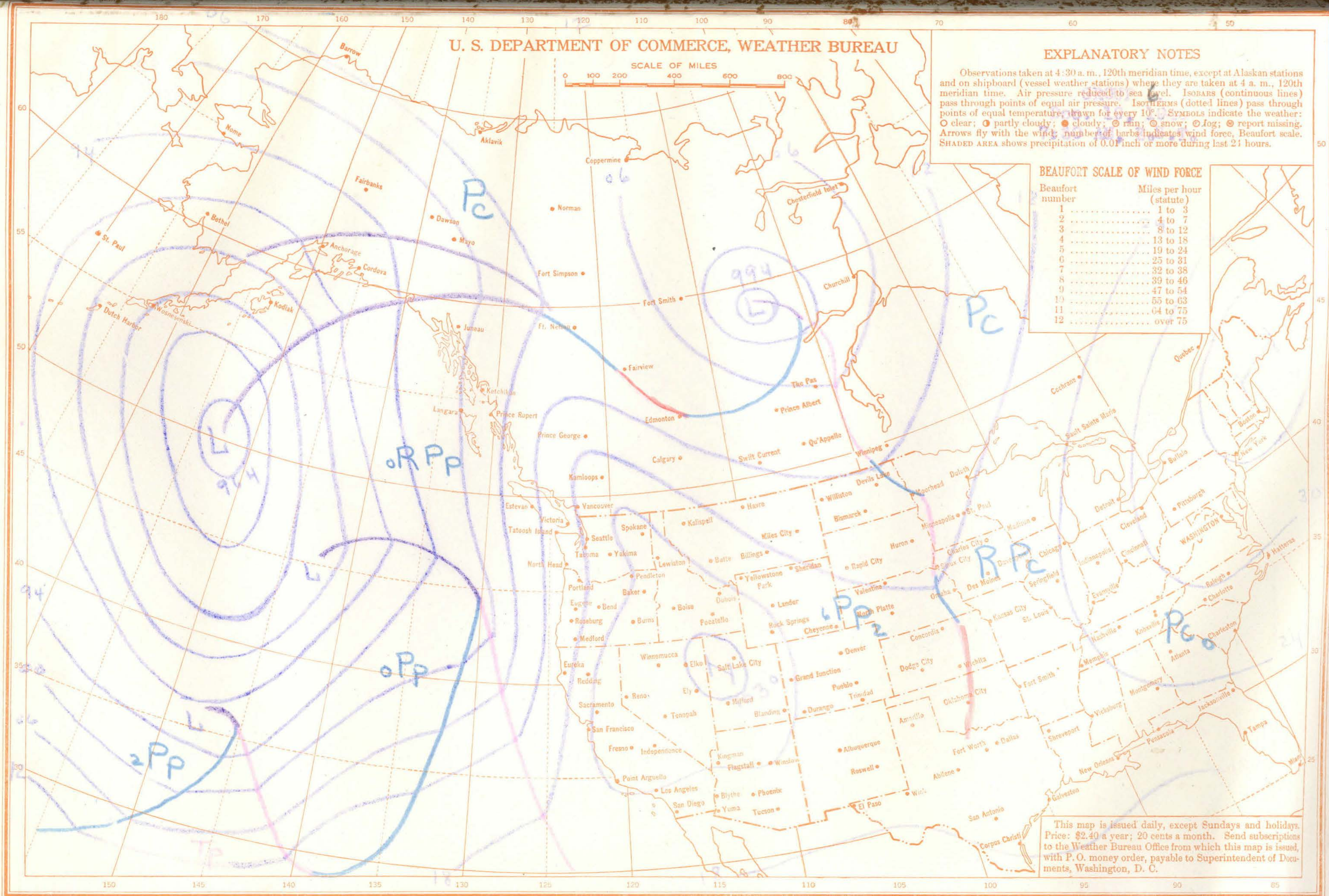
GROUP 7

U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU



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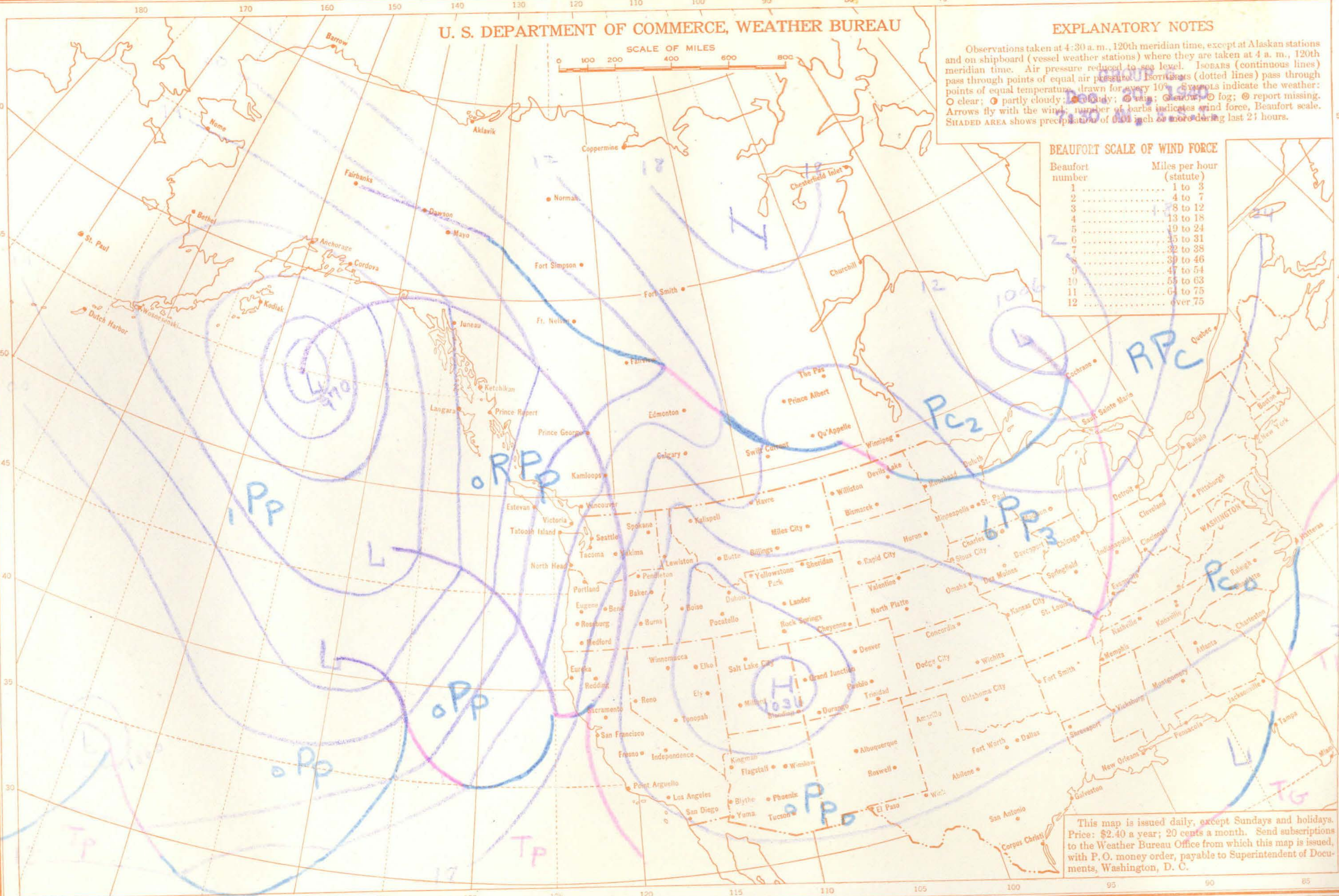
GROUP

U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU



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GROUP 6.
Dec. 20, 1940
7:30 AM, E.S.T.

