Meso-Analysis of a Coastal Snowstorm in New England

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(Manuscript received 8 February 1974, in revised form 1 April 1974)

ABSTRACT

Heavy snow fell on 18 December 1971 in parts of coastal New England, but not in Boston proper, as intense synoptic-scale cyclogenesis occurred over the Gulf Stream to the southeast. Mesoscale analysis of surface data shows that part of the snowfall was attributable to shallow instability in onshore flow, but that a substantial portion was associated with a small and short-lived cyclone which formed at the mouth of Boston Harbor.

This analysis, together with consideration of the few pertinent upper-level soundings, indicates a similarity between this cyclone and the "polar low" which produces heavy snow in the United Kingdom. The mechanism of this cyclone appears to be qualitatively similar to that of synoptic-scale baroclinic cyclones. Its small size is attributed to the low hydrostatic stability produced by heat flux from the relatively warm water of Massachusetts Bay and to the restricted vertical depth of the associated atmospheric baroclinic zone. There is a remote possibility that a significant part of the heat flux in this case may have been from an anthropogenic source.

1. Introduction

While the synoptic situation shown in Fig. 1 hardly portends balmy weather for New England on 18 December 1971, one would hardly guess that it produced a foot of snow northeast of Boston, a fall which in some communities has not since been exceeded at the time of this writing. The detailed pattern of snowfall over southeastern Massachusetts, in Fig. 2, shows only one or two inches in Boston proper and northwest toward Reading, but a depth of twelve inches or more over an area bounded roughly by the towns of Peabody, Ipswich, Gloucester, and Marblehead. The gradient of depth was extraordinarily strong, the entire difference in depth occurring in the six miles between Revere and Peabody. South of Boston, amounts between six and twelve inches along the coast and on outer Cape Cod decreased more gradually to depths of one inch about 25 mi inland. The variations of snow depth are the more remarkable because their usual cause in New England, a quasistationary line separating snow from rain, was entirely absent. No rain fell in this case.

Away from New England, the development on synoptic scale was far from lackluster; explosive surface cyclogenesis occurred over the Gulf Stream in typical response to the approach of an upper-level vorticity maximum. A weak cyclonic circulation at the surface over New England at 0000 GMT was replaced by vigorous northerly flow twelve hours later as the synoptic-scale cyclone deepened some 250 n mi to the southeast. The small amount of snow at Nantucket and Martha's Vineyard, however, (cf. Fig. 2) demonstrates that the heavy falls farther to the northwest were not attributable to this cyclogenesis. The thickness from 1000 mb to 500 mb over New England indicates the presence of unusually cold air for so early in the winter season.

In these circumstances, convective snow showers occur not infrequently along lee shores of the New England coast, but the maximum north of Boston is not easily accounted for on this basis, nor are the great depths over substantial areas. Consequently, a detailed analysis of the flow pattern over southeastern Massachusetts and adjacent coastal waters was undertaken, with the aim of discovering mesoscale circulations to which the heavy snow might be attributed.

2. Surface mesoanalyses

A set of detailed surface analyses at three-hourly intervals from 0000 GMT through 2100 GMT on 18 December was prepared from all available surface observations. These included, aside from the synoptic observations made every six hours, airways observations made hourly at a reasonably dense network of locations, and observations made at three-hour intervals (except at 0300 GMT) at the Portland, Boston, and Nantucket Light Vessels and at a number of Coast Guard stations along the coast. The location of all observations appears in Fig. 3.

