Propagation of thunderstorms: a review

Ruedy, R.

https://doi.org/10.4224/21273338

NATIONAL RESEARCH COUNCIL OF CANADA

PROPAGATION OF THUNDERSTORMS
A REVIEW

BY

R. RUEDY

RESEARCH PLANS AND PUBLICATIONS SECTION

OTTAWA

JULY, 1945

PRICE 25 CENTS

N. R. C. NO. 1321

C O N T E N T S

F O R E W O R D

It is customary to consider a thundershower as the result of the excessive growth of a cumulus or a cumulo-nimbus cloud, that is, as the result of the condensation of moisture in a vast column of vertically rising moist air. On the average the entire column is perhaps 40 miles long and 20 miles wide; the base is one mile, the top five or even six miles above the ground; the cloud is contained in a long band of other clouds that may reach across the continent, from the Gulf of Mexico to Hudson Bay. At the lateral boundaries dried and cooled air descends to earth.

From the practical point of view, however, the most important feature of this overgrown cloud is not alone its size but its travel east or notheast across the country, in summer at the average rage of 20 to 30 miles an hour, and the fact that the rising motion is sometimes maintained or renewed for a few hours in succession.

When it becomes necessary to take precautions against approaching storms, be it in order to fight forest fires or to cope with damage to transmission lines caused by lightning, information must be available on the propagation and size of the storm. The most reliable information is secured, at present, by telephonic warnings from a grid of stations, which report when the first thunder is heard-lightning flashes may escape detection during daylight hours. By plotting these points on a map, the front of the storm(isobront) may be traced, and from successive reports its advance deduced. The number of stations that must be established if such a warning service is to be provided can be judged from the descriptions, in the text, of the propagation of thunderstorms.

The usefulness of these maps is not restricted to the geographical areas shown on them, since the general pattern of storm distribution and movement is quite similar all over the world.

Hence, it is hoped that this review, which is based largely on reports of thunderstorms in American and European countries, will be found of interest and value to Canadian electrical and hydraulic engineers.

1. Introduction

Interest in the study of the propagation of thunderstorms in North America was at its height 50 or 60 years ago, not long after the first definite announcement had been published that in temperate and northern latitudes thunderstorms have a definite position relative to low pressure centres(Marié-Davy, in Davis, p.57), a conclusion later confirmed, but only in part, by other European services and by H.A. Hazen in the United States. The observation of thunderstorms was chosen as a special subject of investigation by the New England Meteorological Society during the summers of 1885 and the years 1886 and 1887. Financial assistance was given by the U.S. Army Signal Corps and the Bache Fund of the National Academy of Sciences. About 300 observers kept records throughout the summer or throughout the year, mainly in central and eastern Massachusetts. Depending upon the smaller or greater number of records received for the same storm, the time of rain beginning was charted on maps six miles to one inch, or 17 miles to one inch, or 35 miles to one inch. If the progression of the rain front appeared clearly, lines showing its probable position at various times of the day were drawn; these lines enabled determinations of the direction and velocity of the storm to be made.

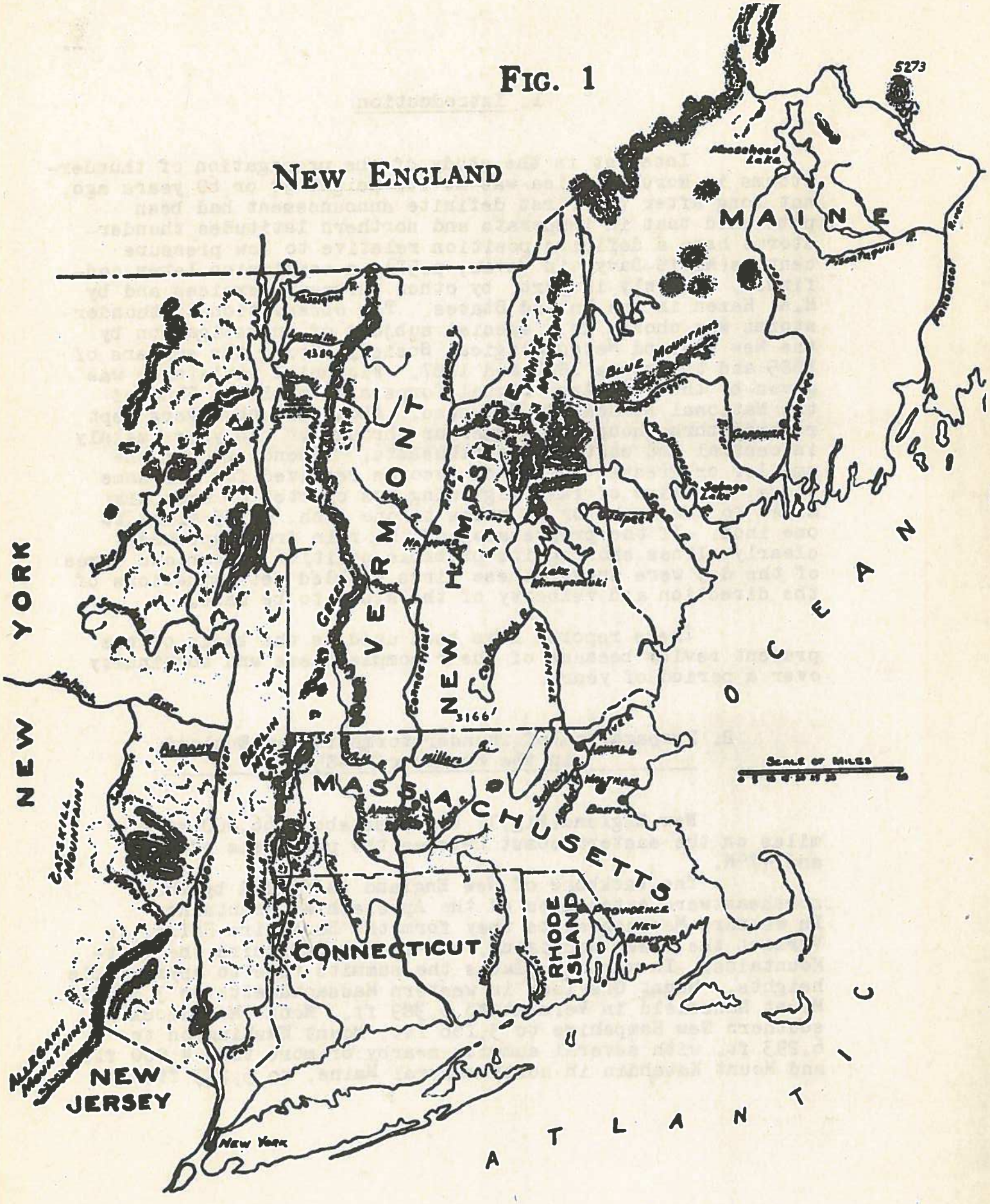
These reports have been used as the basis of the present review because of their completeness and continuity over a period of years.

2. Propagation of Thunderstorms in New England in the Summer of 1885.

New England(Fig.1) occupies about 66,000 square miles on the eastern coast between the parellels of 41°N and 47°N.

The backbone of New England is formed by the northeastward extensions of the Appalachian Mountains. In western Massachusetts they form the Berkshire Hills, in Vermont the Green Mountains, and in New Hampshire the White Mountains. In various places the summits rise to appreciable heights. Mount Greylock in western Massachusetts to 3,535 ft., Mount Mansfield in Vermont to 4,389 ft., Mount Monadnock in southern New Hampshire to 3,166 ft., Mount Washington to 6.293 ft. with several summits nearby of more than 4,000 ft., and Mount Katahdin in north central Maine, to 5,273 ft.

FIG. 1


NEW ENGLAND
MAINE
VERMONT
NEW HAMPSHIRE
MASSACHUSETTS
CONNECTICUT
RHODE ISLAND
NEW YORK
NEW JERSEY
OCEAN
ATLANTIC
5273
4389
3166'
Mount Katahdin
Moosehead Lake
Penobscot River
Androscoggin River
Kennebec River
Lake Winnipesaukee
Connecticut River
Merrimack River
Hudson River
Mohawk River
Albany
Boston
Providence
New Bedford
New York
Catskill Mountains
Adirondack Mountains
Allegany Mountains
Berkshire Hills
Green Mountains
White Mountains
Blue Mountains
Scale of Miles

Hilly sections, less than 500 ft. above sea-level, form the transition zone between the mountains and the coastal lowland, which varies in width from a few to 100 miles.

The ocean has a dominant influence on a narrow coastal belt only. Occasionally a sea breeze may blow inland for 30 or 40 miles, but the temperature effect vanishes within 10 miles of the ocean, because the shallow wind becomes heated, or cooled, by the land. In eastern Maine, there is a region, just back from the coast, having an altitude higher than 500 ft. and an area of 1000 square miles; its average temperature differs from that of the remaining coastal belt(Church).

A large part of southeastern Massachusetts around Taunton and Middleboro also has temperatures different from those of the neighbourhood on account of the presence of swamps which stay cool and dry out slowly in spring and summer.

The mean winter temperatures differ by more than 22°F. at Van Buren 10.6°F., and at Nantucket 32.9°F., a contrast caused by the frequency of northwest winds during this season. In summer there is only a small difference(8°F.) in temperature from north to south. Southwest winds prevail at this season.

The average precipitation(48 year average) is 41.75 in. Hanover, N.H. and Burlington, Vt., have low values and may represent stations sheltered by the Green Mountains(Hanover) or the Adirondack Mountains(Burlington).

During the first days of the month of June, 1885, an area of low pressure, advancing from southern Michigan to the New Jersey coast, brought the first thunderstorm of the season to southwestern Connecticut and central Rhode Island (Davis).

During the second week of June, New England was occupied by a high-pressure area coming from the northwest, while from 11 to 15 June, 1885, a low-pressure centre descended the St. Lawrence valley. Another low-pressure centre appeared on 16 June, 1885, over Lake Superior and led to a storm of small size that arose around two o'clock on that day in northeastern Connecticut and moved eastward across northern Rhode Island and southeastern Massachusetts at a rate of about 35 miles per hour.

Between 17 and 21 June, 1885, a high-pressure area moved from the Mississippi valley to the Middle Atlantic coast, and another followed this path between 23 and 25 June.

Then, on the morning of 27 June, 1885, an area of slightly diminished pressure appeared north of Lake Superior

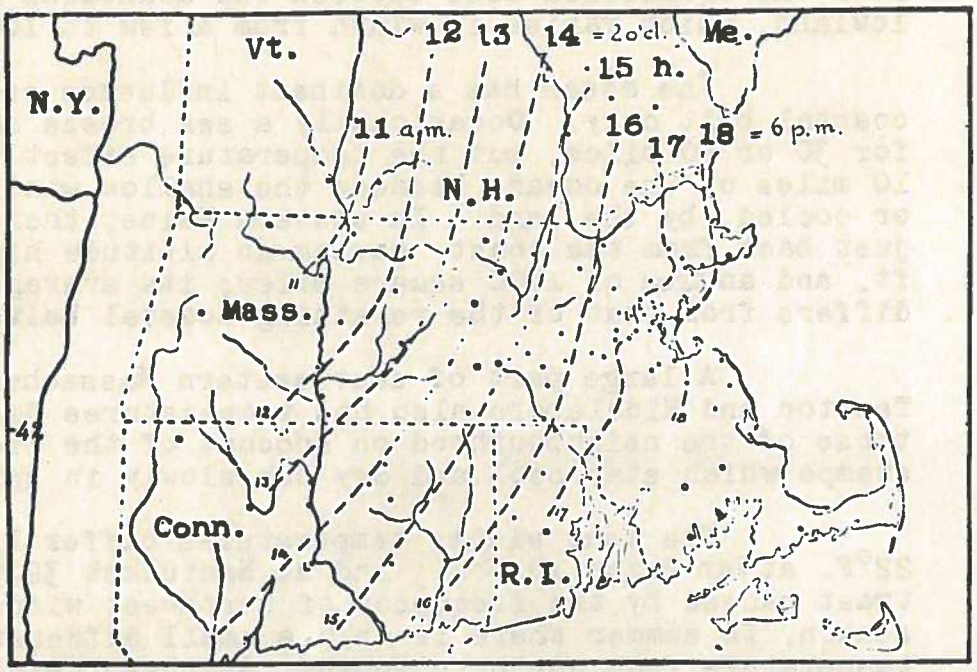

N.Y.
Vt.
12 13
14 = 2 o'cl.
Me.
15 h.
11 a.m.
16
17 18 = 6 p.m.
N.H.
Mass.
42
Conn.
R.I.
29 June, 1885

FIG. 2.

