MESOSCALE CYCLOGENESIS: THE MASSACHUSETTS MINI-SNOWSTORM OF DECEMBER 1971

by

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ABSTRACT

An unusual mesoscale snowstorm is analyzed. It occurred on December 18, 1971 and affected a large area of eastern Massachusetts with up to 12" of new snow in a highly localized area, mainly in the Marblehead-Peabody region. The snow was associated with a closed cyclonic circulation in Massachusetts Bay which later was steered by low-level northwesterlies to Cape Cod Bay and affected that area with gale force winds and moderate to heavy snow. Oceanic heating is felt to be the important effect in the development of the mesocyclone but man-made heating is also a possibility.

A search is made to see if this type of weather event is at all regular. Three possible cases are isolated, two along the Massachusetts coast and one in England.

A statistical analysis is made on a time series of mean vorticity values in Massachusetts Bay. Contrary to what was expected, frictional effects are found to be most important for relative vorticity induction in the Bay. This implies that cases like the December 18th meso-snowstorm are an extreme rarity.

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I. Introduction

For New England snow watchers heavy snows are a relatively frequent occurrence, their appetites being satiated at least once every winter. Also, large snow depth gradients, especially in coastal areas, are equally frequent. Yet, a heavy snowstorm on December 18, 1971 was of unusual interest. Besides being unexpected, which is not uncommon, it occurred in an indifferent synoptic environment and on a very small scale.

The routine National Meteorological Center (NMC) surface and 500 mb. charts from 00 and 12 GMT on the 18th are given in Figures 1a and 1b. Despite their innocuous appearance, by 12 GMT and a few hours afterward several areas in Massachusetts had recorded what was to be their heaviest snowfall of the season. The snowfall distribution is given in Figure 2.

This and the radar charts from the National Weather Service (NWS) radar at Chatham, Massachusetts were all the initial clues that the author had when he began the analysis of this event. The radar pictures (shown later as part of Figures 4a-h) suggested that the heavy snow on the North Shore was part of a closed circulation system, that it had a character of its own. Surface weather observations, routinely available from teletype data, were used in studying the event further. It became obvious that a mesoscale cyclonic circulation had developed in the Massachusetts Bay and was responsible for much of the weather that occurred on the 18th. It was unusual because it was the first of its type to be seen or documented.

When an unusual weather event occurs, it is natural for a cause to be sought. An hypothesis is presented for the origin and maintenance of the mesocyclone. However, the observations that were used are not suited for the detailed mesoscale studies that would be necessary to prove the hypothesis conclusively. These observations include NWS observations at several first order stations and U.S. Coast Guard observations at stations along the New England Coast. A more desirable observational network would have provided a higher frequency of observations and greater time and space detail in the vertical. The NWS surface observations were hourly and the Coast Guard ones 3-hourly when available. The resolution in the vertical was limited to 12-hourly radiosonde measurements at Portland, Maine and Chatham. While it is the presence of the Coast Guard observations that make the attempt at mesoscale analysis feasible, their lack of high quality prevent an analysis more sophisticated and conclusive than that presented in this thesis. Therefore, the second part of this thesis is concerned with an indirect route: to test whether or not the hypothesis is plausible. It is tested out on a time series of past surface observations at the aforementioned Weather Service and Coast Guard stations, namely Boston (Logan Airport), Gloucester (Eastern Point), Scituate, and the Boston Light Vessel. These stations ring Massachusetts Bay with the exception of the Light Vessel which is anchored in the Bay proper. From this series of conventional data it is concluded that a semi-enclosed body of water such as the Massachusetts Bay has the ability to create mesoscale wind circulations but probably does so very infrequently. It is one of these, the December 18th meso-snowstorm (DMS), that is the main subject of the thesis.

The plan will be a description of the origin and movement of the storm, a review of the synoptic environment in which it occurred, and a detailed description of the chain of meteorological events in the New England region on the 18th. A description is also included of the various techniques used in analyzing the storm and the test of the hypothesis as to its cause. An interesting hypothesis as to the possibility of man-made causes is presented on the basis of some simple calculations. Other possible mesoscale snowstorms are presented including one in England. After the statistical analysis, suggestions for further research and some general observations are presented.

II. Significant Features of December 18, 1971

The snowburst on the North Shore of Mass. (the 12" maximum in Figure 2 which encloses Marblehead, Manchester, Gloucester, Peabody, and Ipswich) began shortly after 3 AM EST (08 GMT). It was accompanied by a thunderstorm (Boston Globe, Dec. 19, 1971), sub-gale winds and constant temperatures and ended by 07 EST (12 GMT). The larger area of heavy snow to the southeast of Boston began after 07 EST and ended by late afternoon. Evidence of time separation between the two events is an eyewitness report from Marblehead.

This report (Prof. Sanders of MIT) indicates that all the necessary snow shoveling had been completed by 07 EST. However, the author in Cambridge that morning noted moderate to heavy snow that began and continued for a short period after 0730 EST and lasted until 0900 EST. Another report, described later, indicates that heavy snow and gale force winds arrived at Cape Cod that same morning, after 1000 EST. The regular observations from NWS stations corroborated these informal reports. From an area southeast of Boston to Cape Cod gale force winds were experienced with the heavy snow and temperatures fell sharply shortly after snow onset.

The map of snowfall distribution given in Figure 2 was arrived at from a combination of informal reports from cooperative and cooperating observers. These supplemented the regular NWS stations and reports from local newspapers (e.g. Boston Globe Dec. 19, 1971). The small scale of the cyclone is shown by the extraordinarily sharp gradient in snow amount between the Revere and Marblehead-Peabody areas, only ten miles apart. Gradients of this intensity are not infrequently seen in New England in the presence of melted or melting precipitation which will prevent snow from accumulating. However, in this case no rain was reported and the inference is that Figure 2 also represents a distribution of total precipitation, the snow amounts being divided by the appropriate proportionality factor of snow depth to liquid water equivalent. The sharp gradient caused havoc among motorists ill-prepared for the early season storm and unaware of the sharp depth gradient. Route 128 north of Boston was especially susceptible to this feature. It stretches from Reading eastnortheastward to the vicinity of Gloucester, right through the area of heaviest snow and sharpest snow depth gradient.

A third area of heavy snow occurred near the Mass.-New Hampshire border. The snowfall was heaviest here at about mid-morning of the 18th. Thus the distribution in Figure 2 has a broader maximum to the north in Northern Mass. than it does in the south. This last heavy snow area was the result of low-level convergence along a coastal front which developed after the meso-cyclone and apparently was unrelated to it except that it formed in the same favorable synoptic environment. Since coastal fronts are a fairly common occurrence along the New England coast (Bosart et al, 1972), this third area of heavy snow will be documented only after a full description of the Massachusetts Bay mesocyclone. It is included because it was an important weather event of December 18, 1971.

III. Synoptic Picture

Figures 1a and 1b describe the synoptic situation. At 00 GMT of the 18th a weak surface trough is moving eastward toward a position off the New England coast. It is the surface reflection of the intense cyclonic vorticity maximum near Detroit (DET) at 500 mb. This upper air low was one of the most intense seen during the winter of 71-72 and it was not surprising that the surface configuration at 12 GMT evolved. In light of intense positive vorticity advection at 500 mb., intense cyclogenesis occurred at the surface well off-shore of New England. The cyclogenesis was so intense that it changed the circulation at the surface radically over a large area of eastern United States in a period of less than 12 hours. Petterssen (1956) noted that the contribution of cyclonic vorticity advection in the mid-troposphere leads to positive vorticity production at the surface. The weak surface trough at 00 GMT is nowhere to be found at 12 GMT since it had been absorbed by the main cyclone center over the Atlantic.

Over New England the trend was from a relatively quiescent and variable wind situation to a steady flow of much colder air. The 17th had been unseasonably mild and pleasant, continuing the trend of the previous week. The synoptic change on the 18th thus represented a major change in the circulation over New England. However, the mesocyclone affected northern Mass. before 12 GMT. The upper air low was still in a favorable position for surface vorticity production and the mean tropospheric flow was from a southwesterly direction. Yet, the chain of events described before indicates that the mesocyclone moved from northwest to southeast, normal to the mean flow but with the surface flow at 12 GMT. Thus, this phenomenon was of a very shallow nature, somewhat different from the off-shore cyclone.

With a progression of events of this type, light snow might be expected in those coastal areas closest to the off-shore cyclone center and in the hilly regions of Vermont and New Hampshire. Boston's Logan Airport reported 1.6" of new snow, most of which fell between 10 and 15 GMT, about the time the off-shore cyclone was closest to Boston. Bedford (BED), Worcester (ORH) and Providence (PVD) reported light snow during the transition period from light winds to moderate northwesterlies which had ended by 15 GMT. One would expect this sequence to have verified the NWS forecast at 05 GMT, December 18 for Mass. and Rhode Island:

> " Rest of tonight chance of light snow developing ending by late Saturday morning or afternoon and followed by clearing...."

The consensus of the forecasting group at MIT for the 24 hr. period precipitation at Boston ending at 18 GMT was 57%. The probability of precipitation amount was inclined toward low amounts with 21% in the .01 to .04 category. Certainly the snowfall distribution given by Figure 2 cannot be explained in terms of the synoptic events. Without a meso-scale analysis, any attempt at an explanation becomes futile.

IV. Analysis of the meso-cyclone

A. Data

A mesoscale analysis is possible along the New England coast from conventional data sources due to the density of NWS, U.S. military and Coast Guard stations. The stations that were available are given in Figure 3. Some of the stations, however, were received only erratically on the 18th or not at all. Future mesoscale analyses of New England weather might do well and try to recover observations at the stations in Figure 3 that didn't report on December 18, 1971. The observations used in this analysis was strictly from teletype data from the A, C, and local circuits. It may be that there are other observations not reported on teletype but available from other sources such as the Coast Guard or National Climatic Center (NCC) in Asheville, North Carolina. Table 1 names the stations that appear in Figure 3 in abbreviated form or numeric code. Generally, coded stations are NWS or military and named stations are Coast Guard.

B. Surface Analyses

1. Winds

The surface analyses from the 18th are given in Figures 4a-h. The station wind and weather are plotted but not temperature or dew point. This was done to relieve diagram congestion. Streamlines are drawn as close as possible to the observed wind. This was done by analyzing the wind direction field and drawing isogons, lines of equal wind direction. Where the observed wind was hard to believe, it was either adjusted prudently or left out. The latter was the case for several hours on the 18th at Portsmouth C.G.S. and the former at Chatham C.G.S. Streamlines were then drawn closely adhering to the restrictions placed by the isogons. This method proved helpful in displaying the complex

Table 1

Names of Stations

Station		Locations
ACK	506	Nantucket,Mass.
ALB	518	Albany, N.Y.
AUG		Augusta, Me.
BDL	508	Hartford, Conn.
BDR		Bridgeport, Conn.
BED	490	Bedford, Mass.
BGR	607	Bangor, Me.
BID	505	Block Island, R.I.
BOS	509	Boston, Mass.
BTV		Burlington, Vt.
CEF		Springfield, Mass.
CON	605	Concord, N.H.
EEN		Keene, N.H.
EFK	612	Newport, Vt.
EWB		New Bedford, Mass.
EWR	502	Newark, N.J.
FMH		Falmouth, Mass.
GFL		Glens Falls, N.Y.
GON		Groton, Conn.
HPN		White Plains, N.Y.
HVN		New Haven, Conn.
ISP		Islip, N.Y.
JFK	486	Kennedy Intl. Airport, N.Y.C.,N.Y.
LCI		Laconia, N.H.
LEB	611	Lebanon, N.H.
LEW		Lewiston, Me.
LGA	503	LaGuardia Airport, N.Y.C.,N.Y.
MHT		Manchester, N.H.
MPV		Montpelier, Vt.
MVY		Martha's Vineyard, Mass.
MWN	613	Mt. Washington, N.H.
NCO		Quonset Point, R.I.
NHZ	392	Brunswick, Me.
NYC		Central Park, N.Y.C.,N.Y.
NZW		South Weymouth, Mass.
OLD		Old Town, Me.
ORH		Worcester, Mass.
OWD		Norwood, Mass.
PBG		Plattsburgh, N.Y.
POU		Poughkeepsie, N.Y.
PSM		Portsmouth, N.H.
PVD	507	Providence, R.I.
PWM	606	Portland, Me.

Table 1 (con't)

Station		Location
RKD		Rockland, Me.
RUT		Rutland, Vt.
SLJ		Salem, N.H.
SWF		Stewart Air Force Base, Newburgh, N.Y.
TEB		Teterboro, N.J.
WST		Westerly, R.I.
	393	Portland L/V, Me.
	493	Nantucket L/V
	614	St. Johnsbury, Vt.
	615	Wolfeboro, N.H.
	616	Peterborough, N.H.
	618	Rumford, Me.

pattern exhibited at 00 GMT and 06 GMT and was a definite improvement over free-hand analysis (not shown). The weather symbols shown are those commonly used, as are the units of wind speed, knots.

2. Pressure

The surface pressures represented a unique problem as it was difficult to draw a sensible pattern using the observed values. It is well-known that stations of first order quality often observe pressure with a systematic bias. This bias can be due to reduction to sea level errors or slight miscalibrations. While often sufficient for operational synoptic purposes, the surface pressures had to be modified for mesoscale analysis. A method described by Fujita (1963) was helpful in overcoming this deficiency. A time series of hourly pressure observations was compiled at most of the stations shown in Figure 3 for the period December 17 and 18. Where missing observations occurred, bogus pressures that represented reasonable guesses in light of pressure trends at the beginning and end of the missing period and pressures at neighboring stations were substituted. All of the time series were summed and averaged. A map of mean pressure was drawn with smoothness taking the highest priority. It was assummed that small variations would be eliminated by averaging over a large enough period. The difference between the interpolated mean pressure at a particular station from the mean map and the actual calculated mean pressure represented the correction applied to all hourly observations at that station. This was done for all stations and observations. These corrected observations were analyzed and the pressure analyses in Figures 4a-h are the result. These analyses were a vast improvement over the raw analysis (not shown) and are well worth the effort. The method worked best at first order stations. The Coast Guard station pressures were less responsive to these corrections due to inconsistencies in the pressure record. It is felt that some of these resulted from non-meteorological causes e.g. difficulty in converting from millibars to inches or vice versa.

C. Development of the meso-cyclone

The most important mesoscale feature at 00 GMT is a shear line between Gloucester, Mass. and Portsmouth, N.H. There are also a number of small inflow and outflow as well as hyperbolic points but none had any bearing on subsequent weather. The 03 GMT map shows basically the same pattern. However, an easterly flow has become established along the coast. The flow is weak and is dominated by a weak trough tracking through the region. Note the difference between the mesoscale analysis of the weak trough and the synoptic analysis of 00 GMT (Figure 1a). The 03 GMT map suffers from a lack of Coast Guard data and serves as a comparison with 00 GMT for the detail that the Coast Guard stations add to the analysis. The striped areas are regions of calm winds.

Note the ageostrophic winds at 00 GMT along the northern Maine coast.

A closed cyclonic circulation has developed in the Boston Harbor between BOS and BOS LV at 06 GMT, and increases in intensity for the next three hours. This is seen in the vorticity charts, Figures 6b and 6c. The observation at BOS LV was believed despite its difference from the Logan Airport observation because the vectorial wind shifts there and at Gloucester between 00 and 06 GMT were of the same magnitude. At Race Point a similar wind shift occurred between 06 and 09 GMT. The shaded areas represent radar echoes from the NWS WSR-57 scope at Chatham. These echoes were transposed from a facsimile record of fair quality and as such are inaccurate up to an estimated 10 miles in position. The outline of the echoes was indistinct and it was difficult at times to separate the echo from the ground clutter and the superposed map background. The appearance of an echo is noted at 09 GMT just off-shore from BOS and in Massachusetts Bay. This was associated with the meso-cyclone. Other echoes are probably associated with the strong surface cyclone off-shore that is getting organized at this time. The pressure field also indicates a slight depression with the meso-cyclone. It was only due to the the pressure corrections applied that this feature becomes apparent. In pressure traces at Cambridge and Marblehead (not shown) no sudden drop in pressure was recorded with the inception of the mesoscale disturbance. Thus the cyclone developed in a favorable area, a weakness in the pressure field, but did so with only a small pressure drop.

[illegible]. Tes [illegible]

1. Test of barograph traces

A test of the pressure measurements around the Bay can be made by considering the following equation:

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\vec{\nabla} p \qquad (1)$$

where

$\vec{V}$: horizontal wind vector

t : time

ρ : density of air

p : pressure

$\vec{\nabla}$: horizontal del operator

In equation (1) the acceleration of the horizontal wind is related to the horizontal pressure gradient. It can be applied under the hypothetical case where no forces besides pressure influence the wind motion. If the period prior to 06 GMT is considered to represent an equilibrium state from which a vector acceleration, $\frac{d\vec{V}}{dt}$, takes place, then accompanying this change should exist a horizontal pressure gradient. This treatment ignores friction but can serve to illuminate the magnitude of the quantities involved. If a vectorial wind shift of 20 knots in three hours is substituted in equation (1) (about the change at BOS LV between 03 and 06 GMT), a horizontal pressure gradient of 0.2 mb. $(20 \text{ km})^{-1}$ results. This would be too small to measure accurately and falls within the limits of instrumental uncertainty. Thus it is not surprising that the traces at MIT (Cambridge) and Marblehead (about 15 miles NNE of Boston) show no significant perturbations at the time of mesoscale cyclogenesis.

2. Vorticity and divergence analyses

Associated with the meso-cyclone is strong convergence just south of Gloucester at 06 and 09 GMT. This is where the heaviest snow fell. Vorticity and divergence fields were calculated to get an order of magnitude value on the circulation and ability to produce precipitation via vertical motion. This was done directly by a subjective analysis of the scalar fields of northward (v-component) velocity and eastward (u-component) velocity. The vorticity, ζ , and divergence, δ , are represented by

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

$$\delta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

where x,y are horizontal distance. The differencing was on a grid of 10 n. mi. spacing. Factors arising from map projections and scale variations are negligible in this case. The value of the vorticity or divergence assigned to a grid point was determined from values arrived at by interpolation from the subjective analysis 5 n. mi. on a side around the point. Thus the differencing was a centered scheme. The resultant analyses are given in Figures 5a-g and 6a-g. The units are 10^{-1} hr^{-1} but may be converted to the more familiar

10^{-5} sec^{-1} by Table 2. The 03 GMT map has been left out due to the lack of data which makes a scalar map of u,v, components meaningless. This once again points out the value of the Coast Guard stations in this study.

The vorticity maximum in the Massachusetts Bay is seen in Figures 6b and 6c. The low-level convergence is seen in Figures 5b and 5c. By 12 GMT a dramatic increase in the geostrophic wind has taken place. Winds in excess of 20 kts. which previously were confined to the Maine and New Hampshire coast have now spread to the Bay area. The packing of the isobars between BOS and BED indicates that a small scale wind burst is about to come upon the mesocyclone. Shortly after 12 GMT this wind burst is experienced in the Bay with many stations reporting winds in excess of 40 knots. The tightening of the gradient over the region has been taking place all the while by the action of cyclogenesis off-shore and a high moving eastward toward New England. However, this wind burst must have been a very localized phenomenon. It served to make the mini-snowstorm almost a mini-blizzard.

D. Passage over the Cape

Although the meso-cyclone is no longer evident as a closed circulation at 12 GMT, its presence is indicated by the radar echo which persists along the coast. It is likely that as the overall flow has increased, the features of the mesocyclone have been lost. The vorticity analysis at 12 GMT , which should recover these features, cannot do so

Table 2

Conversion from hr^{-1} to 10^{-5} sec^{-1}

10^{-1} hr^{-1}	10^{-5} sec^{-1}
3	8.35
6	16.6
9	24.9
12	33.4
15	41.8
18	50.1
21	58.5
24	66.9
27	75.2
30	83.5
33	91.9

due to lack of data. The cyclone at this time has probably begun to move southeastward and into the Cape Cod Bay, where no observations exist. There is one exception and that is an observation at 12 GMT to the west of Race Point. It is a British ship which headed down the Maine coast toward the Cape Cod Canal through the period. It appeared that the relative wind was observed by the ship, contrary to normal practice, but even after correcting for estimated ship motion, the observation is highly suspect. There is still strong convergence south of NZW at 15 and 18 GMT and some evidence of cyclonic vorticity near the Cape after 12 GMT. The radar pictures indicate that the original echo has indeed moved southeastward. Since the mean tropospheric flow was southwesterly throughout this period, the cyclone was steered by the low level northwesterlies. Thus the picture of the mesocyclone being stationary for several hours and then moving under the influence of a steering current leads to the conclusion that both heavy snow areas in northern Mass. and southward to Cape Cod resulted from the same storm.

The last statement must be amended with the observation that some of the snow on the North Shore, especially north of Gloucester, was due to convergence along a coastal front. There is moderate to heavy snow along the N.H. coast at and after 12 GMT. There is no radar echo to indicate this activity because of the radar's inability to see what are generally shallow snow echoes at a distance greater than 60 km. This area is distinst from the meso-cyclone and will be discussed in more detail later. There seems to be enough convergence along the front to produce the heavy snow but there are no well-defined cyclonic circulations to indicate the presence on non-frontal mesoscale activity. The vorticity is mostly anti-cyclonic, probably frictionally induced by lateral differences in roughness between land and sea.

V. Maintenance of the mesocyclone

The mesocyclone, being the unique aspect of this snow-storm, was the main object of the author's inquiry. The main question to be answered is: given the favorable synoptic conditions for cyclogenesis, why did it occur preferentially and uniquely in one area, the Massachusetts Bay? Once it did form, how was it maintained against the dissipative forces of friction and mixing so that it was able to move from Mass. Bay and affect southeastern Mass. and Cape Cod? The strategy taken to answer that question was to consider several basic hydrodynamical priciples in light of the observed data and to suggest the most plausible result.