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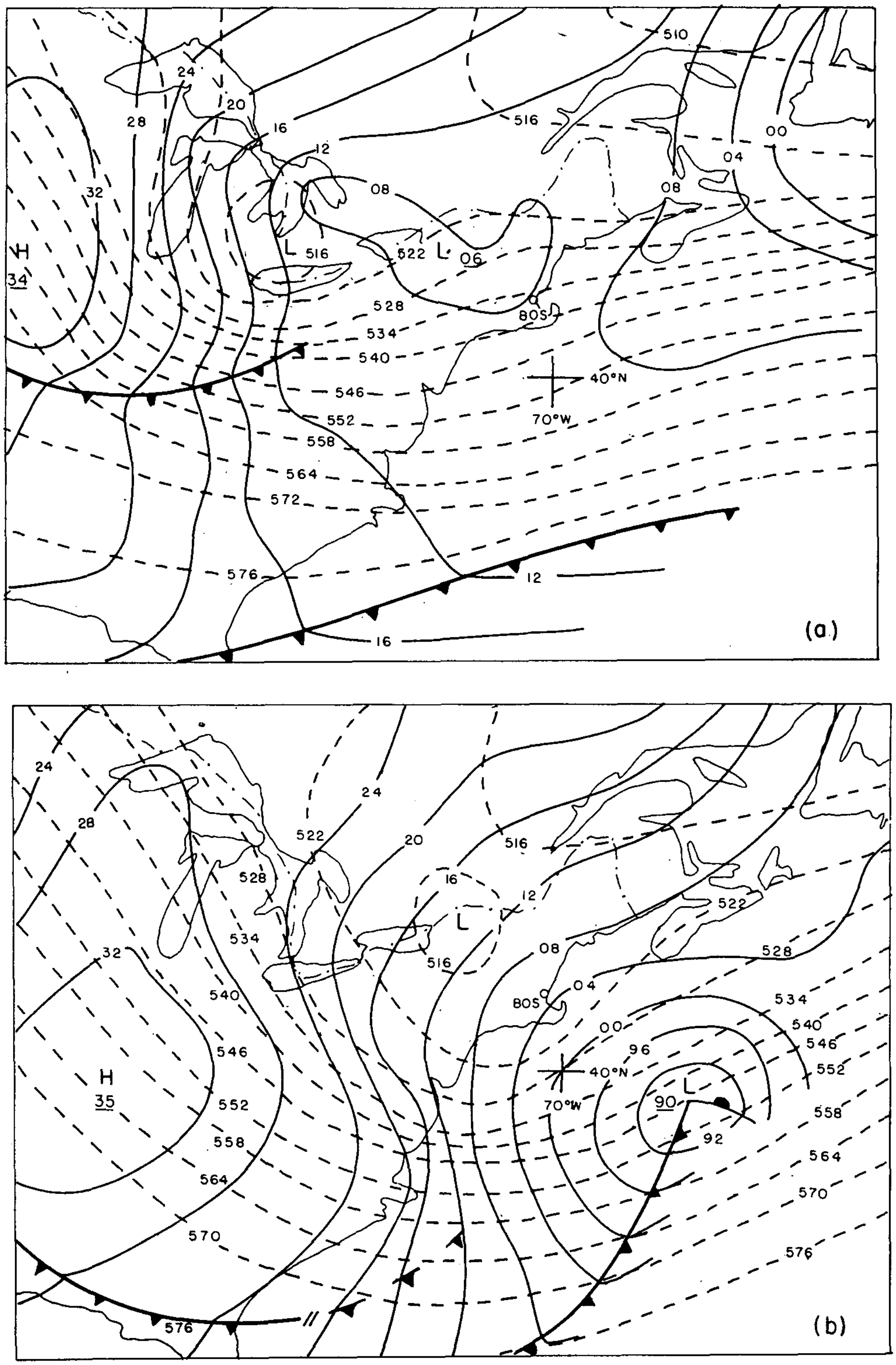

FIG. 1. Synoptic situation at (a) 0000 GMT and (b) 1200 GMT 18 December 1971. Solid lines are sea-level isobars at 4-mb intervals. Dashed lines are contours of thickness of the layer from 1000 mb to 500 mb, at intervals of 6 decameters. Fronts, highs, and lows are designated in the usual way. The position of Boston (BOS) is shown.