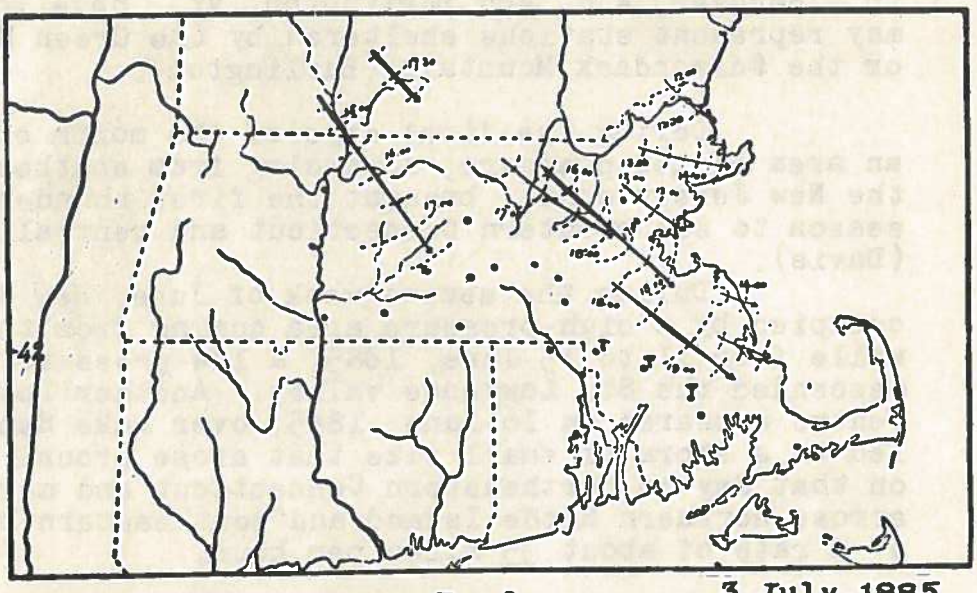

42
3 July, 1885

FIG. 3.

and moved eastwards bringing warm weather to Ontario and to New England. During the afternoon, several rather strong storms occurred in northeastern Massachusetts. On the afternoon of 28 June, while the centre of the low-pressure was over Lake Ontario, thundershowers were reported from New England. Towards night, the thunder died away, but the rain increased. The low-pressure centre moved to northern New York during the night, and to Massachusetts Bay during the day. The morning of 29 June, 1885, was cloudy. Just before noon a thunderstorm began in, or a little west of, the Connecticut valley, and moved east or east-southeast, 18 to 25 miles an hour, vanishing before sunset as it approached the eastern and southern coast.(Fig.2.)

The storm broke out north of the low-pressure centre, at that time near Massachusetts Bay; its front was not very marked since there was seldom any pronounced change in the direction or strength of the wind. A peculiar feature was the easterly wind charged with low foggy clouds that kept blowing towards the storm just before and during most of the rain.

The northern and southern ends of the storm seemed to fade away while the central part increased in strength as it approached the coast. Lightning strokes seemed to follow the heaviest downpour.

On 30 June, 1885, the centre of the low-pressure lay over the Gulf of Maine; on 1 July, 1885, it moved northward across western Maine, and the weather became cool; during the morning hours of 2 July, 1855, it advanced westward but then returned to northern Vermont, and on 3 July travelled from Mt. Washington to the St. Lawrence valley. A number of separate storms appeared in the afternoon in central and southern New Hampshire and in close succession in central and eastern Massachusetts. At least 10 storms moved southeast or east-southeast, at different times, at a velocity averaging 16 miles an hour(Fig.3.). In several of the storms the clouds observed were merely cumulus clouds of huge size in others the ordinary high-level cirrus overflow was seen.

A very severe storm with heavy rain and hail and incessant lightning passed eastwards in the evening of 5 July, 1885, crossing central and northern New Hampshire. The pressure was high over New England, low over Minnesota.

On the morning of 8 July, 1885, a new centre of low pressure appeared in Dakota. Violent thunderstorms broke out south of the Great Lakes but none formed in New England despite rapidly rising temperature mean maximum of 7th: 80°; of 8th, 87°). The centre moved eastward, north of the Great Lakes, and in the afternoon of 9 July, it stood near Quebec. The mean maximum temperature had risen to 91°,

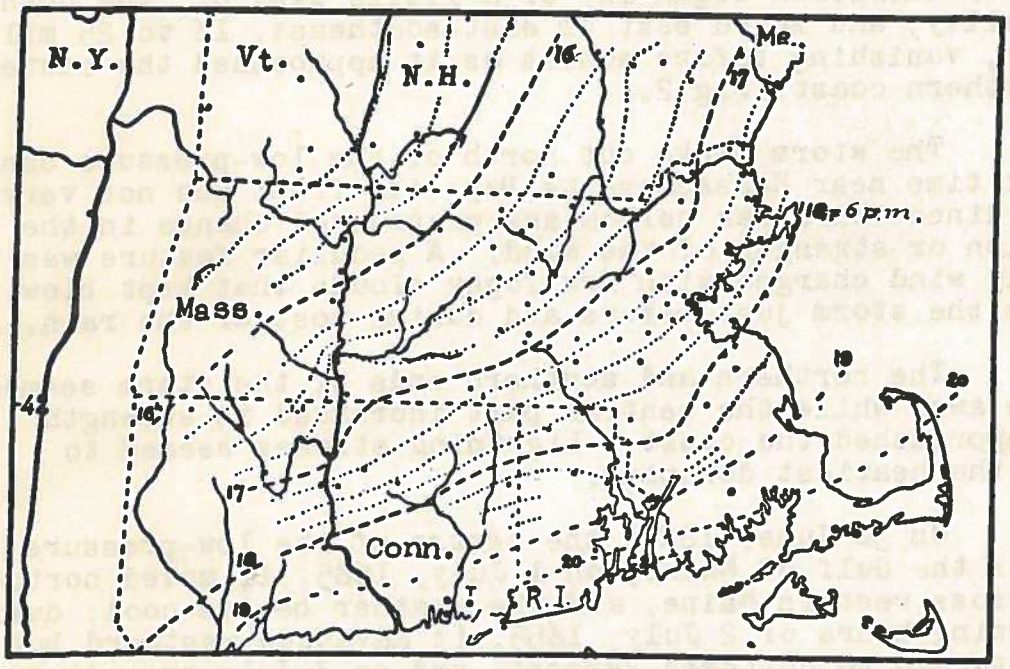


Fig. 4. 9 July, 1885

and the largest New England storm of the 1885 summer developed, extending from northeastern to southwestern New England.(Fig.4). With the formation of destructive funnel clouds at two places, Kent's Hill, Me. and West Brookfield, Mass., it reacned tornado strength.

At Burlington and Charlotte, Vt., the storm appeared at about 1 p.m. Two hours later it stretched northeastward from southern Vermont to the angle of the Androscoggin river in Maine. North of an east-west line through Concord, N.H., the storm advanced faster than south of this line. The average velocity along an east-by-south direction from southern Vermont to Cape Cod was about 37 miles an hour; in some places in New Hampshire it may have reached 50 miles an hour. The rate of advance seemed to diminish as the storm faded away after sunset on nearing the coast.

At a number of stations the cirrus overflow was often seen two or three hours before the rain began; its edge passed the observer's zenith from an hour to an hour and a half ahead of the rain. The thunder-clouds were often visible an hour or more before rain fell.

A rapid fall of temperature followed the storm front, one degree F. in one to three minutes.

The period from 11 to 20 July, 1885, was almost free from thunderstorms. The travel of a low pressure centre down the St. Lawrence valley about 12 July, 1885, was not accompanied by electric disturbances, nor did a low pressure centre coming from the west to Lake Huron and passing thence into Lower Canada, north of the St. Lawrence, produce storms, although it brought the hottest mean maximum temperature of the summer(92°F) to New England.

After this long period of inaction, a low pressure centre that had been lingering in Dakota during 18 and 19 July, 1885, began to move rapidly eastward on the 20th, so that it arrived north of Lake Huron on the morning of 21 July, and at 3 p.m. in southwestern Maine, travelling at a speed of 60 miles an hour.

The mean maximum temperature of the day was high (90°F.), and several storms were associated with the low-pressure area.

The first storm to be mentioned had been active in the state of New York at Palermo, Oswego Co., at 6.20 a.m. (time of loudest thunder), and at Constantia, Oswego Co., where the thunder was heard first at 6.45 a.m.; the storm lasted for about two hours. Peterborough, Madison Co., had the loudest thunder at 7.22 a.m. Hensonville, Greene Co.,

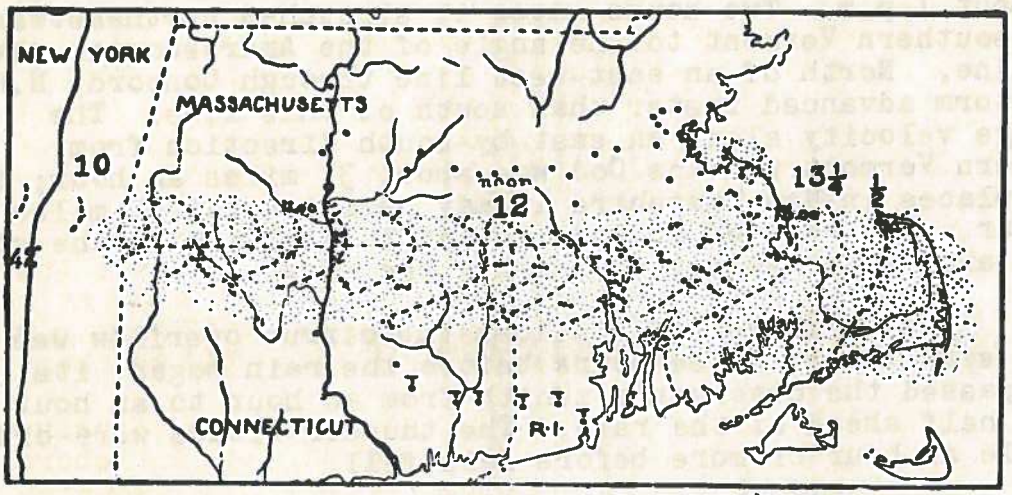


FIG. 5. 21 July, 1885

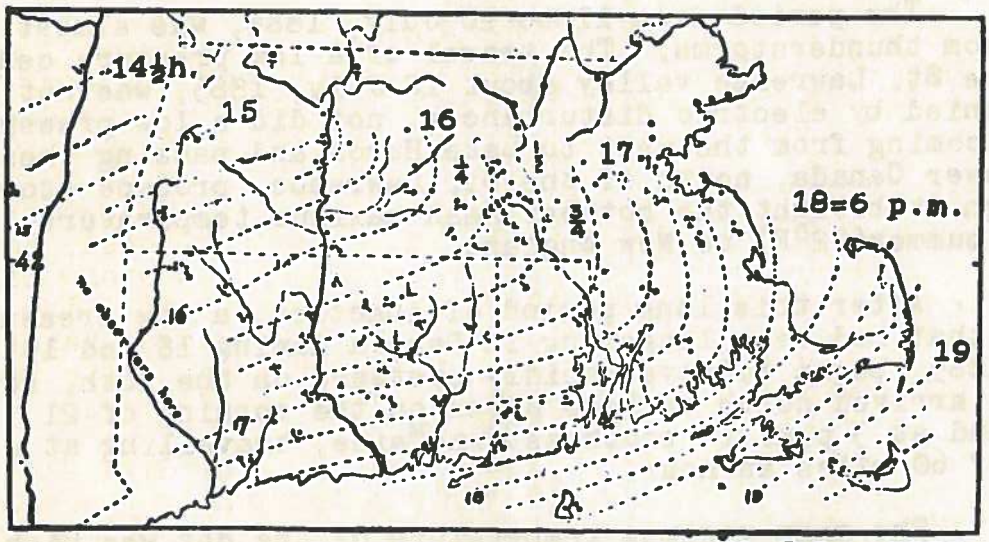


FIG. 6. 21 July, 1885

had rain at 9.22 a.m. while the temperature fell from 81 to 71°F. in two minutes. The squall entered New England near the western end of the Massachusetts-Connecticut boundary at about 10.10 a.m.(Fig.5). Great Barrington, Mass., reported rain at 10.40 a.m. with heavy clouds and continuous thunder. Winsted, Conn. reported clouds rising in the north at 10.33 a.m., light rain at 11.08 a.m. with moderate northwest wind, end of showers at 11.35 a.m. Springfield, Mass., had a heavy wind from 11.20 to 11.35 a.m. with a few drops of rain, Chicopee, Mass., light rain with westwind about 11.10 a.m. At Thompson, Conn. a short-lived shower began about 11.45 a.m.; lightning struck a church spire.

The storm then entered Rhode Island. At North Scituate the clouds passed the zenith at 12.15 p.m.; there was a sudden rain, heavy thunder and high west wind at 12.19 p.m. Woonsocket had rain in torrents at 12.22 p.m. Pawtucket at 12.27 p.m.(temp. 94°F., at 12.45 p.m. temp.77°F.)

Finally the storm crossed southeastern Massachusetts, and at the same time spread northeastward. At Attleboro, it was at its height at 12.25 p.m. At Norton, the temperature before the storm was 94°F., the highest of the season; about 11.00 a.m. o'clock clouds appeared; about 12.00 a dense black fog was in the west, rain fell from 12.15 p.m. accompanied by terrific lightning and thunder. Between 12.20 and 12.30 p.m. trees were broken and uprooted along a front three-quarters of a mile wide. Plymouth reported strong southwest wind at 12.45 p.m., rain at 12.50 p.m., and damage by lightning. Provincetown had rain between 1.30 and 2.00 p.m.

The average velocity of the storm's progress was 48 miles per hour, in a direction a little south of east. No definite effect on the course or velocity of the storm was exerted by the terrain over which the storm passed: The Catskill Mountains, over 2,500 ft. high, the Hudson Valley, the mountains of Western Connecticut and Massachusetts reaching in places up to 2,500 ft; and the Connecticut Valley.

An afternoon storm(Fig.6) on this same date 21 July, 1885, crossed the Hudson river below Albany while the temperature in New England had risen to over 90°F. A thin front of high cirro-stratus was visible in the northwest at least three hours before the rain began. In Connecticut the short-lived squall wind reached a destructive strength and was accompanied by hail. In Massachusetts the storm wasbrief but rather violent around Worcester, where numerous lightning strokes(L) were reported. Like the storm in the morning it was peculiar in approaching the sea-coast with scarcely diminished strength.