A. Effect of heating

The most obvious effect considered was that of heating due to sensible heat and latent heat exchange between ocean waters in the Bay and the atmosphere. The configuration of the coast-line makes the Bay a semi-enclosed body of water. On December 18th the Bay water temperature was 7.3° C and the air temperature was 3-4 $^{\circ}$C at the time of mesocyclogenesis. Thus, there existed a well-defined potential for heating. The effect of heating can be seen from Petterssen's (1956) development equation

$$\frac{\partial \zeta_0}{\partial t} = A_\zeta + \vec{V}_0 \cdot \vec{\nabla} \zeta_0 - \frac{R}{f}\left(\nabla^2\left[\frac{g}{R} A_T + S + H\right]\right) \quad (2)$$

ζ_0 : relative vorticity at 1000 mb. (surface)

A_ζ : advection of absolute vorticity at level of non-divergence

$\vec{V}_0 \cdot \vec{\nabla} \zeta_0$: advection of relative vorticity at 1000 mb.

R : universal gas constant for air

f : coriolis parameter

A_T : thickness advection in 1000 mb. to level of non divergence layer

S : stability parameter

H : heating parameter

$\vec{\nabla}$: horizontal del operator

∇^2: horizontal Laplacian

The heating function, H, can produce positive vorticity when it has a negative Laplacian. This condition was met On December 18th with the juxtaposition of radiatively cooling land and heating in a partially enlosed harbor.

Petterssen (1956) has noted the similar effect of daytime heating on cyclones over the Scandanavian peninsula in summer. The vorticity is enhanced where the coastline is most cyclonically curved and where the rate of heating is the greatest. An analogous effect may be considered here. Heating by the ocean water where the Massachusetts coast has the greatest degree of cyclonic curvuture likely contributed to the cyclonic circulation in the mesocyclone. This has been seen on occassion by the author when a weak trough passes through the Boston area and off the coast. The surface geostrophic flow develops its highest vorticity in the area of the Bay resulting in a persistance of bad weather. This has been seen mostly in the winter when the ocean acts as a heat source. One might expect a similar effect for anti-cyclones in the summer but this has never been documented.

The other effects in equation (2) are synoptic scale in character. There is no reason to expect that the mid-tropospheric advection of absolute vorticity and thickness was a maximum only over the Bay. The stability parameter is a possibility but there is no data available to give the horizontal variation of the vertical stratification of temperature and moisture through the Bay area. The NWS radiosonde measurements are taken only as close as Portland (PWM) and Chatham. There is a low-level sounding which is released at MIT in Cambridge by the NWS air pollution unit, but since the 18th was on a weekend the sounding was not taken. There is a possibility that the stability was a minimum over the Bay since low level heating would destabilize an atmosphere. However, it is felt that the low level heating by itself was the most important producer of positive vorticity directly and not indirectly through the stability term.

B. Friction

Friction is left out of Petterssen's development equation (2) because the primary application of that equation is to synoptic scale cyclogenesis where friction is not an important consideration. However, it can be important on the mesoscale because of the wide variations in the frictional drag coefficient between the atmosphere and the underlying surface over a small horizontal distance and the inherent small vertical structure of mesoscale disturbances. For instance, a northerly wind along a north-south coastline would induce anticyclonic vorticity in the immediate vicinity of the coast due to the greater wind speed over the ocean. If one considers the coastline along the Mass. Bay to have a general north-south orientation, then one would that a southerly wind existed prior to the formation of the mesocyclone. Although a southwesterly wind exists at BOS at 00 GMT, at 03 GMT BOS has a northeasterly wind and there is no reason to expect that a southerly component existed at any station shortly prior to 06 GMT, at about the time of meso-cyclogenesis. Another effect to consider is frictional convergence. The same northerly wind considered before in the hypothetical example would have to encounter an east-west oriented coastline in order for convergence to take place, but even so the convergence would take place over land. Convergence could not be induced in the Massachusetts Bay in any manner since any wind blowing from the land to the ocean would be accelerated by the decreased surface friction. This would result in divergence over the water and tend to decrease cyclonic vorticity by an effect to be shown later. This simple qualitative treatment of the role of friction leads to the conclusion that friction would tend to prevent cyclogenesis rather than aid it.

An appeal to Ekman dynamics is justified here on the premise that cyclonic vorticity should be positively correlated due to skin friction (Hess, 1959). But the idealized model of Ekman may not be valid here because of the lack of equilibrium conditions.

Friction may be considered from a third point of view. A vortex would be dissipated (spin-down) simply because its motion would be dissipated. In general, friction from all points of view given the conditions which existed in this case, has to be considered inhibitory to the development of the mesocyclone.

Heating, having been identified as the important effect in the development of the mesocyclone, must have continued to play an important role in the maintenance of the storm. Where heavy snow fell over water (probably just off the coast near Marblehead-this is indicated by radar), evaporative cooling would have reduced the boundary layer temperature several degrees. However, the water remained at the same temperature and thus the air-sea exchange would be enhanced since this exchange is proportional to the temperature difference between water and air.

C. Dynamical considerations

It is also helpful to consider the convergent component of the wind. If the vorticity equation is considered without the so-called tipping terms, advection of vorticity by the vertical motion, and external forces (including friction), the role of convergence is clear.

$$\frac{d}{dt} \ln(f+\zeta) = -\delta$$

δ: horizontal divergence of the wind, $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$

ζ: relative vorticity, $\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$

f: coriolis parameter, $2\Omega \cos\phi$

A negative value for δ (convergence) increases the cyclonic vorticity. The equation is written in the Lagrangian sense. An air parcel has its absolute vorticity doubled in three hours if δ is about 2 hr^{-1}. This is close to the calculated value for δ in Figures 5b and 5c. The mesocyclone was maintained then by the heating which produced a convergent wind. This presents a self-contained system which is plausible because the cyclone seemed to be unaffected by the large scale environment before 12 GMT. The low-level steering wind was generally weak and the motion of the storm and associated weather echoes was small.

It is interesting to note that the mesocyclone resembled its synoptic scale counterpart. In particular, precipitation occurred downstream in the thermal wind sense from the low center. This is where quasi-geostrophic theory would predict ascending motion. The observation here suggests that at least some intermediate scales of motion may be governed at least qualitatively by a similar set of quasi-geostrophic equations which describe synoptic motions.

There is a calculation that was made to check the wind measurements to see whether the resulting values of convergence were reasonable. This is done by checking if the observed convergence was sufficient to generate a snowfall rate of 3 in hr^{-1} on the North Shore of Mass. The soundings from 00 and 12 GMT at Portland and Chatham were used to deduce the vertical profile of temperature and humidity over the heavy snow area north of Boston, called NE Mass. in Figure 8. The Chatham and Portland soundings are in Figures 7a-d. The implied sounding represents a compromise between the Chatham and Portland soundings. The passage of an upper tropospheric trough is noted at Portland. Therefore, the 500 mb. temperature is anchored at -38°F (almost all the way through the front) and the surface at 30° F (-1°C). Initially the surface temperature was in the mid 30's but evaporative cooling probably reduced that figure by several degrees shortly after snow onset time. The sounding is assummed saturated up to 500 mb. The vertical motion, $\omega = \frac{dp}{dt}$, is related to the horizontal divergence in the x,y,p coordinate system by

$$\frac{\partial \omega}{\partial p} = -\delta$$

Assumming $\delta = -65 \times 10^{-5}$ sec^{-1} and a thickness, dp, of 50 mb., a vertical motion of 32.5 cm sec^{-1} results at the top of the 1000-950 mb. layer. The moisture content in 50 mb. layers can be calculated from the implied NE Mass. sounding. The whole layer is lifted and cooled moist adiabatically so that a new mean temperature in the layer results. The difference between the new and old mean mixing ratios is considered to fall out as precipitation. A reasonable profile of vertical motion, one where the maximum is in the surface boundary layer and decreases to zero at 500 mb. is assummed. Since the greatest contribution is in the lowest layers due to the large amount of moisture available there, it isn't crucial what vertical motions are assummed above 750 mb. If a 10-1 snow depth to liquid water content is used, the preceding assumptions lead to a snowfall rate of 1.4 in hr^{-1}. Local increases in the convergence, snow depth to liquid water ratio and the depth of the ascending motion could conceivably increase the calculated snowfall rate by a factor of two, enough to give the observed rate.

D. Convective instability

The intensity of this snow burst and a report of a thunderstorm at about 03 EST (08 GMT) suggest that the sounding near Gloucester was convectively unstable. The implied Gloucester sounding (NE Mass.) almost parallels the moist adiabat. With the large amount of latent heat released in combination with the passage of the upper front, there could have been periods of convective instability over the heavy snow area. Surface heating in Massachusetts Bay further destabilized the sounding. It is possible there was an additional flux of latent as well as sensible heat from the Bay to the atmosphere.

Thus the surface wind data yields a plausible picture of the mechanics of the mesocyclone. It formed as a result of synoptic interaction with the surface topography. It was maintained against the dissipative force of friction by a localized heat flux from the sea. The convergence took place in an unstable atmosphere yielding very heavy snow amounts. Since hydrostatic stability tends to discourage development of small circulations, the small stability was likely of dynamical importance here.

VI. Man-Made Heat Source (?)

The embryonic ingredients for the mesocyclone were probably a shear line located at 00 GMT north of Gloucester and the weak trough that tracked across New England. The mesocyclone didn't form there because the factors which produce vorticity were greatest in the Massachusetts Bay area. Since ocean heating had such an important role in this process, heating from man-made sources was also considered.

The Boston Edison Company operates three major power plants around Boston, each of which produces large quantities of heated water on a continuous basis and pumps it directly into the Bay. A calculation was made to see if this could be considered as a possible source of localized heating.

The necessary data was graciously supplied by Mr. M. J. Feldmann of Boston Edison and it details hourly volume and temperature of condenser effluents. The water was assummed to remain near the surface of the Bay because it was warmer than the underlying waters and the natural large stability in the upper layers. It released sensible heat to the atmosphere and the underlying water in the ratio of 3:1 until it cooled to ambient water temperature. The heat was distributed over an area 100 km^2, about 20% of the actual Boston Harbor area. Table 3 lists the hourly combined power plant discharges.

The specifics of the calculation were the following. It was assummed that 3×10^8 gallons day^{-1} of condenser effluents were pumped into the Harbor at an average temperature of 55^oF. Since the water temperature was 45^oF, the treated sewage cooled 10 F^o. If a layer of air 100 m thick above the Harbor is heated, the resultant heating rate is 4.19×10^{-2} ^oC hr^{-1}. To arrive at this figure the density of air was assummed to be 10^{-3} g cm^{-3} and the specific heat of air at constant pressure, 1 joule gm^{-1} $^oC^{-1}$. The figures in Table 3 indicate that four times as much water was pumped into the Harbor on December 18,1971 at an average temperature of 60^oF. This yields a heating rate approximately six times as great as that given above or 0.25 ^oC hr^{-1}. However, it is also felt that the unrealistically small area used for the Harbor yields a heating rate about 4.5 times too large. Thus, one consideration cansels out the other. Therefore, it is concluded that a heating rate in excess of 0.1 ^oC hr^{-1} is unlikely.

It would seem that this heating rate is much too small to have contributed materially to the mesocyclone. However,

Table 3

Hourly Boston Edison Condenser Effluents

DATE	TIME (GMT)	Volume of Water Pumped, 10^3 gal hr^{-1} (TOTAL)	Avg. Temp. ^oF
Dec. 17	17	55,896	63
	18	55,896	63
	19	55,896	62
	20	55,896	60
	21	57,696	61
	22	57,696	64
	23	57,696	65
Dec. 18	00	57,696	64
	01	57,696	63
	02	55,896	64
	03	53,436	63
	04	48,516	65
	05	48,516	59
	06	48,516	56
	07	48,516	55
	08	48,516	54
	09	48,516	56
	10	48,516	56
	11	48,516	55

the heating term in Petterssen's development equation (2) should be considered. It is the Laplacian of the heating rate that is important in vorticity production, not the heating rate itself. Petterssen et al (1962) have calculated that a sensible heat flux, H, of between 1 and 1.5 cal cm^{-2} min^{-1} occurs over the Gulf Stream in winter off the east coast of the U.S. during the development of synoptic scale cyclones. If the numbers from the last paragraph are used, a sensible heat flux, h, of 2.4×10^{-3} cal cm^{-2} min^{-1} results. However, H occurs over a length scale, L, of magnitude 10^3 km. h occurs over a mesolength, l, of 10 km, about .01L. If the Laplacian has the units $\frac{1}{L^2}$ then

$$\nabla^2 h \approx \frac{h}{l^2} \approx \frac{10^{-3} H}{10^{-4} L^2} \approx 10 \frac{H}{L^2} \approx 10 \nabla^2 H$$

This argument indicates that the contribution to vorticity production by man-made sources on December 18 was very important in the formation and development of the mesocyclone and that the small heating rates are misleading.

One is reluctant to "put the rap" on Boston Edison for 12" of snow at Marblehead. Climatological studies have shown that there is a greater amount of cyclogenesis over inland or partially enclosed waters (Petterssen, 1956) and therefore, not unreasonable to identify the heat source in this case as natural and not man-made. However, the previous calculation indicates that man-made influences are at least a possibility and as such, such be the topic of further investigation.

VII. Subsequent movement of the mesocyclone

The identity of the mesocyclone was lost as a separate circulation shortly before 12 GMT. It was not possible to find the circulation again due to the lack of sufficiently detailed and high quality observations. However, radar echoes and weather observations by surface stations indicate that the storm took a southeastward track after 12 GMT. This is seen in Figures 4e-h.

The pressure gradient increased dramatically over New England so that by 12 GMT there was a vigorous flow of one circulation or another over the whole region. The off-shore cyclone was at peak intensity and proximity to New England and the high over the Great Lakes was moving eastward. The freshening of the gradient can be seen with the breakout of snow showers over northern Vermont and extreme northeastern New York at 06 GMT. The winds have increased there and the packed isobars begins to move southeastward. The leading edge of the fresh northwesterlies can be traced on the 09 and 12 GMT surface charts to a position near Boston. However, at 12 GMT a curious burst of particularly strong winds is present between BOS and BED. The isobars are very tightly packed and shortly thereafter winds in excess of 40 knots are observed at BOS LV and Scituate. These strong winds in combination with the heavy snows of the mesocyclone produced blizzard-like conditions over southeastern Massachusetts and Cape Cod. Note that BOS LV and Scituate continue to report moderate snow at 18 GMT, after all the snow has stopped at

BOS. This is due to the feature described before of the precipitation occurring downshear from the surface cyclone. If the mesocyclone was situated somewhere to the south of BOS LV and Scituate, it is possible that the snow shield from the storm extended northward and covered those two stations. It is curious that no radar echoes were recorded after 15 GMT in the Mass. Bay despite the heavy snow reports. This could've been due to the difficulty of the radar beams in penetrating the heavy snow activity that was occurring at that time on the Cape.

A. An eyewitness report

The nature of the mesocyclone after 12 GMT on its arrival at the Cape was described graphically by an eyewitness report from duckhunters who were located at the Barnstable Marshes north of Hyannis, Mass. (HYA) (Mr. George Budd Jr. of Middleboro,Mass.). This report indicated that the sunrise was visible or at least that the sky was not heavily overcast at sunrise. However, shortly thereafter at 14 GMT, a very dark squall cloud moved in from the north accompanied by very strong winds, estimated at 40-50 mph. The winds soon abated to more reasonable levels but heavy snow began and accumulated to about 6". The burst of high winds experienced on the Cape was probably the same noted between BOS and BED at 12 GMT.

B. Some other considerations

High values of cyclonic vorticity in the Cape Cod Bay at 12, 15, and 18 GMT (Figures 6d-f) are noted. These values are of significance because when the vorticity maximum no longer exists at 21 GMT (Figure 6e), all of the major weather has ceased on the Cape. The vorticity maximum was maintained because the convergence persisted on the Cape through 21 GMT (Figures 5d-g) and produced positive vorticity by the effect noted before.

Intense minima in the vorticity and divergence fields developed near Scituate at 15 GMT and thereafter. It is felt that these are due mostly to frictional causes. Certainly one would expect the wind velocity to be greater at Scituate on the coast than at NZW, farther inland. However, some of the variation of the wind between those two points is felt to be spurious and may represent high frequency phenomenon, too high for mesoscale analysis.

The track of the mesocyclone is also indicated by the snow depth isolines in Figure 2. Note the NW-SE tilt of the 3" line running from south of BOS to the Cape Cod area. The evidence described above is in full agreement with this item.

VIII. North Shore coastal front

The third area of somewhat lighter snowfall mentioned earlier is indicated in Figure 2 near the New Hampshire border. The weather and visibility observations in Table 4

Table 4

Visibility (in miles) and weather observations on 12/18/71

Station	06 GMT	09 GMT	12 GMT	15 GMT
Portsmouth Hbr.	OVC/08	SNOW/02	SNOW/02	SNOW/½
Boon Island	OVC/15	RAIN/ SNOW/05	SNOW/00	SNOW/½
Isle of Shoals	OVC/12	OVC/10	SNOW/½	SNOW/½
Merrimac	OVC/6	SNOW/03	OVC/2000 yds.	SNOW/25 yds.
Gloucester	OVC/22	PC/22	SNOW/100 yds.	SNOW/500 yds.

indicate that the snow at Gloucester was, for the most part, not related to the mesocyclone since the heaviest snow there began after the cyclone had begun to move away from the Bay area. A coastal front is noted along the New Hampshire and Maine coasts beginning at 06 GMT with the omset of snow at Portland, Me. Coastal fronts here are due to converging northeasterlies and northwesterlies each supplying moist and cold air respectively. It is not unusual for these fronts to either enhance precipitation in an already well-defined synoptic scale system or to produce independent effects. A snowfall of several inches is not unusual. The increased flow of northwesterly winds increased the convergence along the front and hence the intensity of snowfall along the front. Four inches of snow was reported in most areas of the New Hampshire coastal region and this amount increases to 7" just south of the border. Observations at Haverhill, Mass. (Dr. Lowenthal) indicates that the heaviest snow there, as at Gloucester, occurred at 15 GMT. No intense cyclonic circulations developed along the front to compare with the Mass. Bay mesocyclone and thus this last event is only of passing interest.

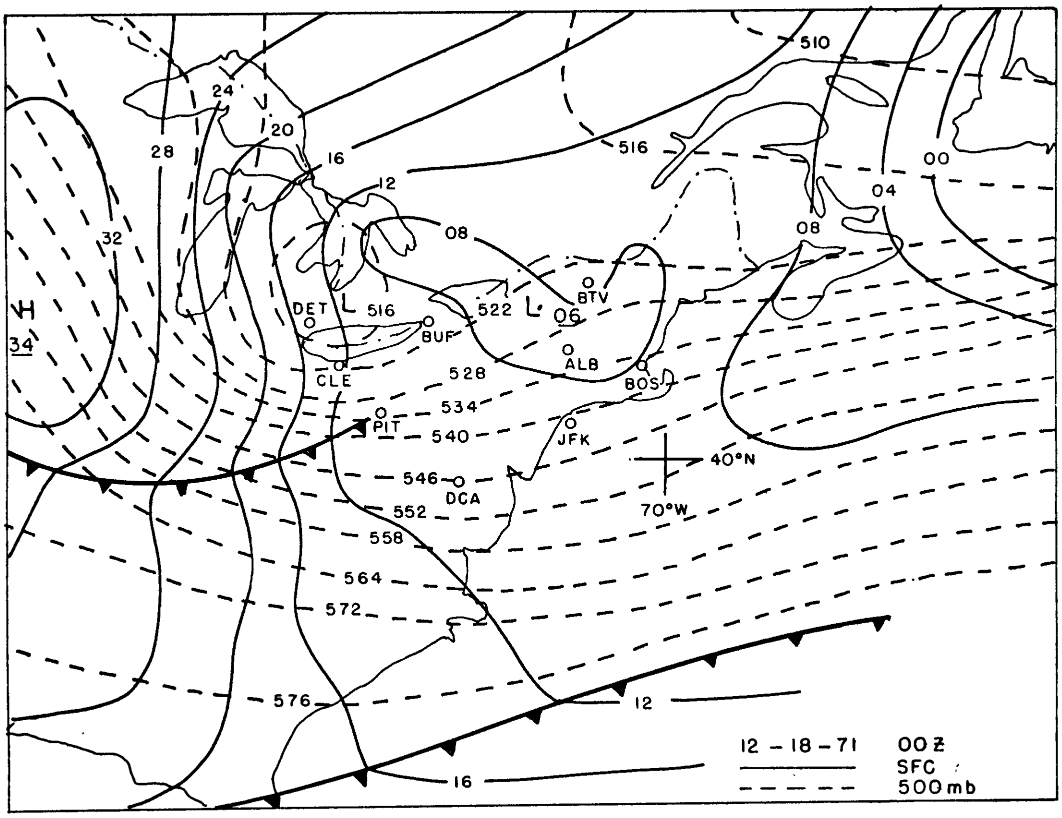
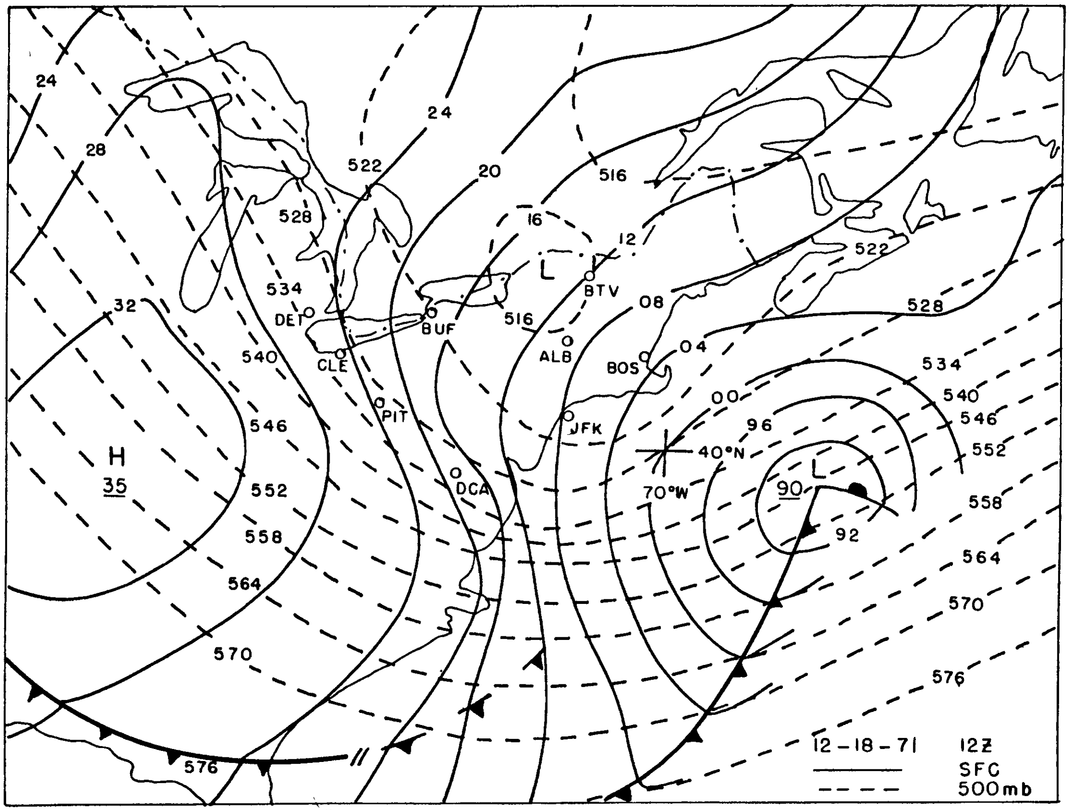


Figure 1a- National Meteorological Center (NMC) synoptic analysis. 500 mb. contours in decameters, dotted lines. surface isobars, mbs., solid lines.