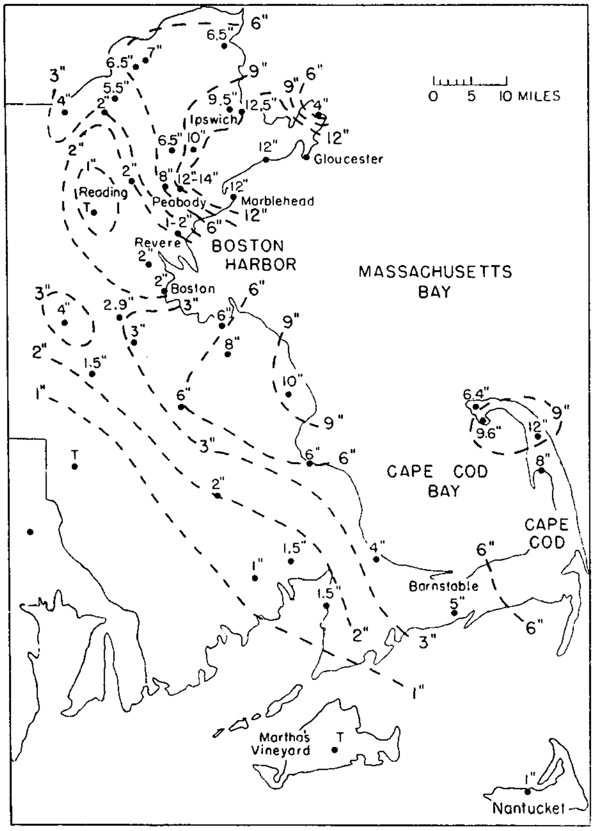

FIG. 2. Depth of snow produced by the storm of 18 December, 1971, in inches.

To enable the construction of detailed analyses of sea-level pressure, we made a special effort to remove systematic errors from the observations. Time series of reported pressures at each station for a period of 30 hr, containing the interval under study, were averaged and the results mapped. A smooth analysis was then prepared, on the basis that mesoscale structure would not appear in the average over such a period. At each station, the difference between the computed average pressure and the interpolated pressure from the smooth analysis was taken as a systematic correction to be applied to the individual observations. Except at the Coast Guard stations, this correction was typically about 0.5 mb, with maximum values about 1.5 mb. The Coast Guard pressure observations were evidently of relatively poor quality, displaying large systematic errors and some apparent instances of large random errors in individual observations. (The wind observations at these stations, however, were crucially important and appeared to be relatively reliable.) Continuity in the mesoscale aspects of the resulting pressure analyses was quite satisfactory over successive three-hour intervals, and we estimate the residual uncertainty in the analyses to be not more than 0.5 mb.

The mesoscale pressure analysis at 0000 GMT, shown in Fig. 4a, generally resembles its synoptic-scale counterpart shown in Fig. 1a. A weak east-west trough of low pressure along the northern border of Massachusetts is somewhat better defined in the detailed analysis, which also reveals a low center in northwestern Massachusetts. Surface winds in the interior were weak and subject to extremely local influences, for the pattern shows little spatial coherence, even on the mesoscale. A well defined northerly current along the Maine coast, however, was separated from westerly flow over southeastern coastal New England by a pronounced shear line. Relative vorticity, estimated from the wind analysis and averaged over an area of 100 n mi^2, reached a peak value of 25×10^{-5} sec^{-1} over extreme northeastern Massachusetts, just south of this shear line. Generally speaking, the wind currents, even where well defined, did not at this time conform well with the familiar synoptic model of balance among the pressure-gradient, Coriolis, and surface frictional forces, but it seems highly unlikely that the discrepancies stem from inadequacy of the analysis, being due to the small space and time scales of the features of interest.

The next time at which a satisfactory analysis of conditions along the coast could be made was 0600 GMT, since observations from the Coast Guard stations were not available at 0300 GMT. The analysis for the later time, Fig. 4b, shows that large shifts had occurred at Gloucester and at the Boston Light Vessel. The report of southeasterly wind at the Light Vessel was difficult to accept at face value, since it represented the only observation of a southerly component in the area, since the wind at Scituate (only 9 n mi away) was westerly, since the wind at Logan Airport (only 12 n mi away) was northwesterly, since communication errors are not infrequent, and since relatively inexperienced observers sometimes err by 180° in reporting the wind direction. The report was confirmed, however, by inspection of the observer's log, by the report three hours later, and by the consideration that the vector shift at this location was not substantially larger than the shift observed simultaneously at Gloucester and later at Race Point and at other locations. Thus we accepted it, finding that the shear line had moved south into Massachusetts Bay and that a small cyclone had developed at its shoreward extremity. The peak relative vorticity in this cyclone was the same as the peak value associated with the shear line six hours earlier.