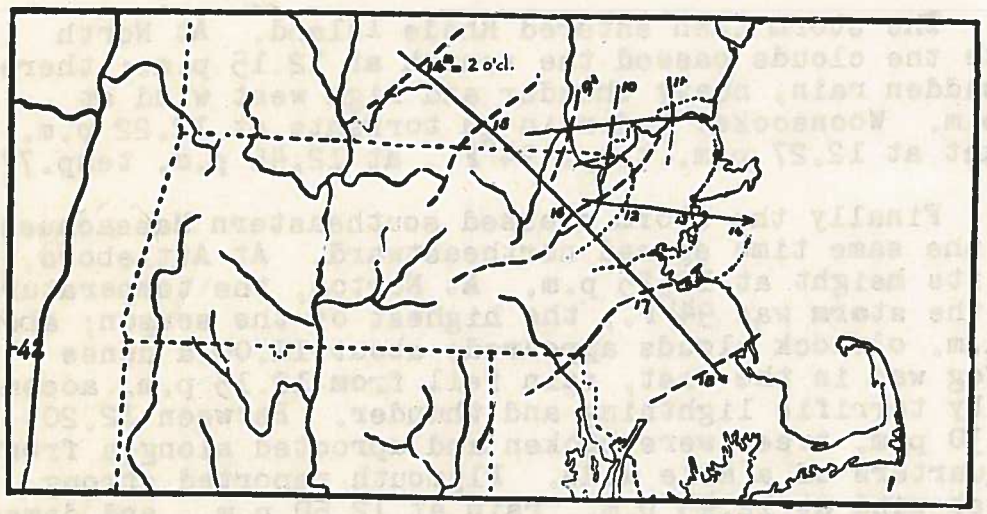


FIG. 7. 29 July, 1885

An area of low-pressure moved from Lake Michigan on 24 July, 1885, north of the St. Lawrence, and was north of the Gulf on the afternoon of the 25th. Several storms occurred in southern New England, after an oppressively hot day. But they did not bring any distinct change in weather. The mean maximum for the 25th was 88°F., for the 26th 87°F.; although this day was oppressively hot, only two thunderstorms occurred, one shortlived, near Amherst, Mass., the other in southeastern Massachusetts. (Taunton 1.50 p.m.).

During the rain the temperature dropped about 10°F. The next days brought higher pressures.

On 29 July, 1885, a slight depression lay north of Quebec and set up warm weather in the region swept by south-westerly winds. Five separate storms were traced for this day by H.H. Clayton. (Fig.7).

The first storm came early in the morning, being reported in northern Vermont at 2 a.m. It reached eastern New Hampshire about 8 a.m., having travelled over a narrow path to the east southeast at a rate of perhaps 18 miles an hour, without apparently reaching the sea-coast.

The second storm advanced eastward along the boundary of New Hampshire and Massachusetts at a rate of about 20 miles an hour. It passed out to sea at noon.

The third thunderstorm developed in northeastern Massachusetts about noon, and moved eastward at the same rate as its predecessors. The clouds were dark and heavy, light-ning struck in various places.

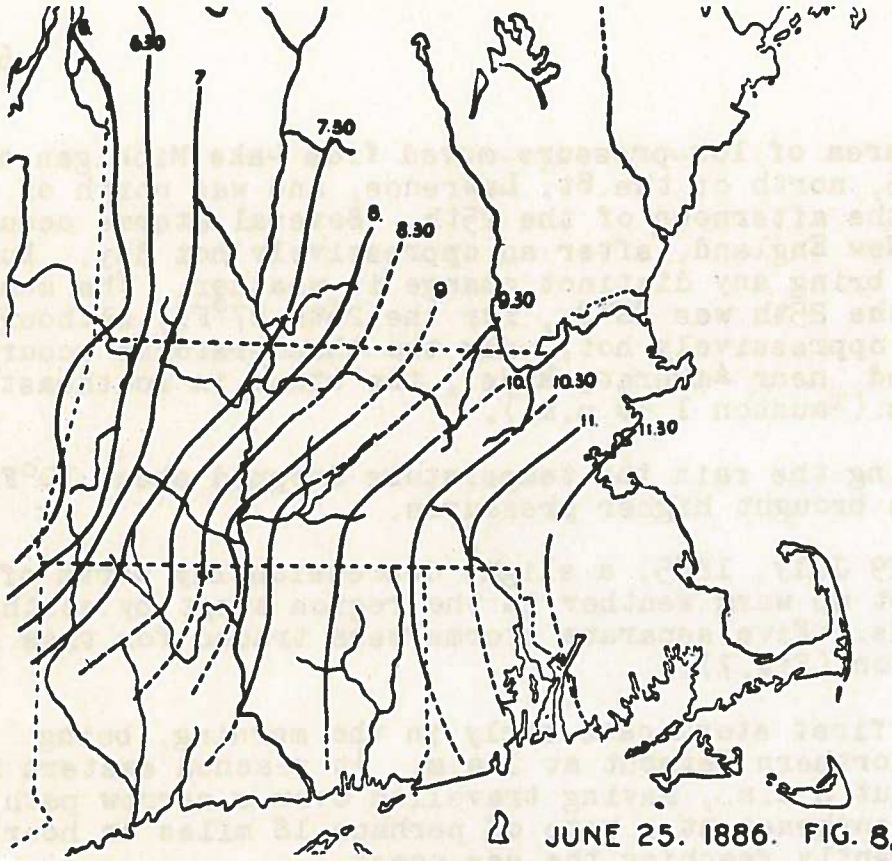
A fourth storm broke out in central Connecticut in the middle afternoon.

The most extensive storm of the day began in New Hampshire at about 2 p.m. and moved to the southeast at a speed of 25 miles an hour.

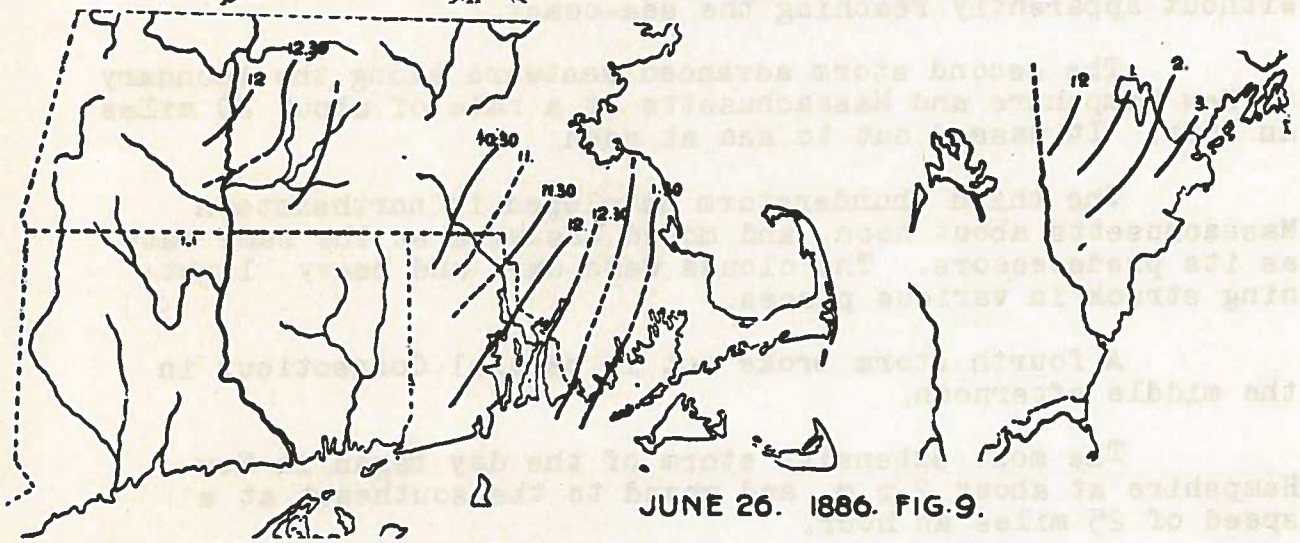
3. Propagation of Thunderstorms during the Summer of 1886

In 1886, June as a whole had a low average temper-ature and a small rainfall. There were a number of thunder-storms, some of them reported from only one locality

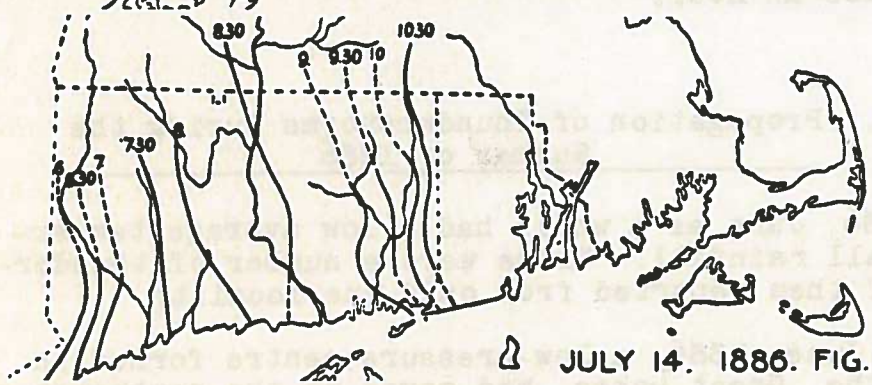
On 25 June, 1886, a low-pressure centre formed in the region of the Great Lakes, had moved to the northeast and



JUNE 25. 1886. FIG. 8.



JUNE 26. 1886. FIG. 9.



JULY 14. 1886. FIG. 10.

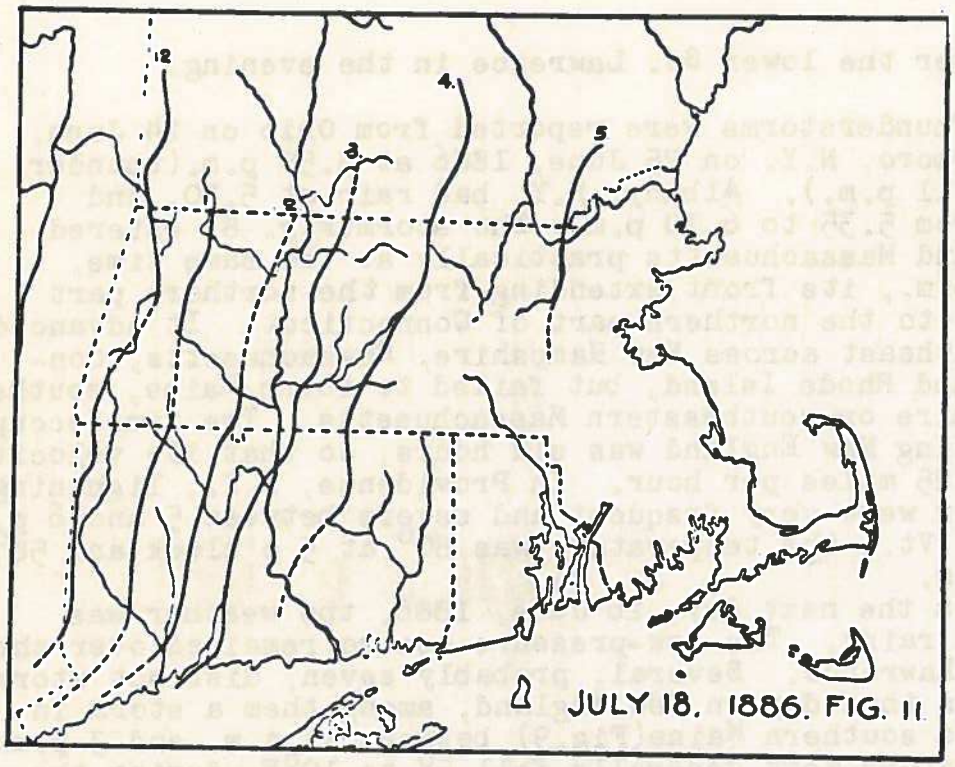
arrived over the lower St. Lawrence in the evening.

Thunderstorms were reported from Ohio on 24 June, from Peterboro, N.Y. on 25 June, 1886 at 3.50 p.m.(thunder, rain at 4.11 p.m.). Albany, N.Y. had rain at 5.50, and thunder from 5.35 to 6.10 p.m. The storm(Fig. 8) entered Vermount and Massachusetts practically at the same time, around 6 p.m., its front extending from the northern part of Vermont to the northern part of Connecticut. It advanced to the southeast across New Hampshire, Massachusetts, Connecticut and Rhode Island, but failed to touch Maine, southern New Hampshire or southeastern Massachusetts. The time occupied in traversing New England was six hours, so that its velocity was about 25 miles per hour. In Providence, R.I., lightning and thunder were very frequent and severe between 5 and 6 p.m. At Pawlet, Vt., the temperature was 80° at 5 o'clock and 58° at 7.30 p.m.

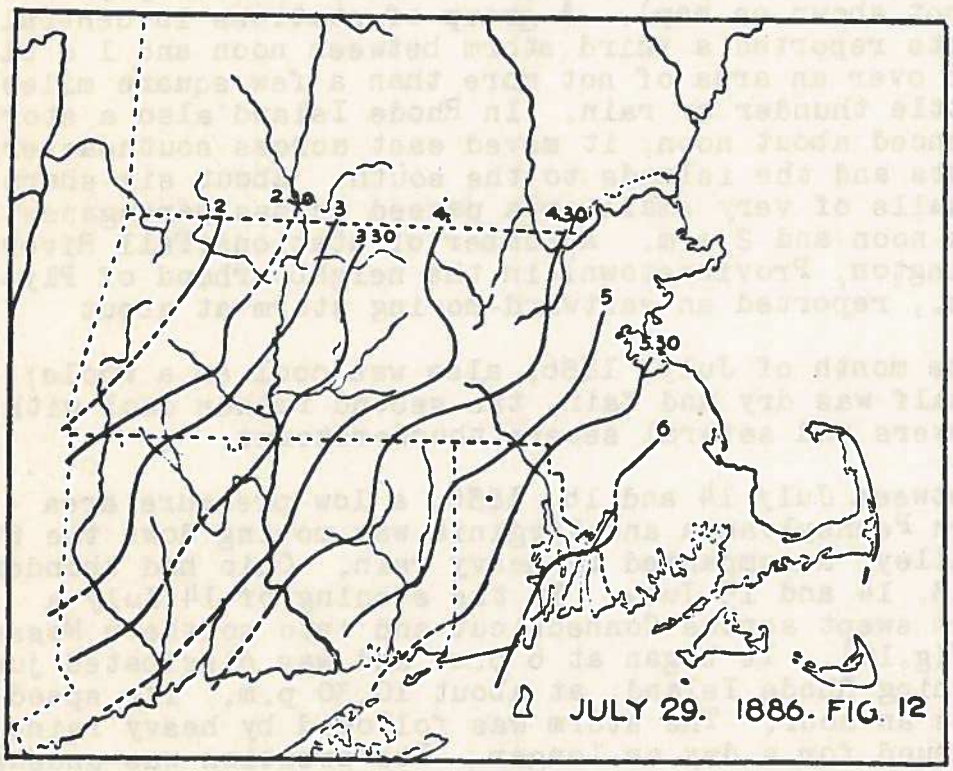
On the next day, 26 June, 1886, the weather was cloudy and rainy. The low-pressure centre remained over the Lower St. Lawrence. Several, probably seven, distinct storms occurred on this day in New England, among them a storm in central and southern Maine(Fig.9) between 11 a.m. and 3 p.m. The temperature very generally fell 5° to 10°F. during the rain but increased at Limington. A second small storm moved across the same area; from Andover to Alna, between 5.30 and 8.30 p.m.(not shown on map). A group of stations in central Massachusetts reported a third storm between noon and 1 o'clock; it extended over an area of not more than a few square miles and had little thunder or rain. In Rhode Island also a storm was experienced about noon; it moved east across southeastern Massachusetts and the islands to the south. About six sharp thunder-squalls of very small area passed across Narragansett Bay between noon and 2 p.m. A number of stations(Fall River, West Worthington, Provincetown) in the neighbourhood of Plymouth, Mass., reported an eastward-moving storm at about 1 o'clock.