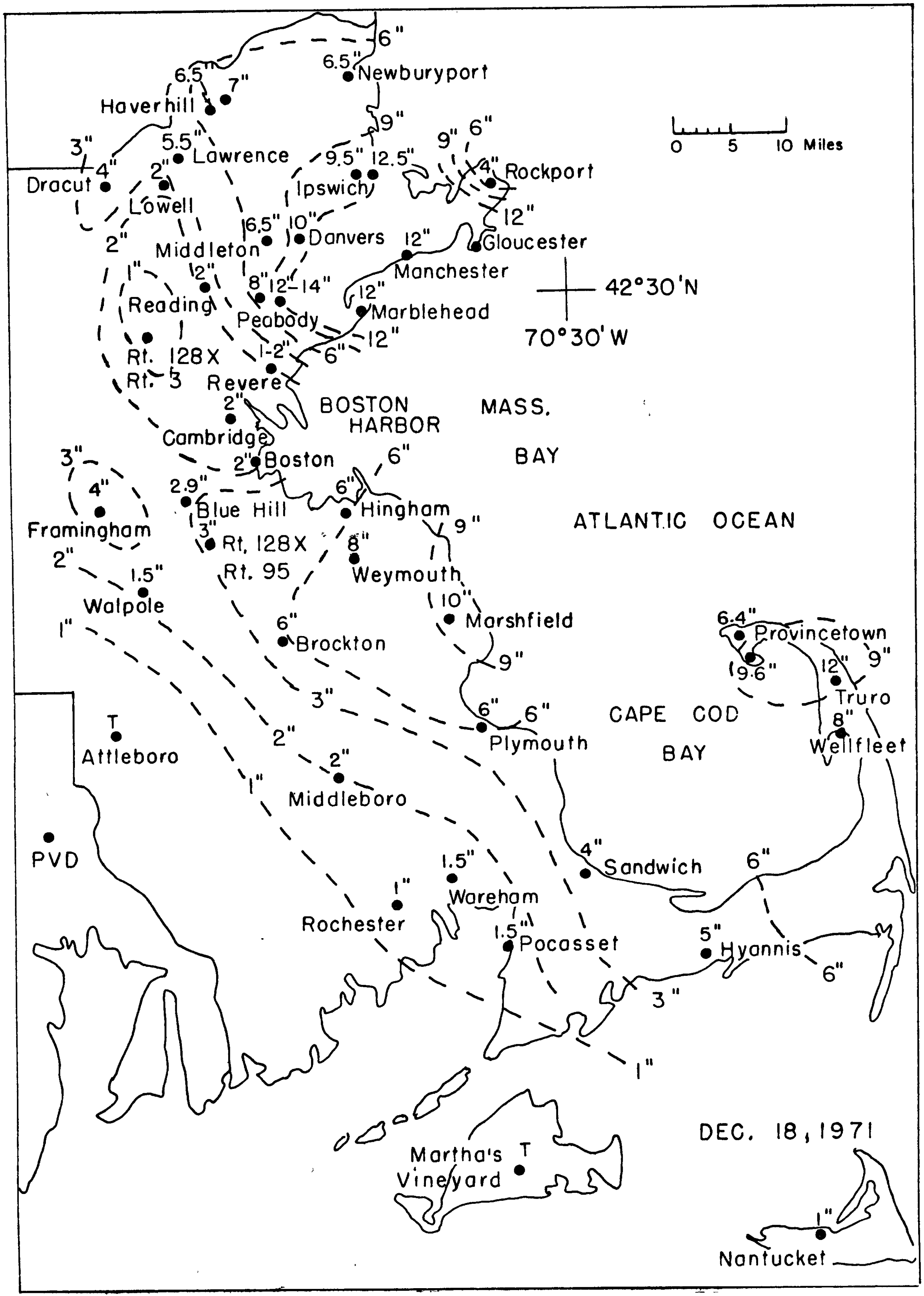


Figure 2- Snowfall distribution for December 18, 1971

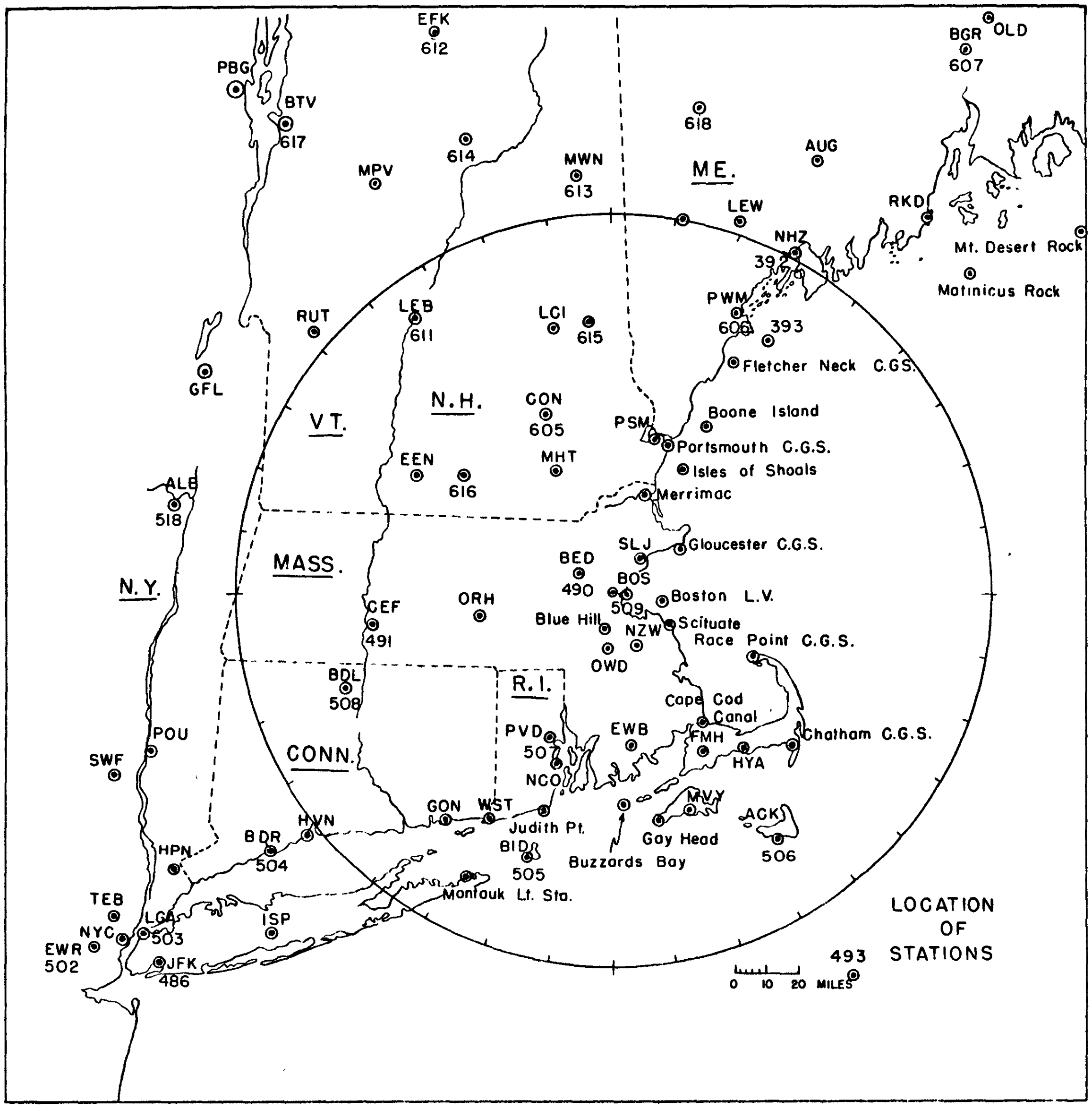

EFK
612
BGR
OLD
607
PBG
BTV
617
618
614
AUG
MWN
613
MPV
ME.
LEW
RKD
NHZ
Mt. Desert Rock
392
Matinicus Rock
PWM
606
393
RUT
LEB
611
LCI
615
Fletcher Neck C.G.S.
GFL
N.H.
CON
605
Boone Island
VT.
PSM
Portsmouth C.G.S.
EEN
616
MHT
Isles of Shoals
ALB
518
Merrimac
SLJ
Gloucester C.G.S.
BED
490
MASS.
BOS
509
Boston L.V.
N.Y.
CEF
491
ORH
Blue Hill
NZW
Scituate
Race Point C.G.S.
OWD
BDL
508
R.I.
Cape Cod Canal
POU
PVD
507
EWB
FMH
Chatham C.G.S.
SWF
CONN.
HYA
NCO
MVY
GON
WST
ACK
HVN
Judith Pt.
BDR
504
BID
505
Gay Head
506
HPN
Buzzards Bay
Montauk Lt. Sta.
TEB
LGA
503
ISP
LOCATION OF STATIONS
NYC
EWR
502
JFK
486
493
0 10 20 MILES

Figure 3

Following are Figures 4a-h representing mesoscale surface analyses from 00,03,06,09,12,15,18, 21 GMT of December 18, 1971. Thick lines are streamlines.

Thin solid lines are isobars in millibars, according to convention.

Dotted, thin lines are half-millibars and are included where needed.

Thin line segments with barbs are wind symbols, according to convention.

Striped areas represent regions of calm winds.

Shaded areas represent radar echoes.

Weather symbols where needed, according to convention.