BEAUFORT SCALE OF WIND FORCE

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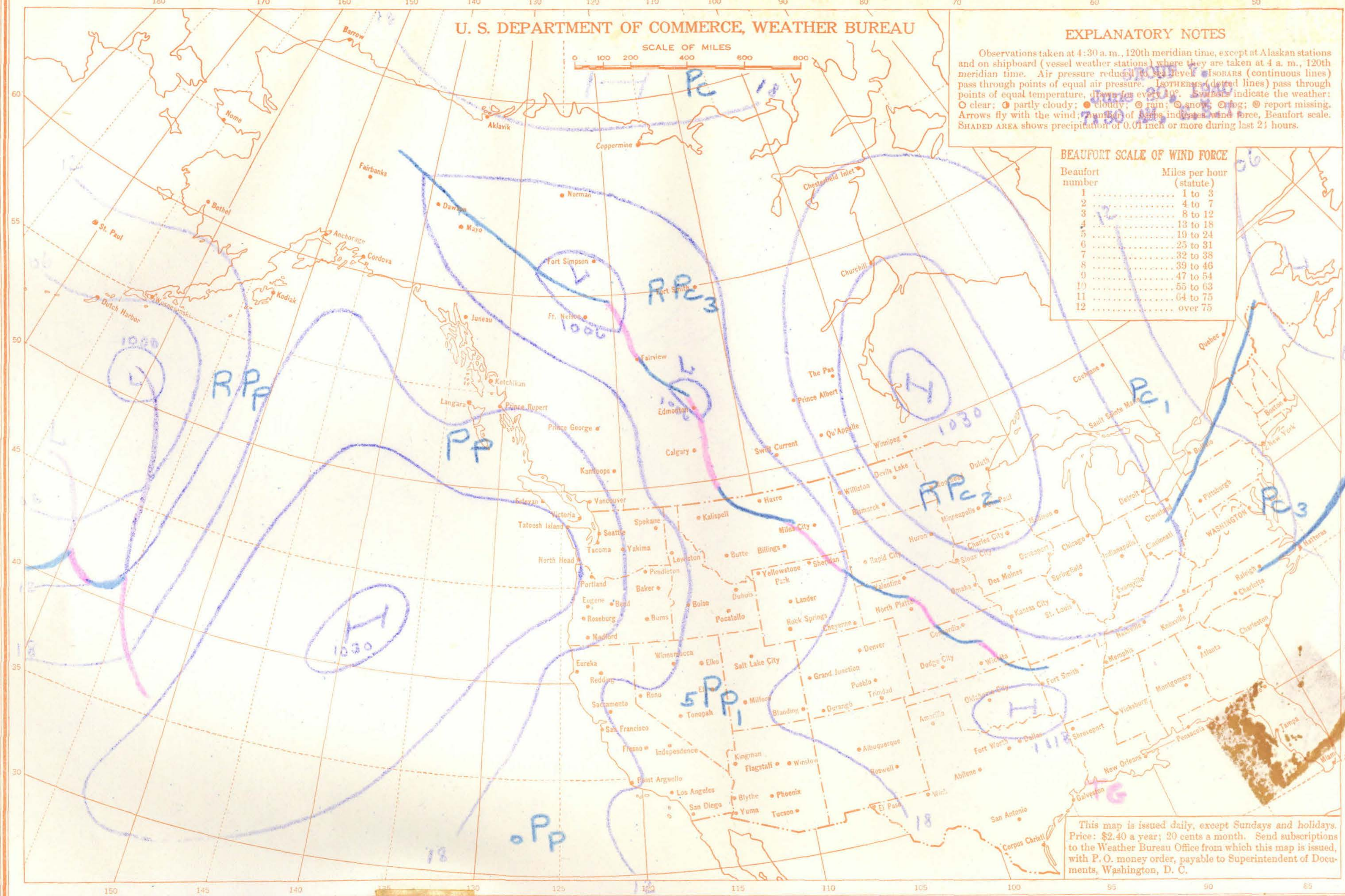

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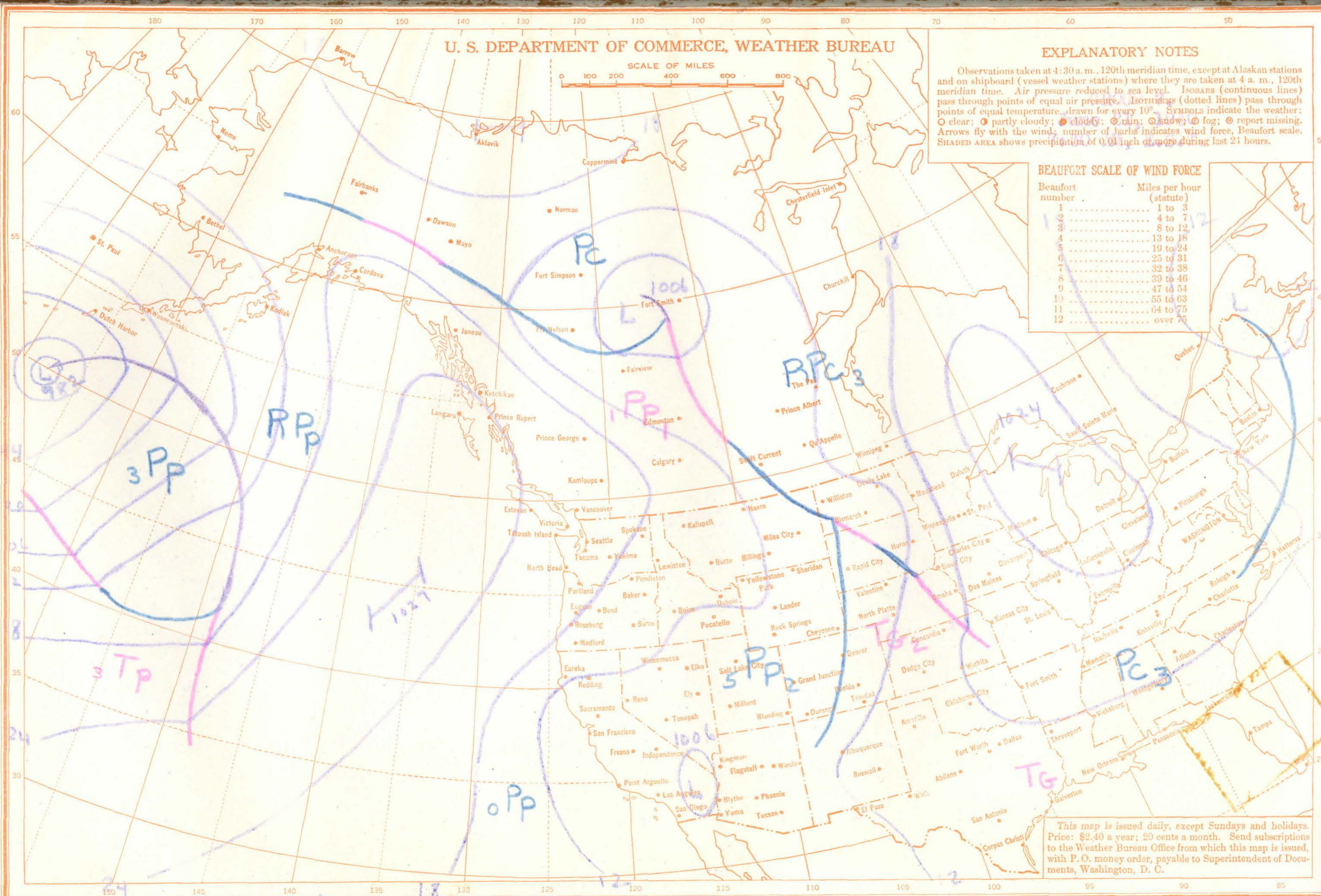

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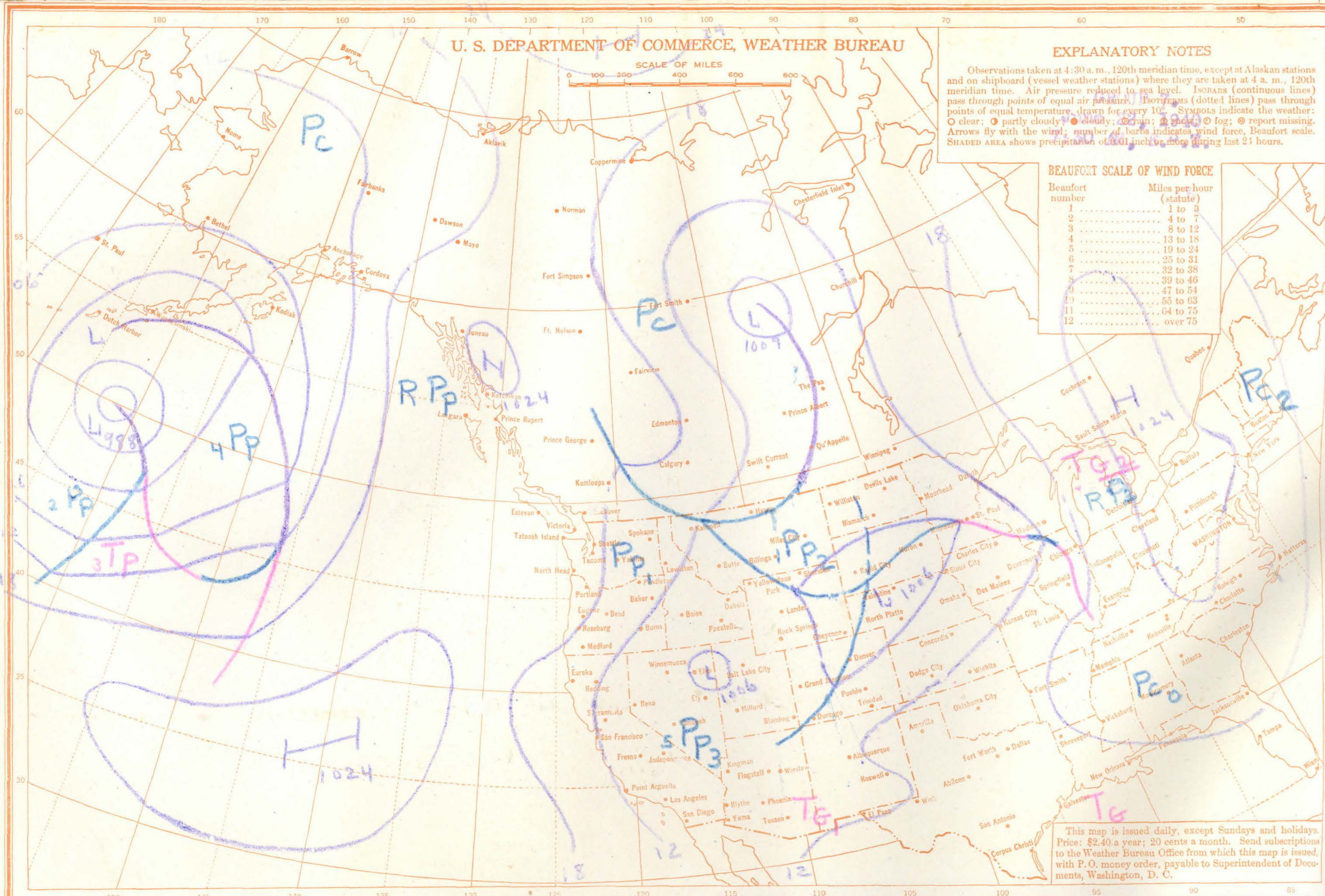