The month of July, 1886, also was cool as a whole; the first half was dry and fair, the second rather cool with copious showers and several severe thunderstorms.

Between July 14 and 16, 1886, a low-pressure area from western Pennsylvania and Virginia was moving down the St. Lawrence Valley, accompanied by heavy rain. Ohio had thunderstorms on 13, 14 and 15 July. In the evening of 14 July a thunderstorm swept across Connecticut and into southern Massachusetts.(Fig.10). It began at 6 p.m. and was dissipated just before reaching Rhode Island, at about 10.30 p.m. Its speed was 20 miles an hour. The storm was followed by heavy rains which continued for a day or longer. Its position was unusual; it broke out northeast of the low-pressure centre, located at that time in southwestern Pennsylvania, that is, it occurred in the northeast quadrant of the depression.



JULY 18. 1886. FIG. 11



JULY 29. 1886. FIG. 12

Another storm showing the same relation to the cyclonic centre, then in Western Virginia, came early at 2 a.m. on the following day, 15 July, 1886, to western Connecticut, the northeastern corner of Massachusetts(5 to 8 a.m.) and southeastern New Hampshire and Maine. The temperature was stationary, the day foggy and cloudy, the wind light.

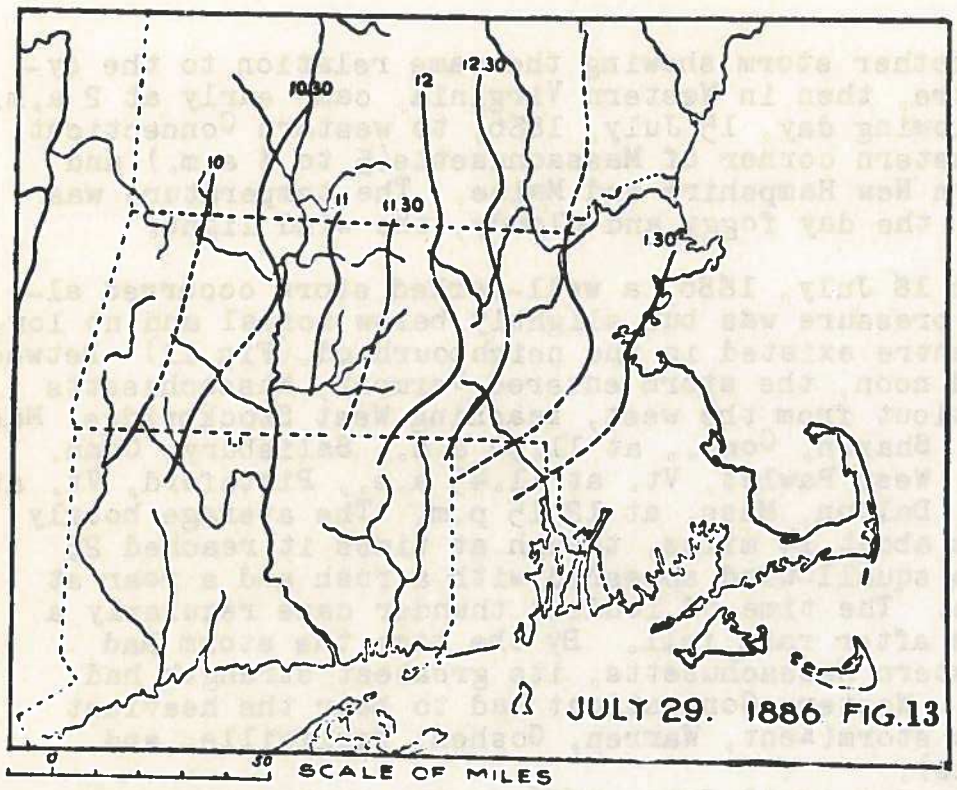
On 18 July, 1886, a well-marked storm occurred although the pressure was but slightly below normal and no low-pressure centre existed in the neighbourhood.(Fig.11) Between 11 a.m. and noon, the storm entered Vermont, Massachusetts and Connecticut from the west, reaching West Stockbridge, Mass. at 11 a.m., Sharon, Conn., at 11.30 a.m., Salisbury, Conn. 11.35 a.m., West Pawlet, Vt. at 11.45 a.m., Pittsford, Vt. at 12.02 p.m., Dalton, Mass. at 12.15 p.m. The average hourly advance was about 14 miles, though at times it reached 25 miles. The squall-wind appeared with a rush and a roar at many places. The time of loudest thunder came regularly a few minutes after rain fell. By the time the storm had reached eastern Massachusetts, its greatest strength had been spent. Western Connecticut had to bear the heaviest part of the storm(Kent, Warren, Goshen, Tarifville, and Collinsville).

The day of 19 July, 1886, seems to have brought a succession of more or less violent showers, most severe in Maine in the early afternoon, considerable damage being done by hail and lightning.

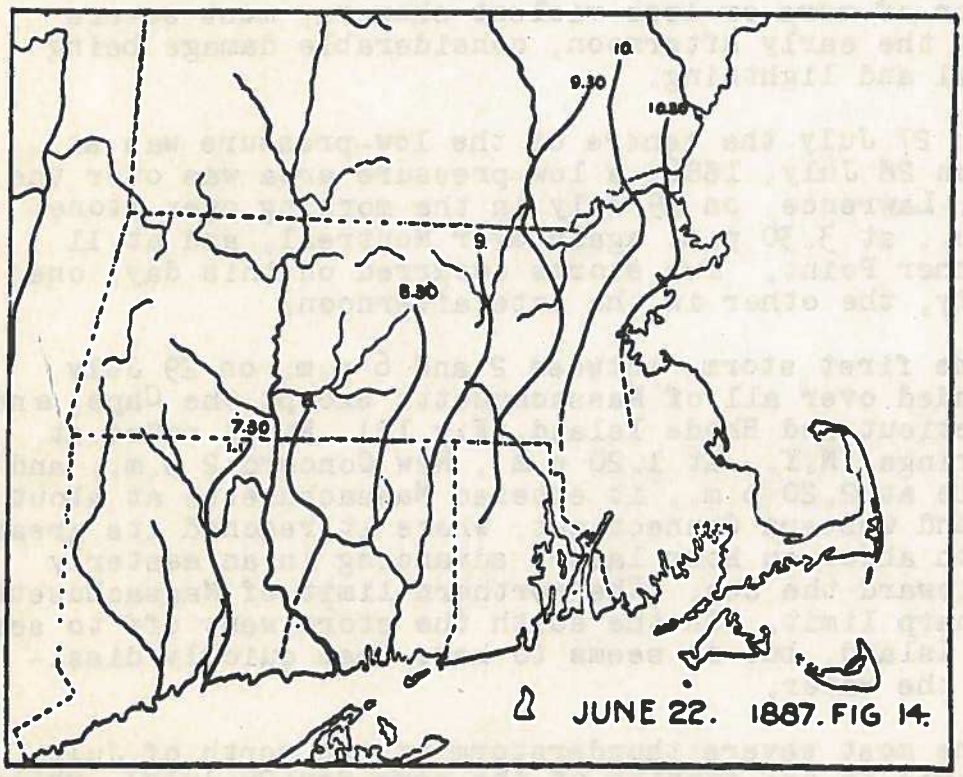
On 27 July the centre of the low-pressure was at Montreal; on 28 July, 1886, a low-pressure area was over the Gulf of St. Lawrence, on 29 July in the morning over Stonecliffe, Can., at 3.30 p.m. again over Montreal, and at 11 p.m. at Father Point. Two storms occurred on this day, one in the early, the other in the late afternoon.

The first storm, between 2 and 6 p.m. on 29 July, 1886, extended over all of Massachusetts except the Cape, and over Connecticut and Rhode Island.(Fig.12) First noted at Lebanon Springs, N.Y., at 1.20 p.m., New Concord 2 p.m., and Poughkeepsie at 2.20 p.m., it entered Massachusetts at about 1.30 p.m. and western Connecticut, where it reached its greatest strength about an hour later, advancing in an easterly direction toward the sea. The northern limit of Massachusetts formed a sharp limit. On the south the storm went off to sea from Rhode Island, but it seems to have been quickly dissipated over the water.

The most severe thunderstorm of the month of July, 1886, followed in the evening of the same day(29 July), while the low-pressure centre moved from near Father Point(11 p.m.) into the Gulf(7 a.m.) The storm crossed Massachusetts and Rhode Island between 10 p.m. and 1.30 a.m. The rate of advance was



JULY 29. 1886 FIG. 13



JUNE 22. 1887. FIG 14.

35 miles an hour.(Fig.13) Other storms followed on 30 and 31 July, 1886. At least five storms arose in various parts of New England during the afternoon of 30 July, 1886.

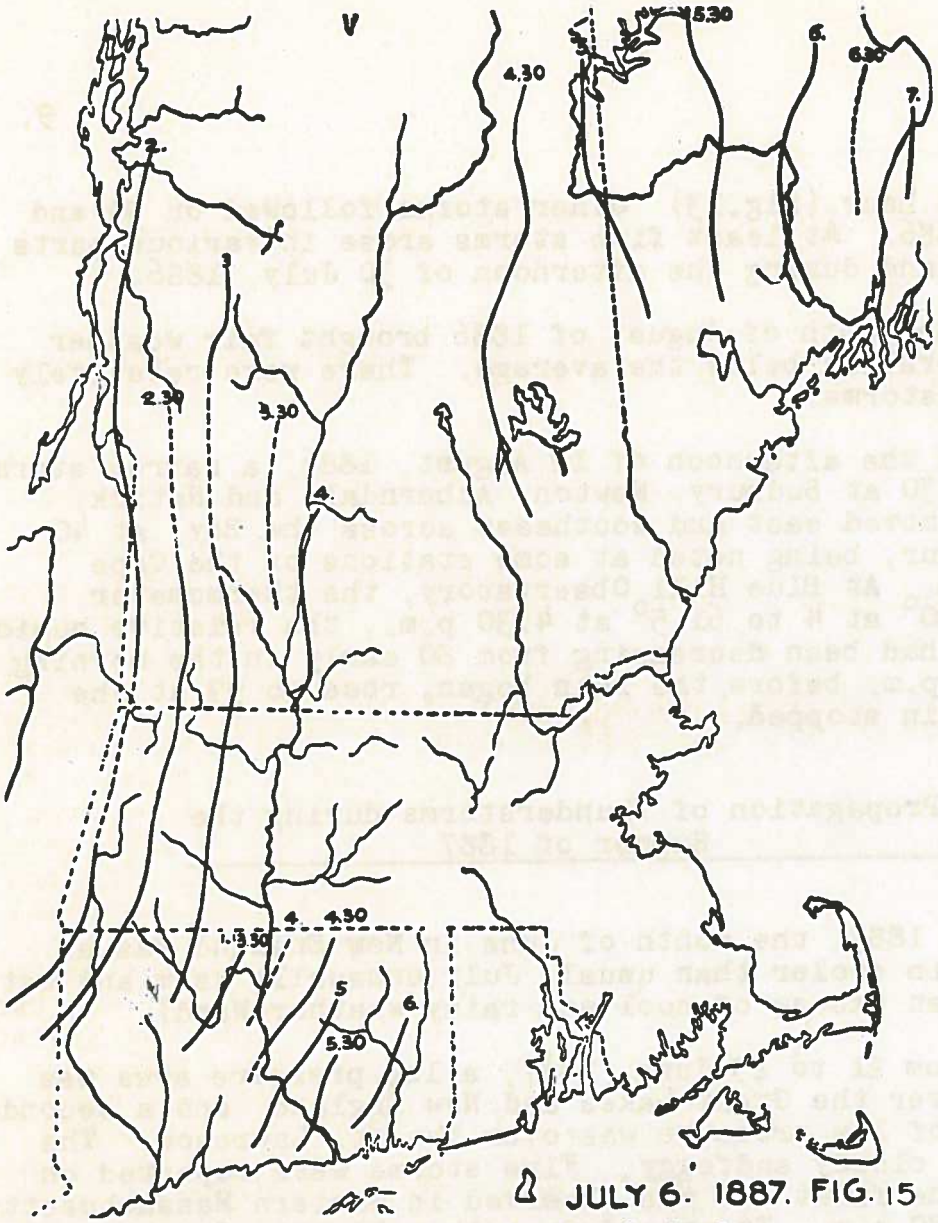
The month of August of 1886 brought fair weather and a temperature below the average. There were relatively few thunderstorms.