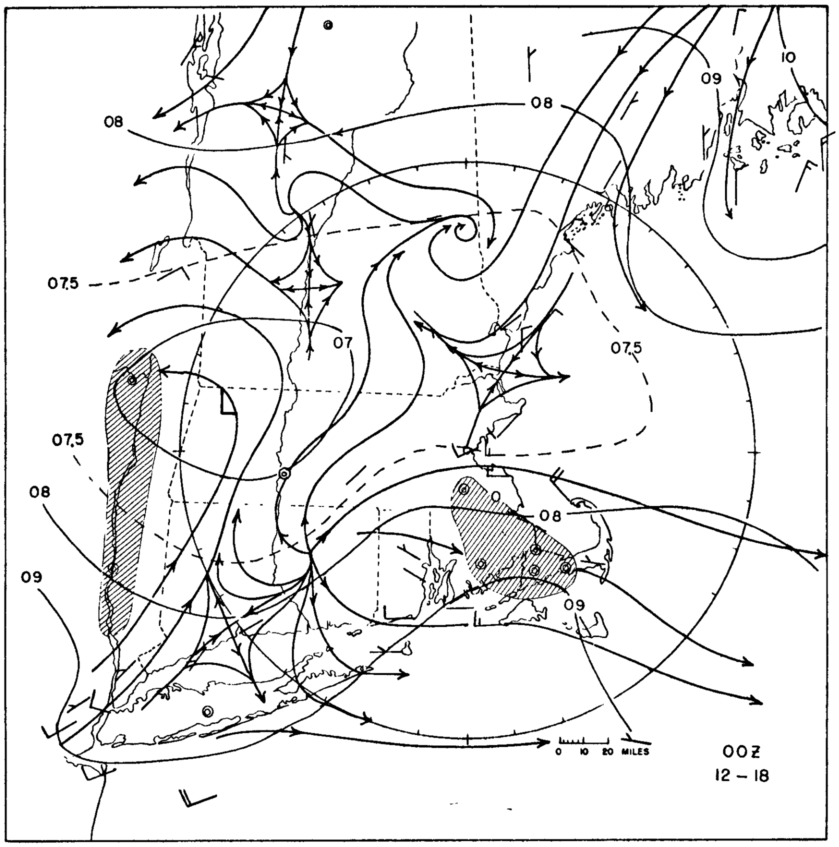


Figure 4a

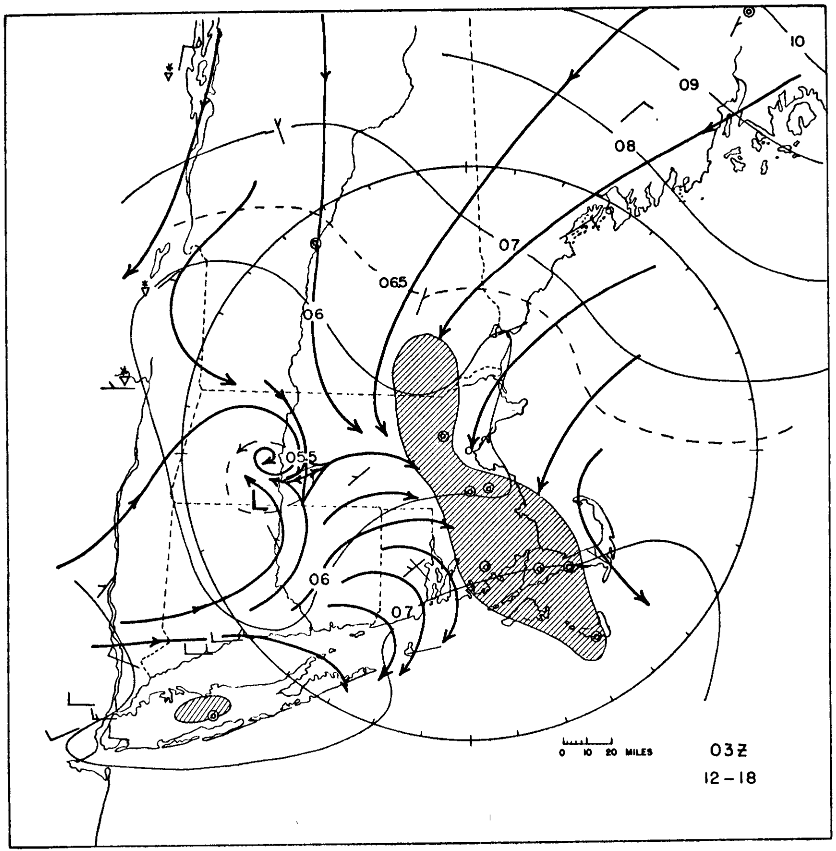


Figure 4b

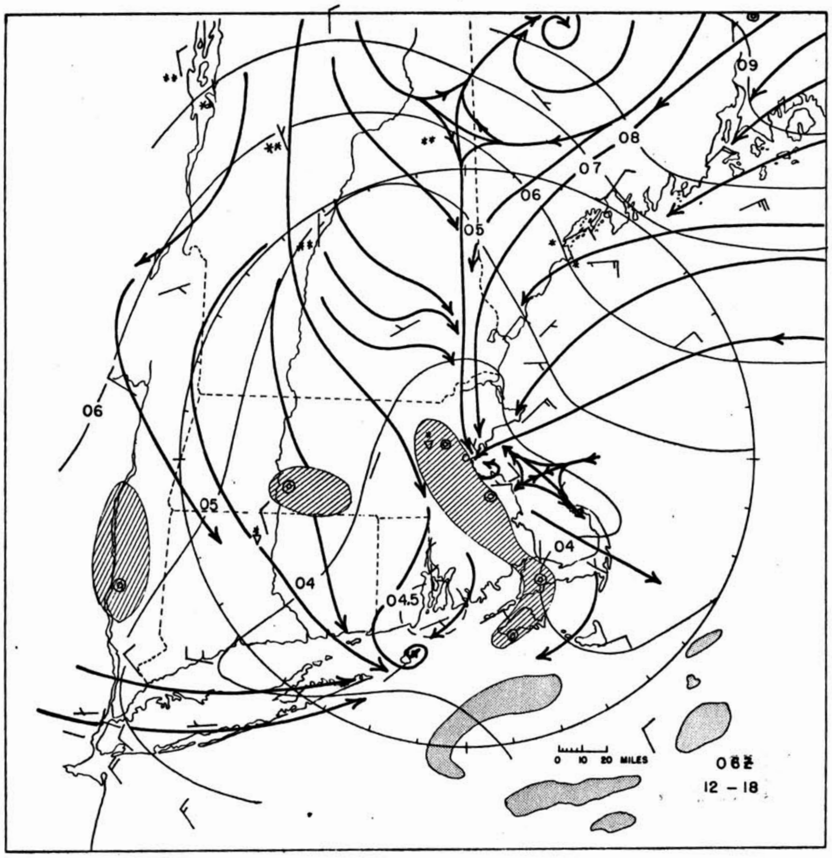


Figure 4c

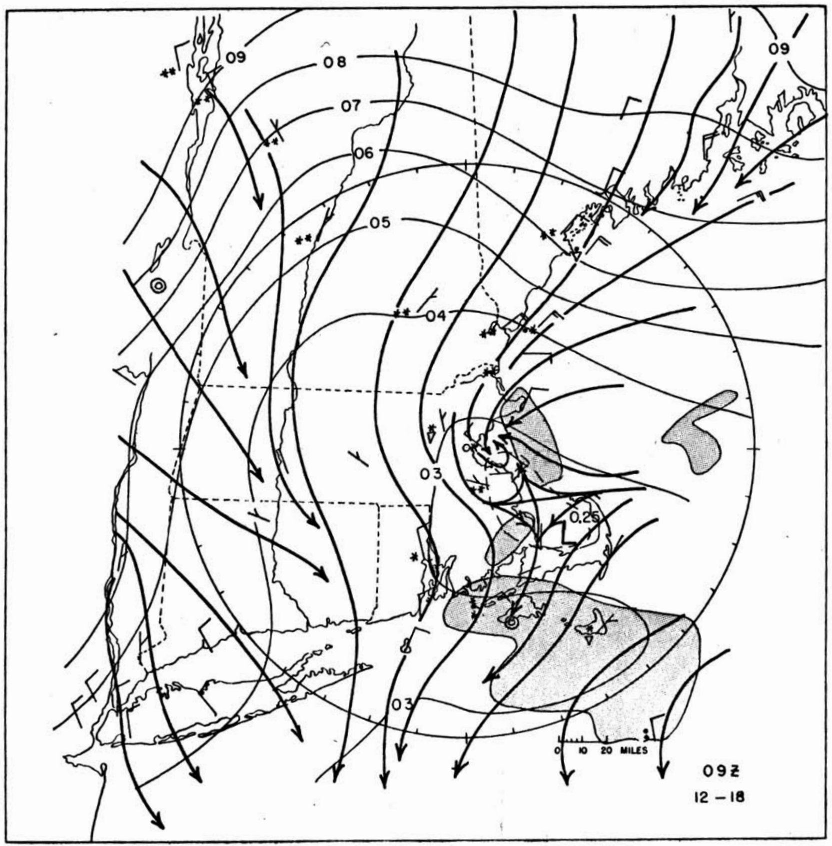


Figure 4d

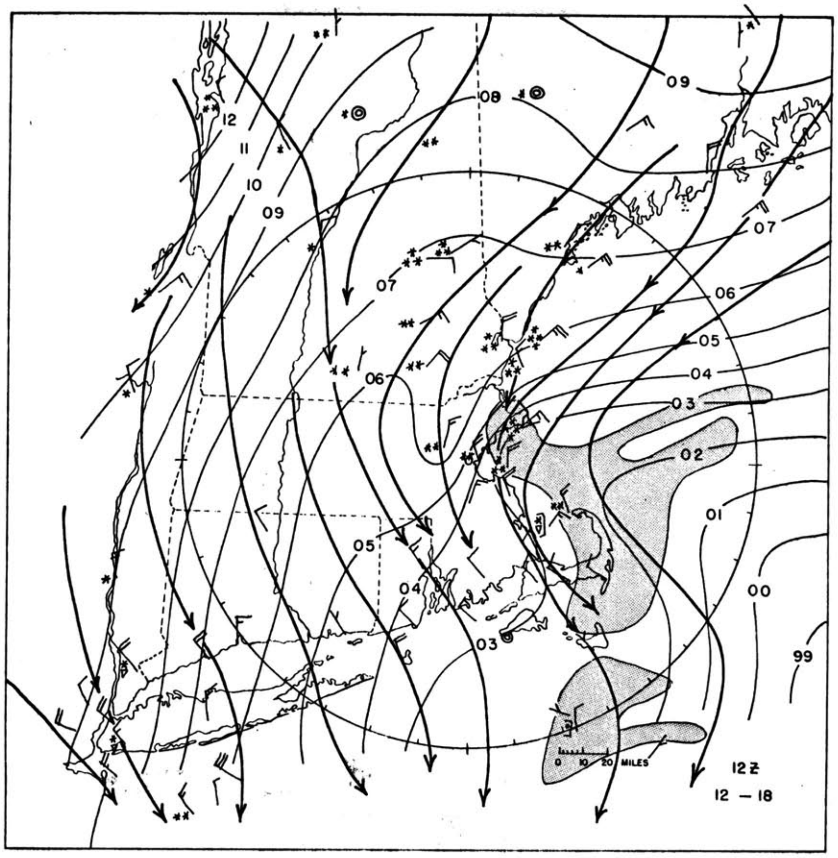


Figure 4e

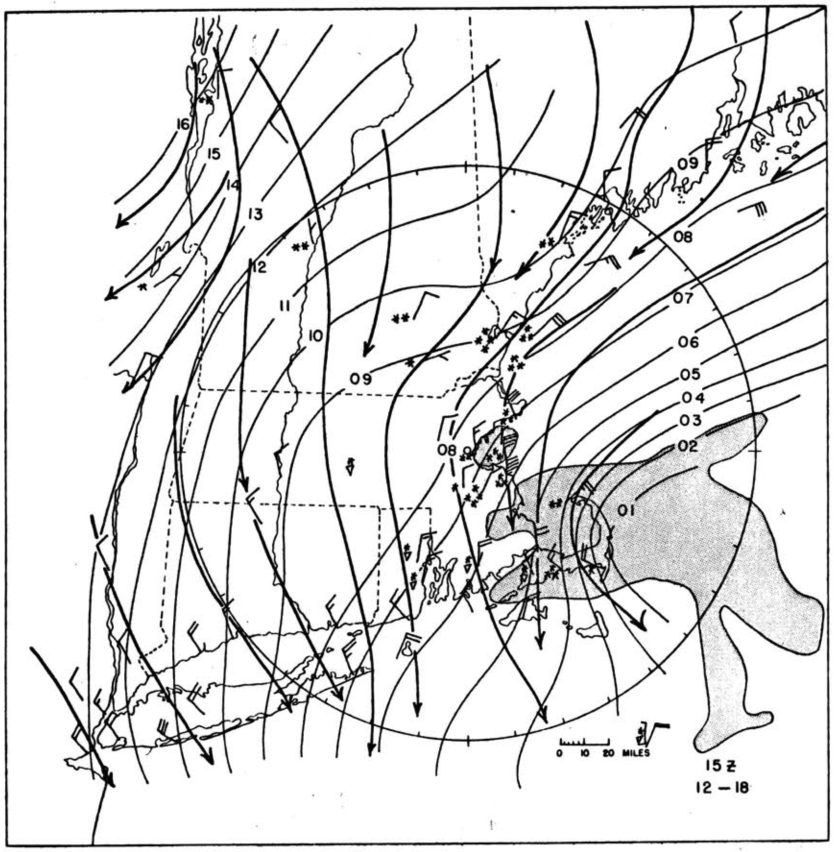


Figure 4f

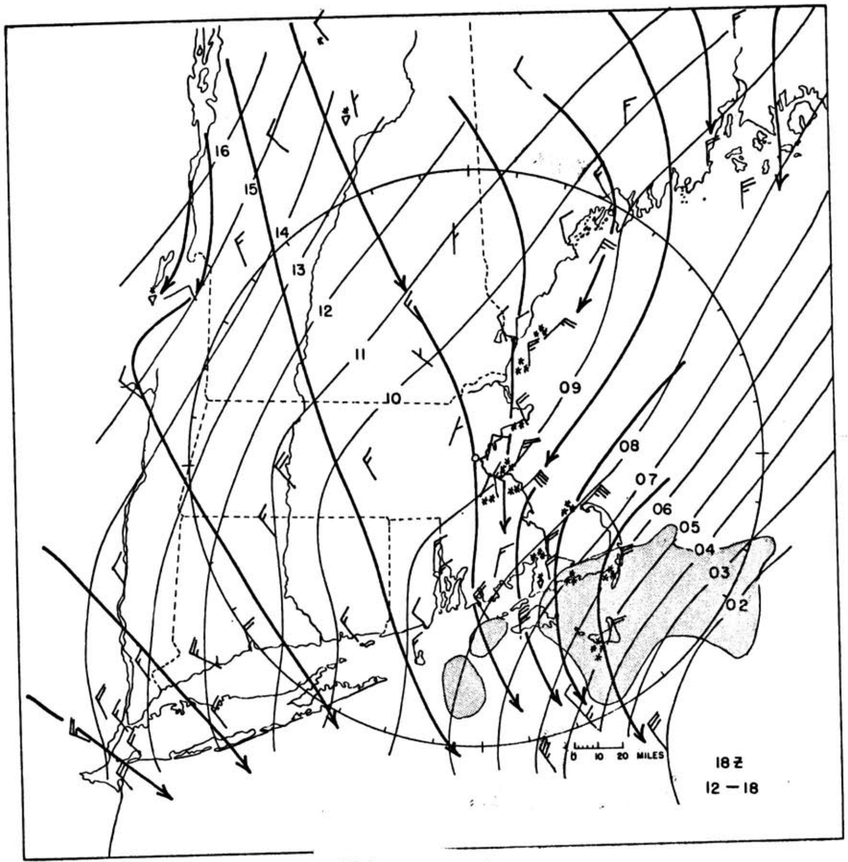


Figure 4g

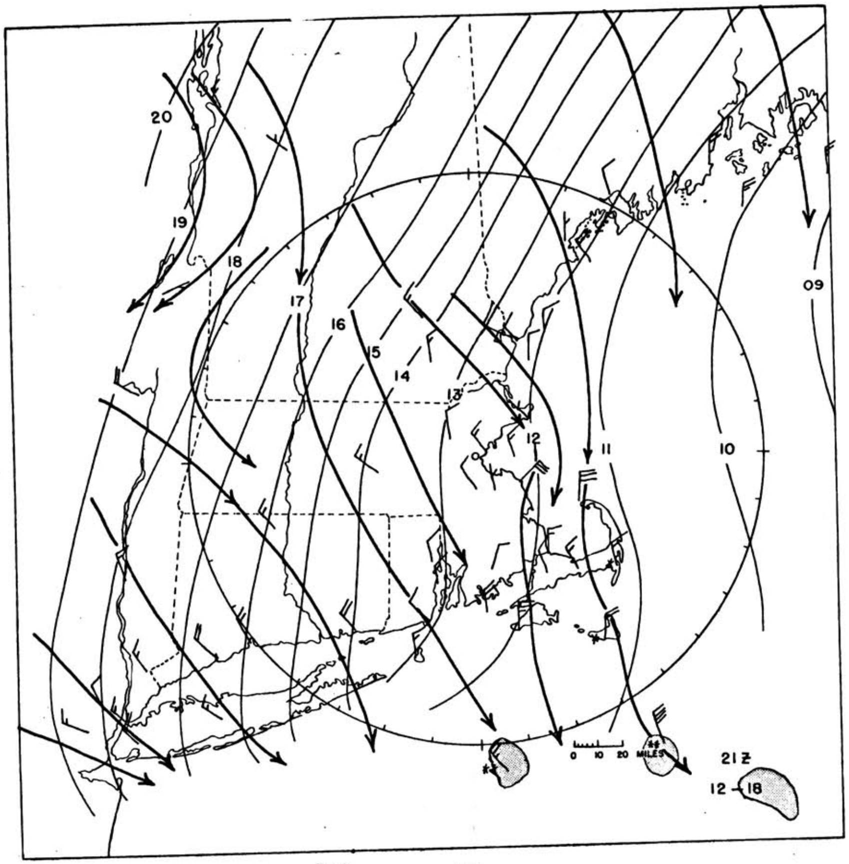


Figure 4h

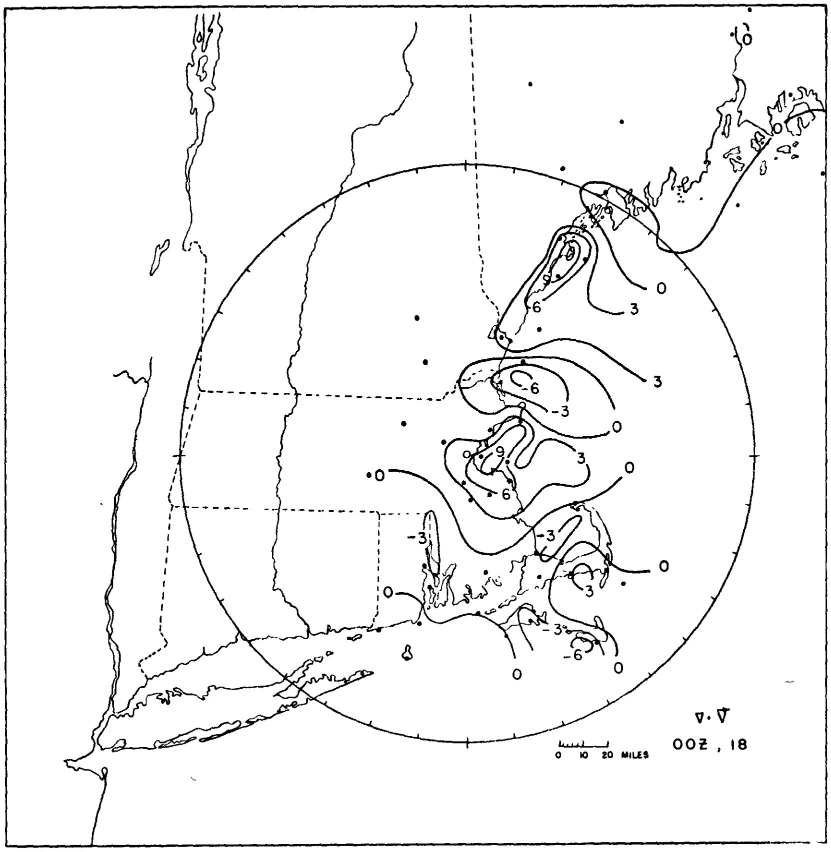


Figure 5a

Figures 5a-g are fields of divergence in 10^{-1} hr^{-1} units for December 18. Dots indicate stations used for computations. Conversion to 10^{-5} sec^{-1} units are given in Table 2