U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU
SCALE OF MILES
0 100 200 400 600 800
EXPLANATORY NOTES
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PART II

TURBULENCE IN THE FRONTOGENETICAL FIELD

Introduction

The purpose of this study is to determine the effects of turbulence in the development and movement of warm fronts between Polar Pacific and Polar Canadian air masses in the Northern Great Plains.

The synoptic situations favorable for the development of this type of frontal system and resulting stable or unstable waves have been outlined in Part I of this paper. Hence, only a few of the general characteristics will be reviewed before taking up the problem of turbulence present in the frontogenetical field.

During the colder months of the year the region east of the Rocky Mountains in the Northern Great Plains becomes a favorable location for frontogenesis and cyclogenesis. This is a result of the intensification of the Pp and Pc currents and the differences in their characteristic properties in the winter season.

With the semi-permanent Aleutian low located in the Gulf of Alaska an intense flow of Pp air is maintained with occlusions entering the British Columbian and Washington coasts at periods of 24 to 36 hours. As this flow continues the Pp air will be forced over the Rockies arriving east of the mountains as a warm dry air mass, heated by loss of moisture and compression in crossing the ranges. This effect produces the foehn winds of this region and aids in the development of warm fronts.

If a Pc air mass is present east of the mountains the Pp air will be forced over the cold air and will continue to overrun it as long as the flow from the Pacific persists. Since both air masses in this development are quite dry and stable there is, usually, only high or intermediate cloudiness produced. Only in cases with a very deep Pc current will there be sufficient lift to cause precipitation.

The Pp current will, in time, be able to displace the Pc air through turbulent mixing and reach the ground, near the divide, forming a surface warm front between the two masses. It is this problem that is to be studied.

Turbulence.

Turbulence can be defined as an irregular motion which appears in fluids when they flow past solid surfaces, or between streams in the same fluid that flow past or over each other. Thus the wind flow in air masses along a frontal surface would be expected to exhibit turbulence.

This turbulent eddy motion between the air masses will cause small bodies of air from one mass to be forced into the other. These bodies of air will carry with them their own properties such as horizontal momentum (velocity) and potential temperature and be absorbed into the other layer. With potential temperature and momentum increasing with height, turbulence will act to transfer heat and velocity downward. Thus in the problem of cold air being overrun by a warmer, more rapidly moving air mass, it would be expected that the temperature and velocity of the underlying air current would be increased at the expense of the current above.

The transport of these properties can be expressed as

$$T = \frac{A\,dq}{dz}$$

Where T is the net transport of the property, A a coefficient measuring the intensity of the eddy exchange, and $\frac{dq}{dz}$ the the rate of increase of the property with height.

With the upper layer moving more rapidly than the layer immediately below it, a frictional force called the shearing stress will be applied to the lower layer. This force can be expressed as

$$\tau = \eta \frac{du}{dz}$$

where τ is the shearing force, $\frac{du}{dz}$ the increase in velocity with height, and η a coefficient measuring the eddy visocity of the fluid.

This expression for the horizontal shearing stress is identical to the equation for the vertical transport of property except for the difference in the coefficients. Thus the downward transport of momentum and temperature is directly proportional to the shearing stress.

The effect of the stability of the atmosphere on turbulence must also be considered. A stable structure will tend to work against the turbulent energy and subdue any eddys produced. Richardson has given a criterion to determine whether turbulence will increase or decrease. He has shown that turbulence will be maintained if the supply of turbulent energy obtained from the kinetic energy of the motion is as great as the work done against the stabilizing forces that tend to subdue the eddy.

The work done by the eddy stresses per unit volume is $\tau_{xz}\frac{\partial u}{\partial z} + \tau_{yz}\frac{\partial v}{\partial z}$

or

$$A\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right].$$

The amount of work done against gravity in unit time for a unit volume is $A g \frac{1}{\theta}\frac{\partial \theta}{\partial z}$.

Thus for turbulence to be maintained or increase

$$A\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] > A g \frac{1}{\theta}\frac{\partial \theta}{\partial z}$$

For application this can be used as

$$\left(\frac{\partial V}{\partial z}\right)^2 > \frac{g}{\theta}\frac{\partial \theta}{\partial z}$$

where $\frac{\partial V}{\partial z}$ is the resultant wind velocity normal to the frontal surface.

Hence, the turbulent activity between a stable Pc air mass and a warmer, overrunning Pp air mass gives the means by which the cold air may be displaced. The displacement would be:

a) Inversely proportional to the stability of the air being displaced.

b) Directly proportional to the amount of shear at the frontal boundary and the warmth of the overrunning air.

<u>Effect of Turbulence in Warm Front Movement.</u>

In applying these criteria for the turbulent removal of cold air to situations as they appear on the daily weather map means of estimating the degree of stability of the cold air being displaced, the amount of shear, and the temperature difference at the frontal boundary must be determined. The actual amount of cold air displaced can be obtained by measuring the depth of the cold air in this region and the distance the warm front has moved during a certain time interval.

In estimating the stability of the cold air being displaced and the temperature change between the two air masses, the temperature difference across the front at the surface was used. In order that representative temperatures can be obtained, the following factors were considered.

1. The diurnal temperature variations in each air mass. This has the effect of showing less temperature difference on the A.M. maps than on the P.M., the evening map giving the most representative values. Any extensive cloud system present, however, tends to counteract the diurnal range of temperature. Hence, both the cloud cover and the evening temperatures were considered in obtaining the temperature values used.

2. Variations due to local conditions and in areas where the ground layer of cold air was not displaced. These effects were most noticeable on the morning maps.

They were accounted for by taking mean temperatures in each air mass.

The amount of shearing force at the frontal surface was estimated by using the pilot balloon data as entered on the synoptic charts. Since the wind velocities are entered in terms of the Beaufort wind scale a mean value of velocity for each Beaufort force was used.

Observations made in the cold air mass being overrun show the change from the low velocity southerly wind in the Pc air to the stronger winds from the west in the Pp air. Components of the wind velocity in each air mass, normal to the frontal surface, were computed and their algebraic difference used to approximate the shear stress. No more than a close approximation of this value can be expected due to the methods of transmitting and entering upper air data.

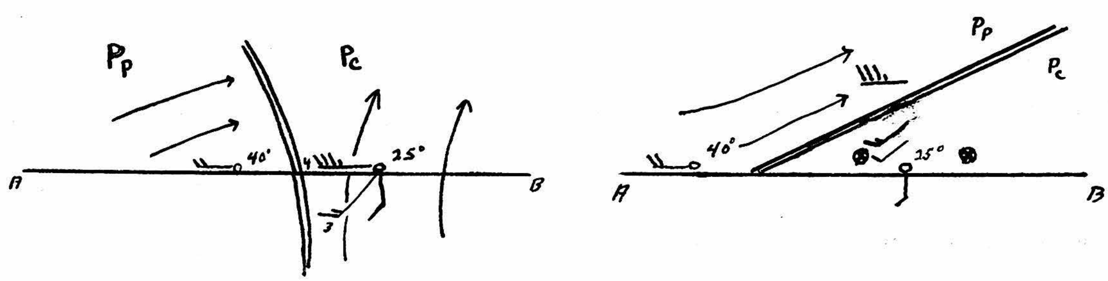
The pilot balloon soundings also indicate the depth of the cold air being overrun. Here again great accuracy is not possible and only the approximate thickness can be determined.