In the afternoon of 12 August, 1886, a narrow storm began at 3.30 at Sudbury, Newton, Auburndale and Natick, Mass., and moved east and southeast across the Bay, at 40 miles an hour, being noted at some stations on the Cape after 5 p.m. At Blue Hill Observatory, the thermometer fell from 80° at 4 to 61.5° at 4.30 p.m., the relative humidity, which had been decreasing from 80 early in the morning to 60 at 4 p.m. before the rain began, rose to 99 at the time the rain stopped.

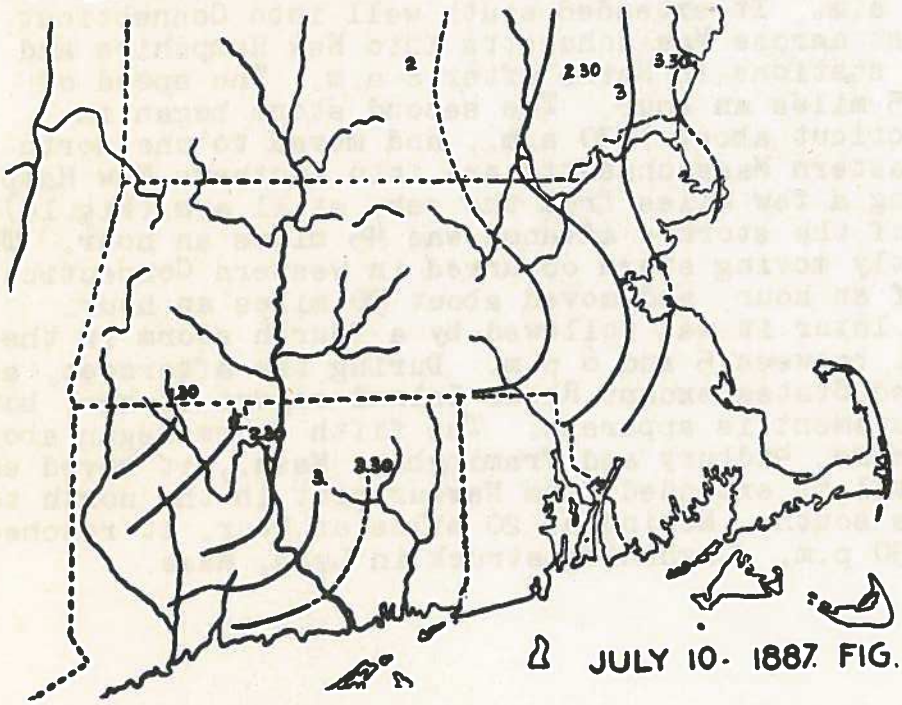
4. Propagation of Thunderstorms during the Summer of 1887

In 1887, the month of June in New England was as a whole again cooler than usual, July unusually warm and wet, August had an excess of cool and rainy weather(Ward).

From 21 to 23 June, 1887, a low-pressure area was spreading over the Great Lakes and New England, and a secondary centre of low-pressure was over the St. Lawrence. The weather was cloudy andfoggy. Five storms were reported on 22 June. The first one was observed in eastern Massachusetts early at 4.30 a.m. It extended south well into Connecticut, moved northeast across Massachusetts into New Hampshire and reached a few stations in Maine after 8 a.m. The speed of advance was 35 miles an hour. The second storm began in central Connecticut about 7.30 a.m., and moved to the northeast across eastern Massachusetts and into southern New Hampshire, stopping a few miles from the sea, at 11 a.m.(Fig.14). The velocity of the storm's advance was 45 miles an hour. The third distinctly moving storm occurred in western Connecticut. It lasted half an hour, and moved about 50 miles an hour. Several hours later it was followed by a fourth storm in the same district, between 5 and 6 p.m. During the afternoon, all the New England States except Rhode Island report storms, but no distinct movement is apparent. The fifth storm began about 6 p.m. at Concord, Sudbury and Framingham, Mass., it moved east and spread until it extended from Newburyport in the north to Taunton in the south. Moving at 20 miles an hour, it reached the sea at 7.30 p.m. Lightning struck in Lynn, Mass.



JULY 6. 1887. FIG. 15



JULY 10. 1887. FIG. 16

On 23 June, 1887, three reports from near the coast of Massachusetts mention thunder, then the weather changed to fair. The month of July, 1887, was sultry and moist and thunderstorms were frequent and severe.

The month opened with clear hot weather and westerly winds. Although the pressure was above normal, a small storm developed on 1 July, 1887, at 3.30 p.m. in southeastern Massachusetts. A second storm of small extent, represented by not much more than a single cloud, moved east in eastern Massachusetts between 6 and 7 p.m.

On 4 July, 1887, a faint depression was approaching from the Upper Great Lakes bringing southerly wind and cloudy weather to New England. The heat was excessive until 6 July. On this day, a distinct storm(Fig.15) began in western Vermont, Massachusetts and Connecticut at about 2 p.m. and moved east across New Hampshire into Maine, where it dissipated around 7 p.m. without reaching the sea. Solon, Me., reported a fall in temperature of 10° in 15 minutes during the rain. From Massachusetts there were no reports after 3 p.m., the storm having died away in the western part of the state. In Connecticut, on the other hand, it continued to move southeast until 6 p.m., so that a gap about 50 miles wide existed in the storm front. The storm was strongest, in the north, reaching tornado force at Alstead, N.H. During the next two days, the low-pressure area reached the Gulf, and New England had fair weather and southwest winds. But in the morning of 9 July, another moderate depression appeared over the upper Lakes; on the following day, at 7 a.m., it passed north of Montreal, while the weather became cloudy and showery. Between 1.30 and 3.30 p.m. on 10 July, 1887, there was a storm in western Connecticut(Fig.16), moving southeast at a velocity of 30 miles an hour. Another storm developed at about the same time in eastern Massachusetts and moved east at a speed of 25 miles an hour, reaching the sea at 3 p.m. The convex front was clearly marked.

On 18 July, 1887, the reports from Connecticut, though unfortunately scattered, seem to show a distinct storm moving south from Massachusetts across eastern Connecticut between 1 and 3 p.m., an unusual trajectory. At the time the storm occurred the centre of the low-pressure was in southern Delaware.

After a day of high pressure and fair weather(20 July, 1887), with southerly winds, a depression appearing in central Illinois and passing over the Lakes and across eastern Canada, brought a wet period with scattered thunderstorms from 21 to 24 July, 1887. During the last stages of the influence of the low-pressure wave, while the pressure already was increasing, a small narrow storm began in northeastern Connecticut at 1.30 p.m. on 24 July, 1887, and moved at a little less than 30 miles an hour into central Massachusetts, disappearing at 4 p.m. in the

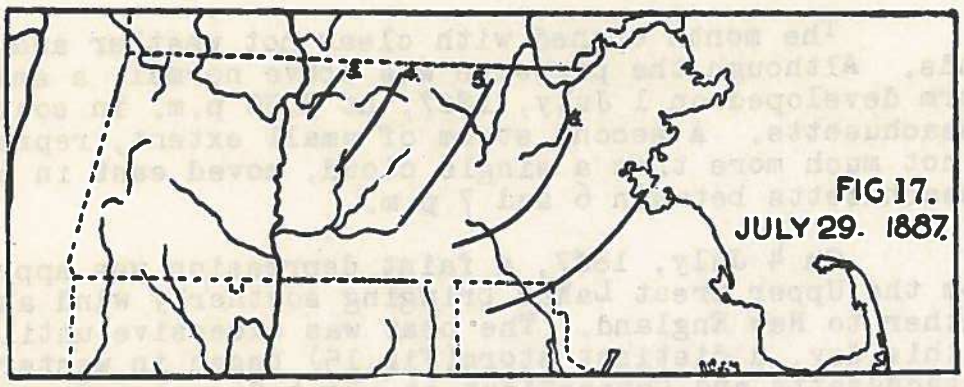
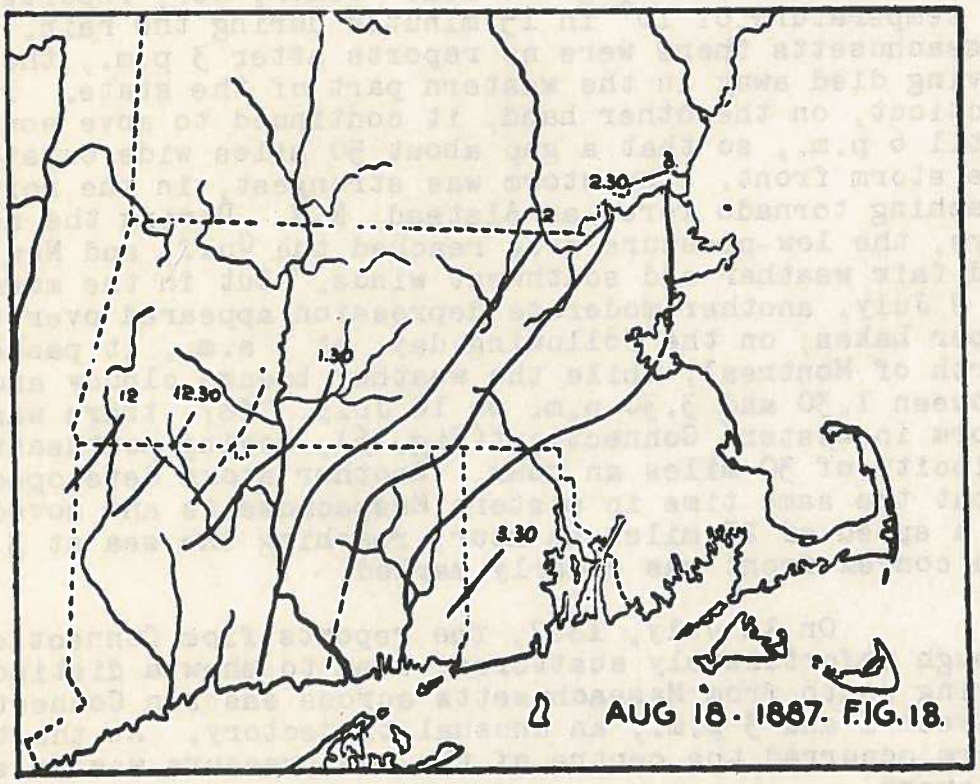


FIG 17.
JULY 29. 1887.



AUG 18. 1887. FIG. 18.

SCALE OF MILES

neighbourhood of Worcester. The storm covered a strip less than 10 miles wide.

The pressure remained quite even for a few days. Scattered thunderstorms caused probably by overrunning warm air occurred on 28 July, 1887. At Berlin Mills, N.H., it was noted that the altitude of the storm was apparently great, as the time between lightning and thunder, while directly overhead, was several seconds. At Pine Plains, N.Y., the cloud mass moved west to south. A well defined storm entered northwestern Vermont at 3 p.m. and moved at 30 miles per hour to th e south east across New Hampshire and southern Maine, reaching the coast after 10 p.m.

A number of stations in New Hampshire and Maine report heavy thunder on 29 July, 1887, between 1 and 5 p.m. At Quincy it is recorded that the air is cool at the beginning of the storm but muggy at its close. A distinct storm with some features worthy of note developed during the same afternoon(Fig.17). It started east of the Connecticut River in Massachusetts at about 3 p.m. and moved southeast at a speed of 25 miles an hour, spreading in area and covering all of eastern Massachusetts. It reached the sea after 7 p.m. One station in northern Rhode Island also felt the storm. At College Hill, the wind veered from southwest to east just before the rain began, and the temperature fell 10°F. in half an hour. At several stations, after the disturbance had passed, it seemed to come back again from the east(College Hill at 5.30 p.m., Holyoke, Newburyport at 5.15 p.m., South Weymouth, Worcester at 5.40 p.m. and Hingham at 6.45 p.m.), and then continued its "interrupted" course to eastward. At Newburyport, thunder was first audible in the northwest; the head of the storm moved northeast and remained north of the station for 30 minutes, at 4.45 a northeast wind brought it southward nearer to the station; it continued to move south until the Merrimack River was reached. It followed theriver, passing two miles southeast of Newburyport, moved along the coast until it was about eight miles away, then it changed its direction, and again approached the station but from the south. At 7.20 p.m. the storm retreated towards the east.

The month of August, 1887, brought an excess of cool and rainy weather to New England, the temperature being low on account of the presence of clouds and frequent northerly winds. On 18 August, 1887, a cyclonic disturbance coming from Illinois crossed New England, brought a thunderstorm in the morning, and following a clear interval a second storm in the early afternoon. In the early morning a storm crossed northern Massachusetts from west to east at 30 miles an hour(3 a.m. at Shelburne, 7 a.m. in the northeastern corner of the state). Later in the morning warmer winds started to blow. The second thunderstorm(Fig.18) entered northwestern Connecticut just after noon; moving east, it spread out to northeastern Massachusetts and

southern Connecticut. The storm reached the sea in the north at 3 p.m., but vanished in Rhode Island at 3.30 p.m. The rate of movement was 50 miles an hour.

During the last three days of the month of August, 1887, the pressure in New England was high and the winds came from the north or northeast. But despite the generally fair and clear weather thunderstorms occurred every day. Between 1 and 5 p.m. on 30 August, 1887, thunderstorm action was widespread in southern New England, chiefly in Massachusetts, Connecticut and Rhode Island. At Blue Hill it appeared to be a stationary thunderstorm, the only one observed during the summer of 1887. In many places the wind, lightning and hail were violent.

5. Review and Discussion

The numbers of days on which thunder was reported from at least one station in New England are as follows:

	1886	1887
June	18	18
July	26	29
August	17	20

The numbers of days on which the progress of the storms could be traced are given below.