Three hours later, at 0900 GMT, the mesoscale cyclone had moved little but had intensified, as attested by the freshening of wind at Logan Airport and at the Light Vessel (Fig. 4c). The relative vorticity was 50×10^{-5} sec^{-1}, double the peak value three hours earlier. Perhaps most importantly, radar echoes as viewed from the WSR-57 site at Chatham had appeared for the first time in Massachusetts Bay, having hitherto been restricted to the ocean south of New England, where the influence of the developing synoptic-scale cyclone was being felt. The precise outline and detailed configuration of the echo pattern was difficult to determine because of the limited quality of the fascimile transmission. The time and place of its appearance, however, together with large values of estimated surface convergence of about 50×10^{-5} sec^{-1} at 0600 GMT and 0900 GMT over a 100-n mi^2 area northeast of the mesoscale cyclone, and the observation by one of the authors (FS) that the snowstorm at Marblehead reached its peak near the latter time, all indicate that the rapid development of the cyclone was accompanied by a vigorous mesoscale updraft which was responsible for the major part of the heavy snow along the north shore of Massachusetts Bay, though not beyond Gloucester.

As a closed cyclone, this mesoscale storm was evidently short-lived, for no center appears in the detailed analysis for 1200 GMT. The wind at the Light Vessel had shifted to northerly, as seen in Fig. 4d, suggesting a southeastward motion of the center, but at Race Point, the next station likely to be influenced, the wind remained in a northerly sector at this time and later. The merchant ship, *Gypsum Empress* on a southwest-bound passage toward the Cape Cod Canal, produced the only other observations that might have aided the identification of the center. The reported wind observations from this ship, however, disagreed with nearby observations by a vector amount which was in rough agreement with the ship's course and speed, leading us to the conclusion that the apparent winds rather than the true winds were being reported. After an appropriate correction, the observations fit reasonably well but must still be regarded with some suspicion. Of course, in the presence of the strengthening synoptic-scale flow from the north over the entire region (as evident in Fig. 4d) the disappearance of a center in the streamline pattern does not necessarily mean that the dynamically more important vorticity center had weakened. A vorticity analysis at this time, however, failed to disclose values as high as those found earlier. The radar echo had developed toward the southeast, indicating nevertheless that the system continued to have an active updraft.

At 1200 GMT a second remarkable development occurred. Though the mesoscale cyclone itself produced a barely detectable pressure perturbation, the pressure between 0900 GMT and 1200 GMT rose 2 mb at Portsmouth and 3 mb at Bedford while changing little at the Light Vessel and at Gloucester. This increase of pressure gradient had been foreshowed earlier along the southwestern coast of Maine, as can be seen by comparison of Figs. 4b and 4c. An immediate consequence was increase of the onshore component of both geostrophic and actual wind between Gloucester and Portsmouth, accompanied by lee-shore snow flurries of considerable intensity. Stations in this region experienced visibilities ranging from zero to one-half mile between 1200 GMT and 1500 GMT. (The lack of radar echoes from this region on the Chatham scope may be taken as evidence of the low tops of the cloud, or of the poor radar visibility of even heavy snow.)

A second consequence of the enhanced pressure-gradient force was the burst of strong northerly winds by 1500 GMT over Massachusetts and Cape Cod Bays, as shown in Fig. 4e. The sudden appearance of 40-kt winds at the Light Vessel and at Scituate was not matched at any of the regular observations on Cape Cod, but an informal account from the Barnstable marshes[2] tells of the squall-like arrival of a "black wall" of clouds from the north at about 1400 GMT, accompanied by heavy snow and winds of about 40 kt. This development apparently rejuvenated the vorticity field of the earlier mesoscale cyclone, the peak value at 1500 GMT equalling the value at 0900 GMT. Subsequently, as seen in Fig. 4f, the trough in the pressure field and in the streamlines, as well as the associated radar echo, moved southward into the Atlantic and was lost from view. Snow in significant amounts never penetrated as far west as Boston proper.

