HIGH ALTITUDE OROGRAPHIC CLOUDS OVER SOUTHERN MAINE

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1. INTRODUCTION

Can a low mountain range produce and modify clouds at high altitudes? Before that can be discussed, a few principles of atmospheric behavior should be explained.

In a frictionless atmosphere, over a rotating earth, the wind flows perpendicular to, and to the right of, a constant pressure gradient force. The wind does not flow toward lower pressure in this case, because it is balanced by an equal and opposite Coriolis force. These forces, acting on a parcel of air, would look like this:

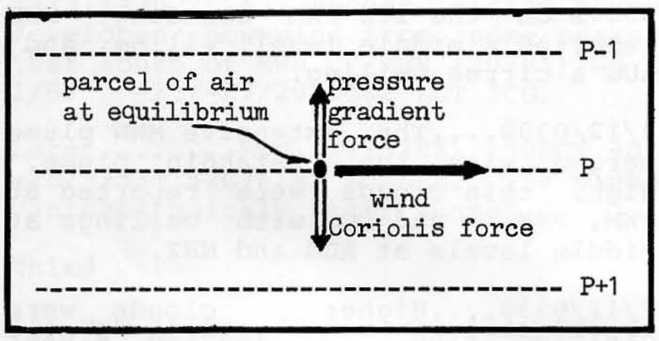

Figure 1

The earth's atmosphere, from about 1000m up, in most cases, behaves like Figure 1. This region is called the "free atmosphere." (1)

The atmosphere, within about 1000m of the earth's surface, is called the "planetary boundary layer." Friction acts on the wind in this layer. The source of the friction is mechanical and convective turbulence, and drag due to the roughness of the earth's surface (1).

If friction is acting opposite to the direction of motion of a parcel, then a different balance of forces is possible. The vector sum of friction and the Coriolis force is then equal and opposite to the pressure gradient force. Figure 2 shows this:

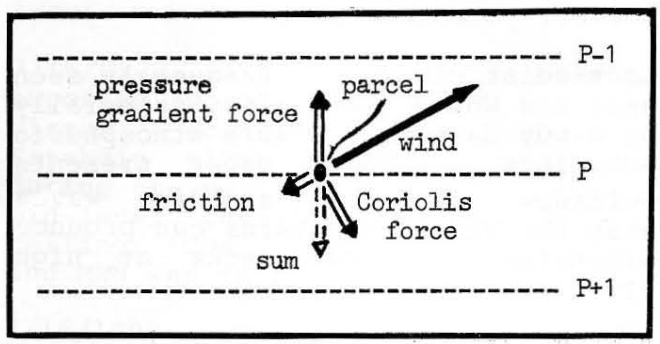

Figure 2

Friction lowers wind speed and allows the wind to angle toward lower pressure.

The planetary boundary layer is bordered on top by a discontinuity called the "gradient level." The gradient level can be seen from a high hill or from an airplane on a sunny day. Above the gradient level, the air is very clear and the sky is a deep blue. Below this level, a thin milky or brownish haze is visible, shrouding all objects below. Distant mountains appear like islands, jutting out of a translucent ocean.

Winds of the free atmosphere flow as though the gradient level is a frictionless surface supported by a rigid planetary boundary layer. Hills or buildings within the planetary boundary layer have no significant effect on the free atmosphere. A mountain that juts up through the gradient level, however, often acts on the free atmosphere as a submerged boulder acts on a river, setting up large standing waves.

If moisture is available in the free atmosphere, the waves near and downstream from mountains become visible as clouds. These stationary lenticular clouds resemble stacks of dishes or lenses.

The White Mountains of northern New Hampshire poke into the free atmosphere. The highest of these mountains, Mount Washington, is an eroded peak 1917m high. MWN, an observation station on Mount Washington, is just west of the Maine border.

Lenticular clouds are frequently seen near the White Mountains, especially on windy days with stable atmospheric soundings. This paper presents evidence that some standing waves near the White Mountains can produce extensive cloud decks at high altitudes.

2. ANALYSIS

During the past year, large cirriform decks were observed to be associated with the White Mountains on three occasions. These three cases are described below. In all three cases, surface observations are in English units.

First Case:

3PM EST 11 Feb 79 through 8AM EST 12 Feb 79...

The afternoon of February 11th was clear, gusty, and cold across northern New England. The only clouds in the area were cyclonically curved bands of stratocumulus over the Gulf of Maine. No clouds were reported within 1000km upwind. Surface winds were gusting to 12 to 14mps, or 24 to 28 knots across Maine. Surface temperatures were between -15 degrees C and -20 degrees C in this area, and -25 degrees C upwind.

Date/time EST Description

2/11/1514....MWN (2014Z) CLR 90 -30/-36/3055G65/M/ INTMT FOG

2/11/1730....A thin cirrus plume downwind from MWN first appeared on the infrared satellite picture.