	1886	1887
June	14 days (10)[x]	7 days (6)[x]
July	22 " (14)	16 " (9)
August	9 " (6)	13 " (6)

There are, therefore, months in which more than half the days bring thunder to some place in New England.

The study of the relation of thunderstorms to low-pressure areas during the three years 1885-87 sufficed to show that while the majority of thunderstorms are south or east of the low-pressure centres, the 7 a.m. weather maps of those days on which the depression was north of New England and thunderstorms occurred, did not differ appreciably in pressure, rainfall, direction and force of the wind from the maps for days without storms in which the lows occupied similar positions.

---

[x] The numbers in parentheses indicate the number of days with thunder during which a low-pressure centre was located north of the St. Lawrence or over the Great Lakes at 7 o'clock in the morning.

It must be mentioned, however, that the influence of relative humidity was disregarded.

That despite similar conditions pressure distributions favourable to thunderstorms may not result in thunderstorms was also the result of a survey covering the ten years 1925 to 1934 in Oregon and Washington National Forests(25 million acres, one-fourth the area of the two states). To determine the percentage of occurrences of the pressure types which were not attended by thunderstorms all occurrences for the months of June, July and August were tabulated. Of all the days on which one of four favourable types(trough, east or west of Cascade Range, between high pressure areas, southwest or southeast quadrant of regularly formed low-pressure area) prevailed, 15 per cent were without thunderstorms(R.A. Ward).

Most individual lightning storms on these forests affect an area 11 to 60 miles in length, or appear to move through that distance, generally in a northerly direction. But one storm in Washington is known to have been at least 280 miles long(Morris).

Similar observations are reported from Europe(Winter). There are many instances, between 1926 and 1935, where strong westerly winds carried cool masses of air from the Atlantic into the strongly heated continent without causing thunderstorms, even, at times, without causing rain. In other instances a slight breeze from the west ended in wide-spread storms. In some years every inflow of western air causes thunderstorms, in other summers only one-third of the invasions are attended by electrical disturbances. The differences in the behaviour are no doubt connected with the amount of moisture present in the warm air over the continent.

During May, June, July and August, 1886, storms occurred most frequently between 5 and 7 p.m., in 1887 between 3.30 and 5.30 p.m. The thunderstorms of the winter months occurred mainly in the evening or during the night, and near the sea-coast.

In many instances, Ohio, Pennsylvania and New York had storms that preceded the disturbances in New England. A storm on 14 June, 1886, in Iowa was followed by a storm in Ohio on 16 June, and in New England on 17 June. Dakota, Iowa and Nebraska had storms on 6 June, Ohio 9 June, New England 10 June; on another occasion the dates were 20, 24 and 25 June. Records from Ohio show that 13,14,15,17,26 and 30 July, 1886, were days of extended thunderstorms; one day later storms broke out in New England. In August, 1886, thunderstorms were not very frequent and the sequence was less complete; Ohio reported storms on 1, 11, 13, 14, 16 and 22 August; New England on 12 and 14 August. The storms of 11 August in Ohio

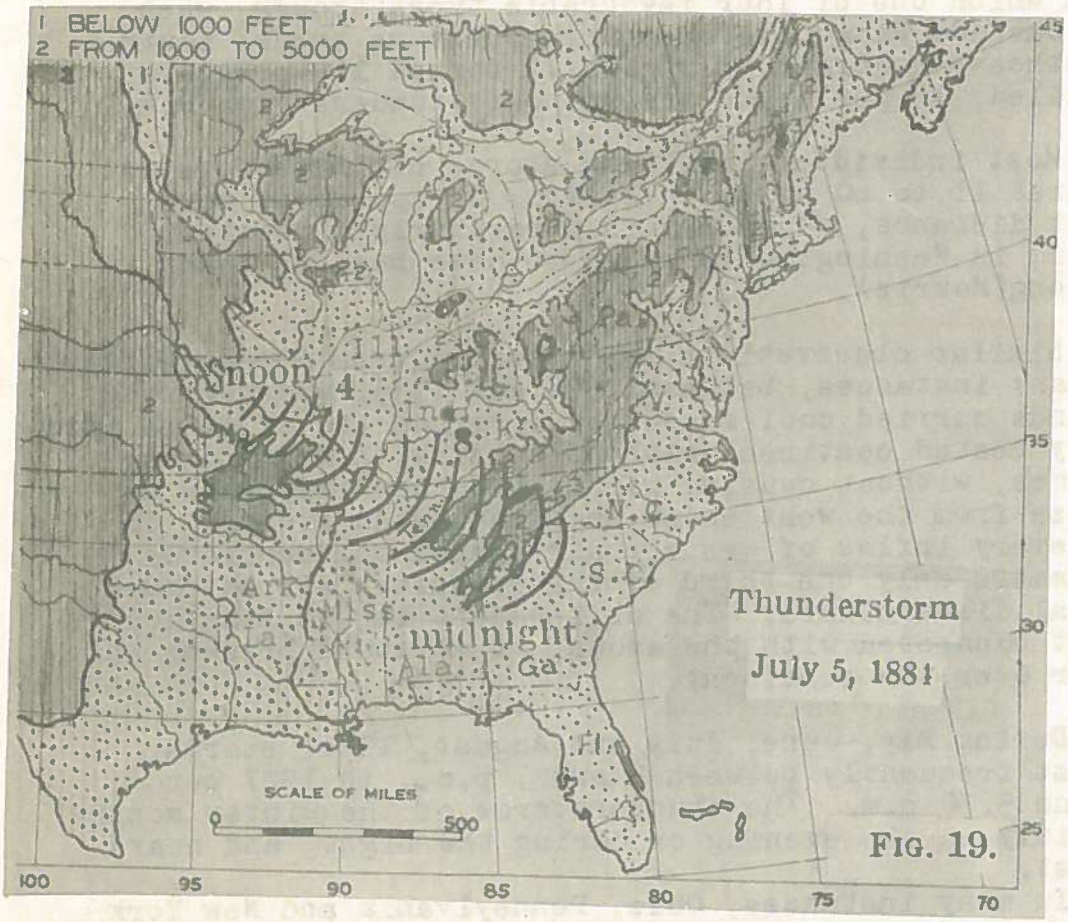

1 BELOW 1000 FEET
2 FROM 1000 TO 5000 FEET
noon
4
8
midnight
Thunderstorm
July 5, 1881
SCALE OF MILES
0
500
45
40
35
30
25
100
95
90
85
80
75
70

FIG. 19.

and those of 12 August in New England occurred mostly between 3 and 5 p.m., the storms of 13 August, 1886, between 2 and 7 a.m., those of 14 August, 1886, in New England from 9 a.m. to 2 p.m. with no change in temperature. Both storms had a speed of 40 miles per hour in New England.

In order to obtain a clear idea of the size of a storm, the observations must extend across at least half the continent. A thunderstorm, distinguished by its marked squall wind, began in northeastern Missouri, about noon on 5 July, 1884, and moved southeastward, with a convex front(Fig.19), at the rate of over 50 miles an hour, dying out in South Carolina and Georgia at midnight, not far from the Atlantic coast, after a journey of over 600 miles(Clayton).

6. Propagation of Thunderstorms in Mountainous Regions(Alps)

A classification of the types of thunderstorms observed in the region of the Alps, published in 1925, is based on thousands of observations and records made during that year at more than 400 meteorological stations(Lugeon).

The following type of thunderstorms occurred.

(a) the thermal thunderstorms of the flat low regions, of short duration and restricted to the daylight hours. They occur in the hilly country, in front of the steep slopes of the Prealps and of the Alps;

(b) the orographic thunderstorms of the mountain slopes, of short duration, occurring most often during daylight hours in the Alps and in the Jura mountains;

(c) the falling wind or foehn thunderstorms, special examples of orographic thunderstorms, are under the control of the Channel lows and arise when the anticyclonic foehn yields to the low-pressure foehn. Enormous masses of moisture condense on the southern slopes of the Alps, and thunderstorms form. Lightning is observed in the mountain valleys and a day later in the hilly region. Apparently, as the warm air descends the northern slopes, it draws thunderclouds along with it so that the storms extend into the highest valleys north of the divide(Weixlederer). But the falling movement of the air soon brings an end to the electrical storm;

(d) the thunderstorms of the cold front or of the frontal occlusions, appearing in various forms as thundersqualls, distinguishable as to the origin of the air masses involved, their

Isobronts

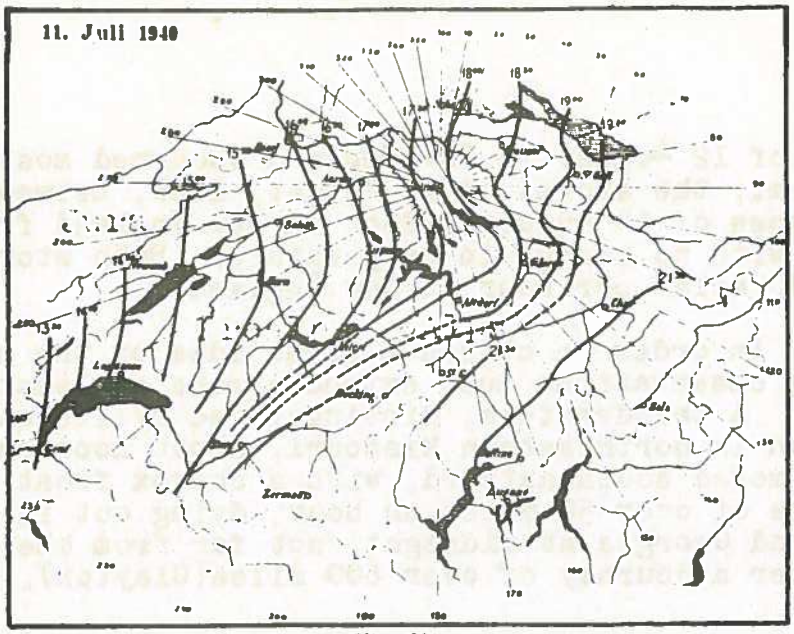


Fig. 20.

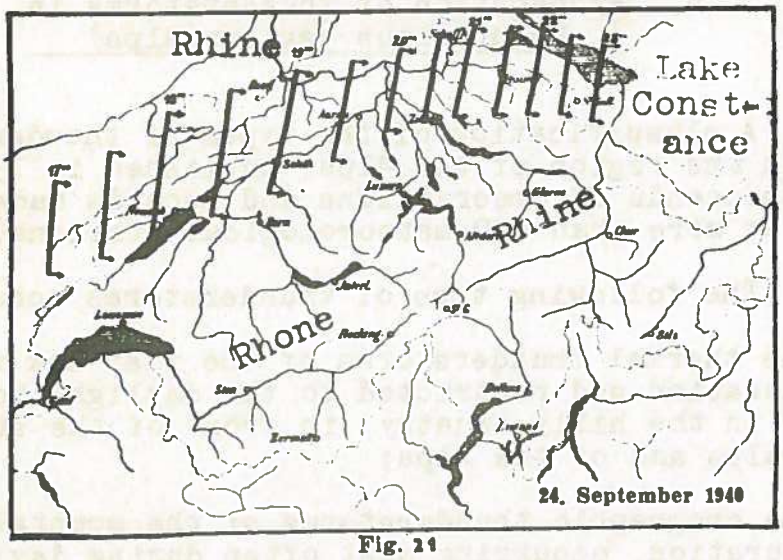


Fig. 21

Fig. 22.

turbulence, and their dependence upon the earth's relief. They appear along the surfaces of discontinuity, are accompanied by a sudden reduction in temperature and may advance with speeds as high as 50 miles per hour. They cross the highest mountain chains without difficulty.

(e) the thunderstorms of the warm front, attending the advance of warm air masses that enter the country from the southwest after having crossed the Jura ranges. They advance slowly, vary with the direction of propagation, and the barometric gradient in the depression as it travels from France to Czechoslovakia.

When the pressure is high over the northern or northeastern part of Europe and low in the south, in particular over the Adriatic Sea and the Balkans, the warm front thunderstorms may appear to come from the east(east thunderstorms). These storms occur in the cooler part of the continent only, at places where wedges of warm air begin to overrun the cooler and denser air at the ground, and tend to become saturated with moisture. Cool winds(20°C) blow from the northeast across the continent, warm winds(30°C) run into them from the southeast. The thunderstorm regions advance slowly or remain stationary, at the boundary surface between warm and cold air, bringing a repetition of storms at the same place, sometimes for days on end(5 to 14 June, 1939). All these storms seem to come from the south or southeast (Scherhag). Thunderstorms that follow the arrival of cool air are, of course, also observed in North America. In the sector occupied by the warm air the weather remains fine. The downpours are invariably producing higher temperatures and greater humidity than before, whereas the heat in the low-pressure region continues unabated. The cool winds seem to bring, not to follow, the thunderstorms, regardless of whether, depending on the pressure distribution, the cool air is spreading to the west and south or the warm air to the east.

A cold front thunderstorm(Fig.20) approached Switzerland from the west on 11 July, 1940; at 1.30 p.m. it was over Geneva, having crossed the Jura mountains, at 2 o' clock it swept across the hilly country between Lake Geneva and Lake Neuchâtel, reached the capital at 4.30 p.m., extending from the Rhine to the Rhone. At 5.50 p.m. hail falls heavily at Zurich. An hour later the strength begins to ebb. Where the front meets the slopes of the Alps, its progress is seriously retarded. At 9.30 p.m., the last reports are heard from the southeastern portion of the country, after a part of the storm has succeeded in crossing some of the highest mountain chains. The average speed of the storm was close to 30 miles per hour. About 200 observers sent reports of its progress(Zobrist).