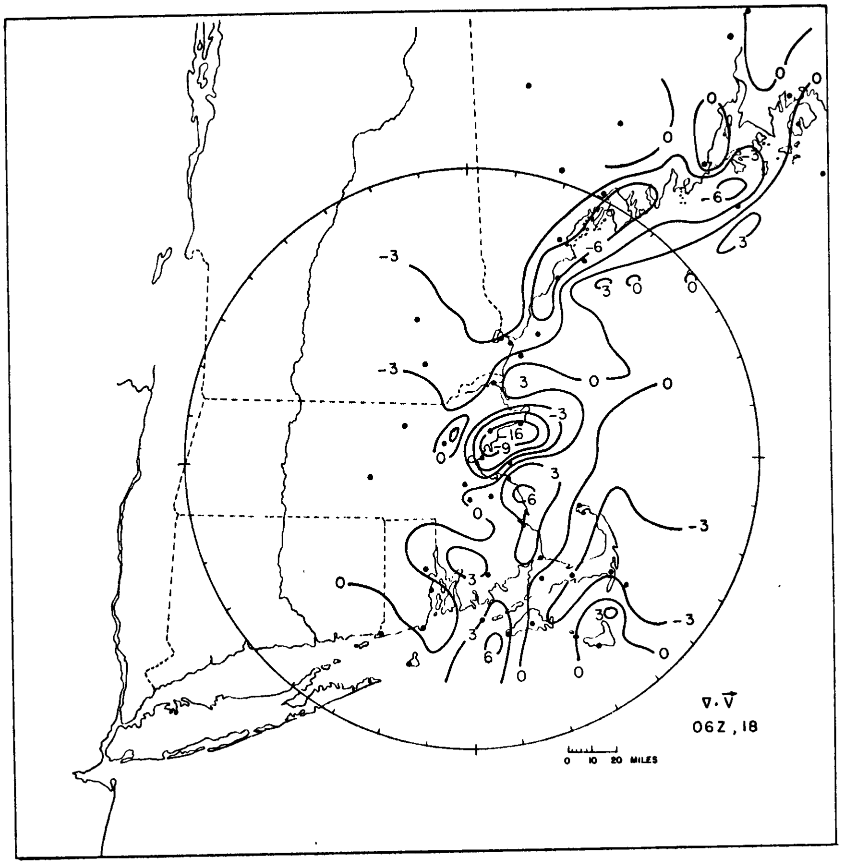


Figure 5b

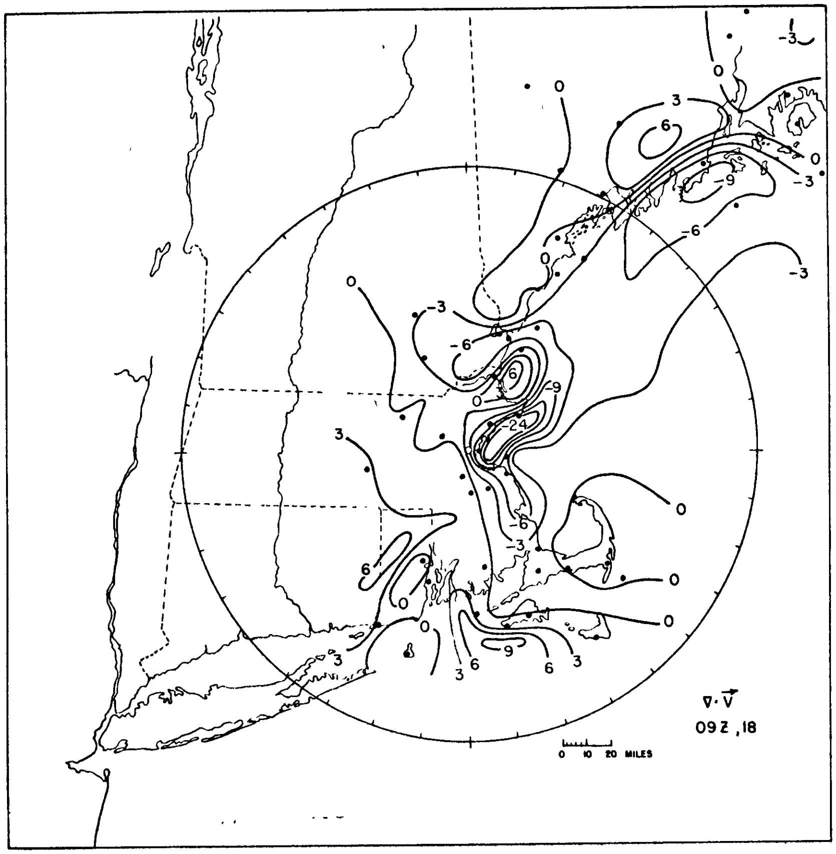


Figure 5c

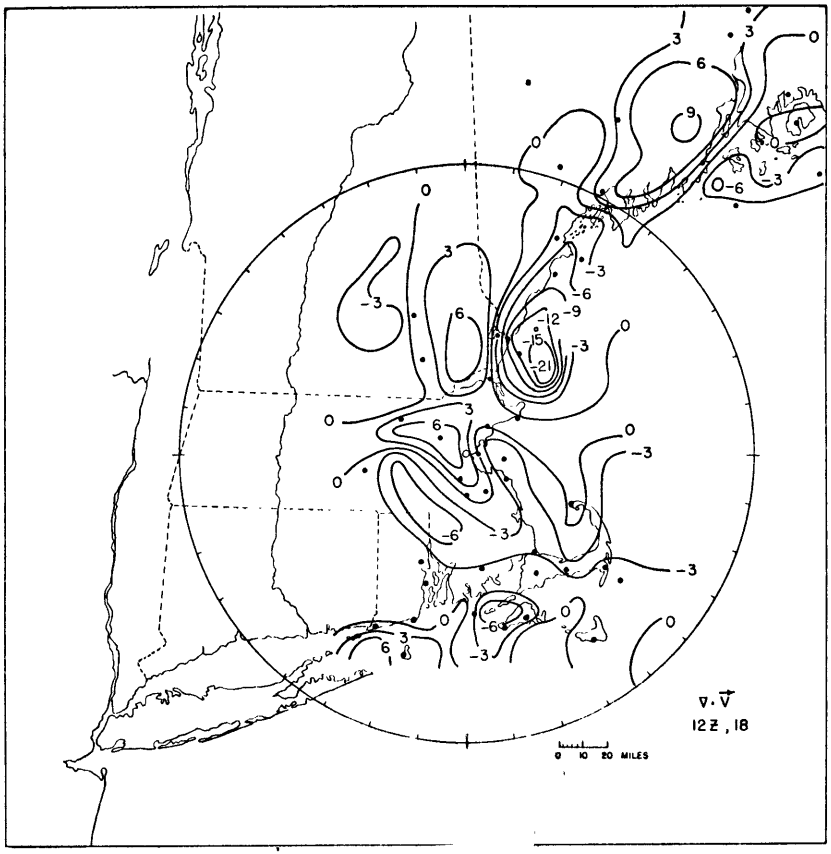


Figure 5d

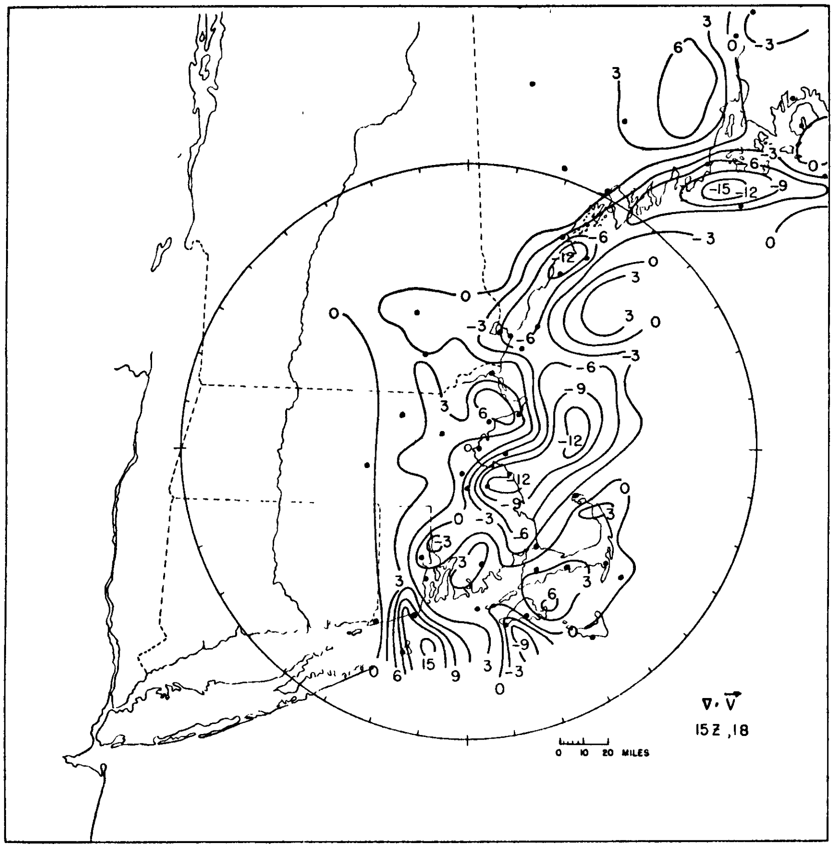


Figure 5e

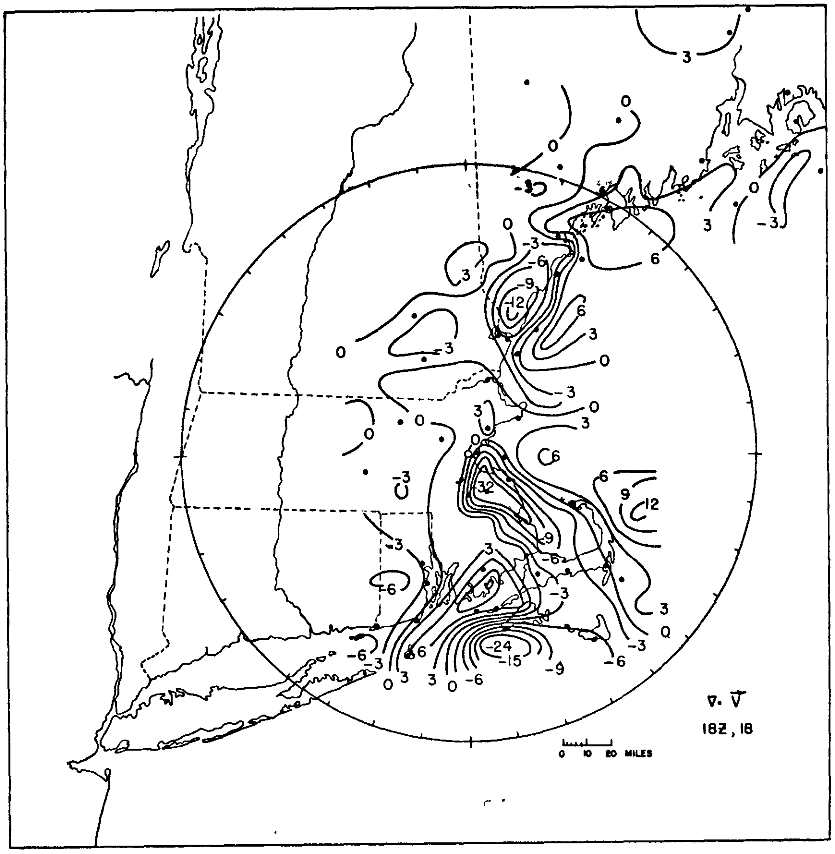


Figure 5f

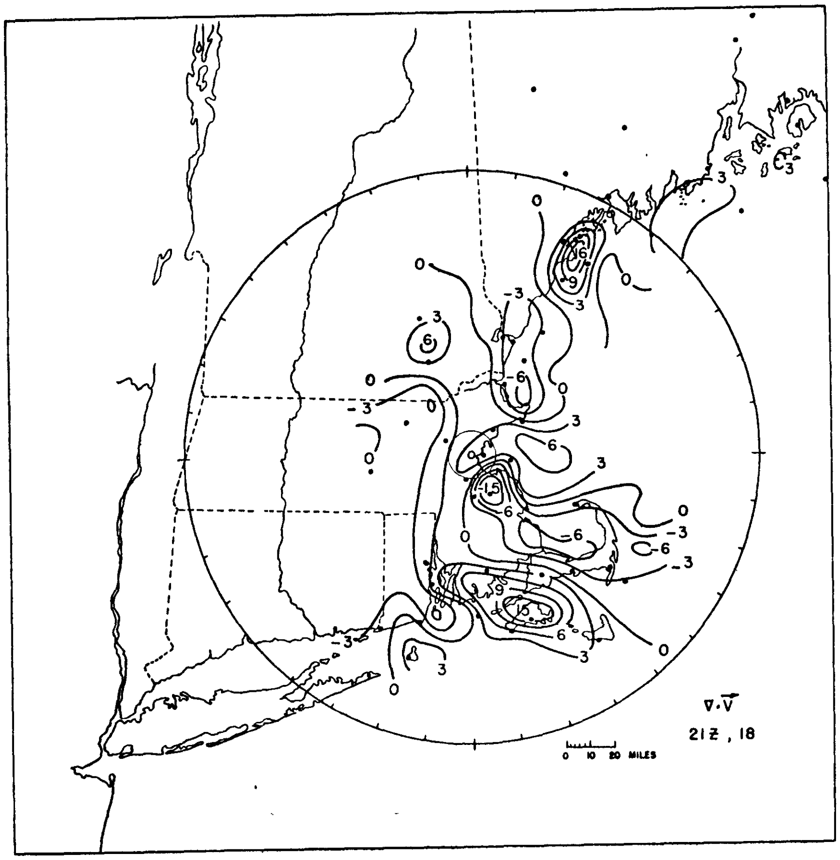


Figure 5g

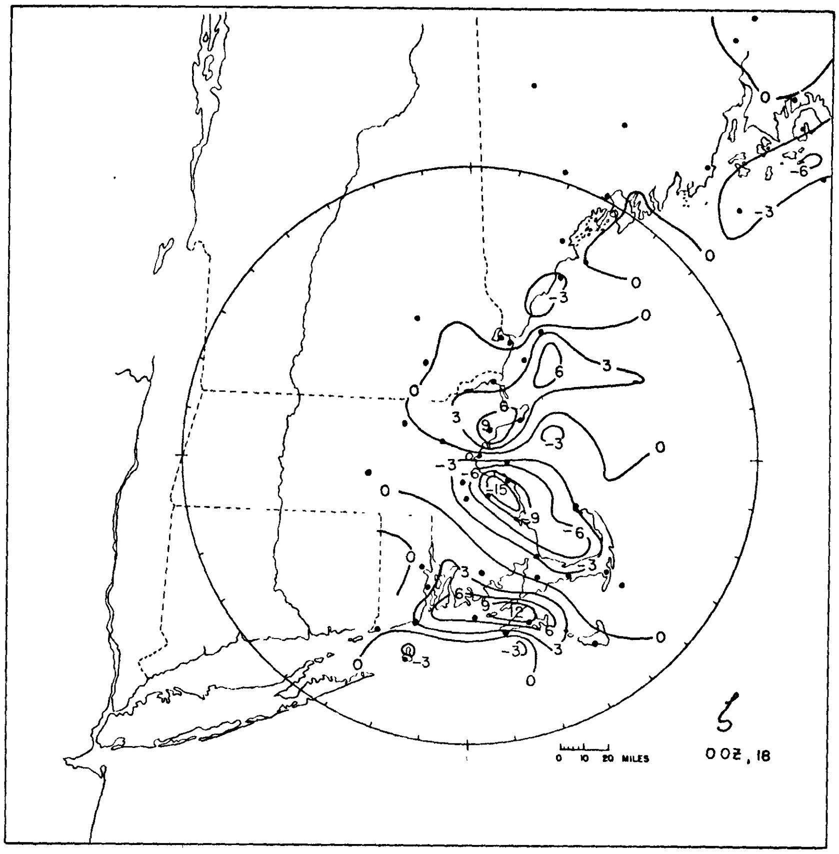


Figure 6a

Figures 6a-g are fields of relative vorticity in 10^{-1} hr^{-1} units for December 18. Dots indicate stations used for computations.

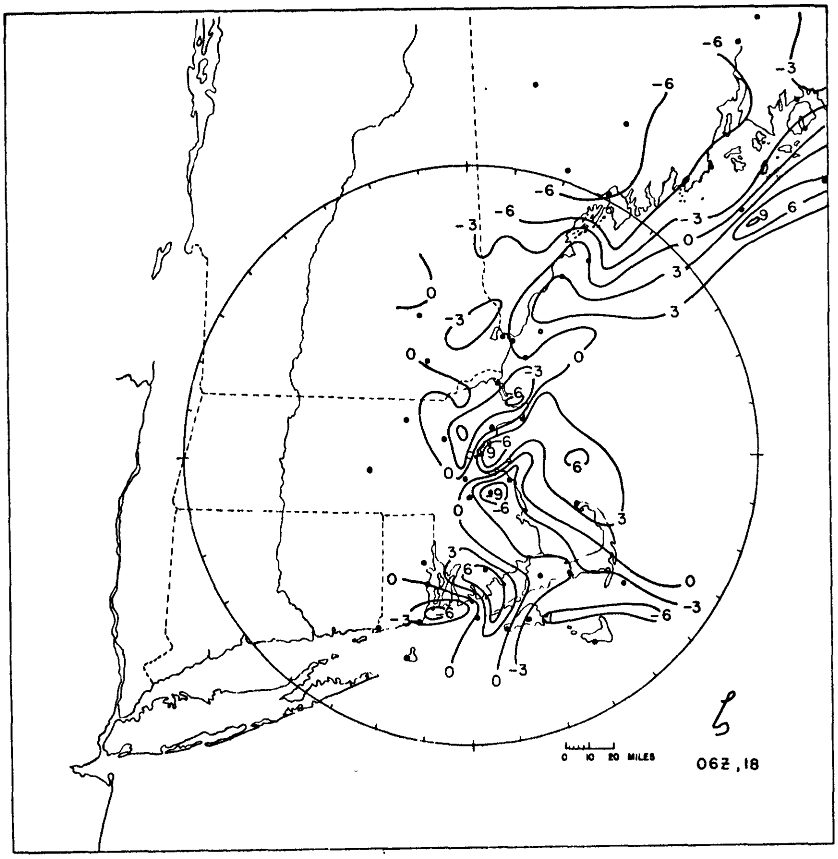


Figure 6b

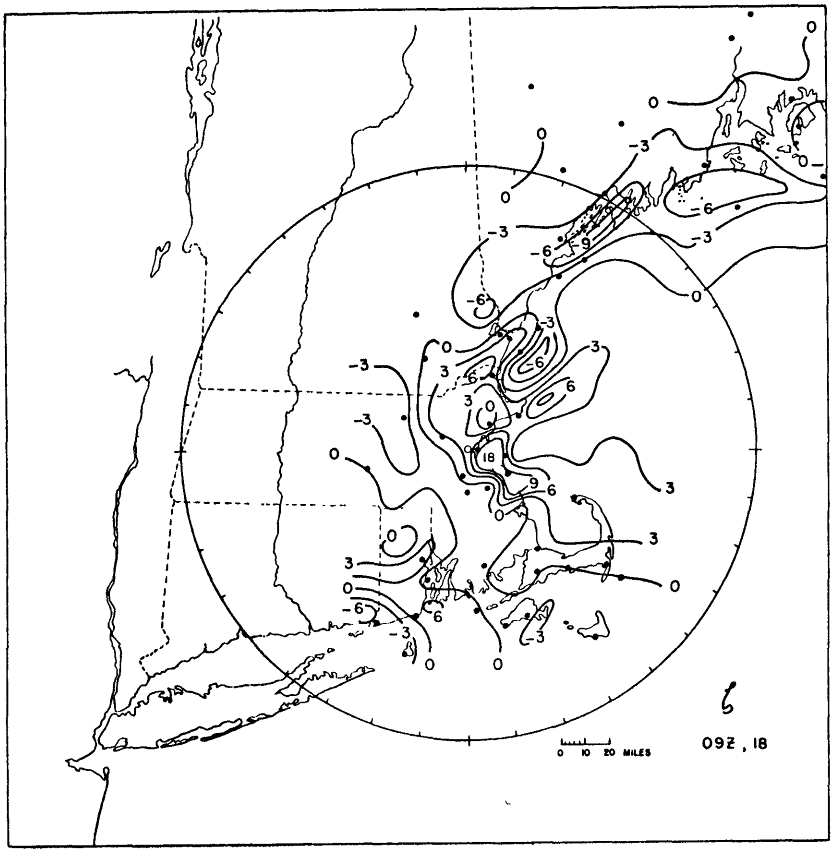


Figure 6c

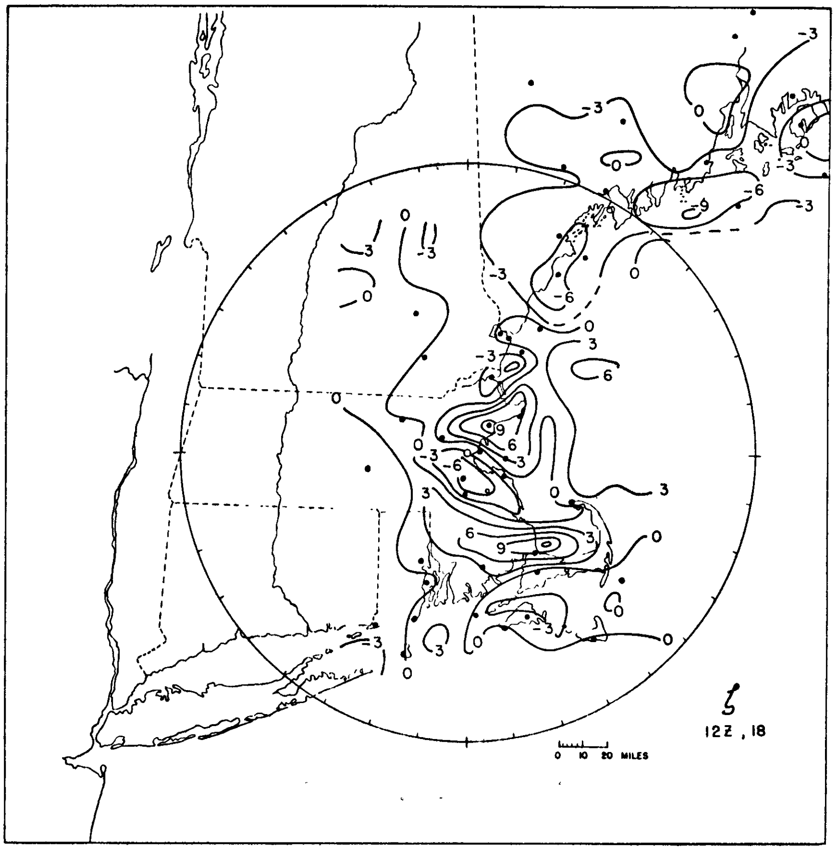


Figure 6d

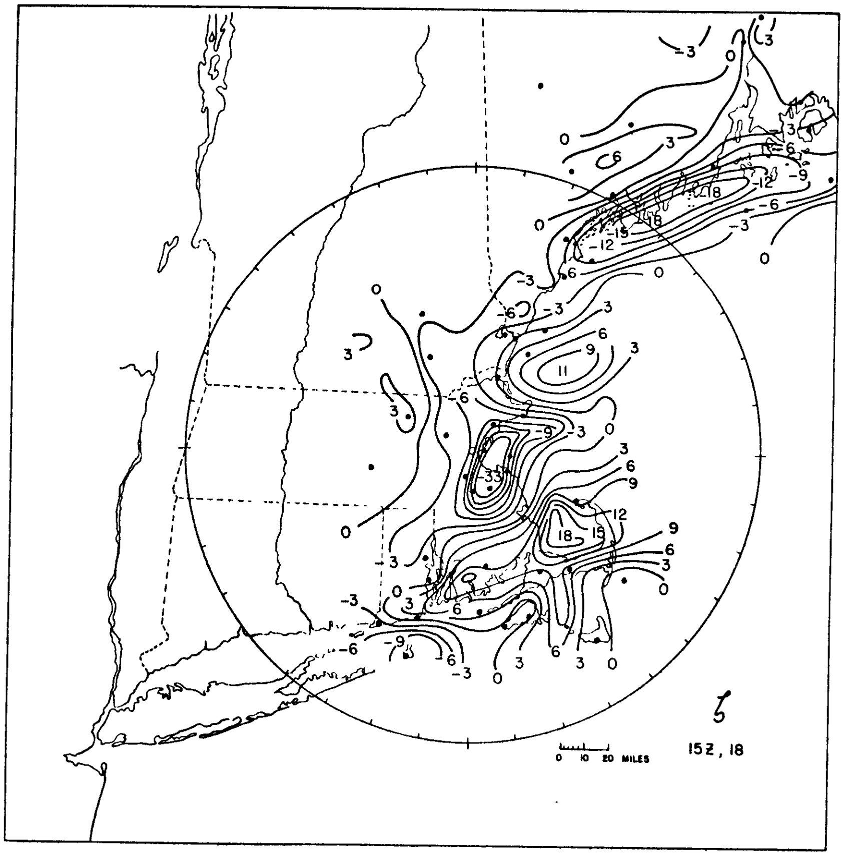


Figure 6e

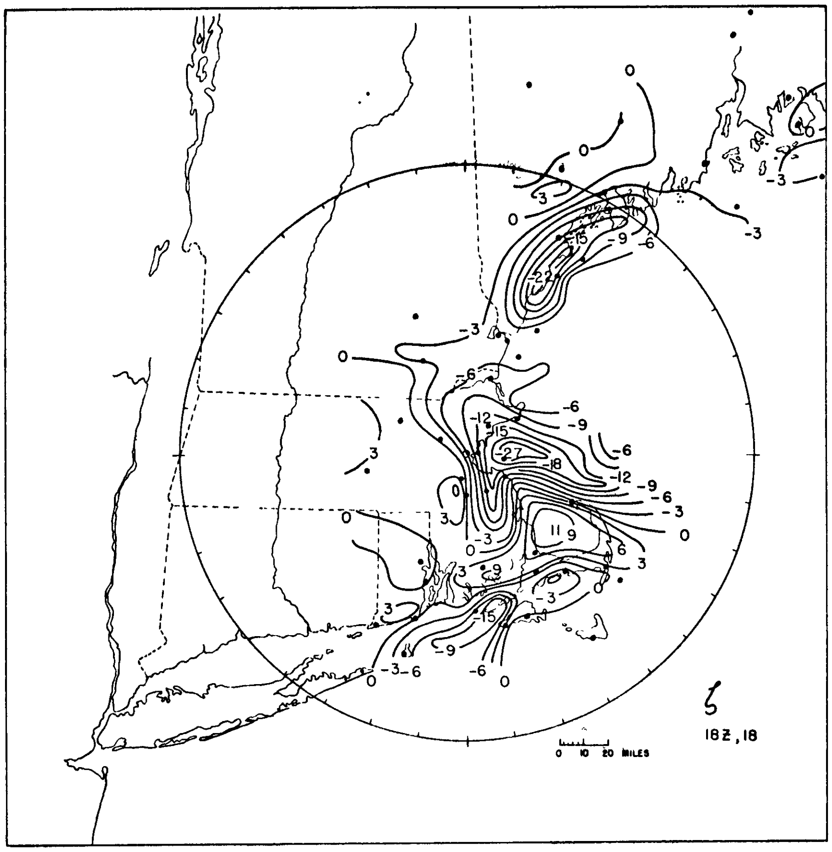


Figure 6f

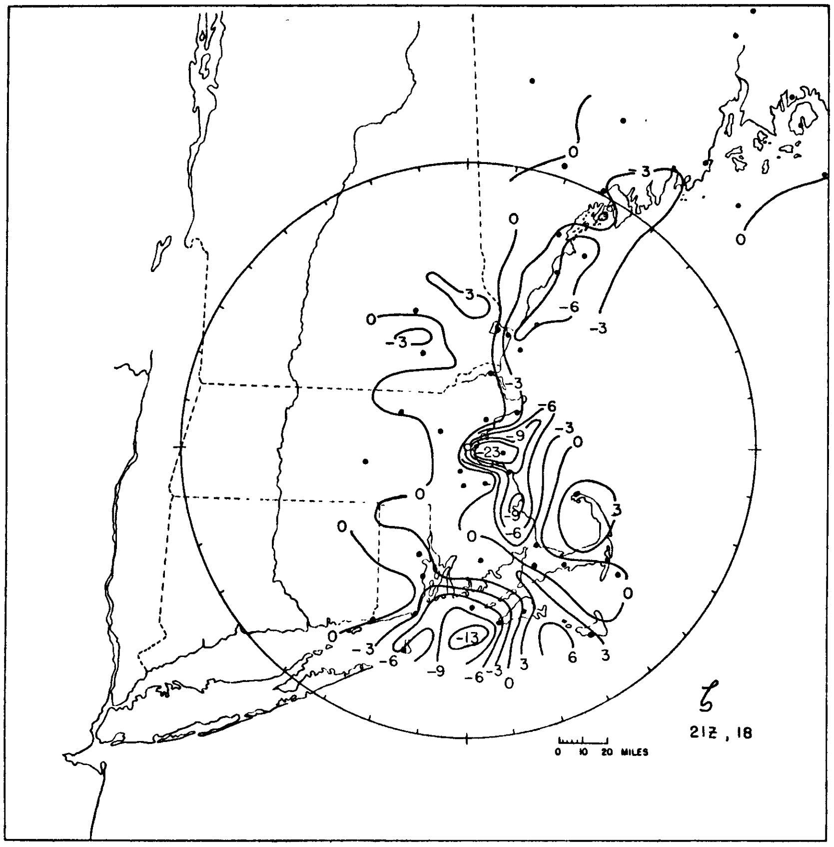


Figure 6g

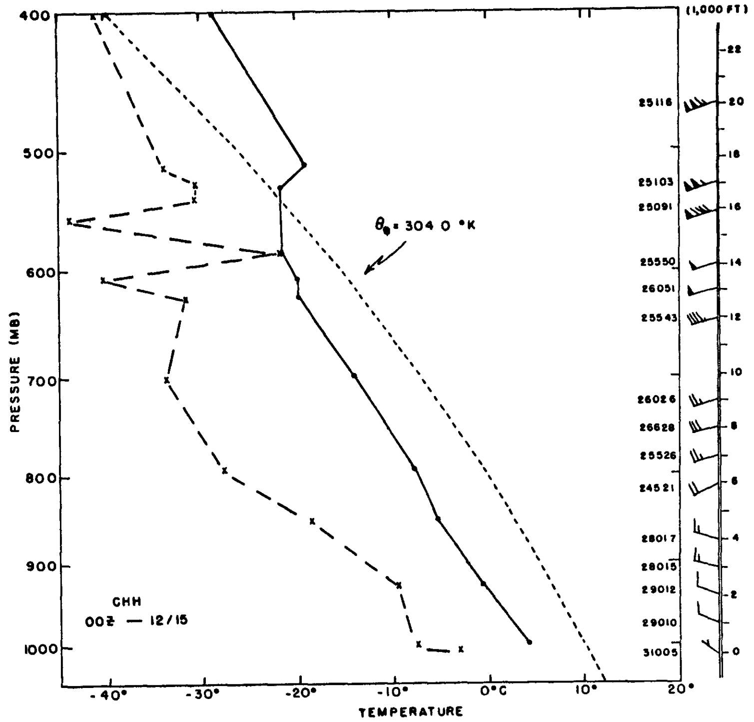


Figure 7a- Radiosonde sounding for 00 GMT 12/18 at Chatham.

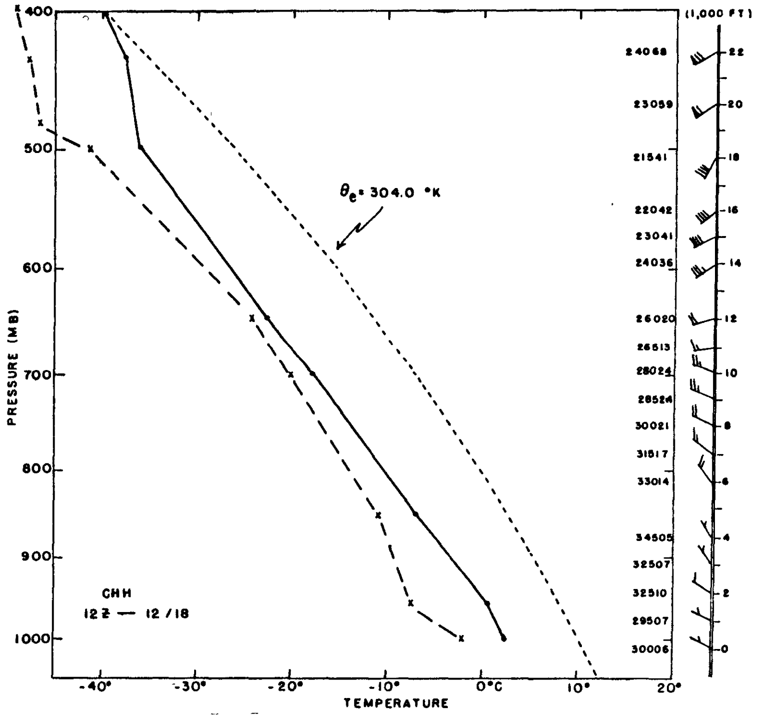


Figure 7b- Radiosonde sounding for 12 GMT, 12/18 at Chatham.
Solid line is temperature in Centigrade.
Large dotted line segments are dew point.
Small dotted line segments form pseudo-adiabat indicated.