3. The meso-cyclone as an American "polar low"

In the United Kingdom there has been considerable recent interest in small-scale snowstorms occurring in broad-scale northerly flows (e.g., Lyall, 1972). Embedded within this flow are associated circulation patterns encompassing a considerable range of horizontal scales, from about 250 km (Stevenson, 1968; Pedgley, 1968; Canovan, 1970) to about 1500 km (George, 1972). Depths of snow ranged from one or two inches to 12 to 18 inches, the larger depths being associated with the larger storms. In our example the scale was at the short end of this spectrum, to judge from the distance between trough and downstream ridge in the northerly flow in Figs. 4c–e, while the snowfall was near the high end of the range.

Many of the British examples display prominent centers of low pressure, which are denoted "polar lows," presumably to denote their development within air of more-or-less polar origin. In our example, a weak pressure minimum was present only briefly but a powerful vorticity maximum was characteristic of the entire duration of the case. The thickness of the layer from 1000 mb to 500 mb at the point of origin of the mesoscale cyclone must have been about 5290 m, to judge from Fig. 1a, a value distinctly below normal for the place and time of year. The thickness in the major belt of contrast displayed in Fig. 1 ranges from about 5040 m to about 5700 m, so that the cyclogenesis can fairly be said to have occurred in polar air.

Our storm formed within the airflow in the northwest quadrant of a vigorously deepening synoptic-scale cyclone. Some of the British examples (Pedgley, 1968; Canovan, 1970), but by no means all, occurred within the western quadrant of larger cyclones centered over southern Scandinavia or the Baltic Sea.

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[2] Personal communication from G. Budd, Jr., of Middleboro, Mass., who was hunting ducks.