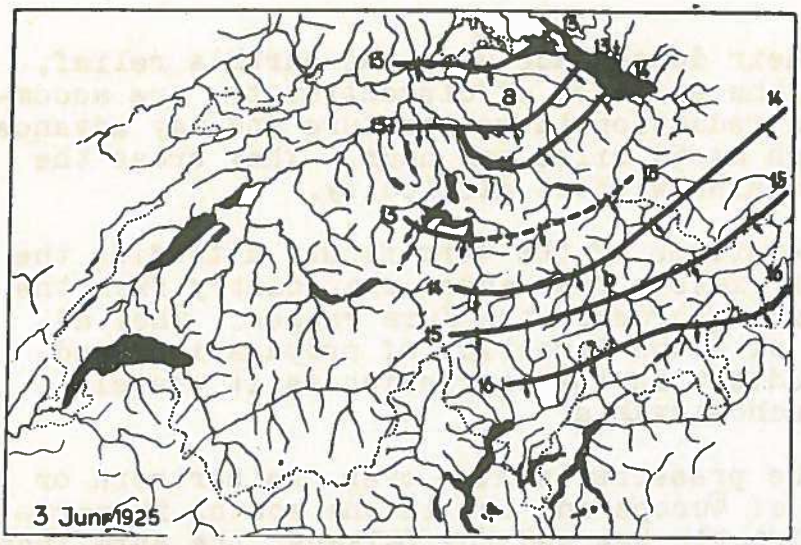


Fig. 23.

Isobront

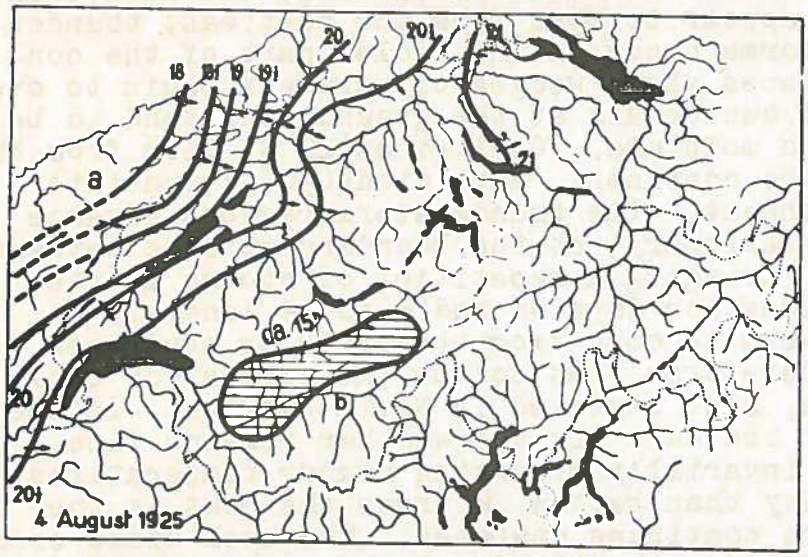


Fig. 24

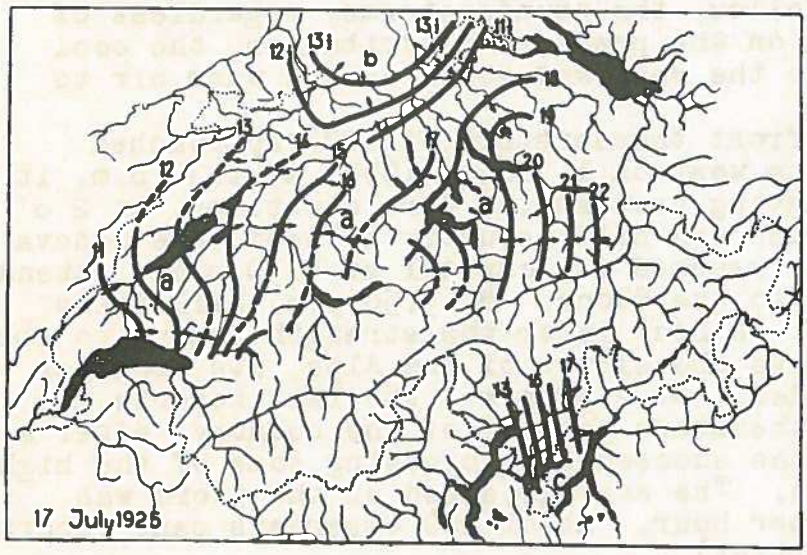


Fig. 25

A storm covering a much narrower band occurred on 24 September, 1940. It came again from the west, across the Jura ranges, passing Neuchâtel shortly after 6 p.m. without spreading into the lower hill country to the south so that the width of the front measured never more than 30 miles. At 11 p.m. it arrived at the eastern end of Lake of Constance where it was joining a storm already in existence. The speed was 25 miles per hour.(Fig.21).

A similar storm advancing nearly due east was reported from 24 May, 1933, between 7.30 and 11 p.m. Its direction of travel was parallel to that of the Rhine; it ended south of Lake of Constance(Fig.22).

Cold front thunderstorms also occur when the cold front of an old depression whose centre has crossed Denmark and the Baltic Sea, sweeps across the mountains. A thunderstorm caused by the advance of a cold front developed on 3 June, 1925(Fig.23). A wedge of cold air, advancing from Denmark toward Dulmatia, entered northern Switzerland along the Rhine from Zurzach to Lake Constance, reached the line Lucerne and Sargans at 1 p.m., and made its exit along the line Bellinzona-Shuls Tarasp(4 p.m.) followed by the main discontinuity. Two thunderstorms developed on that day. The western part of the country remained undisturbed(Lugeon).

A warm front thunderstorm arose on 4 August, 1925. The centre of a young low-pressure area of elliptical shape was advancing between 3 and 5 August, 1925, from Spain toward Germany, at a speed of 37 kms. per hour, following a southwest to northeast direction, to the west of the Swiss border. On 4 August, 1925, at 1 p.m., the first cirrus clouds appear in the west and at 3 p.m. the upper portion of the warm air comes into contact with the summits of the Bernese Alps(Fig.24). Both slopes of the Alps(Gsteig, Lauterbrunnen in the north, Sion in the south) become the seat of thunderstorms. Then, toward 7 p.m., the lower portion of the warm mass attended by rain ascends the slopes of the Jura mountains in the west and occasions thunderstorms. (Such a succession might be interpreted as a returning thunderstorm).

On 17 July, 1925, thunderstorms develop in the saddle between two discontinuities; one of the surfaces extending from Toulouse to Hamburg, the other from Bordeaux to the Zuider Sea(Fig.25). This zone reaches the western border first without causing thunderstorms; then its activity is renewed and thunderstorm and squall lines are reported from all parts of the country.

The map showing the lines along which the first thunder was heard on 13 June, 1925(Fig.26) shows the complications that arise when conditions favourable to thunderstorms exist on

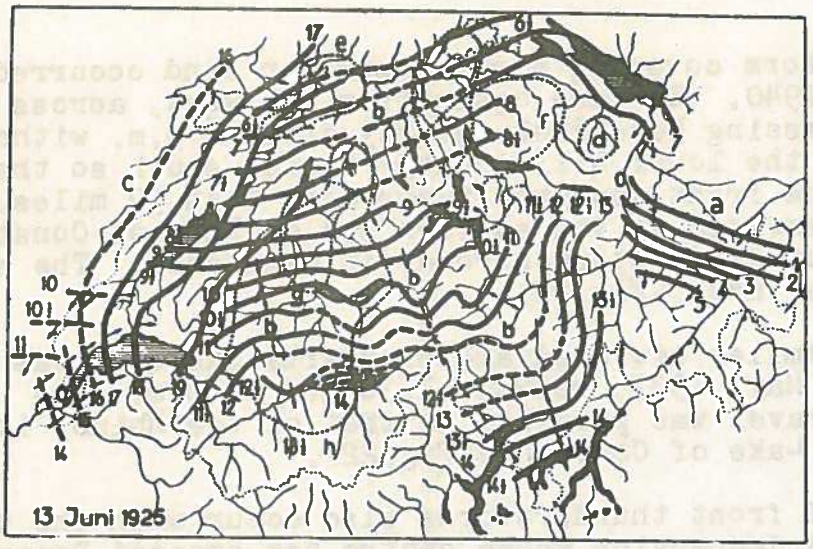


Fig. 26

Isobronts

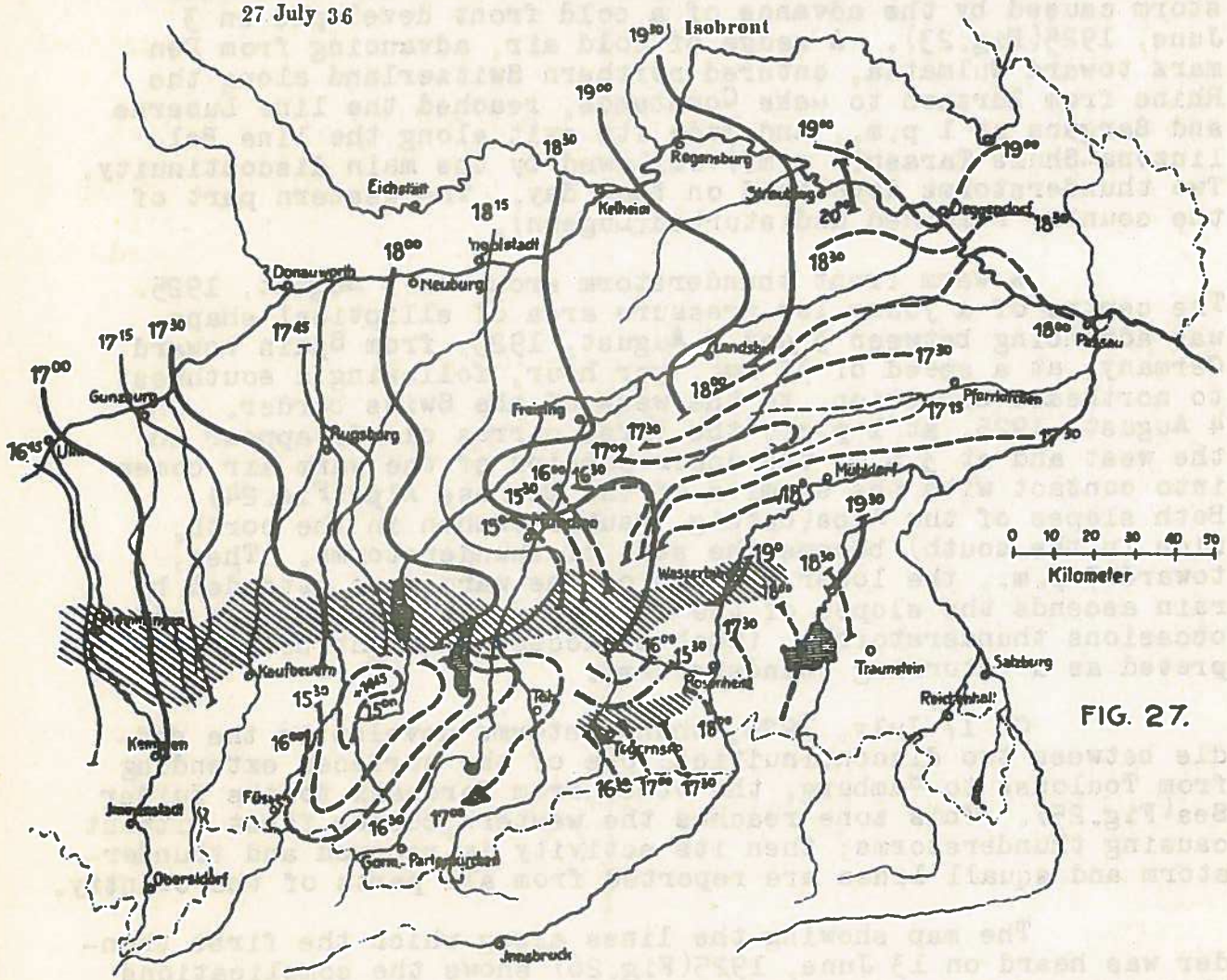


FIG. 27.

both slopes of the Alps, complication which explain why the forecasting of thunderstormsis a difficult problem. This storm was remarkable also for the large number of buildings hit by lightning; out of a total of 7,048 buildings reported to be struck by lightning during the thirteen years, 1925-1937 or about 12 per week in the area covered, no less than 110 were hit on this single day, according to verified reports (Morel).

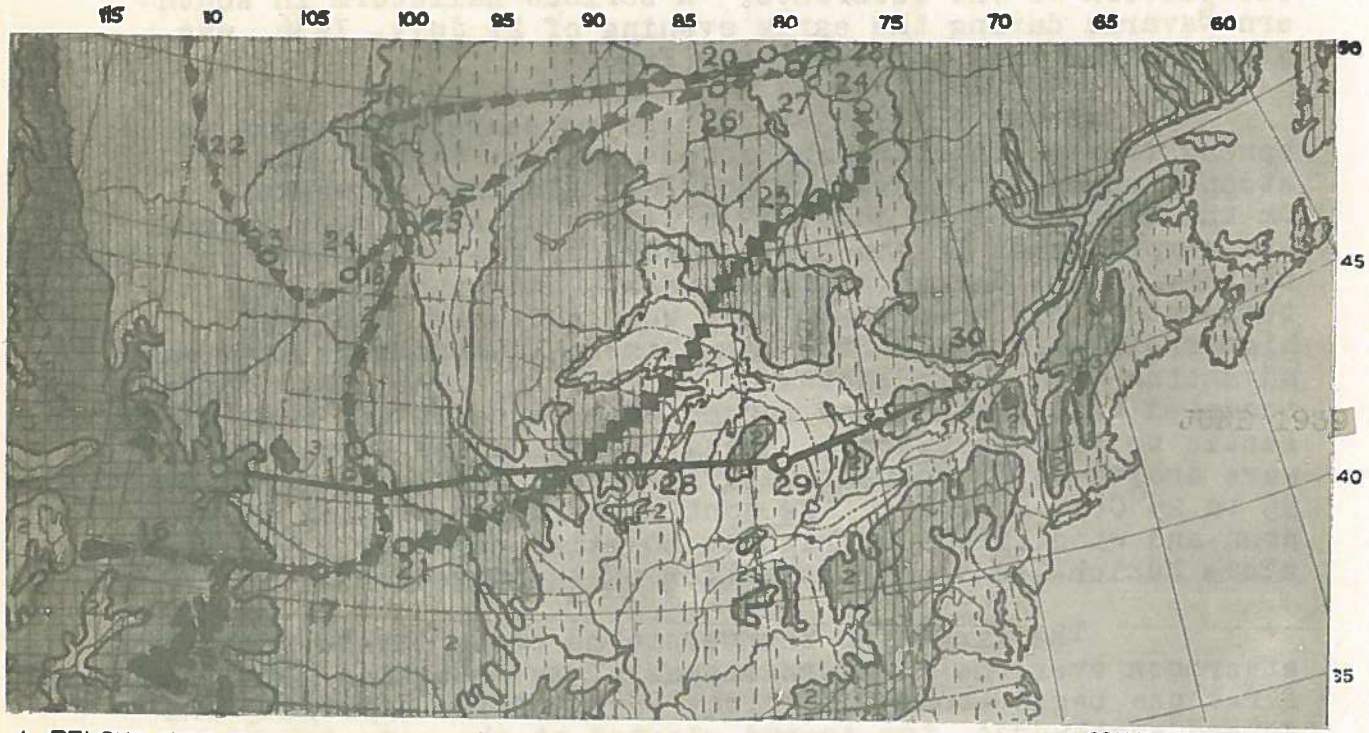
Of particular interest in the study of the propagation of thunderstorms is the distribution of hail within the pattern of the isobronts. A serious hailstorm in southern Bavaria during the early evening of 27 July, 1936, was studied from this point of view(Fig.27).