Finally, the rate of turbulent displacement of the cold air was determined from the charts by using the distance the surface warm front moved in a twelve hour period.

The method of determining these various factors and the appearence of a typical warm front situation as observed on the synoptic charts is shown in figure 1. The wind flow in the RPc current is generally from the south and parallels the warm front. The change in direction and velocity of the upper air, and the heights of these changes above sea level, as the warmer air current is reached is indicated. The surface wind and temperature discontinuity is also shown. Figure 1 (b) illustrates the same development in a cross section diagram.

Thus, in this figure, there is illustrated a resultant wind component between the two air masses of about 28 m.p.h., depth of cold air 3000 feet, and a temperature difference of 15 degrees F.

(a) Figure 1 (b)



In order that a large enough number of such developments could be examined so that fairly accurate mean values of displacement would be obtained, synoptic charts for the colder months of three years 1938-39, 1939-40, and 1940-41 were examined.

Table I gives the occurrence of the warm front development between the Pp and Pc air masses by months for these three winter seasons in the Northern Great Plains area. From this table it can be seen that the systems occur when the frontogenetical field east of the Rockies reaches a maximum in intensity in the coldest months. However, in months in which a continued flow of intense Pc air occurs, this development is retarded and in many cases the frontal boundary is moved westward to the Pacific coast. February 1939 and January 1940 illustrate this condition and show little or no frontal development in the region being studied.

Table II gives a summary of the displacement of cold air in a twelve hour period depending on the factors mentioned above, namely:

1. The strength of the resultant wind velocity normal to the frontal surface. This is given in miles per hour.

2. The temperature difference across the front. In making the summary these differences were divided into three groups: 10 degrees or less; 10 to 20 degrees; and greater than 20 degrees.

3. Depth of cold air as indicated by the pilot balloon observations. This was classified as: shallow--2000 feet or less in thickness; moderate--2000 to 8000 feet; and deep--greater than 8000 feet. Since balloon run data is entered in feet above sea level, the values used were corrected to give actual depth of the Pc air mass.

The data as entered in the table shows the average wind velocity necessary for movements in 100-mile intervals, for each classification of depth and temperature difference.

TABLE I

FREQUENCY OF WARM FRONT DEVELOPMENT

	1938-39	1939-40	1940-41	Totals
October	0	8	6	14
November	3	6	8	17
December	4	5	10	19
January	12	4	16	32
February	0	7	9	16
March	7	3	7	17

TABLE II

Average wind velocities in miles per hour for warm front movements as a function of temperature difference and depth of cold air:

Depth of cold air:	2000 ft. or less		2000 to 8000 ft.		
Temp. difference:	0 - 10	10 - 20	0 - 10	10 - 20	20
Distance in miles	Resultant wind velocity in m.p.h.				
0 - 50	--	--	--	12 (5)	--
50 - 150	11 (6)	16 (7)	15 (4)	19 (8)	28 (5)
150 - 250	19 (6)	24 (12)	25 (3)	32 (12)	--
250 - 350	25 (11)	30 (16)	31 (5)	39 (2)	--
350 - 450	35 (4)	40 (5)	--	--	--
450 - 550	42 (4)	52 (2)	--	--	--
>550	50 (1)	--	--	--	--

TABLE III

The number of observations in each group are indicated in parentheses in the table above. From the summary the following conclusions can be made:

(a) With a shallow Pc air mass and small temperature difference (2000 feet and 10 degrees or less) the warm front will move at a velocity approximately equal to the resultant wind component.

(b) With depth of Pc current 2000 feet or less and temperature difference 10 to 20 degrees the distance moved will be about 8/10 of the resultant wind component.

(c) Moderate Pc air mass and small temperature difference (depth 2000 to 8000 feet, and 10 degrees or less) the displacement will again be about 8/10 of the resultant wind component.

(d) With depth 2000 to 8000 feet, temperature difference 10 to 20 degrees, the movement will be about 6/10 of the resultant wind component.

(e) Depth 2000 to 8000 feet, temperature difference greater than 20 degrees, the movement will be about 3/10 of the resultant wind component.

In shallow Pc air masses being overrun no temperature differences of more than 20 degrees were observed. With deep Pc currents of thickness greater than 8000 feet, no movement of the warm front was observed.

Table III gives the number of observed displacements in each category as given in Table II. This indicates that the usual movement of the warm front with a shallow cold air mass being overrun is of the order of 200 to 300 miles; with moderate depth of the cold air the distance is 100 to 200 miles in a twelve hour period.

With the increased stability during the night in a Pc air mass it would be expected that the movement of the warm front from the evening to the morning map would be reduced below that observed during the day, other factors being the same. Also the possible effect of insolational heating of the Pc air mass being overrun, and giving a very rapid warm front movement during the day must be considered.

To see if these effects could be noticed within the groups of displacement values given in Table II, the movements of the fronts from the morning and evening maps were summarized separately. In cases with sufficient number of observations to give a fairly accurate mean value the data indicated a movement of 10 to 20 miles further during the day. This is shown below:

Average distance moved in 12 hrs.	50 - 150	150 - 250	250 - 350
Increased distance moved during day hours (in miles)	9.6	20.2	11.5

The Weather Development of November 13 to 17, 1940.

The weather development from November 13 to 17, 1940 is an interesting case of the type of warm front that has been discussed. It is reviewed in some detail to show the magnitude and speed of the weather changes that occurred as the warm front and wave that developed moved across the entire country. Figures 2, 3, 4, 5 and 6 show the movement of the frontal system during this period.

On November 13 almost the entire country was covered by a Pc air mass extending to west of the Pacific coast. In the northeast Pacific Ocean and Gulf of Alaska a series of occlusions had been approaching the Alaskan and British Columbian coasts for several days. The front associated with the first of this family of cyclones entered the coast on the morning of the 12th. By the following morning this front was located in central Alberta and extended into the Northwest Territory.

By the 14th the occlusion of the previous day had developed into an extended warm front from the Northwest Territory to Denver, Colorado with two small waves, one near Sheridan, Wyoming, and the other in southwestern Saskatchewan. The temperatures in the Pc high over the Dakotas and Nebraska were 8 to 10 degrees below zero, while west of the warm front the temperatures were in the low thirties. The Pc air mass west of the Rockies was still present at the surface but was being overrun by the Pp air under the influence of the frontal systems entering the coast. This is shown by the θ_e values for the RAOB flight made at Sand Point on the 14th increasing from 275° at the surface to 303° at 1900 meters.

By the morning of the 15th the warm front had moved to a north-south line from a weak center in northern Manitoba through the Dakotas, Nebraska, and Kansas. Temperatures west of the front had risen to 30 to 40 degrees while to the east the temperatures range was from 2 to 7 degrees. The high wind velocities in the Pp air prevented the formation of waves along the front and indicated the intensity of the flow of air from the Pacific. The sounding at Sand Point showed θ_e values of 285° at the surface increasing to 303° at 1100 meters and indicated the increase in the warmth and moisture of the Pp air.

The morning map of the 16th shows the further movement of the warm front from the low center north of Lake Superior SSW to the Texas Panhandle. The maintenance of the flow of Pp air and absence of any cold air in northern Canada had prevented the occlusion of the frontal system and had continued the rapid displacement of the cold air. By this time the overrunning ahead of the warm front had reduced the Pc air to a shallow layer with temperatures only slightly lower than those in the Pp mass.

On the 17th the front was located in the Eastern Great Lakes and with the slight temperature differences and stable wave system it moved rapidly, passing off the eastern coast by that evening.

It is interesting to note the persistence of the high pressure system in the Great Basin area during the warm front development. It is characteristic of this weather situation and is present whenever an active warm front forms east of the Rockies. Its aid in maintaining the flow of air from the Pacific due to its circulation, and in heating the air through subsidence is readily seen.