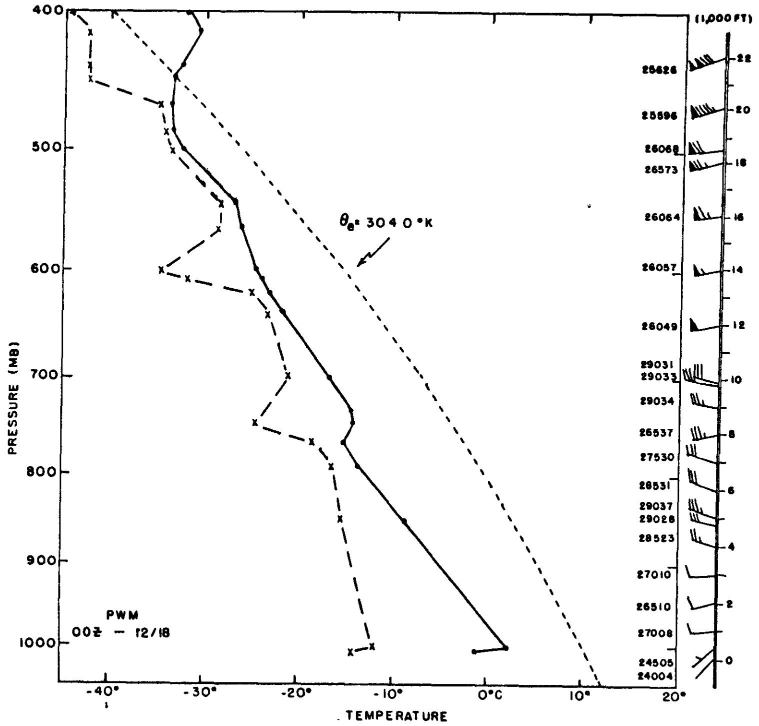


Figure 7c- Radiosonde sounding for 00 GMT, 12/18 at Portland.

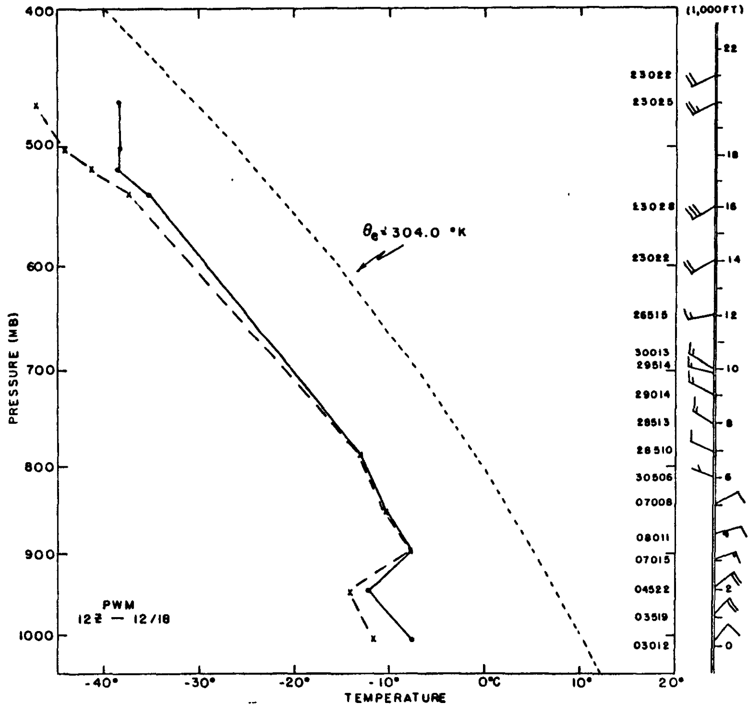


Figure 7d- Radiosonde sounding for 12 GMT, 12/18 at Portland.

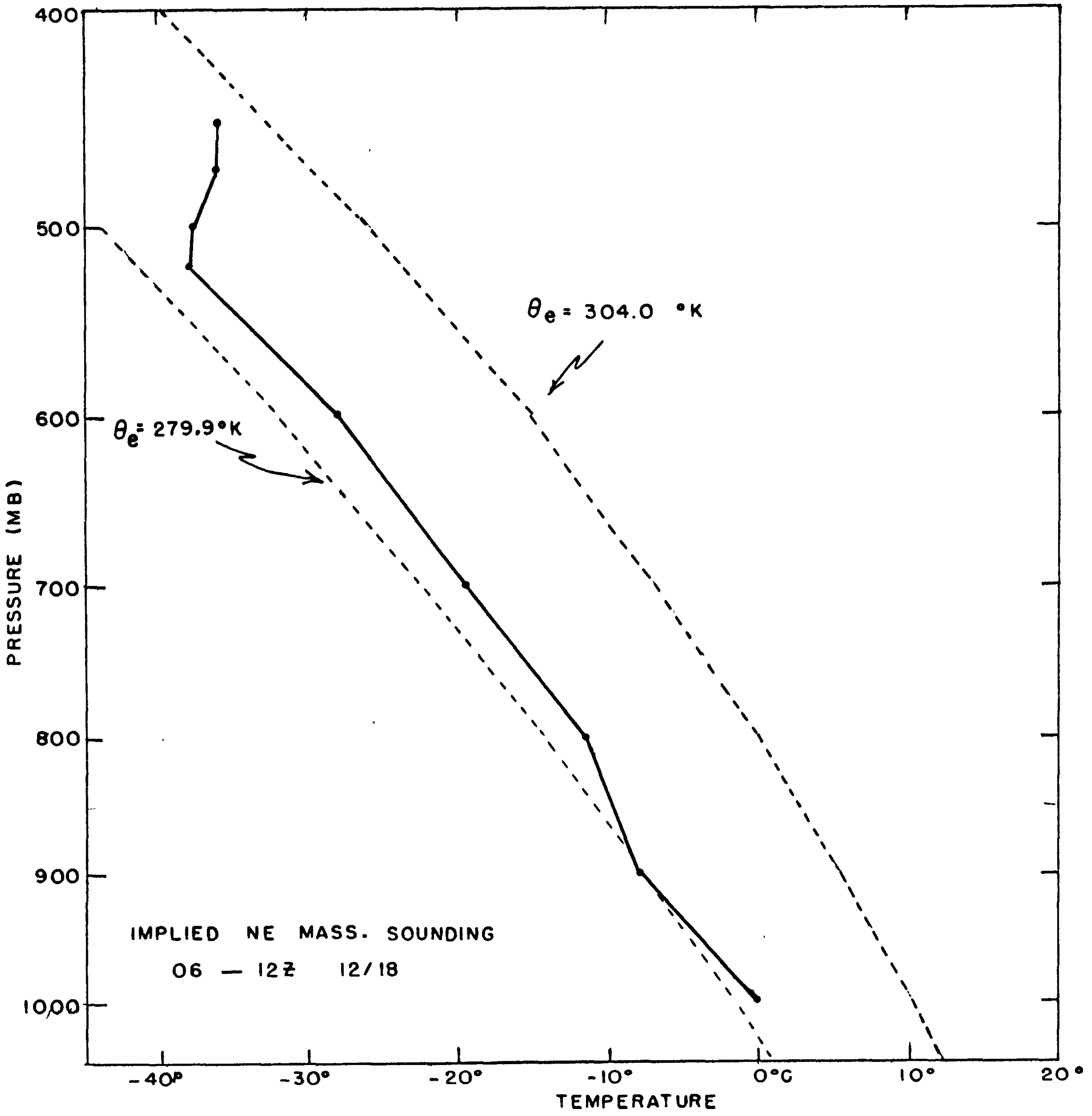


Figure 8- Implied Gloucester sounding deduced from Figures 7a-d and assummed saturated to 500 mb.

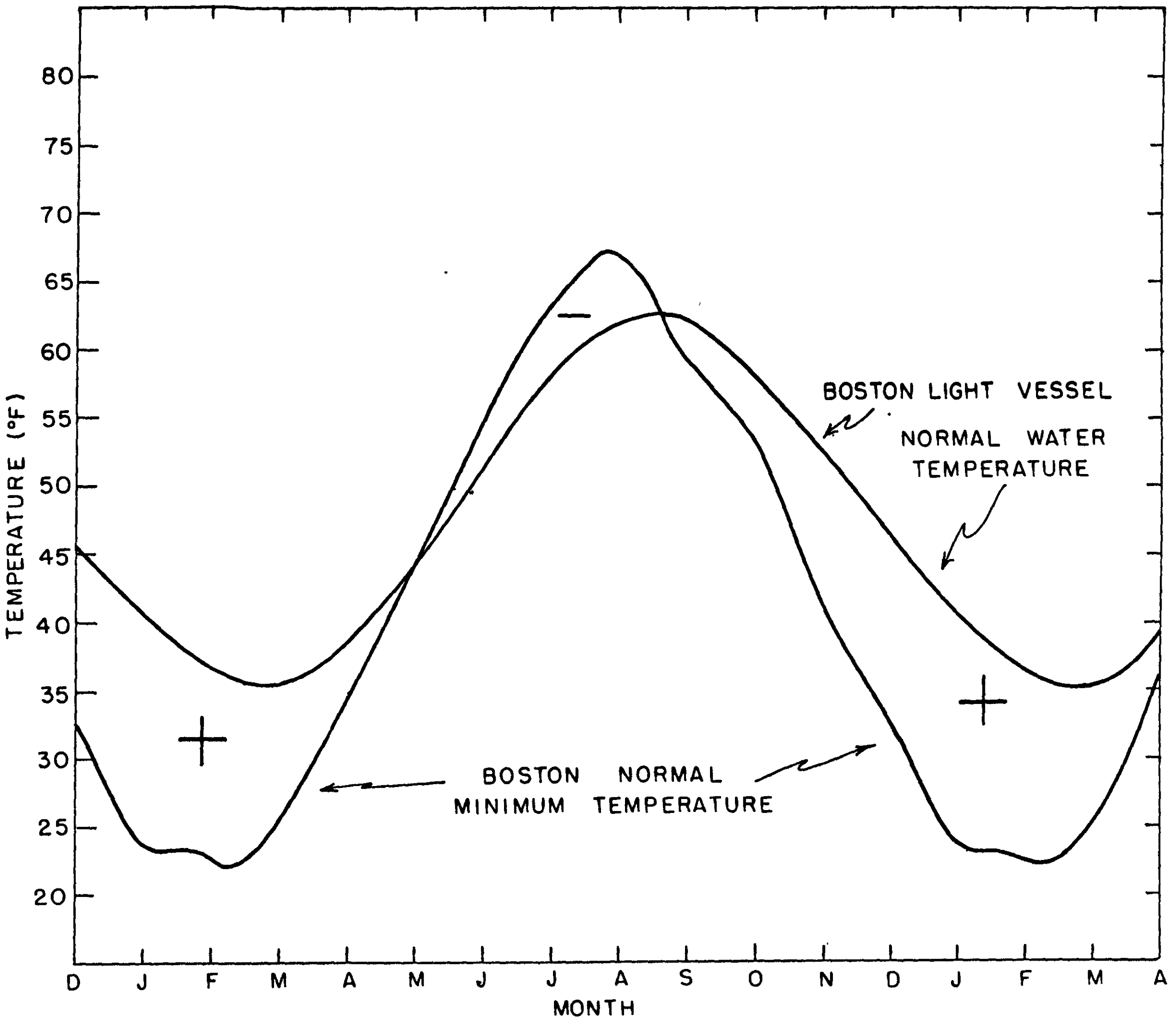


Figure 9- Mean oceanic heating potential as difference between Boston (Logan Airport) minimum temperature and Boston Light Vessel (BOS LV) normal water temperature. + indicates ocean heating; - ocean cooling.

IX. The search for the ideal snowstorm

A. Conversations

The mesoscale snowstorm of December 18, 1971 having been described and tentatively explained, one wonders whether an occurrence like this is at least an infrequent but recurring event along the Massachusetts coast or elsewhere. The first attempt at defining the problem was to interview several long-term New England weather watchers in the hope that they would remember small-scale snowstorms of the past. However, at the outset this approach was not expected to be productive because the author's advisor, Professor Frederick Sanders, himself a veteran New Englander, could not remember any case quite like the December 18th meso-snowstorm (DMS). Thus subsequent contacts with Mr. Don Kent of WBZ radio and TV, Mr. Peter Leavitt of Northeast Weather Services in Bedford, Mass., and Mr. Bob Lynde of the NWS at Logan Airport, Boston yielded interest in the topic at hand but no definitive recollections of small-scale heavy snow producers to rival the DMS. They were familiar with the effects induced by ocean heating or cooling on synoptic scale disturbances but did not have any organized memory of similar mesoscale effects. Thus, the uniqueness of the DMS was more firmly established.

B. Library Research

The second approach in attempting to isolate similar mesoscale snowstorms was to investigate past issues of the monthly National Oceanic & Atmospheric Administration (NOAA) publication, Storm Data. This publication describes weather events that caused damage with brief descriptions of the characteristics of the event. In this case the term "small-scale" or "unusual" snowstorm were looked for as these were the descriptions in Storm Data of the DMS. This approach was more successful than the first one as two storms described as unusual or small-scale were isolated. These were the February 4,1966 and November 15,1967 cases, described below.

1. February 4, 1966

This case is described in Storm Data as follows:

> " ... one of the most unusual snowstorms with respect to distribution and amounts of snowfall. Spotted communities received up to 11 inches while hardly a trace was recorded in other communities only a few miles away. East Point in Gloucester reported 11 inches while E. Boston had barely more than half-an-inch (sic). Jamaica Plain received 5 inches. This unusual pattern resulted from a combination of unstable air from the Atlantic and pockets of cold air at high altitudes."

Since there is no record of any analysis of the storm and since the relevant teletypewriter data is no longer available at MIT, it is impossible to describe this case in detail comparable to that used in describing the DMS. All that is available are newspaper clippings archived at the state climatologist's office and historical weather maps maintained at Northeast Weather Services as well as peripheral sources such as NOAA's Local Climatological Data (LCD) and Climatological Data (CD) summaries. From this it was apparent that the snow which began during mid-morning and continued in some areas through most of the day was heaviest to the north and west of Boston, along the coast as far north as Gloucester and as far west as Bedford and Worcester. Some observed snowfalls are given In Table 5. The locations are the same as the stations in Figure 3 and Table 1. An unofficial measurement at Bedford claims a fall of 10" while nearby communities received less than one inch. A comparison of snowfall distributions between this case and the DMS is appealing due to the similarity of area covered and the sharp gradient in snow depth.

The major synoptic feature during this period (not shown) was the passage of a weak surface trough from the Great Lakes across northern New England to a position off-shore by 00 GMT on the 4th. Meanwhile a strong low pressure center developed off-shore during late-morning and early afternoon of the 4th. The synoptic scale geostrophic wind at Boston was very slight although a northeast wind of 10 knots was observed at Logan at 06 GMT of the 4th. The wind veered to ESE by 12 GMT while a light snow shower, which had begun the previous night, persisted through the morning. At the same time, Nantucket was

Table 5

Snowfall amounts, February 4, 1966

Station	Amount (in.)
Bedford	4.3
Blue Hill	0.3
Boston (Logan Airport)	0.6
Brockton	0.0
E. Wareham	Trace
Haverhill	1.5
Nantucket	0.0
New Bedford	Trace
Reading	1.0
Rockport	2.0
Salem	7.0
Worcester	3.4

experiencing fair weather and a northwesterly wind. The sparsity of available data makes it impossible to identify mesoscale features but it is likely that the wind at Logan Airport was influenced by mesoscale circulations around areas where snow was falling. The reference to cold air at high altitudes in the Storm Data review suggests that the atmosphere was convectively unstable and that there was possibly an upper-air trough passage during the period. Since the temperature along the coast was near 30°F on the 4th, the potential for ocean heating existed. One may argue that lake-effect type snowfalls accounted for the observed snows. Lake-effect snowfalls are associated with bands of clouds resembling Bènard convection. They primarily result from low-level heating and do not have closed circulations. They have been seen often in the Great Lakes to be steered by the winds aloft (Peace and Sykes, 1966). The organization of the snow in this case allowed for persistance of moderate to heavy snow in an area similar to the heavy snow of the DMS. This suggests that a similar situation may have existed here. Certainly a comparison of synoptic circumstances reinforces this hypothesis.

2. November 15, 1967

The second suspicious case, November 15, 1967, is better documented due to a report by Pierce (1968). This event is notable because of the catastrophic effect it had on Boston area traffic. Synoptically, a major off-shore cyclone center was tracking northeastward from North Carolina to Nova Scotia while a weak pressure trough tracked through New York State to a position off the New England coast. Light rain had fallen at Boston during the morning but had ended after passage of the trough off-shore. The temperature, which was around 40° F during the morning, dropped suddenly to below-freezing late in the afternoon as light snow began to fall. The combination of melting snow on warm pavement in contact with sub-freezing air caused an icy film to develop over much of metropolitan Boston's highways, just in time for the evening rush hour. Also, most motorists were not equipped with snow tires due to the early season date of the storm. As might be expected, the result was traffic congestion which took hours to unravel and innumerable fender benders.

The list of snow depths from the November 15th case is given in Table 6. Again, the station names can be identified using Table 1 and Figure 3. Belmont is several miles northwest of Cambridge. Like both cases described previously, the heaviest snow occurred north and west of Boston, both along the coast and inland. It is obvious that this case was primarily of interest because of its timing and circumstance. However, the analysis by Pierce (1968) suggests that strong similarities between this case and the DMS exist. Pierce calls this storm a mini-blizzard.

Radar at Logan Airport indicated echoes near Lowell which were persistant through most of the morning of the 15th.

Table 6

Snowfall amounts, November 15, 1967

Station	Amount (in.)
Bedford	4.0
Belmont	4
Blue Hill	4.0
Boston	2.2
E. Wareham	0.0
Haverhill	8.5
Lawrence	6
Lowell	7
Nantucket	2.2
New Bedford	1.3
Reading	7.0
Rockport	6.0
Sandwich	Trace
Worcester	5.7

Moderate snow fell during that period in the Lowell-Lawrence area and was responsible for the heavy snow amounts recorded there. The surface geostrophic wind, meanwhile, developed a distinct increase in cyclonic vorticity in the vicinity of the Boston Harbor in the aftermath of the weak trough passage. Mean sea water temperature is in the low 50's during mid-November, so the potential for ocean heating was quite large and probably the reason for the increase in vorticity. The area of moderate snow moved eastward to a position near the coast when it suddenly intensified and moved southwestward,toward the Boston metropolitan area. The flow in which the echo was originally embedded was northwesterly, to the rear of the surface low. However, there must have been northeasterly flow along the coast. Pierce notes that the radar echo never reached Boston itself and therefore, the trajectory of the snowflakes must have been from northeast to southwest. No Coast Guard stations were used by Pierce in his surface analyses so there is no way of pin-pointing mesoscale circulations. However, all of this occurred, like the DMS, in an area of strong mid-tropospheric positive vorticity advection ahead of a sharp trough aloft over New England. The atmosphere was also becoming increasingly unstable since a low level pibal at Logan Airport indicated that warm air advection was occurring above the friction layer with cold advection aloft. The only effect that could have uniquely caused the movement and intensity of the snow area had to have been related to the configuration of the coast line and heating. It is these same factors which contributed heavily to the development and maintenance of the DMS.

C. Historical Map Search

A third approach in attempting to isolate probable historical meso-snowstorms was to peruse past surface and 500 mb. analyses in the hope of identifying suspicious synoptic sequences. This sequence would be the passage of a weak surface trough through northern New England in advance of a deep 500 mb. trough. The passage offshore of the surface trough would be followed by a flow of much colder air over New England induced by strong cyclogenesis well off-shore. Weak surface features are necessary to insure that localized heating will have sufficient time to get organized. The passage of a strong upper air trough insures cold air aloft (potential instability) and positive vorticity advection along the coast. Also, the most likely months for this to occur would be November through the first part of February when the potential for ocean heating is the greatest. This can be seen in Figure 9 where the normal minimum temperature at Logan Airport is compared with the normal sea water temperature at the Boston Light Vessel.

This approach, however, was found to be too cumbersome and unrevealing considering the sparsity of data available. It was similar to a search for the proverbial needle-in-the-haystack. The time series of surface analyses searched was made available by Mr. Peter Leavitt and went back to the late 1940's. The author found the synoptic scale analyses too coarse and the task too overwhelming to pursue further. The looked for sequence of synoptic events was found several times a year for the few years searched. Therefore, it is felt that a more leisurely hunt through the historical records by several people would be more fruitful.