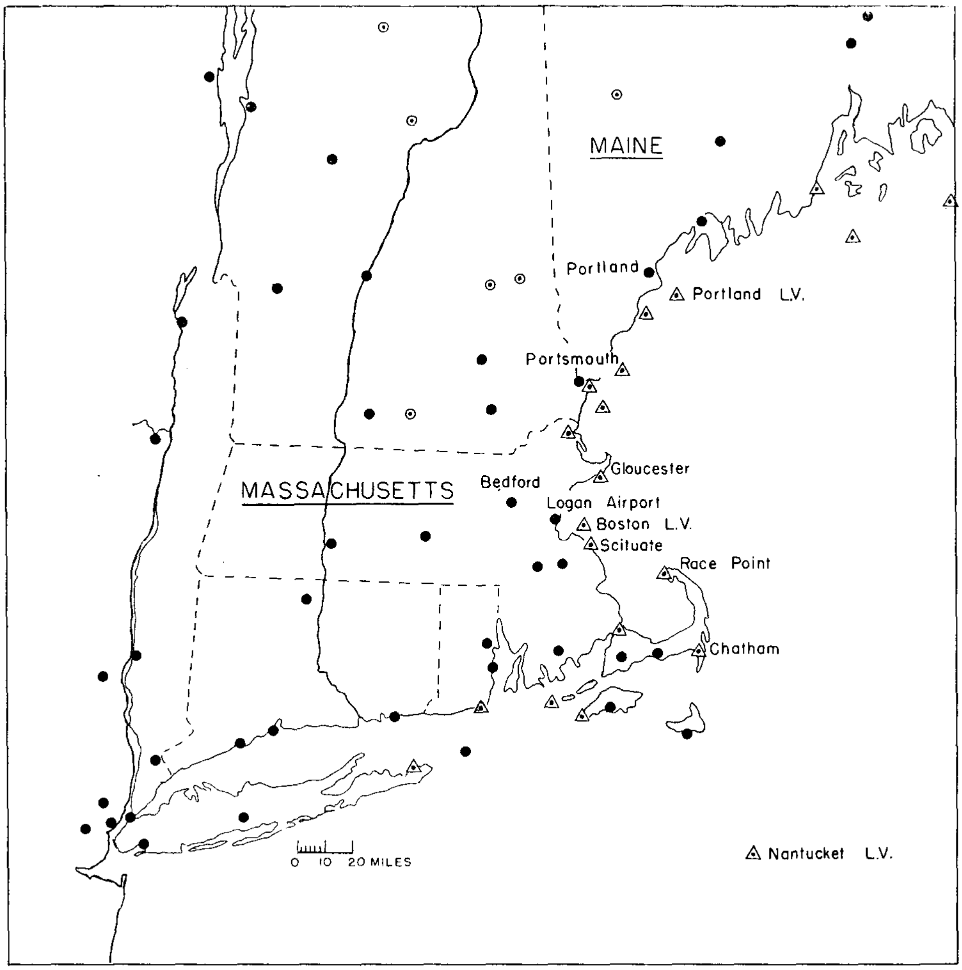

FIG. 3. Locations of surface observations. Large filled circles indicate stations making hourly observations, circled dots stations making six-hourly observations, and dots within triangles Coast Guard stations making three-hourly observations.

Harrold and Browning (1969) have argued that the polar low should be regarded as a baroclinic disturbance, similar in dynamical kind to ordinary extratropical cyclones, and that cumulus convection over the relatively warm sea, previously thought to be an essential feature of these, is in fact only incidental to the cyclogenetical process. Their illustrative case study shows clearly that the polar air low was creature of shallow baroclinicity within the cold air beneath an extensive and powerful upper-level frontal zone, and that the major updraft and downdraft corresponded, respectively, to the regions of warm and cold advection at low levels, as one would ordinarily expect.

In our case, relevant upper-level soundings were few indeed. Those made at Portland and at Chatham at 0000 GMT and 1200 GMT of the 18th, the only ones near the time and place of the mesoscale disturbance, are given in Fig. 5. They show clear indications of two levels of maximum baroclinicity: one in the lower troposphere as seen from the contrast in the two soundings in the layer from 1000 mb to 900 mb at 1200 GMT and from the strong wind shear at 0000 GMT from the surface to 4000 ft at Portland; the other in the middle troposphere as evidenced by large temperature contrast between the soundings and the strong vertical wind shear at both locations at 0000 GMT in the layer from about 550 mb to 450 mb. Between these layers temperature differences and vertical wind shears were relatively small. The mesoscale disturbance was no doubt associated with the lower baroclinic zone.

The direct influence of the upper zone was evidently slight, because it has already produced very large temperature falls at Chatham by 1200 GMT in the layer from 600 mb to 400 mb, while little cooling had occurred near the surface and the mesoscale system still lay some distance to the northwest. Thus, disturbances in the two baroclinic zones could hardly have been in phase.

Some aspects of the behavior of the mesoscale cyclone are in qualitative accord with concepts which emerge from quasi-geostrophic theory and which are