Another interesting feature during this type of front development is observed through the examination of the soundings taken at Medford and Sand Point during the winter season of 1940-41. A comparison of the values of the equivalent potential temperatures on the day before and the day of formation of the warm front east of the Rockies with the values observed during the other days gave the following results:

Average values of θ_e:

	2 - 4 km.	4 - 6 km.
During warm front formation	306	312
All other days	299	305

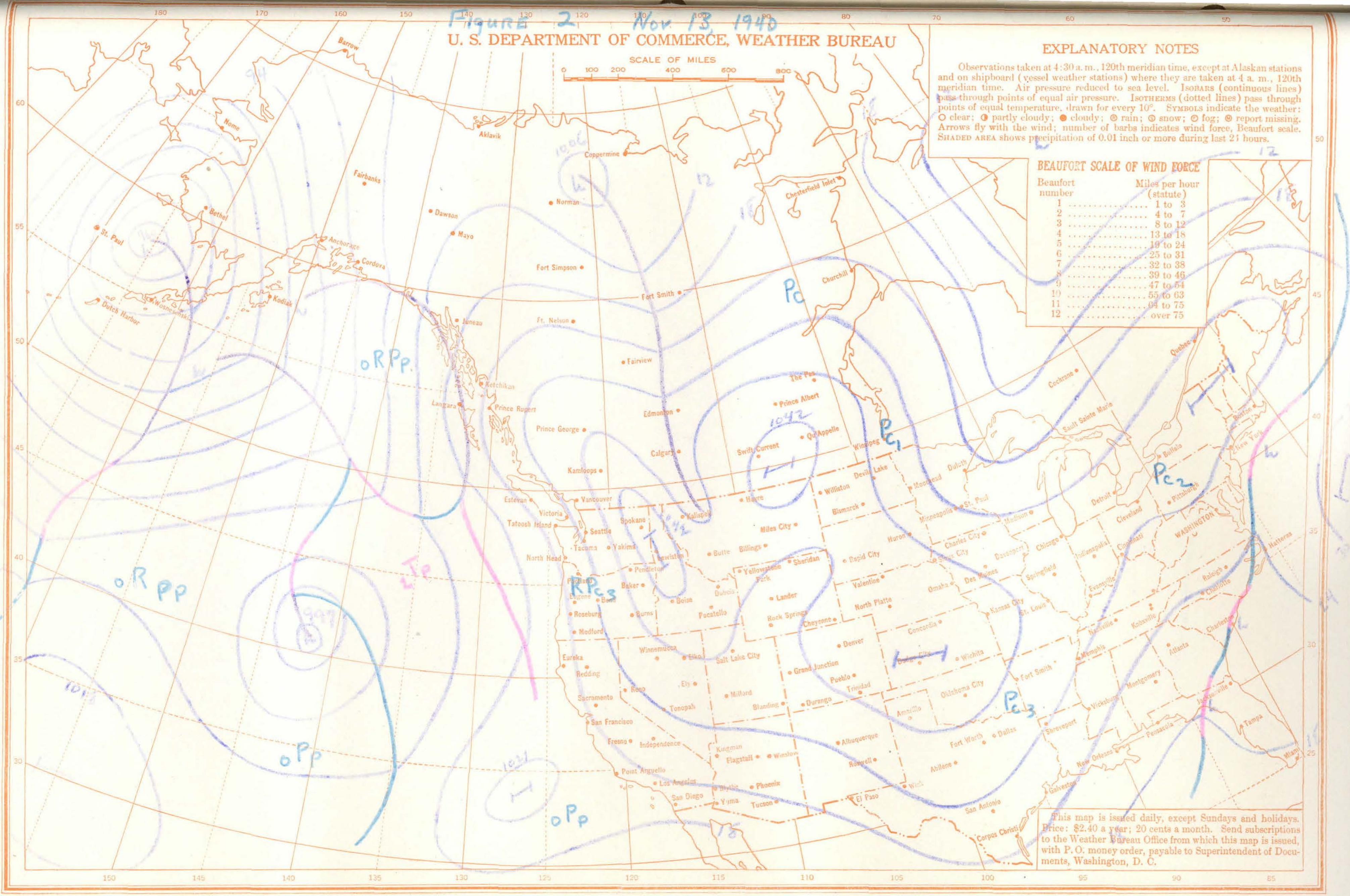


Figure 2 Nov. 13, 1940

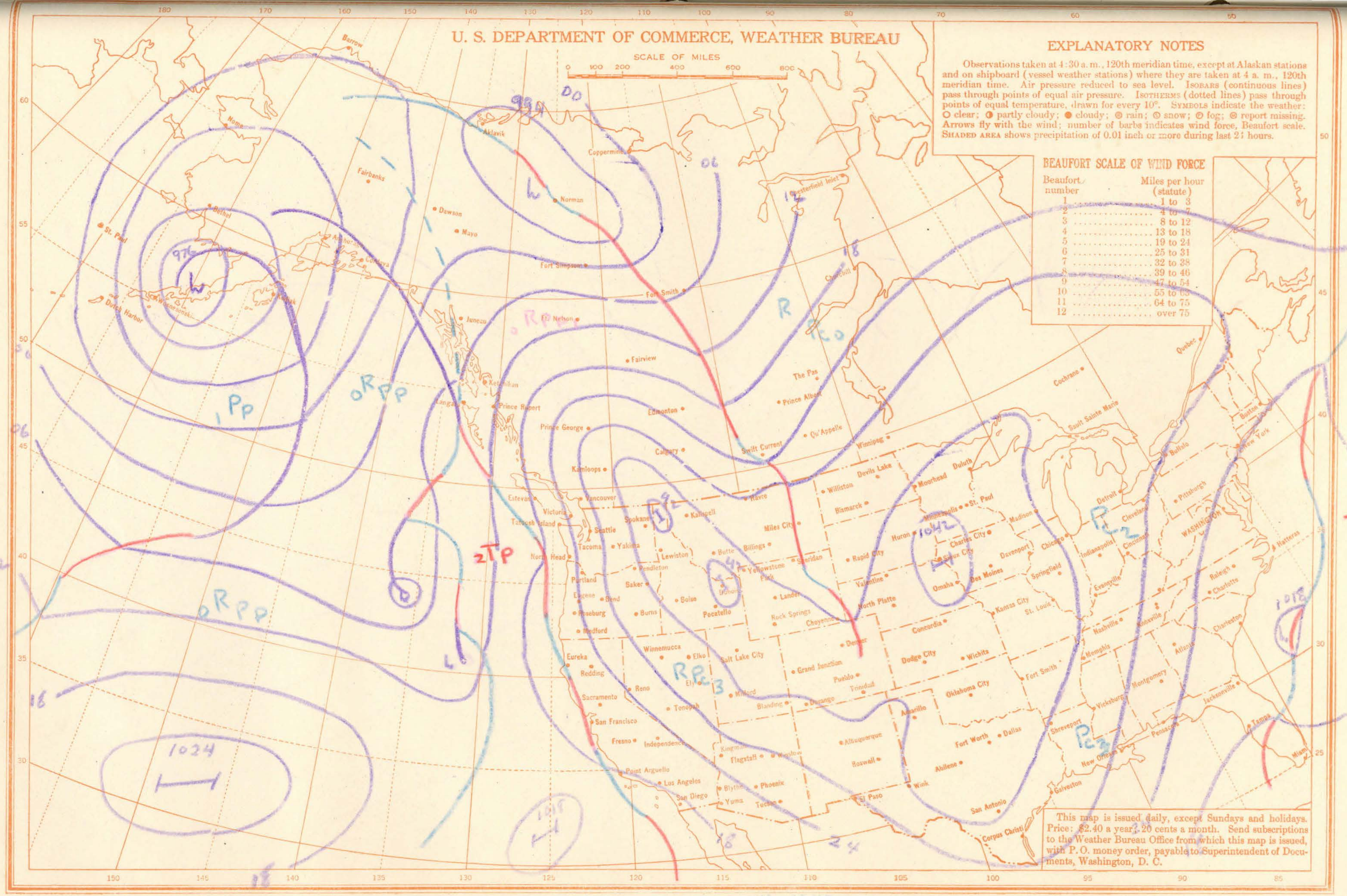


Figure 3 Nov. 14, 1940

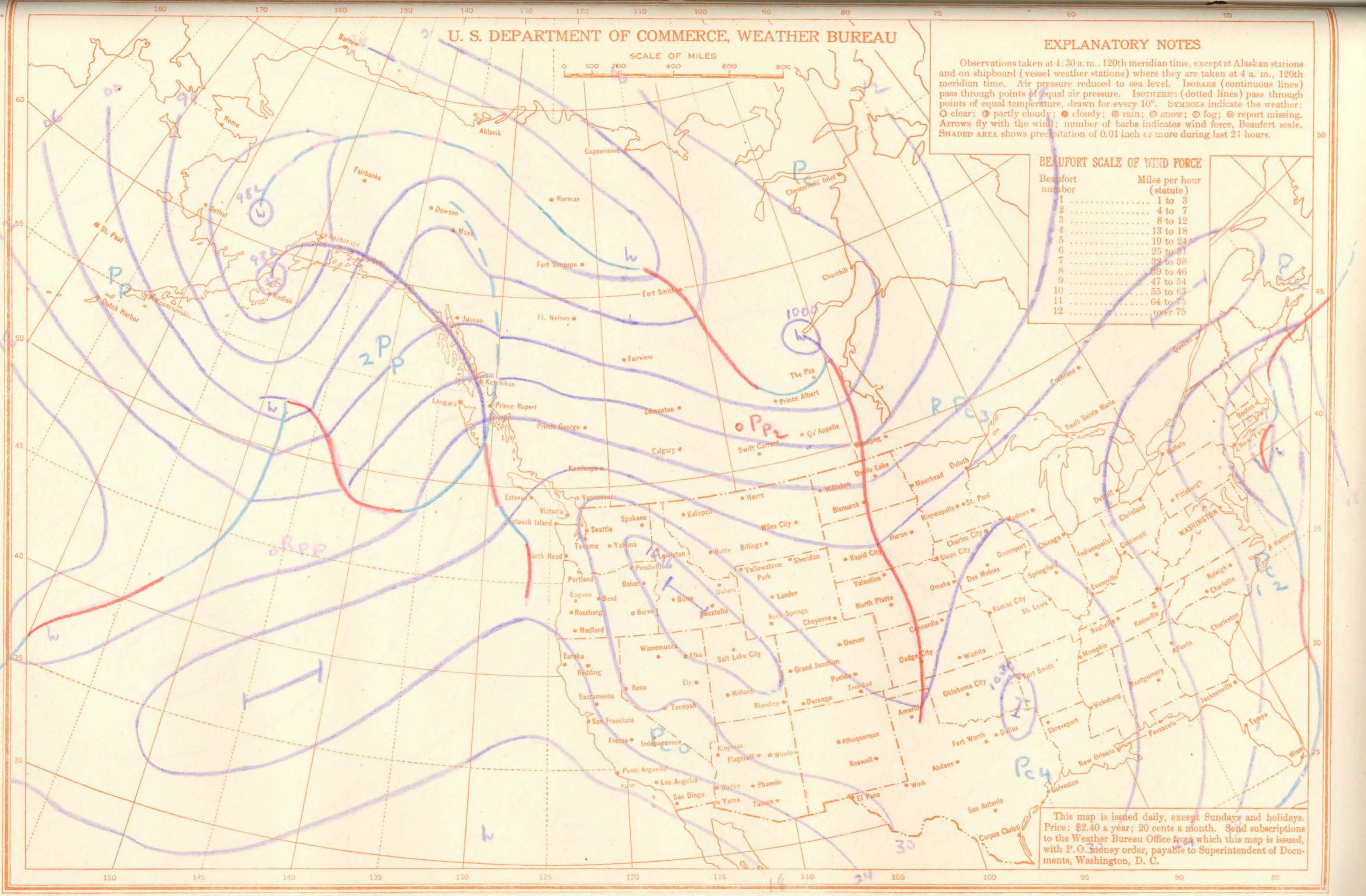


Figure 4 Nov. 15 1940

18

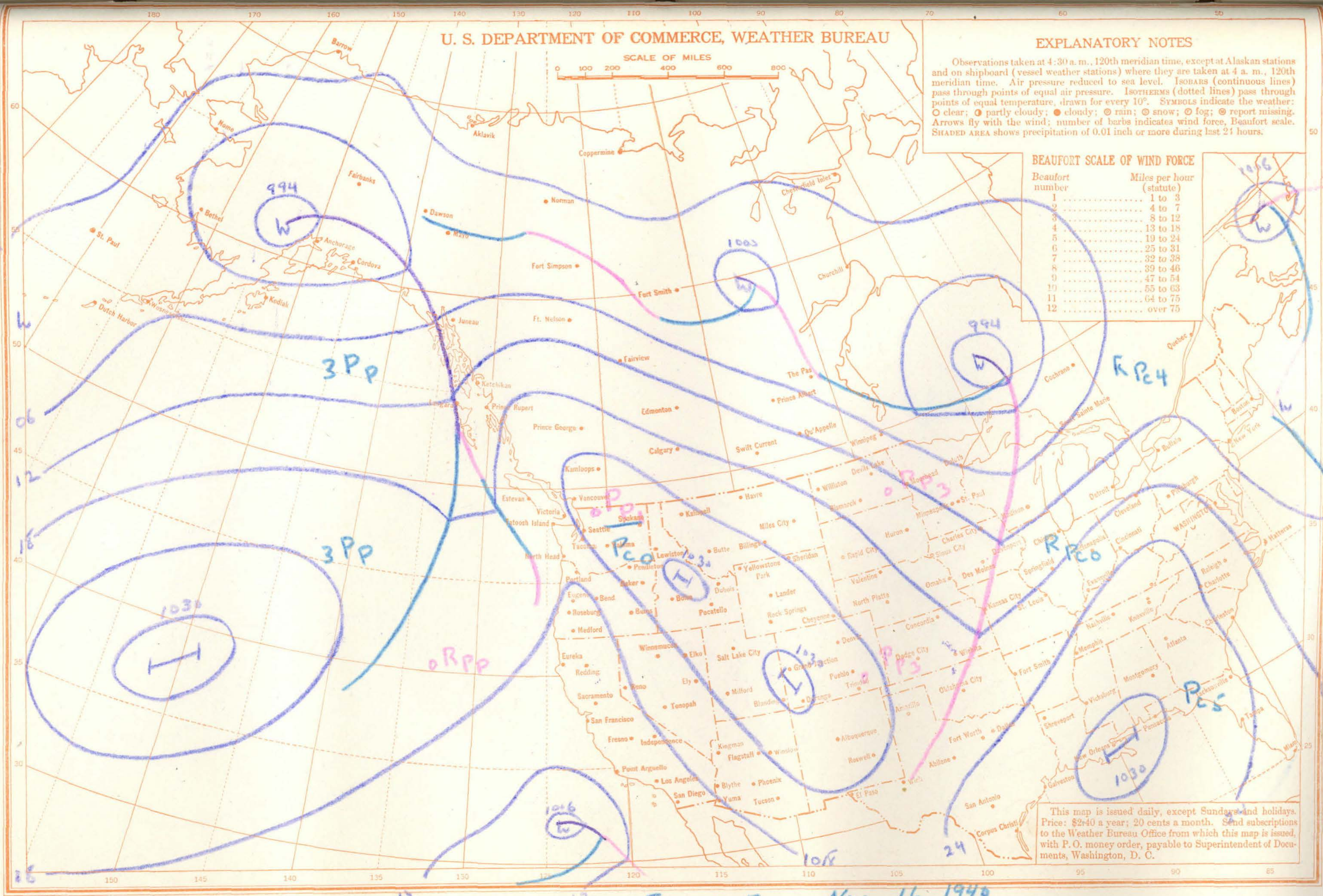


Figure 5 Nov. 16, 1940

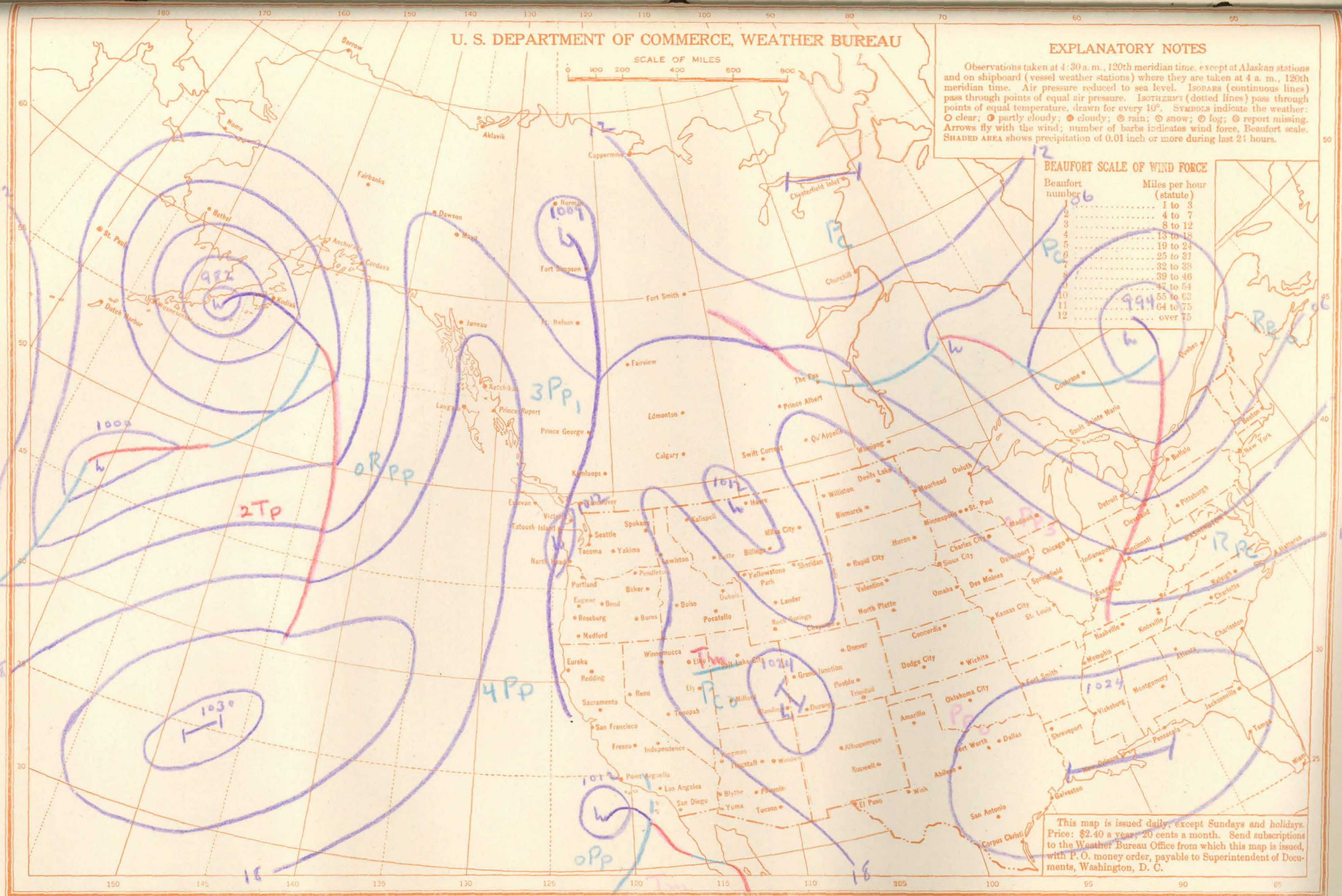


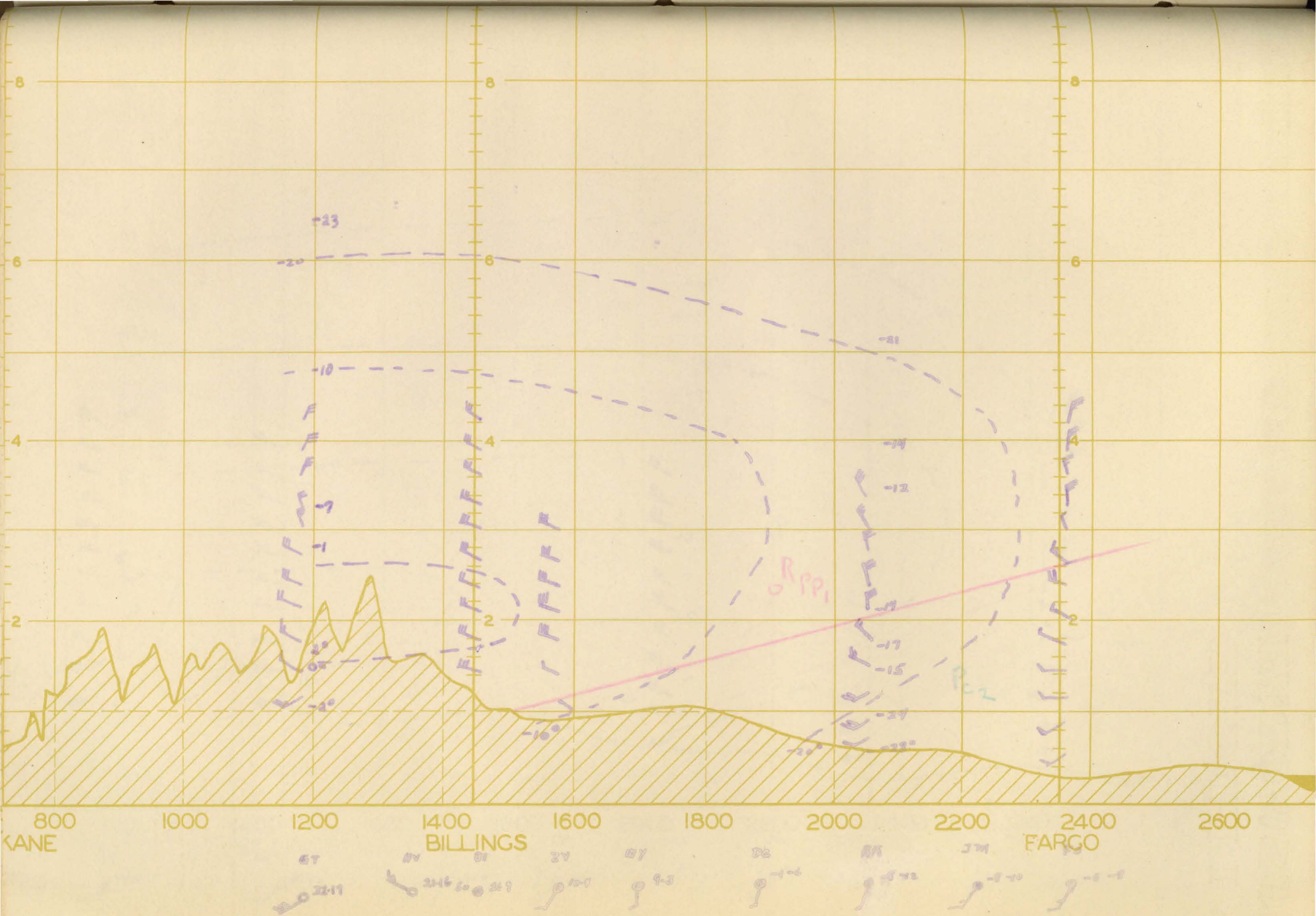
Figure 6 Nov. 17, 1940