On 25 July, 1936, a high pressure area began to spread from southern Ireland across Central Europe, and stopped the west winds that had been blowing for weeks. On the morning of 27 July, 1936, its centre was over Poland. The temperatures in the lower layers of the atmosphere increased rapidly in the German south and east, and with them, the temperature differences between west and east, above all at higher elevations. At the same time a low-pressure area was advancing from Spain eastward; on 27 July, 1936, its centre occupied Switzerland, and caused cool westerly air from the Atlantic to flow eastwards. Along the Rhine the temperatures were around 16°C. whereas over the upper Danube they reached 25 to 29°C(at Passau). The continued inflow of cool air at noon-and wind speeds as high as 50 miles per hour 2 1/2 mi. above Munich-led to the formation of thunderstorms.

The first two thunderstorms broke out in the early afternoon over the northern slopes of the Austrian Alps; the first one began around 3 o'clock south of the Ammersee, and spread southwards, the second started at the same time just east of Munich and travelled east in the direction of the river valleys. Both disturbances were essentially thermal storms induced by the heated mountain slopes.

The storm that arrived from the west at 4.45 p.m. along the Iller, however, owed its existence to the encounter of different masses of air, moist warm air being underrun by cold air. The storm advanced in a general east northeast direction at a speed that reached almost 50 miles north of Munich. While mountains or rivers proved to be no obstacle to its progress, its strength vanished completely in those regions east of Munich that had been the seat, two hours earlier, of one of the heat thunderstorms over the eastern edge of the Alps. It was maintained north and south of this zone.

Hail fell along the southern edge of the storm, along a strip from 3 to 10 miles wide(the shaded area in Fig. 2). In the first two miles from the northern and southern



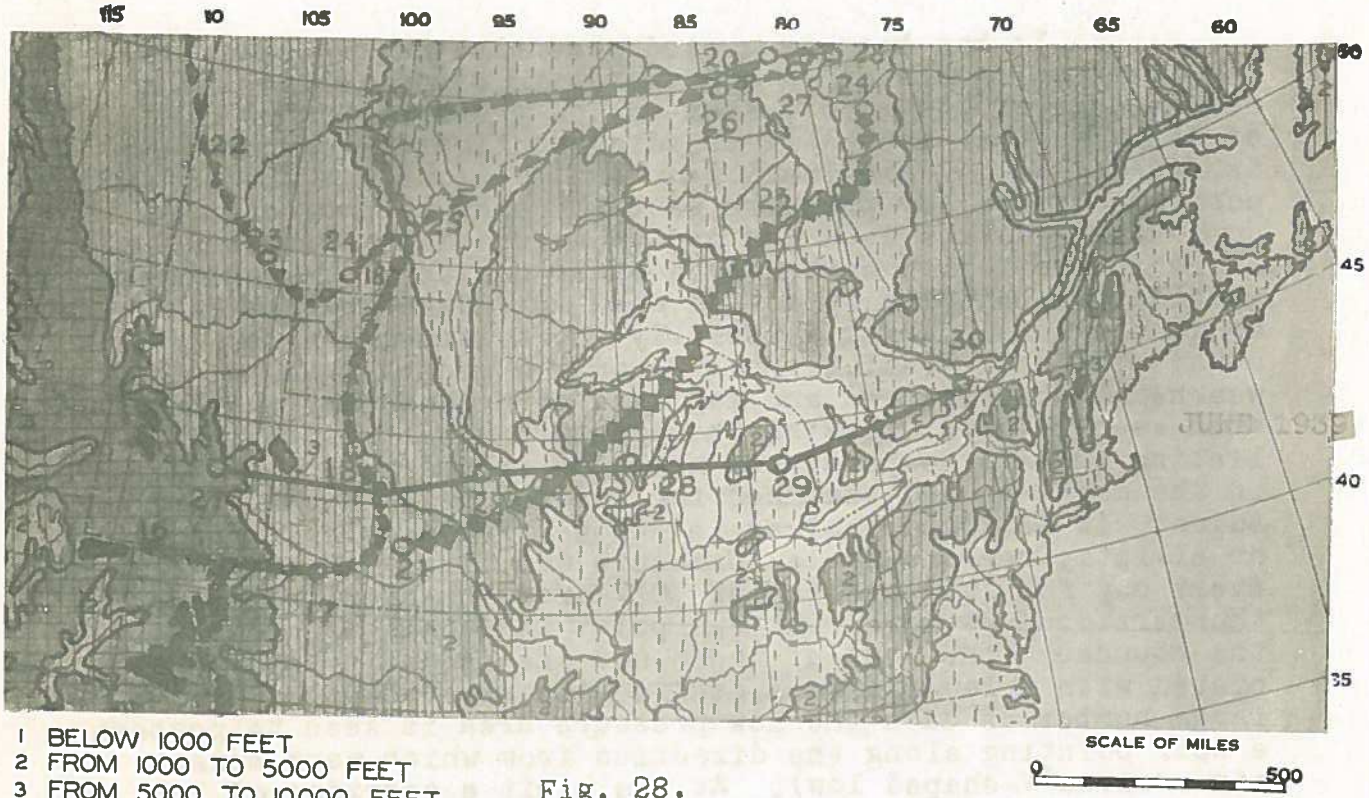
1 BELOW 1000 FEET
2 FROM 1000 TO 5000 FEET
3 FROM 5000 TO 10,000 FEET
4 ABOVE 10,000 FEET

Fig. 28.

edges of this strip the size of the hail stones increased from pea to walnut and to egg or even fist size. The harvest was almost totally destroyed, hens and sheep killed at one place. The hail fell exclusively in the belt of greatest precipitation(Piersig).

7. Examples of thunderstorm conditions

It has been suggested recently that in practice, for instance in designing and operating transmission lines, use be made of the information on low-pressure tracks and of daily weather maps. If the distribution of weather maps is speeded up, an examination of the previous and the actual position of the low-pressure centres ought to indicate the approximate future location and the probability of a thunderstorm in the region served by a power company. Farmers would also derive benefits at a time when advantage must be taken of good weather during a possibly short summer season. The usual broadcast predictions give only a general idea of the weather to be expected and may lead to unnecessary caution. When weather maps, showing the pressure distribution and listing the air temperatures near the ground at 8 o'clock in the morning, are examined for the months June, July and August, it is found that as in Europe, few simple circular or elliptic regions of low pressure are found. Practically every map for July and August 1937, for instance indicates thunderstorms at more than one point in Canada or close to the boundary line, but of these not one is definitely associated with a low-pressure centre of simple shape. On a large number of days the low-pressure area is seen to possess a spur pointing along the direction from which warm moist air arrives(V-shaped low). At the limit a corridor of low pressure extends from north to south throughout the continent, to the Gulf of Mexico in North America and to the Mediterranean in Europe. The corridor is bounded on both sides by high pressure, and the winds along one side blow directly opposite and at close range to those on the other side. Strips covering a great extent in latitudes become the seat of thunderstorms which drive freely from west to east. However, when and where the storm will break out and how strong it will be is difficult to determine in advance. The speed of the winds varies in different regions, and the area of lowest pressure changes in shape and position from hour to hour. How irregular the shape and the so-called tracks followed by low-pressure centres are is shown by the map recording the positions of the centres for the second half of the month of June, 1939(Fig.28). On 13 June, the pressure over most of Arctic Canada was low, that over continental Canada was high. In the evening of this day, a depression appeared east of



1 BELOW 1000 FEET
2 FROM 1000 TO 5000 FEET
3 FROM 5000 TO 10,000 FEET
4 ABOVE 10,000 FEET

Fig. 28.

Helena, Mont., and another west of Salt Lake City on the morning of 15 June. Both lived only for about two days. In the evening of 16 June, a low formed still farther south and east, centred near Rock Springs, Wyo., at the point common to Utah, Wyoming and Colorado. During the night it travelled east to North Platte, Nebr.; where it appeared with a southward extension on 17 June, it stopped and turned northward, reaching the junction of the Cheyenne with the Missouri north of Pierre, So. Dak. on the morning of Sunday 18 June and crossing North Dakota during the same day. In its northward course, parallel to the direction of its longer axis, the depression (29.4 in.) draws warm winds into Dakota and Minnesota up to a height of 2 km. and when the cold front sweeps into Minnesota, between 3 and 4 p.m. the disturbance develops, 15 miles northeast of Minneapolis, into a tornado. A funnel-shaped cloud brings destruction along a path 25 miles long and about 700 yards wide crossing the Mississippi(Hoyde). Thunderstorms were numerous in the east-central counties of the state. From Brandon, Man., reached in the evening, the centre(29.4 in.) moved then to the north of Lake Winnipeg and in the course of the next day, 19 June, to Port Nelson, Man. The Hudson Bay was traversed from the evening of 19 June to the evening of the twentieth; then, although the pressure began to decrease, the disturbance disappeared on 21 June over Northern Quebec. On this day the pressure was low all across Canada south of the Arctic circle probably along the boundary of arctic and polar air, and a spur of low pressure extended south along the slopes of the Rocky Mountains with a vague centre near Pierre, So. Dak.(29.9 in.). By next morning, 22 June, 1939, the southern portion of the low had reached Marquette, Mich.(29.6 in.); it crossed Lake Superior to White River during the day, without producing thunderstorms on the north shore, continued to Moosonee(22 June,(29.5 in.) and was gradually filled up east of James Bay(29.5 in on 23, 29.7 on 24, 30 on 25 June).

In the meanwhile, the northern portion of the low starting from Great Bear Lake in the morning of 21 June, was south of Great Slave Lake in the evening, south of Lake Athabaska next morning, crossed Saskatchewan in the following 24 hours, stopped and deepened in North Dakota, and drifted back north to Saskatchewan on the morning of 24 June and to Lake Winnipeg next day(25 June). After speeding through Manitoba to James Bay(26 June), stopping almost completely for a day and extending the area of low pressure in western Canada, it crossed Hudson Bay and Ungava Bay from 27 June to 29 June, 3 or 4 days after the depression sprung from the southern trough.

While these depressions were still advancing through the Prairies, a fourth disturbance ran its course from Wyoming (28 June, 1939) across Lake Michigan and Lake Huron(29 June) to Ottawa(30 June). The various cyclones were so staggered

in time and place that from 20 to 30 June, 1939, pressures tended to be low over most of northern Canada while for days a complete corridor of low pressure extended south to the Gulf of Mexico. Two or three fronts are often in action at the same time, and under these difficult conditions reliable forecasts, a few hours in advance of the outbreak, can be secured only with the aid of the curves indicating when the first thunder is heard in a grid of observation points(isobronts). When the front occupied by the advancing storm is traced at half-hour intervals, that is for the normal speed of propagation of low pressure centres-20 mi. p.h. in summer and 25 mi. p.h. in winter-after an advance of 10 miles, the direction and rate of travel is deduced without great difficulty. Where it is not feasible to construct the curves of the isobronts, the inclusion of the relative humidity determinations in the daily weather map would be of help in forecasting thunderstorms.

8. References

Church, P.E. Monthly Weather Review 63:93-98. 1935.
Church, P.E. Geographical Review 26:283-292. 1936.
Clayton, H.H. Amer. Meteor. Journal 1:263-272. 1884/85.
Davis, W.M. Proceed. Am. Acad. Arts Sciences 22:14;1886.
Hoyde, M.R. Monthly Weather Review 67:176-178. 1939.
Lugeon, J. Assoc. suisse Electriciens Bulletin 34:29-43 1943.
Morel, Ch. Assoc. suisse Electriciens Bull. 31:178-186. 1940.
Morris, W.G. Monthly Weather Review 62:370-375. 1934.
Piersig, W. Meteorol. Zeit. 55:48-54. 1938.
Scherhag, R. Meteorol. Zeit. 48:245-254. 1931.
Stevens, W.R. Monthly Weather Review 62:366-370. 1934.
Ward, R.A. Monthly Weather Review 64:37-45. 1936.
Ward, R.deC. Annals Astron. Obs. of Harvard College Vol. 31 Part II. 261-343. 1893
Winter, H. Meteorol. Zeit. 55:91-97. 1938.
Zobrist, W. Assoc. suisse Electriciens Bulletin 34:46-49. 1943.

9. Illustrations