2/11/1900....The cloud plume reached the coast near Portland, Maine (PWM). All nearby stations reported clear skies, testifying to the transparency of the plume. A full, or nearly full, moon during all three cases implies accurate nighttime sky-cover observations.

2/11/2300....Little change on the satellite picture. PWM reported 250 -SCT.

2/12/0200....The plume had now covered most of Southern Maine. Another cirrus plume quickly formed downwind from Mount Katahdin, an isolated 1605-m peak 225km northeast of MWN. Cloudtop temperature, from the satellite picture (2), was about -38C, corresponding to an altitude of 5500m on the 12Z PWM sounding. NHZ reported a middle level ceiling, and AUG a cirrus ceiling.

2/12/0300....The extensive MWN plume merged with the Katahdin plume. High, thin clouds were reported at PWM, PSM, and CON with ceilings at middle levels at AUG and NHZ.

2/12/0530....Higher clouds were disintegrating, leaving a vast mid-level deck. Mid-level ceilings were reported at PWM, PSM, NHZ, AUG, and BOS. BGR reported a high ceiling. Other New England stations were clear.

2/12/0700....This was the first visible picture of the day. The only remaining cirrus was a long, narrow plume downwind from MWN. The mid-level deck was breaking up. Bands of stratocumulus, over the Gulf of Maine, were losing their cyclonic curvature.

2/12/0800....No plume remained. Only scattered clouds were left.

Second Case:

11AM EST 13 Feb 79 through 3PM EST 13 Feb 79...

Midday February 13th was identical to the afternoon of February 11th with respect to surface temperatures, lack of clouds, and wind speeds across northern New England. Cyclonic curvature was again present in the stratocumulus bands over the Gulf of Maine.

Date/time EST Description

2/13/1100....The first shadow of a cloud appeared 35km due east of MWN (3). PWM reported some thin cirrus.

2/13/1200....MWN (1715Z) 3 SCT 30 -26/-26/2950G71/M/ LGT ICG/ INTMT FOG/ TOPS LWR SCT 50. The plume was elongating rapidly.

2/13/1300....The plume had already reached its maximum development, 35km wide and 140km long. NHZ reported a high ceiling; PWM and AUG, scattered cirrus.

2/13/1430....A second cirrus plume developed downwind from some peaks, just south of MWN. MWN (2020Z) W0 X 1/8F -27/-27/2950G62 LGT ICG.

Later........MWN (2320Z) 50SCT 90 -28/-33/3152G76/M/ ACSL E. The plume vanished quickly after sunset.

Third Case:

4AM EST 16 Mar 79 through 11AM EST 16 Mar 79...

The early morning of March 16th was clear and cold across Maine and New Hampshire. Thin patches of cirrus were upwind, in southern Quebec. New York and southern Vermont lay under stratocumulus in the form of mountain waves. Surface winds were light across southern Maine. Temperatures ranged from -10C to -18C across northern New England. Though there was little or no cyclonic curvature over the Gulf of Maine, there was convergence of cloud bands.

Date/time EST Description

3/16/0400....MWN (0818Z) W0 X 0F -17/-17/2946G57/M/ LGT ICG. Scattered cirrus and altocumulus were crossing the Champlain Valley. BTV and LEB reported scattered clouds.

3/16/0700....Thin cirrus and patches of middle clouds had become established over southern Maine and southeastern New Hampshire. A long cirrus plume, about 125km in length, quickly developed downwind from Mount Katahdin. Cloudtops were -40C, corresponding to an altitude of 5400m on the 16/12Z PWM sounding. Mid-level ceilings were reported at NHZ and MHT. The cirrus was thin over PWM, AUG, BGR, CON, and PSM. MWN still reported dense fog.

3/16/0730....Visual satellite picture showing the situation described above.

3/16/0900....The cirrus had thinned, exposing two thick adjacent plumes of cirrus downwind from MWN. The Katahdin plume abruptly disappeared during the past hour. NHZ reported a mid-level ceiling, and PWM a cirrus ceiling. CON reported thin cirrus, and MWN was in fog.

3/16/1000....The plume began to separate, or increase in distance, from MWN. Convergence of the cloud bands ended over the Gulf of Maine. MWN still had fog.

3/16/1100....The plume disintegrated, though PWM still reported scattered cirrus.

The Soundings

To examine the atmospheric structure, in each case, five PWM soundings were drawn up. The first two, 2/12/00Z and 2/12/12Z, were taken near the beginning and end of the February 12th case. Two other soundings, 2/13/12Z and 2/14/00Z, were taken before and toward the end of the February 13th case. The fifth sounding, 3/16/12Z, was taken during the March 16th case. Since the soundings were very similar, they were averaged (Figure 3).