Hence, the amount of moisture and warmth of the Pp air is a good indication of the warm front development.

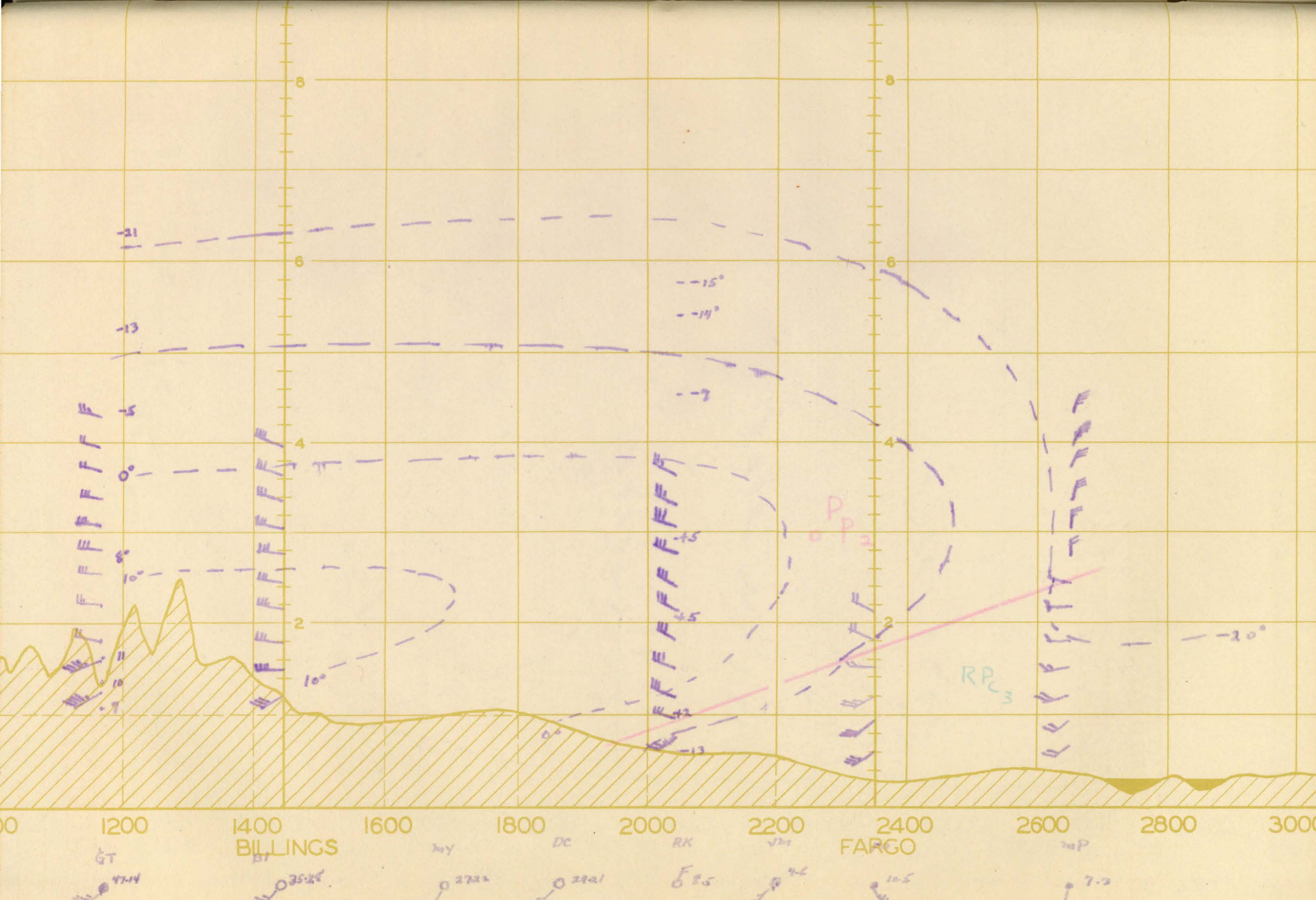
By using cross section charts the warm front movement and weather changes in the Great Plains region during the 14th and 15th of November can be shown to best advantage. Three such diagrams are included showing the structure from Great Falls to Bismarck on the 14th; Miles City to Minneapolis on the 15th; and from Denver to Moline on the 15th. (Diagrams 7, 8, and 9.)