D. An English meso-snowstorm

The hypothesis is that localized ocean heating such as might occur in an enclosed or semi-enclosed body of water could initiate weather-producing mesoscale activity. Another example of this type of activity was a mesoscale snowsystem in England (Pedgley,1968) on November 22, 1965. Although heaviest snow amounts were only around one inch, the early season occurrence of snow in eastern England was of interest. The snow system appeared to originate near the eastern coast of England, just north of the large convex-shaped coastal bulge. Skies were clear and the air cold, all of northern Europe being influenced by fresh northerly winds to the west of a deep cyclone over western Russia. However, shortly after sunrise an area of snow shower activity was noted near the coast and moved south-south eastward under the influence of low-level winds affecting a large area of eastern England (and London) that day but only a limited area at any particular time. The surface geostrophic wind acquired increased cyclonic vorticity in the area of snow shower origination. The coastline curvuture in this area is concave like that of the Massachusetts Bay. A dense network of observing stations indicated surface convergence and cyclonic vorticity in the vicinity of the snow activity. Upper level divergence and positive vorticity advection ahead of an upper trough may have helped maintain the system. Although not noted by Pedgley, there may have been a large amount of ocean heating in the origin area, as it is reasonable to assume that the ocean temperature off the coast of England in late November is warmer than 40°F (U.S. Navy, 1955). Cumulus and cumulonimbus were observed only near the coast indicating that convective activity only occurred there. When the inland areas were affected, mostly stratus was observed. Thus, low-level convergence produced moderate vertical motion and hence, light snow. Areas more than 50 miles from the coast were unaffected. The English meso-snow system is an indication that organized mesoscale activity has been observed under similar conditions as the DMS bit in another part of the world.

X. The statistical approach

In order to study the effect of ocean heating in more depth, it was decided that a statistical approach would be taken. Specifically, the tendency for concentrations of relative vorticity to occur in the harbor area whether from frictional or thermodynamic causes can be measured using a time series of wind observations from stations which follow a curve which generally outlines the shape of the Harbor. In each hour which has observations available, values of vorticity and divergence can be calculated using the method in Appendix A following a curve outlined by Gloucester C.G.S., BOS, Scituate C.G.S. and the BOS LV, shown in Figure 3.

A. Data sample and plan of attack

Assuming all other variables being equal, one would expect, based on the experience with the DMS, that there be a tendency for cyclonic vorticity in months with oceanic heating and anti-cyclonic vorticity tendencies in months with ocean cooling. Hoping to obtain a continuous and complete observation record, referring to Figure 9, and paying heed to limitations of time and manpower, the author picked June and December 1968 and 1971 as the months of analysis. However, due to the irregularity of Coast Guard observations, it was not possible to assemble a completely homogeneous data sample. As a result, the final compilation consisted of two observations a day, 12 and 18 GMT, for June 1968, 4 observations a day for December 1968, 00,06,12, and 18 GMT, and 7 observations daily for June and December 1971, 00,06,09,12,15,18, and 21 GMT. It was expected that all factors besides oceanic heating would not be equal and that frictionally induced vorticities would be very important, even to the point of completely masking out looked for effects. Thus, a correlation analysis between surface geostrophic wind strengths and the time series of calculated vorticities was also desired. The measure of the geostrophic wind is made from computed pressure gradients. The ones of interest would be those which were related to the meridional and zonal components of the wind. Thus. hourly pressure observations at BOS, PVD, PWM, CON, BDL, and ALB (Figure 3) were obtained so that horizontal pressure gradients could be calculated. Various combinations of station pressures were tried in addition to uncentered differences and all indices are described in Table 7. For instance, PG1 and PG2 are both measures of the southerly component of the geostrophic wind, but PG2 has a slightly more synoptic scale character because of the larger distance involved. PG7 and PG8 are also measures of the southerly component but in a more centered sense on Boston. Similarly, PG4 and PG5 measure the strength of the easterly component to the south and north of Boston while PG6 is also included in order to determine whether it is the strength of that component over the whole region or in a preferred direction away from Boston that is more effective in relative vorticity induction. The distances and directions from Boston and between the various stations are also included so as to point out the specific nature of each index. For all the statistical work, a normal distribution about the mean is assumed for the vorticity values.

Table 7

Description of Geostrophic Indices

INDEX	DESCRIPTION	
PG1	BOS - BDL	+ for southerly (161°)
PG2	BOS - ALB	+ for southerly (191°)
PG3	CON - BOS	+ for easterly (66°)
PG4	BOS - PVD	+ for easterly (108°)
PG5	PWM - BOS	+ for easterly (101°)
PG6	PWM - PVD	+ for easterly
PG7	(PVD - BDL) + (PWM - CON)	+ for southerly
PG8	(PWM - ALB) + (PVD - ALB)	+ for southerly
PG9	(PWM - PVD) + (CON - BDL)	+ for southeasterly

Distances between stations, n. mi.

Station Pair	Distance
BOS, BDL	81.9
BOS, ALB	126.4
CON, BOS	54.6
BOS, PVD	44.6
PWM, BOS	82.4
PWM, PVD	126.5
PVD, BDL	58.9
PWM, CON	58.9
PWM, ALB	162.2
PVD, ALB	123.5
CON, BDL	93.9

B. Data Acquisition and Processing

Most of the data used was obtained from the National Climatic Center (NCC). The wind data for Boston (Logan Airport) was read off LCD sheets for the respective months. The Coast Guard data was obtained on microfilm from NCC as copies of the original record. Observations were sporadic for some stations, such as Gloucester and Scituate, but the quality of the record improves markedly for 1971 over 1968. Conversations with National Weather Service (NWS) and United States Coast Guard (USGC) personnel have indicated that the observational program for these Coast Guard stations is constantly being improved and that a real effort is being made to train new observers as well as possible. This is a difficult task because of the high turnover of observers at the Coast Guard stations. Mistakes such as "ESW" show up on the observation record but for the most part are easily reconcilable. Part of the difficulty arises from the many duties that Coast Guard observers are required to perform while on duty apart from their meteorological responsibilities. It is necessary in many cases to use observations which are not simultaneous. For instance, it frequently happened that the NWS observation at Logan Airport was taken as much as one hour after the Coast Guard one attributed to the same time. Also, the quality of observing equipment from station to station varied so as to give a heterogeneous look to the record. It becomes obvious after working with the data which observations are incorrect and in some cases, the most obvious errors are corrected for in a subjective manner. The wind observations at Gloucester and Scituate are given in the sixteen cardinal directions, requiring that they be converted to degrees. A certain tolerance, therefore, must be allowed in the interpretation of the vorticities values calculated.

The wind observations at the Boston Light Vessel (BOS LV) represented a special problem. In a way it was these observations that were the most interesting. In the December 18 meso-snowstorm it was the observations at BOS LV that determined the closed cyclonic circulation in the Harbor area. In analyses of coastal fronts, Bosart et al (1972) BOS LV was the first location to become onshore. However, in the record that was sent from NCC, only six-hourly observations were recorded on the form (not the original record), form #72-5. Having worked with BOS LV observations, the author knew that three-hourly observations had been taken there at least in 1971. It was necessary to procure the original log of hourly weather observations from the ship itself for June 1971 and the original ship's log for December 1971. It seems that since the observers there were taking hourly observations for their own use, sending out three-hourly observations to Logan for teletype use, logging four-hourly observations for Coast Guard use, and filling out a separate form of six-hourlies for the NWS, they decided to dispense with the hourly log which was probably never used, anyway. Since it was only very recently that three-hourlies were being filed for the NWS (brought to their attention by the author), the only record available to the author was the original ship's log, which not only had the four-hourlies (a maritime tradition to coincide with the changing of the watch) but other tidbits of nautical information, some of which was of meteorological value. Between the six-hourlies from NCC and the four-hourlies from USCG, only the 15 GMT observation was missing. That observation was bogused when the time series at all four stations showed continuity but left missing when this condition was not met. The preceding details have been included to serve as a caveat in studies where Coast Guard data is desirable. However, it must be added that all data sources, especially the USCG, were most helpful in catering to individual needs.

The pressure data was obtained from NCC on WBAN 10 forms which were on microfilm. Some data was lost when Caribou, Maine was sent for December 1971 instead of Portland. It was necessary at the last minute to use teletype data archive in the MIT meteorology department to obtain the pressure data. However, since the teletype was shut off for the Christmas and New Year's weekends, some data was lost.

All the data, winds and pressure, were put on punch cards and processed at the MIT Information Processing Center by a program written by the author. From the raw data, vorticity, divergence, and the geostrophic wind indices were computed in the manner discussed earlier. Statistical analyses were performed on the time series of calculated data in order to isolate effects which were predominant in producing vorticity in the Bay. This was done by stratifying the data according to month and time of day and computing means and correlation coefficients to reveal the character of the effects being looked for. All the results are given in Tables 8a- m.

C. Expected errors

As noted before, observer error, instrumental error, non-coincidence of supposedly simultaneous observations, and errors due to round-off to cardinal points limit the significance of differences between individual calculated values of vorticity. It is expected that these errors would be random for all times (one cannot suppose that the observers at night were less accurate than those during the day) and would cancel out when sample means are computed or contribute equally to standard deviations. There might be a difference due to the error contributed in June vs. December because for a given error in direction, the error produced in the vorticity is greater when the wind speed is greater. However, since this error is probably small compared to the others, it will be ignored. As estimate of the maximum probable error of 0.5 hr^{-1} in calculated vorticity was made based on a perusal of the time series of vorticities. In all cases this was found to be around

Table 8a

All months

Mean	0.0018
Standard Deviation	0.7200
Maximum	2.2892
Minimum	-2.730
Number of Cases	528

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	.002	-.407	-.510	.119	-.758	-.478	-.578	-.387	-.444	-.432
S.D.	.720	1.167	1.429	1.144	1.368	1.366	1.241	1.133	1.340	1.184

Correlation Coefficients

Vort.	1.0	.199	.265	.123	-.026	.238	.160	.297	.321	.204
PG1		1.0	.867	-.005	.676	.517	.633	.845	.842	.760
PG2			1.0	-.170	.406	.355	.412	.814	.978	.541
PG3				1.0	.344	.657	.605	-.075	-.056	.595
PG4					1.0	.602	.820	.373	.362	.817
PG5						1.0	.951	.630	.489	.904
PG6							1.0	.597	.491	.966
PG7								1.0	.876	.655
PG8									1.0	.603
PG9										1.0

Table 8b

June 1968 + 1971

Mean	.192
Standard Deviation	.558
Maximum	1.571
Minimum	-1.556
Number of Cases	234

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	.192	-.025	-.134	.143	-.658	-.335	-.450	-.069	-.087	-.194
S.D.	.558	.843	.932	.913	1.412	.882	.946	.848	.859	.853

Correlation Coefficients

Vort.	1.0	-.140	.076	-.186	-.386	-.138	-.287	.138	.153	-.278
PG1		1.0	.745	-.205	.667	.494	.651	.733	.661	.728
PG2			1.0	-.462	.225	.199	.239	.751	.964	.309
PG3				1.0	.261	.506	.445	-.437	-.402	.470
PG4					1.0	.554	.863	.103	.068	.847
PG5						1.0	.899	.468	.292	.869
PG6							1.0	.338	.213	.974
PG7								1.0	.827	.368
PG8									1.0	.278
PG9										1.0

Table 8c

December 1968 + 1971

Mean	-.149
Standard Deviation	.796
Maximum	2.289
Minimum	-2.730
Number of Cases	294

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	-.149	-.711	-.809	.100	-.837	-.592	-.681	-.638	-.729	-.621
S.D.	.796	1.294	1.667	1.301	1.329	1.645	1.427	1.263	1.569	1.365

Correlation Coefficients

Vort.	1.0	.242	.268	.243	.159	.333	.302	.296	.321	.326
PG1		1.0	.893	.059	.730	.522	.632	.869	.883	.760
PG2			1.0	-.091	.514	.379	.453	.820	.980	.581
PG3				1.0	.403	.710	.665	.050	.040	.649
PG4					1.0	.665	.828	.535	.516	.846
PG5						1.0	.969	.679	.528	.919
PG6							1.0	.686	.566	.968
PG7								1.0	.885	.731
PG8									1.0	.672
PG9										1.0

Table 8d

June 1968

Mean	.1212
Standard Deviation	.4421
Maximum	1.1969
Minimum	-0.7360
Number of Cases	58

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	.121	.414	.142	.067	.449	.012	.166	.095	.050	.283
S.D.	.442	.938	1.092	1.016	1.456	1.036	1.054	.960	1.033	1.002

Correlation Coefficients

Vort.	1.0	-.405	-.424	.258	-.171	-.075	-.132	-.360	-.379	-.159
PG1		1.0	.844	-.016	.599	.551	.644	.759	.792	.742
PG2			1.0	-.204	.279	.354	.362	.781	.972	.475
PG3				1.0	.458	.644	.635	-.279	-.147	.622
PG4					1.0	.567	.850	.036	.155	.827
PG5						1.0	.916	.488	.448	.897
PG6							1.0	.329	.362	.976
PG7								1.0	.859	.401
PG8									1.0	.471
PG9										1.0

Table 8e

December 1968

Mean	-.030
Standard Deviation	.689
Maximum	2.242
Minimum	-2.706
Number of Cases	121

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	-.030	-.840	-1.097	.027	-.962	-.952	-.960	-.898	-1.057	-.838
S.D.	.689	1.469	1.847	1.633	1.518	2.027	1.719	1.431	1.686	1.578

Correlation Coefficients

Vort.	1.0	.177	.036	.480	.439	.514	.531	.206	.121	.505
PG1		1.0	.891	-.046	.761	.407	.549	.835	.880	.691
PG2			1.0	-.221	.527	.233	.343	.771	.972	.482
PG3				1.0	.372	.708	.660	-.009	-.062	.642
PG4					1.0	.655	.815	.594	.558	.865
PG5						1.0	.972	.643	.429	.908
PG6							1.0	.679	.503	.966
PG7								1.0	.861	.706
PG8									1.0	.612
PG9										1.0

Table 8f

June 1971

Mean	.215
Standard Deviation	.590
Maximum	1.571
Minimum	-1.556
Number of Cases	176

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	.215	-.169	-.225	.169	-1.022	-.449	-.653	-.123	-.132	-.351
S.D.	.590	.758	.858	.878	1.193	.796	.814	.863	.791	.736

Correlation Coefficients

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Vort.	1.0	-.044	.252	-.321	-.475	-.146	-.338	.300	.339	-.318
PG1		1.0	.684	-.285	.636	.411	.591	.728	.601	.677
PG2			1.0	-.591	.112	.067	.100	.732	.964	.158
PG3				1.0	.253	.478	.435	-.505	-.525	.459
PG4					1.0	.495	.833	.071	-.036	.834
PG5						1.0	.893	.442	.186	.844
PG6							1.0	.319	.100	.970
PG7								1.0	.809	.328
PG8									1.0	.143
PG9										1.0

Table 8g

December 1971

Mean	-.233
Standard Deviation	.855
Maximum	2.289
Minimum	-2.730
Number of Cases	173

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	-.233	1.621	-.609	.151	-.750	-.340	-.486	-.456	-.499	-.470
S.D.	.855	1.151	1.501	1.007	1.176	1.261	1.146	1.099	1.442	1.175

Correlation Coefficients

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Vort.	1.0	.323	.479	.073	-.015	.272	.190	.429	.512	.249
PG1		1.0	.898	.202	.691	.684	.740	.911	.892	.839
PG2			1.0	.069	.489	.550	.570	.867	.988	.679
PG3				1.0	.450	.724	.682	.121	.159	.668
PG4					1.0	.685	.853	.457	.464	.823
PG5						1.0	.965	.715	.636	.943
PG6							1.0	.677	.624	.974
PG7								1.0	.905	.750
PG8									1.0	.725
PG9										1.0

Table 8h

Day 1971

Mean	-.0213
Standard Deviation	.792
Maximum	1.754
Minimum	-2.730
Number of Cases	174

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	-.021	-.264	-.330	-.043	-.896	-.497	-.640	-.172	-.261	-.448
S.D.	.792	1.040	1.242	.866	1.297	.986	.978	1.038	1.181	.942

Correlation Coefficients

Vort.	1.0	.234	.423	-.217	-.330	-.041	-.181	.375	.457	-.039
PG1		1.0	.840	-.112	.593	.594	.668	.854	.805	.798
PG2			1.0	-.258	.305	.447	.436	.836	.982	.562
PG3				1.0	.254	.494	.444	-.256	-.190	.444
PG4					1.0	.569	.842	.220	.212	.790
PG5						1.0	.923	.618	.523	.897
PG6							1.0	.509	.442	.959
PG7								1.0	.881	.607
PG8									1.0	.566
PG9										1.0

Table 8i

Night 1971

Mean	.007
Standard Deviation	.741
Maximum	2.289
Minimum	-2.359
Number of Cases	175

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	.007	-.522	-.500	.362	-.878	-.293	-.501	-.403	-.367	-.373
S.D.	.742	.939	1.223	.975	1.079	1.108	1.009	.895	1.167	1.015

Correlation Coefficients

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Vort.	1.0	.300	.455	.056	-.095	.274	.160	.471	.511	.216
PG1		1.0	.843	.215	.641	.602	.672	.849	.834	.798
PG2			1.0	-.026	.326	.388	.400	.815	.983	.532
PG3				1.0	.479	.725	.699	.061	.069	.714
PG4					1.0	.642	.836	.325	.296	.808
PG5						1.0	.957	.646	.500	.921
PG6							1.0	.585	.469	.963
PG7								1.0	.871	.650
PG8									1.0	.590
PG9										1.0

Table 8j

Day June 1971

Mean	.2718
Standard Deviation	.6499
Maximum	1.571
Minimum	-1.556
Number of Cases	99

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	.272	-.033	-.089	-.185	-1.110	-.605	-.785	-.059	-.034	-.461
S.D.	.650	.789	.830	.761	1.283	.684	.749	.842	.774	.666

Correlation Coefficients

Vort.	1.0	-.026	.261	-.237	-.434	-.011	-.269	.327	.379	-.243
PG1		1.0	.676	-.411	.682	.469	.691	.696	.555	.768
PG2			1.0	-.690	.196	.210	.244	.735	.955	.257
PG3				1.0	.045	.169	.128	-.616	-.642	.191
PG4					1.0	.389	.836	.069	-.022	.837
PG5						1.0	.831	.578	.311	.765
PG6							1.0	.386	.172	.961
PG7								1.0	.820	.372
PG8									1.0	.170
PG9										1.0

Table 8k

Night June 1971

Mean	.1416
Standard Deviation	.4980
Maximum	1.249
Minimum	- 1.173
Number of Cases	77

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	.142	-.344	-.399	.623	-.910	-.249	-.483	-.357	-.259	-.210
S.D.	.498	.684	.877	.810	1.064	.885	.866	.687	.799	.799

Correlation Coefficients

Vort.	1.0	-.149	.219	-.426	-.544	-.285	-.426	.192	.255	-.412
PG1		1.0	.674	.043	.649	.509	.620	.746	.646	.722
PG2			1.0	-.457	.033	.018	.026	.713	.975	.131
PG3				1.0	.535	.686	.688	-.213	-.383	.684
PG4					1.0	.640	.859	.147	-.028	.865
PG5						1.0	.943	.503	.145	.903
PG6							1.0	.399	.084	.976
PG7								1.0	.083	.432
PG8									1.0	.174
PG9										1.0

Table 81

Day December 1971

Mean	-.408
Standard Deviation	.799
Maximum	1.754
Minimum	-2.730
Number of Cases	75

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	-.408	-.568	-.647	.144	-.615	-.355	-.448	-.477	-.562	-.430
S.D.	.799	1.241	1.585	.961	1.270	1.271	1.195	1.189	1.518	1.220

Correlation Coefficients

Vort.	1.0	.260	.447	-.082	-.116	.029	-.023	.288	.445	.085
PG1		1.0	.904	.161	.705	.739	.777	.933	.902	.861
PG2			1.0	.022	.513	.596	.605	.887	.991	.703
PG3				1.0	.422	.674	.625	.076	.101	.607
PG4					1.0	.730	.881	.495	.487	.841
PG5						1.0	.967	.737	.661	.956
PG6							1.0	.696	.642	.978
PG7								1.0	.916	.773
PG8									1.0	.738
PG9										1.0

Table 8m

Night December 1971

Mean	-.098
Standard Deviation	.875
Maximum	2.289
Minimum	-2.359
Number of Cases	98

	Vort.	PG1	PG2	PG3	PG4	PG5	PG6	PG7	PG8	PG9
Mean	-.098	-.661	-.580	.157	-.854	-.328	-.515	-.439	-.452	-.500
S.D.	.875	1.082	1.442	1.046	1.095	1.259	1.112	1.031	1.388	1.144

Correlation Coefficients

Vort.	1.0	.402	.515	.172	.100	.448	.365	.555	.571	.389
PG1		1.0	.896	.238	.677	.639	.706	.891	.890	.819
PG2			1.0	.105	.477	.510	.541	.848	.986	.660
PG3				1.0	.483	.761	.729	.159	.205	.718
PG4					1.0	.657	.831	.426	.455	.812
PG5						1.0	.965	.698	.614	.935
PG6							1.0	.662	.611	.971
PG7								1.0	.894	.732
PG8									1.0	.718
PG9										1.0

one standard deviation. However, in all comparisons made, the tolerances desired and sample sizes used were large enough so that the results were significant.

D. Results and discussion

1. All months

The first group of results to be considered is in Table 8a. The form for this table is the same as all the others. Each table represents a statistical summary of a different subset of the total data sample of vorticity. At the top of each chart the mean, standard deviation, maximum, and minimum values of the subset as well as the number of cases are given. Then the means and standard deviations are listed for the vorticity and nine geostrophic wind indices. The linear correlation coefficients are given below. The first row of the matrix contains the correlations between vorticity and the nine indices. Below that, the intercorrelations between indices are given to show relationships between them. The correlation coefficient between two variables x,y is given by

$$r = \frac{N \Sigma_1 xy - \Sigma x \Sigma_1 y}{\sqrt{\left(N \Sigma_1 x^2 - (\Sigma x)^2\right)\left(N \Sigma y^2 - (\Sigma y)^2\right)}}$$

n : # of elements in sample

Σ_1 : summation over sample

As can be seen from the formula, $r_{xy} = r_{yx}$, correlation coefficients are commutative. That is why the summary tables are upper triangular matrices.