Each sounding had a distinct

inversion with a base and, with one exception, a top below 1900m ASL. An average wind, which backed 40 degrees through the inversion, increased 10mps or 20 knots. The temperature increased 2C in an average inversion 36m deep, starting at 865mb. Drying occurred across three inversions, producing a dewpoint decrease of 4C for the five sounding average (see Figure 3). None of the inversions resembled a classic subsidence inversion. The gradient level appeared to be near the base of the inversions, since the change of wind speed and direction was greatest there.

All soundings had similar wind profiles. Windspeed between the gradient level and the tropopause was at least 13mps or 26 knots and increased steadily with height. In each case, windspeed increased rapidly near mountain-top level. There was little variation in wind direction above the gradient level.

The average sounding was dry at all levels, despite three of the soundings having penetrated the cloud plumes.

Most notable about the soundings were the very cold temperatures. The tropopause, at an average of 368mb, was over 3500 meters below the tropopause in the U.S. Standard Atmosphere. Also, the average 1000mb to 500mb thickness was only 4990m. Nowhere did the average sounding

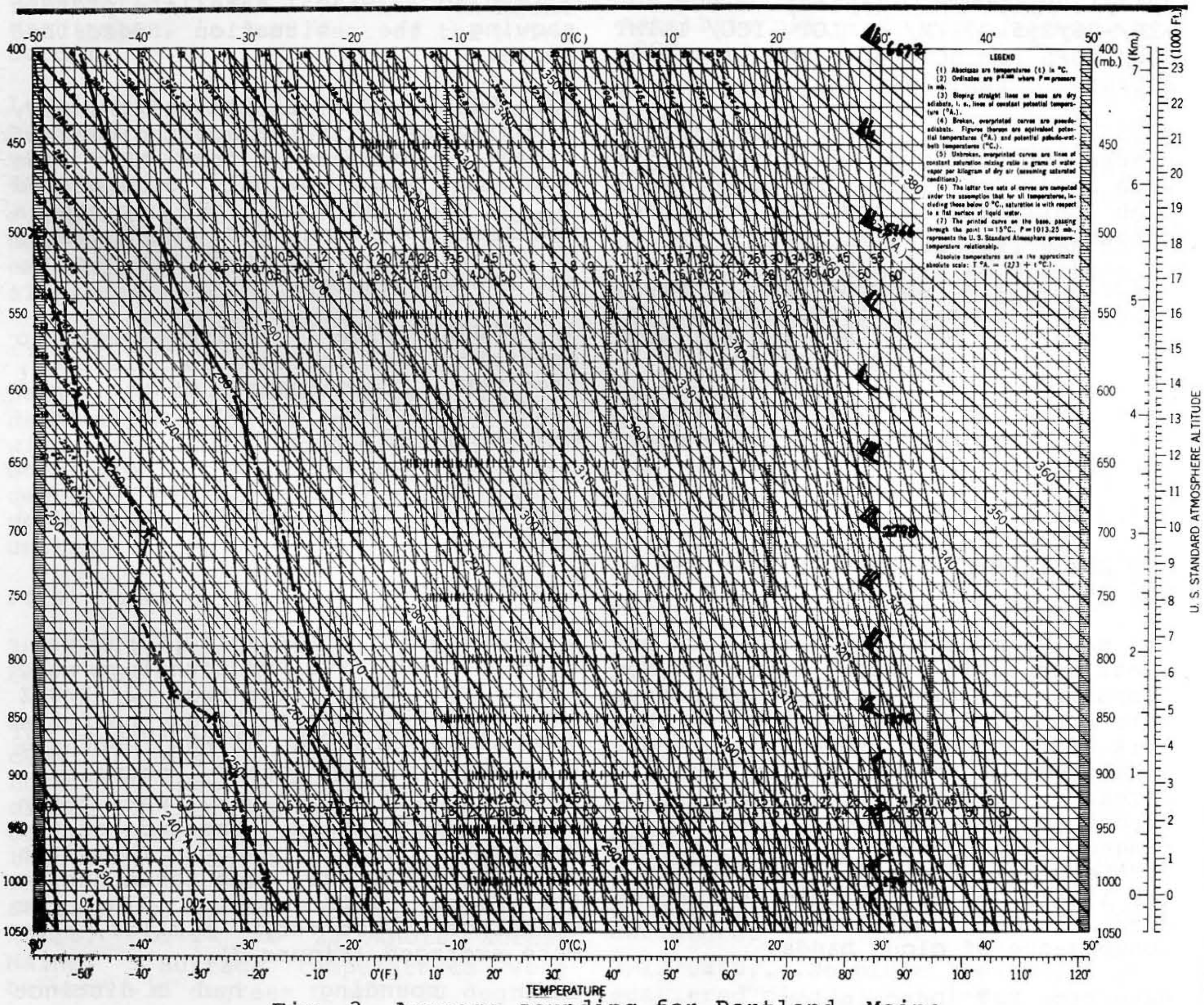

Fig. 3. Average sounding for Portland, Maine.

reach -18C, despite the fact that two of the five soundings were taken near the warmest part of the day, and a third was taken within a week of the Vernal Equinox.