The charts show the frontal surface, the wind and temperature changes across the front, aloft, and at the surface. A comparison of the two cross sections through the Northern Great Plains shows the changes that occurred in wind and temperature values during the 24-hour interval. The cross section through Omaha shows conditions further south and the subsequent location of the frontal surface on the 16th.

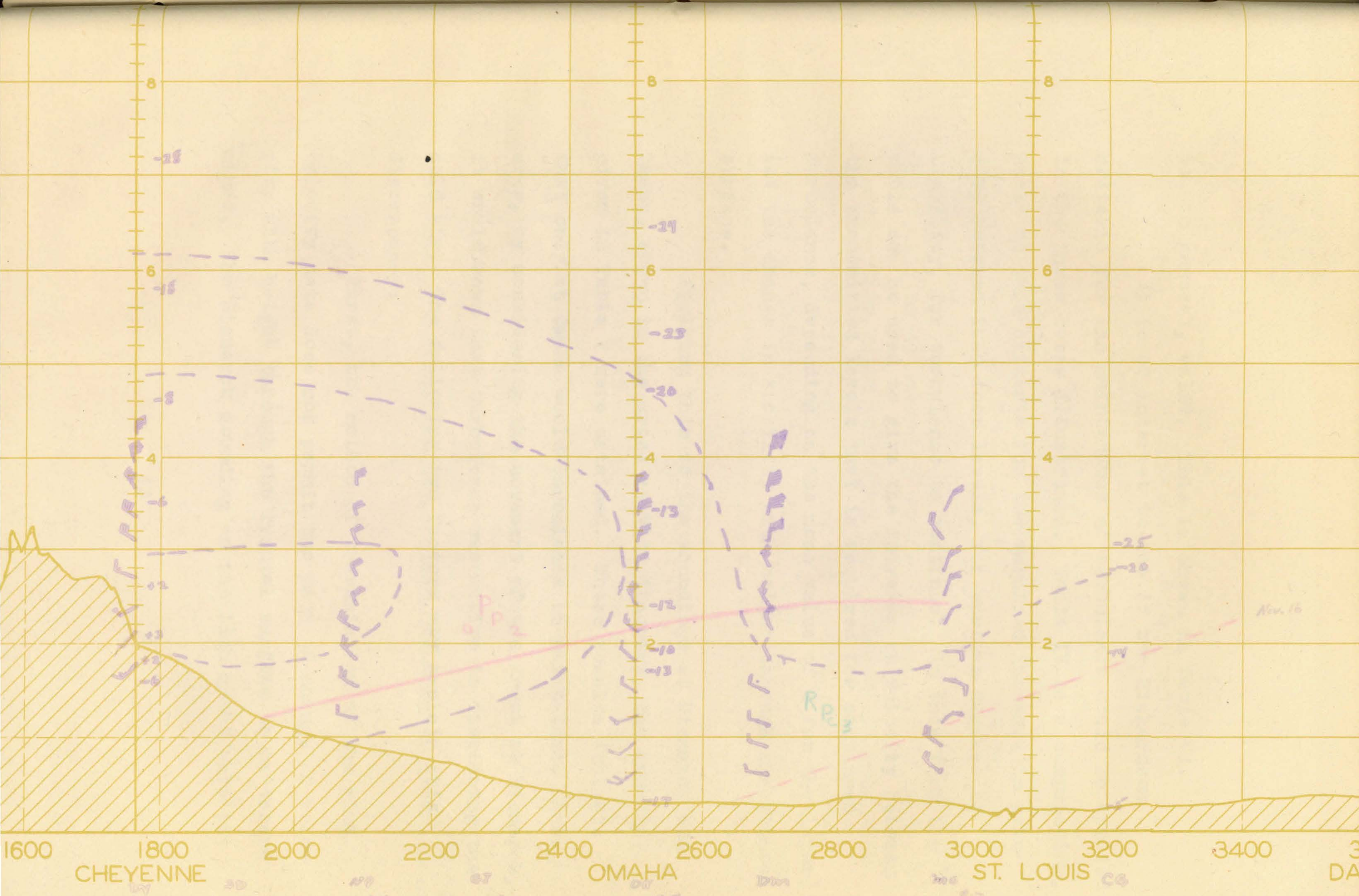
In section III the assumption was made that the value of the temperature difference across the front approximates the change in temperature across the front aloft. A comparison of the temperatures across the front at the surface and at the frontal boundary aloft at Bismarck and Omaha on the 14th and 15th shows that the assumption



November [illegible] 1940 Figure 7



November 15, 1940 Figure 8



November 16, 1940 Figure 9

is, in general, valid. This is shown in Table VI.

It is of interest to see if the Richardson criteria for the maintenance of turbulence could be applied in the three cases illustrated. Table IV is a computation, based on this criteria for the required increase in velocity between 1000 foot levels, for various degrees of stability, for turbulence to continue. In this form the table can be used to give the increase in velocity between the transmitted levels that is required for continued turbulence, depending on the mean value of θ for the layer, and the change in stability with height through the frontal surface.

Applying this to the soundings at Bismarck and Omaha, shown in the cross section diagrams, the results given in Table V were obtained. These results indicate that only at Omaha would turbulence be maintained. However, by considering the movement of the front at Bismarck, it would seem that turbulence was active in displacing the cold air. The following two factors may explain this discrepancy:

First, the method of transmission of the wind velocity data does not permit the rate of change of velocity with height through the frontal surface to be determined. The Bismarck sounding on the 14th shows velocity values of 13 m.p.h. at 5000 feet; 16 at 6000; 25 at 8000; 28 at 8000; and 32 at 9000 feet. Hence, it is quite possible that a different selection of levels could give the required velocity change of 13 m.p.h. to maintain turbulence.

Second, on the morning of the 15th the warm front was quite close to the Bismarck station. Thus the value of $\frac{d\theta}{dz}$ across the frontal surface includes the stable ground layer, giving an extremely stable layer of air to be displaced. This illustrates the case in which the cold air would not be removed, the warm air gliding over the top leaving it undisturbed. However, with the surface heating during the day this shallow layer would soon be destroyed.

TABLE IV

The increase in velocity necessary between 1000 foot levels, for various degrees of stability, for turbulence to continue:

θ \ $d\theta$	1	2	3	4	5	6	7	8	9	
270	7.2	10.5	12.9	14.9	16.7	18.2	19.7	21.1	22.3	m.p.h.
310	6.6	10.0	12.1	13.8	15.6	16.9	18.4	19.7	20.9	m.p.h.

TABLE V

The application of Table IV to soundings at Bismarck and Omaha:

	RK Nov. 14	RK Nov. 15	OH Nov. 15
Observed data $\frac{d\theta}{dz}$	3	12	2
Observed data $\frac{dv}{dz}$	10 m.p.h.	15 m.p.h.	11 m.p.h.
Necessary value for turbulence $\frac{dv}{dz}$	13 m.p.h.	22 m.p.h.	10 m.p.h.

TABLE VI

Comparison of temperatures across the front aloft and at the surface:

	RK Nov. 14	RK Nov. 15	OH Nov. 15
Temperature difference aloft	9° F.	27° F.	4° F.
Temperature difference at surface	11° F.	21° F.	6° F.

Obviously, then this criterion cannot be used to determine the increase or decrease of turbulence with the available upper air data. It does, indicate, however, the order of magnitude of the wind gradients necessary for turbulence and is useful in this respect.

Conclusion.

From this study the following conclusions can be made:

(a) The rate of turbulent removal of cold air and the movement of the associated warm front east of the Rockies, as a function of the resultant wind component normal to the front, the depth of the cold air, and the temperature difference across the front, can be determined from the synoptic charts.

(b) The movement of the warm front during the day is only slightly greater than during the night.

(c) Richardson's criterion gives the correct order of magnitude of increase in velocity with height for turbulence to continue.

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