There are 528 cases for the total data sample. Any case which has a missing pressure or wind observation is deleted from the sample. The mean of the vorticity for the total sample is not significantly different from zero (less than the 40% confidence level).

The means of the geostrophic wind indices (GWI) are interesting. They are all negative with the exception of PG3. This means that the average (resultant) wind for the sample gives northerly and westerly components. The GWI can be converted to wind speed by the following which gives the geostrophic wind.

$$\vec{V} = \frac{1}{\rho f} \frac{\partial p}{\partial |n|} \vec{n}$$

p : pressure
$\vec{n}$: horizontal distance
f : coriolis parameter
ρ : density of air
$\vec{V}$: horizontal wind vector

Knowing the horizontal gradients of pressure (in millibars per 100 km.), one can convert it to wind speed. A gradient of one millibar per 100 km. corresponds to a wind speed of 18 knots. Thus the GWI in Table 8a represent significant resultant winds.

PG3 shows anomalous behavior in its mean as compared to the other zonal GWI and requires further analysis. It gives the strength of the east-northeasterly component as measured by the pressure difference between Concord and

Boston. It is not immediately obvious why the pressure at Concord should behave so differently from the other land stations, Albany (ALB) and Hartford (BDL). Concord is the only station involved in the zonal wind indices that is a continental station. The positive value of PG3 is significantly different from zero at the 98% level and thus the effect is believed to be real. A clue is given in Table 9.

Without applying sophisticated statistical tests, it is immediately obvious that the largest variation is between day and night in June. Diurnal variations are greatest in the summer due to the large differences in insolation between day and night. It is the experience of the author that on days where the sea breeze circulation is developed, inland stations experience a pressure drop compared to coastal stations. During the day, therefore, the pressure at Concord would be expected to be lower than BOS, and this is the case for the day group in June 1971. The geographical location of Concord makes it a favorable place for strong nocturnal cooling. It seems likely that the cooling of the ground by longwave radiation and accumulation of air by subsiding vertical motions at night in June at Concord is strong enough to raise the pressure there. Nocturnal cooling is weak at Boston and thus the effect shows up well in PG3.

However, the sample mean for both June and December show that PG3 has a significant positive value. There isn't

Table 9

Means of PG3 (mbs. 100 km^{-1})

	JUNE 1971	DECEMBER 1971	TOTAL
DAY	-.185	.144	-.043
NIGHT	.623	.157	.362
TOTAL	.169	.151	.160

an obvious physical reason why this occurs. The only obvious reasons are non-random instrumental and/or reduction to sea level errors. The magnitudes involved are up to 1 mb. The station elevation at Concord is 346' above mean sea level as compared to 29' at BOS and 63' at Portland. This results in station pressure differences of about 10 mb. so a reduction to sea level error is a definite possibility.

One might expect similar statistics to show up in the inidces involving Hartford and Albany, both inland stations. However, the effect is not found. It could be that the larger distances between Boston and those stations make the indices which involve those stations reflect more of a synoptic character, that is, the pressure gradients revealed by those stations are affected more by variations on the synoptic scale. It is more likely that Hartford or Albany be under the influence of a slightly different set of synoptic circumstances (the other side of a front, the return flow around a high pressure area) than Boston than would be expected from Concord. Thus local effects should show up more prominently in the index involving the more closely spaced stations. The difference in distance between Hartford and Boston isn't that much greater than the distance between Concord and Boston but it is known from experience that nocturnal cooling is more effective at Concord than at Hartford.

2. Junes vs. Decembers

To look further into the variations of vorticity inducing effects, it is necessary to look at the subsets of the total sample, Tables 8b through 8m. If all things are equal, one would expect the warmer month, June, to exhibit more anticyclonic vorticity than the colder month, December, because of the greater oceanic cooling at that time. Also, the potential for oceanic heating in any month is greater at night than during the day. That is what was hypothesized before the results were known. It became obvious that this isn't how things worked out and much explaining was needed.

From the comparison of Tables 8b and 8c it is apparent that the order of means of each sample is opposite to what was expected. Further, the difference is significant at greater than the 99.99% level. The standard deviations and maximum and minimum values are as expected. The greater strength of the circulation in winter results in larger magnitudes of the vorticity since relative vorticity can be expected to vary like the strength of the wind speed.

3. Day vs. Night

Further analysis into the differences between day and night samples will be revealing. Since a homogeneous as possible data sample was desired, the day night variations were tested only on the 1971 data which is composed of seven observations daily. The daytime observations in in June were 15, 18, 21, and 00 GMT while the day observations in December were 15, 18, and 21 GMT. The nighttime observations were the remaining ones, namely 06, 09, and 12 GMT in June and 06, 09, 12, and 00 GMT in December. The statistics in Table 8j and 8k show only a slight difference in mean vorticity between the two groups, significant at only the 20% level. It is interesting that the extreme values occurring at night were toward the cyclonic side. Four cases of greater cyclonic vorticity than the maximum daytime value occurred at 06 and 09 GMT. A case in point is the DMS when extremes in cyclonic and anticyclonic vorticity occurred on the same day. Perusal of the rest of the data indicates that cases like this are not unusual. Table 10 gives the values of relative vorticity observed on December 18, 1971.

It is interesting to compare these values (Table 10) with that of the hand analyzed values in Figures 6a-f. For all times, except 06 GMT, the hand-analyzed value is greater than or equal to in magnitude the calculated value. The hand-analyzed value is an average over 100 n. mi.^{2} while the calculated value is an average over 146.4 n. mi.^{2} and as such the former would be expected to be larger than the latter. However, at 06 GMT it seems that the contribution of Gloucester to the vorticity in the Bay was greatest. Being outside the grid point square which includes BOS, BOS LV and Scituate, the contribution of Gloucester was diluted in the hand analysis but accounted

Table 10

Mean relative vorticity (hr^{-1}) for Dec. 18, 1971

TIME (GMT)	VORTICITY
00	-0.1781
06	1.7584
09	1.7806
12	0.7064
15	-2.5476
18	-2.7299
21	-1.7406

for in the calculated values. After 06 GMT the prime contributions to vorticity are from stations in the southern part of the Bay and therefore, are accounted for in the hand analysis.

Since the number of cases that display this type of behavior is too small to indicate a significant trend, no conclusions can be drawn concerning the timing of the extreme values. However, the extreme values observed here are quite a bit greater than those in synoptic scale situations. For a comparison to the familiar 10^{-5} sec^{-1} units, the reader is again referred to Table 2.

It becomes clear that differences in data samples based on the potential for oceanic heating during that period do not reflect the expected thermodynamic influence. The alternative is to consider the effects of frictionally induced vorticity.

4. The effect of friction and Ekman dynamics

It was remarked before that if all things are equal, then oceanic heating or cooling should produce one effect or another. However, between June and December all things aren't equal, specifically the strength of the wind. The mean wind speed at Boston, for example, varies from summer to winter and is given below for the four months of the data sample in Table 11. The data is compiled from the LCD for Boston.

Table 11

Resultant winds at Boston (from LCD)

MONTH	RES. DIRECTION, degrees	RES. SPEED, mph	AVG. SPEED, mph
June 1968	130	0.3	12.1
December 1968	280	10.1	15.9
June 1971	230	2.8	10.0
December 1971	290	6.7?	12.5

The northerly component of the wind is greater in December than in June. With the coastline near Boston having a general north-south orientation, the greater the northerly component of the wind, the greater the anticyclonic vorticity induced. The greater negative vorticity induction in winter competes with the greater positive vorticity production by oceanic heating and hence, offsets it. To obtain a clear picture of the mechanism at work, a consideration of Ekman dynamics will be helpful.

The theory of Ekman states that the action of surface friction in an equilibrium situation with only horizontal pressure gradient forces and the coriolis force (surface of a rotating sphere) is to induce a turning of the wind in the vertical through the surface boundary layer and to create a surface wind which is weaker than the surface geostrophic wind and at an angle with the surface isobars, blowing from high pressure to low pressure. The angle of the surface wind over various surfaces with the surface isobars has been determined by experiment and as expected has been found to be greater over surfaces with greater drag coefficients. Thus along a coastline, it is important to know what angle exists over land and ocean individually. Thermal instability will make the angle smaller, strong stability makes the angle greater.

Although Ekman's theory is for an equilibrium model, it is useful to consider because it will give insight into the effect of friction on vorticity. Assume a north-south coastline with north-south isobars. The geostrophic wind in this case will be from the north (high pressure to the west, low pressure to the east). The surface wind will be to the west of north, more so over land, less so over water. If no variation in the y-direction is assumed (north-south), the relative vorticity, ζ , is

$$\zeta = \frac{\partial v}{\partial x}$$

v : northerly component

x : eastward direction

Using results from Petterssen (1956), the northward component (as a percentage of the geostrophic wind) can be calculated. This is shown in Table 12a.

The cross-isobar angle will be greater over land and thus, from Table 12a, any combination will yield anticyclonic vorticity. In all cases the northerly component will be greater to the east (over the water), in the positive x-direction. But this won't be the case for the surface isobars oriented in the east-west direction. Consider an easterly geostrophic wind for this case. Everything is the same as before except that the northerly component doesn't vary linearly with cross-isobar angle. Table 12b summarizes this.

Haltiner and Martin (1957) give characteristic values for the cross-isobar angle in middle latitudes under different thermal stabilities. These are given in Table 13. The land near the coastline may be considered to be between

Table 12a

Percentage of geostrophic wind- Case of northerly geos. wind

Cross-Isobar angle	Northerly component- Pctg. of geos. wind
10	79.8
15	68.2
20	57.2
25	39.4
30	32.0
35	20.5
40	10.7
45	0.0

Table 12b

Percentage of geostrophic wind- Case of easterly geos. wind

Cross-Isobar angle	Northerly component- Pctg. of geos. wind
10	14.3
15	18.7
20	21.4
25	21.0
30	18.5
35	14.3
40	9.2
45	0.0

Table 13

Variation of cross-isobar angle (45^{o} latitude)

Surface	Unstable	Neutral	Stable
Ocean	15	20	30
Land (very smooth)	25	30	40
Land (average)	30	35	45
Land (rugged)	35	40	50

very smooth and average. Under stable conditions, an easterly wind can produce cyclonic vorticity but under all other conditions, anticyclonic vorticity is induced. Thus vorticity induction is a function of thermal stability in this case. Table 14 summarizes the above discussion.

The correlation coefficients were computed for each sub-sample in order to measure the effectiveness of vorticity induction by a particular geostrophic wind direction. Variations can be attributed to a host of possible causes. These causes can be checked with the monthly means of temperature and wind at Logan Airport to see if a plausible picture is developing. The monthly mean temperatures for the analysis months at Boston and the departure from the climatological normal (1931-60) is given in Table 15. From this and Table 11 it will be safe to assume that the 1968 months had more cold advection than the 1971 months.

The conclusion concerning the stability in each month is not immediately obvious. However, it seems plausible to assume that more warm advection in June 1971 makes it a more unstable month than June 1968. June 1968 was a much wetter month (5.65" vs 1.74" for June 1971), but most of the precipitation seemed to occur with lower temperatures and over a longer period of time. This would indicate mostly non-convective activity. The number of days with thunderstorms was about the same for both months, so it seems likely that the warmer month had the greater instability.

In winter, however, the situation will be reversed.

Table 14

Frictionally induced relative vorticity

Geostrophic wind	Stability	Vorticity induced
Northerly	Unstable	Anticyclonic
	Neutral & Stable	Anticyclonic
Southerly	Unstable	Cyclonic
	Neutral & Stable	Cyclonic
Easterly	Unstable	Cyclonic
	Neutral & Stable	Anticyclonic
Westerly	Unstable	Anticyclonic
	Neutral & Stable	Cyclonic

Table 15

Temperature summary at Boston (from LCD)

Month	Avg. Mean Temp., °F	Departure from normal, °F
June 1968	64.9	-2.9
December 1968	30.9	-2.4
June 1971	69.1	1.3
December 1971	36.3	3.0

The colder month, December 1968, will be assumed more unstable because of more instances of cold air over a warm surface, either at the ground or over water. Neither month had any appreciable number of days with snow on the ground, so that wasn't a factor. Even so, the difference in stability between the two months is probably small.

All of the preceding arguments are necessarily qualitative. To calculate the average stability of each month wouldn't make these arguments more accurate because the original assumption of a north-south coastline is also somewhat suspect because of the actual curvuture of the coast in the vicinity of the Bay. However, experience suggests that the above effects are reasonable and thus, will be accepted. However, these conclusions will not be relied on heavily later in the interpretation of results.

The differences in stability between day and night are on firmer ground with the daytime hours being more unstable (Haltiner and Martin, 1957).

5. Discussion of individual months

To make some sense out of the data the approach will be to look at each month in detail, comparing and contrasting the two Junes and Decembers in order to specify the important vorticity producing effects in each month. Then day-night variations for June and December 1971 will be looked at.

a. June vs. June

First, compare the two Junes. They are found in Tables 8d and 8f. June 1971 is more cyclonic than June 1968 but only at the 85% confidence level. There are differences in sample size between the two months that make a comparison like this somewhat hazardous. The 1968 sample is composed of only two observations per day, one that is a night observation (12 GMT) and the other a day observation (18 GMT). Considering the smallness of the sample, June 1968 has a greater variability than 1971. From the GWI it can be seen that the southerly component of geostrophic wind is stronger in 1968 but wasn't effective in inducing cyclonic vorticity. The correlation coefficients in 1971 showed that there was a greater (although not well-defined) tendency toward cyclonic vorticity induction on southerly winds. The conclusion that must be drawn is that June 1968 was dominated by the sea-breeze. Even though a southerly component of wind was well established, it only added oceanic cooling. The winds at Boston were strong through the month but the resultant wind was weak southeasterly because the sea breeze was strong enough to negate the effect of the prevailing westerlies. Table 11 shows this and Table 15 shows that as a result, the mean temperature was well below normal. Although the GWI showed southerly components, their strengths weren't enough to prevent on-shore flows from developing. PG3 shows anomalous behavior that isn't worth considering.

b. December vs. December

The two December months, 1968 and 1971 in Tables 8e and 8g respectively, are a better comparison because of the greater homogeneity they both have. Although December 1968 has only six-hourly observations, they are around the clock and not two times a day, as is the case for June 1968. 1971 is significantly more anticyclonic than 1968 (at the 97% level). The variability as measured by the standard deviations, allowing for differences in sample size, are about the same. All of the GWI in 1968 are greater in strength and variability as compared to 1971. All of the correlation coefficients are positive with the exception of one although most are small. This means that the easterlies and southerlies were inducing positive vorticity and the westerlies and northerlies induced negative relative vorticity. However, the correlations indicate that the meridional winds were effectively inducing anticyclonic vorticity in 1971 whereas it was the zonal components that were inducing what must have been both positive and negative vorticity for the same wind direction. The meridional winds would be unaffected by stability variations by the arguments before, but the zonal winds are affected. Since the correlations involving zonal indices were higher in 1968, easterlies were inducing cyclonic vorticity and westerlies inducing anticyclonic vorticity more effectively in that month. This corresponds to greater instability in December 1968, which was concluded before by independent means. However, the differences in stability between the two months is difficult to show. Also, the differences in the meridional wind correlations is not explained. Despite the meridional wind being stronger in 1968, it is not inducing vorticity (anticyclonic here since the prevailing wind was northerly) as it does in 1971. Thus some of the variability from December 1968 to December 1971 can be explained, and some can't.

c. Day vs. night in June

As shown before, day night differences as compiled from the 1971 sample, are very small and insignificant. Therefore, the individual months must be looked at for a semi-coherent picture to emerge.

It might be expected since the largest differences in day night heating occur in June, it is that month which should show the largest difference in vorticity between the two months. Daytime in summer should be more anticyclonic because of the influence of the sea breeze circulation which depends on differences in the rate of heating over land and water. Nighttime in December might show a greater tendency toward cyclonic vorticity but this difference can be expected to be small. Also, there shouldn't be large differences in the GWI between day and night, especially so in December when synoptic scale influences predominate.

Tables 8j and 8k show day night differences for June 1971. The difference in the mean vorticity is significant at the 85% level, somewhat lower than expected. However, the difference is in the opposite direction from what might have been expected. A look at the GWI indicates thatbthere was less northerly and westerly component during the day, probably induced by the sea breeze. However, the sea breeze was unable to produce sufficient anticyclonic vorticity to turn around the average for the month. From the correlation coefficients it is apparent that the large amount of cyclonic vorticity is related to PG4 in the sense that westerly wind (PG4 was significantly different from zero) produced cyclonic vorticity. This corresponds to westerly winds under more stable conditions. This is quite plausible because although the sea breeze is associated with anticyclonic vorticity due to oceanic cooling, it occurs during the day when the stability is small. Westerly winds predominate at night under more stable conditions. Thus the two effects of stability and ocean heating are competitive and may be the reason for the small difference between the day night groups in June.

d. Day vs. night in December

Finally, the last groups, day and night in December 1971 in Tables 81 and 8m, show the expected effect of ocean heating at night to a highly significant degree. Nonetheless, it is still important to look at the GWI to see if frictionally induced vorticities are acting in the same direction, for a change, as the thermodynamically induced ones. The more cyclonic night group is significantly different from the day group at the 98% level. However, there seems to be slightly more variability at night, though not significantly so. The GWI are quite similar in average and standard deviation between the two groups. The main difference is apparent from the correlation coefficients which show that PG6, the centered ESE index, must have induced more positive vorticity at night in December than during the day. It represents the integrated coastline effect and therein may lie the reason for its higher correlation than the other zonal wind correlations. The differences in stability between day and night in December are probably small. It seems then, for this group, that ocean heating was the important effect in producing positive vorticity at night.

XI. Summary

The statistical approach indicates that the looked for thermodynamic effects were in most instances masked out by other competing effects such as friction and stability. The principle effect looked for was ocean heating but it was found that in six out of the seven group comparisons that it was the effect of friction on vorticity induction that proved dominant. Only in the day vs, night comparison in December 1971 was heating important in explaining differences between the two stratifications. It is interesting that it was in that month that the meso-snowstorm of the first part of the thesis occurred. Possibly ocean heating was important on more than one day during the period but the synoptic scale environment was cooperative only on December 18.

Although not discussed because they were not germane to the topic at hand, the intercorrelations between the GWI were consistent in most cases. This indicates that the data samples, at least in so far as the synoptic scale was concerned, was stable with respect to stratification. It also served as a check on the correctness of the calculations.

The correlation coefficients were compared in a rather off-hand manner. However, these coefficients can be compared in a more objective way by using the so-called z-transformation which transforms linear correlation coefficients to the variable z which is normally distributed (Hoel, 1954). The relationship between z and r, the correlation coefficient, is

$$z = \frac{1}{2} \log_e \frac{1+r}{1-r}$$

The transformed variable has the mean, μ,

$$\mu_z = \frac{1}{2} \log_e \frac{1+\rho}{1-\rho}$$

ρ : estimated r for sample

n : sample size

and standard deviation, σ,

$$\sigma_z = \frac{1}{\sqrt{n-3}}$$

For most of this application the question may be asked whether or not a correlation is significantly different from zero. A correlation will be significant (95% confidence level) if it is more than two standard deviations away from the null hypothesis mean. Thus, for a sample size of greater than 100, the transformed correlation, z, should be more than 0.2 away from zero. For small values of r, $z \approx r$ so they may be interchanged freely. In all the previous discussions differences in correlations of less than 0.3 were not discussed. In retrospect, it is encouraging that although all correlations are small, they were used in a plausible and realistic manner.

XII. Conclusions

Since the hoped for effects did not show up prominently, the hoped for conclusion must reflect this weakness. All that can be safely said is that oceanic heating can be important in special cases but it usually isn't insofar as vorticity production is concerned along the Massachusetts coast. Having encountered difficulty in pinpointing individual cases where the heating may be important, the author used a statistical approach which also showed in large samples that the effect of ocean heating, although present, is small compared to friction.

The data that was used was less than ideal in many respects but adequate. If the limitations of the data are allowed for, a coherent picture can, in most cases, be deduced. The potential for studies of this type which must depend on regular (conventional) data is promising.

XIII. Suggestions for further research

Outside of proposing massive experiments with high accuracy weather instruments, highly trained observers and dense observing networks, the best route for studying coastline interactions is a wait and see method. The alert weather watcher can note cases with unusual or small scale variations near the coastline and make note of them for future study. It may be worthwhile for a group, such as the synoptic division in the meteorology department at MIT, to make note of mesoscale occurrences near the Massachusetts coast, as small and insignificant as they may be, so that a more complete study may be undertaken with a base of information to go on. Probably the best method to study these phenomena is by case studies so that the important and similar characteristics can be isolated and from there explained. That was the method used here, where observational evidence was presented first and possible explanations presented next. Even with several alert people watching for them, mesoscale events will probably remain unusual and infrequent. Thus any group of case studies will require a compilation of data sets and much patience. If these case studies show important trends, then it may be worthwhile for a complete account of the effect of friction to be developed. However, it is felt that this study should be part of more encompassing future studies that will include interactions between coastline variations and all scales of motion. Based on some forecasting experience of the author, this proposal identifies the area where improvement is needed.

Appendix A

Calculation of mean vorticity

Given wind observations at four stations, $\alpha, \beta, \gamma, \delta$ which prescribe any closed curve, the mean vorticity, $\bar{\zeta}$, in the enclosed surface, S, is

$$\bar{\zeta} = \frac{1}{A} \oint_S V_t \, ds \approx \frac{1}{A} \sum_{i=1}^{4} \overline{V_{t_i}} \, \Delta S_i$$

$\overline{V_{t_i}}$: average tangential velocity on a side

ΔS_i: length of side between stations

with

$i=1$, side between α + β

$i=2$, side between β + γ

$i=3$, side between γ + δ

$i=4$, side between δ + α

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