The MWN Observations from Mount Washington

At the beginning of each case, a cap cloud either formed or showed signs of forming around the summit of Mount Washington. These clouds in spite of the relative dryness of the air upstream.

Other features of the observations were noteworthy. Winds at MWN were about twice as strong as they were at comparable altitudes on the PWM soundings. MWN temperatures were considerably lower than the temperature at 1900 meters on the PWM soundings. These temperatures dropped rapidly as windspeed increased. These high windspeeds and low temperatures are caused by apparent Bernoulli effects acting on the smooth terrain around the mountain (4).

3. DISCUSSION

Standing mountain waves are apt to form if:

- Windfall normal to the mountain mass has a speed of 25 knots, or 13mps, or more at mountaintop level.
- A wind profile shows increasing windspeed with altitude near mountaintop level, with a strong steady flow at high altitudes, up to the tropopause.
- An inversion or a stable layer exists below 600mb (5).

Since all the soundings exhibited these conditions, mountain waves almost certainly existed. The existence of Bernoulli effects near MWN seems to amplify such waves. The dryness of the soundings and of the air upwind prevented the formation of lenticular clouds. Any waves would not have been visible.

Jenkins (6) mentions severe turbulence in the planetary boundary layer, and again in a layer near the tropopause. This turbulence exists from the summits of the mountains to about 36km downstream and sometimes further. To quote Jenkins, "The turbulence layers above and below the lenticular levels (mid clouds) are comparable to ball bearings, allowing the atmosphere between to flow through at very high speeds. The juxtaposition of very turbulent and very smooth flow is typical in the wave. There are times when the wind is favorable for a wave condition but not enough moisture is present for the clouds to form."

This is what seems to have happened in the three cases presented: The standing mountain waves existed near and east of the White Mountains and Mount Katahdin. The lack of moisture prevented the formation of lenticular clouds. When a small amount of moisture was blown in from the northwest, it was uplifted, forming cirrus in the turbulent layer near the tropopause. The ice crystals of the cirrus, which sublime very slowly, were then blown out of the mountain waves. In addition, any ice crystals that formed at mid-levels were blown out of the standing waves in the same way.

4. CONCLUSIONS

High altitude orographic clouds are rare over Maine. Although only three cases are presented here, some general conclusions about their formation can be drawn. First of all, in each case, the atmosphere was favorable for the formation of mountain waves. Additionally, very cold atmospheric temperatures seem to be needed, so that ice crystals rather than water droplets will form. Finally, convergence or cyclonic curvature near the surface seems necessary to produce uplift and maintain the large cloud decks. As soon as the evidence of upward motion vanished, in each case, so did the clouds.

The resemblance of these cloud decks to summertime cumulonimbus anvils is interesting. These orographic clouds formed rapidly and quickly reached the size and shape of mature anvils. Furthermore, these orographic clouds disappeared by drifting downstream, the same way a shrinking anvil drifts away from a dying thunderstorm.

Actually, these orographic plumes were formed in much the same way as anvil clouds are. Moisture was suddenly and violently injected into a high-speed, extremely cold upper level flow by the mountain wave. Moisture is similarly injected into high levels by thunderstorms. There was not, however, the huge quantities of moisture that a cumulonimbus is capable of producing.

These mountain plumes can affect forecasts in two ways. First of all, these clouds should alert the aviation forecaster to the possibility of clear air turbulence near the mountains. Secondly, the clouds were thick and persistent enough to interfere with nocturnal radiation. Conditions leading to extensive mountain plumes should be watched for when making temperature forecasts during major arctic outbreaks.

REFERENCES AND FOOTNOTES

(1) Hess, Seymour L., 1959. Theoretical Meteorology, (New York: Holt, Rinehart and Winston), p.279.

(2) Infrared pictures for Case 1 were enhanced by the Cc curve. Case 3 pictures were enhanced by the Mb curve.

(3) On the visual satellite pictures, MWN appears as an elongated white spot, just west of Maine. MWN is brighter than any frozen lakes. The white patch is due to MWN being surrounded by a large area of tundra, above the timberline. Mount Katahdin is a sharp summit of rock, jutting out of a vast forest. Therefore, Mount Katahdin is not visible on satellite pictures.

(4) Parke, Peter S., 1978. The Temperature and Wind on Mount Washington.

(5) George, Joseph J., 1960. Weather Forecasting for Aeronautics, p. 439.

(6) Jenkins, C.F., 1952. Forecasting the Mountain Wave, Air Force Surveys in Geophysics, No. 15.