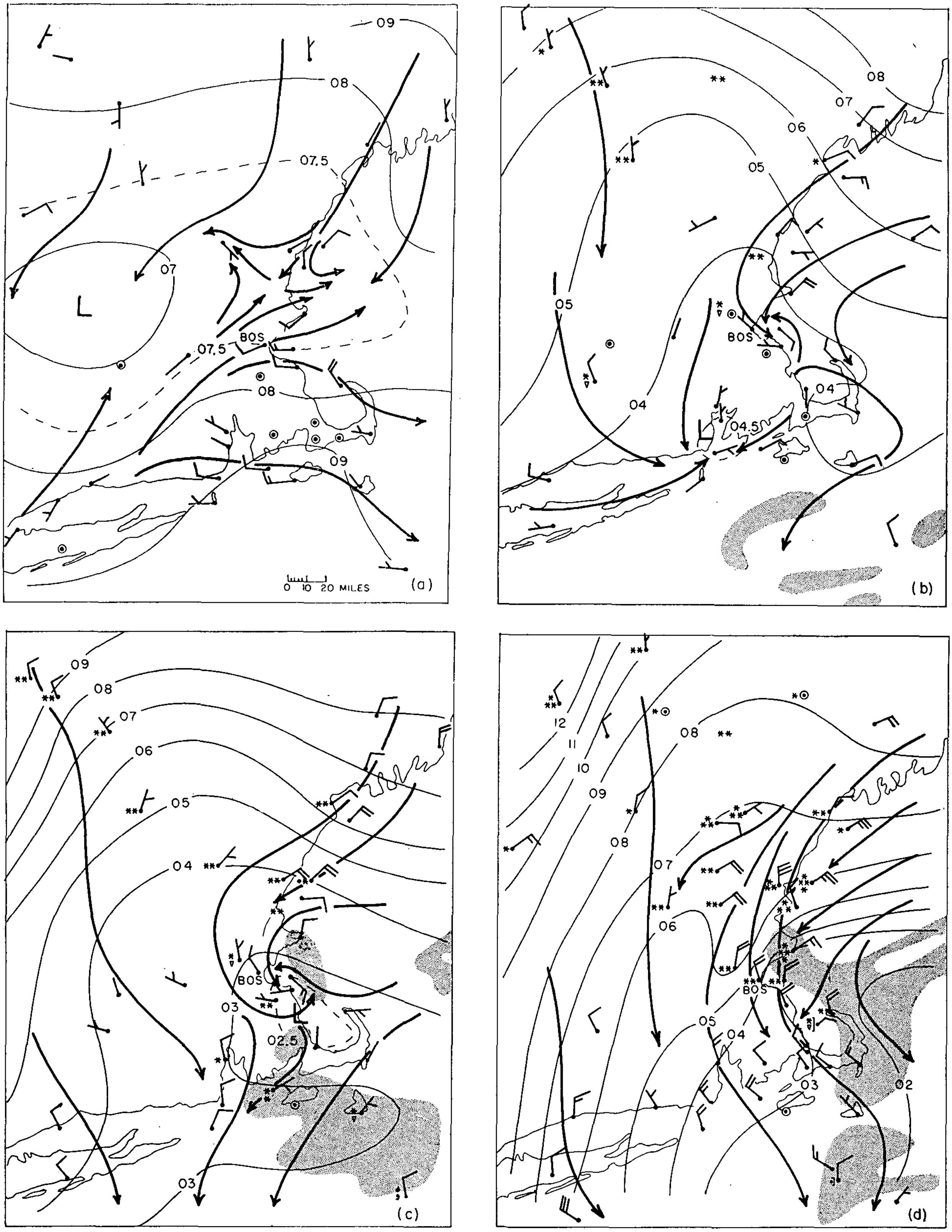

FIG. 4. Surface mesoscale analyses for 18 December 1971, at (a) 0000 GMT, and (b) 0600 GMT, (c) 0900 GMT, (d) 1200 GMT, (e) 1500 GMT, and (f) 1800 GMT. Thin solid lines are isobars at intervals of one millibar. Thick solid lines are streamlines. Stippled areas represent radar echoes observed from Chatham. Wind and present weather are plotted at stations in the usual way.

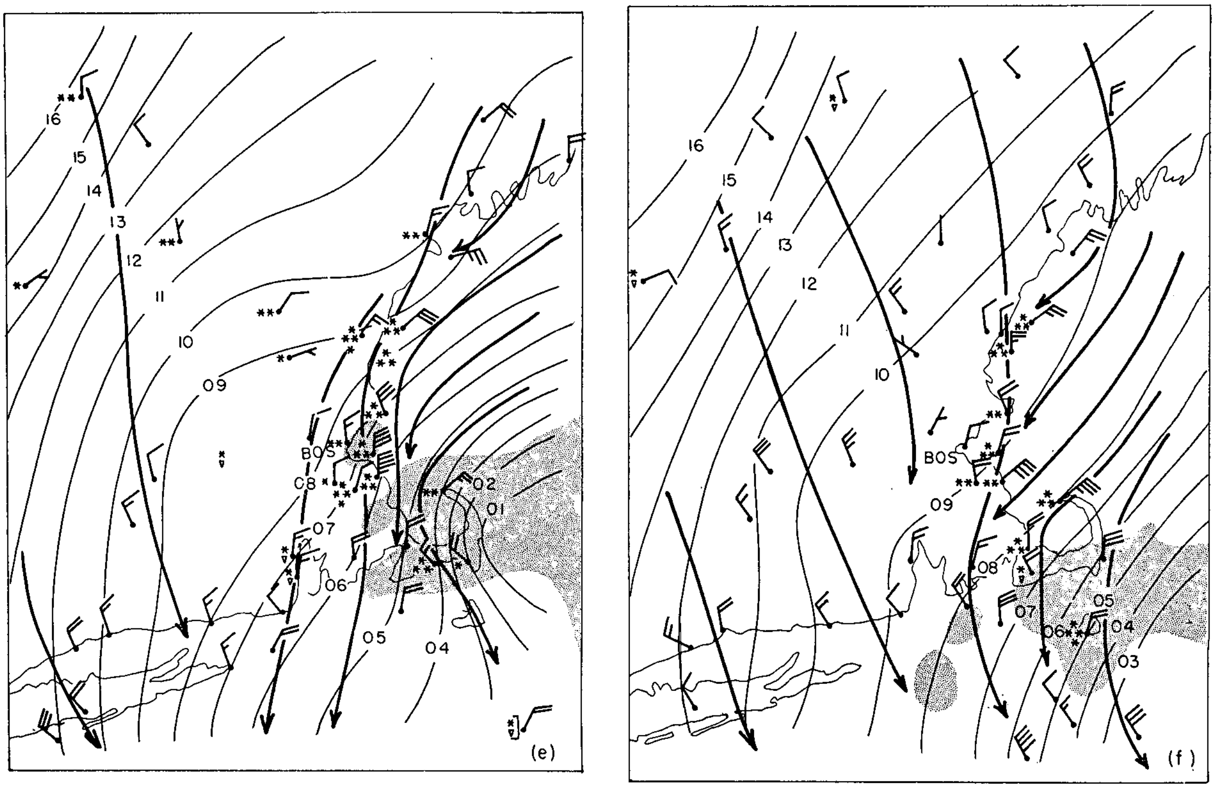

Fig. 4 (*continued*)

quantitatively applicable only to much larger disturbances. For example, the associated radar echo and the heavy snow northeast of Boston lay in a direction down the lower-tropospheric thermal wind from the developing cyclone (cf. Fig. 4c). This region is the expected location of ascent according to Sutcliffe's (1947) "thermal steering" concept and is where Sanders' ω_2 (1971) would be in the upward sense. Later, the heavy snow associated with this system appeared to fall more nearly at the location of the vorticity maximum itself, but the analysis is less certain. Moreover, the shallow but strong northerly current which developed near the surface would have tended to displace the surface snowfall south of the location of the maximum updraft. The updraft, therefore, may still have been located downshear from the surface vorticity center.

The motion of the cyclone, to be sure, appeared to contradict the theoretical expectation, since it was toward the southeast while the thermal wind was toward the northeast. The theoretical motion of the low in a direction parallel to the thermal wind, however, is derived from a model in which there is no basic current at the surface, so that the vorticity advection is small and the cyclone moves solely in response to divergence. In this case, on the contrary, the powerful, developing northerly flow acted as a basic current and produced vorticity advections tending to drive the cyclone toward the south. If we take the motion of the vorticity center, as say, 10 kt toward the southeast between 0900 GMT and 1500 GMT and if we consider the basic current toward the south to be about 15 kt, then the motion of the center was in fact northeastward relative to the basic current and the contradiction is resolved.

Finally, the mesoscale development occurred, as can be inferred from Fig. 1, in a region of synoptic-scale cyclonic advection of thermal vorticity by the thermal wind, thus in a region where Sutcliffe's (1947) "thermal development" effect and where Sanders' (1971) ω_1 would favor generation of cyclonic vorticity in the lower troposphere.

In all, as with Harrold and Browning's (1969) example, this storm seems qualitatively comprehensible within the conceptual framework of larger-scale baroclinic dynamics. An important additional question is what role moist convection might have played.

Convection no doubt occurred. The surface air temperatures were generally colder than the sea-surface temperature in Massachusetts Bay, so that at least shallow convection must have been widespread. In addition, there were a number of informal reports of lightning and thunder during the snowstorm northeast of Boston, a phenomenon often reported in the British storms (e.g., Suttie, 1970).

Examination of the four soundings in Fig. 5, however, discloses that the wet-bulb potential temperature θ_w decreased upward only a in few superficially thin layers.

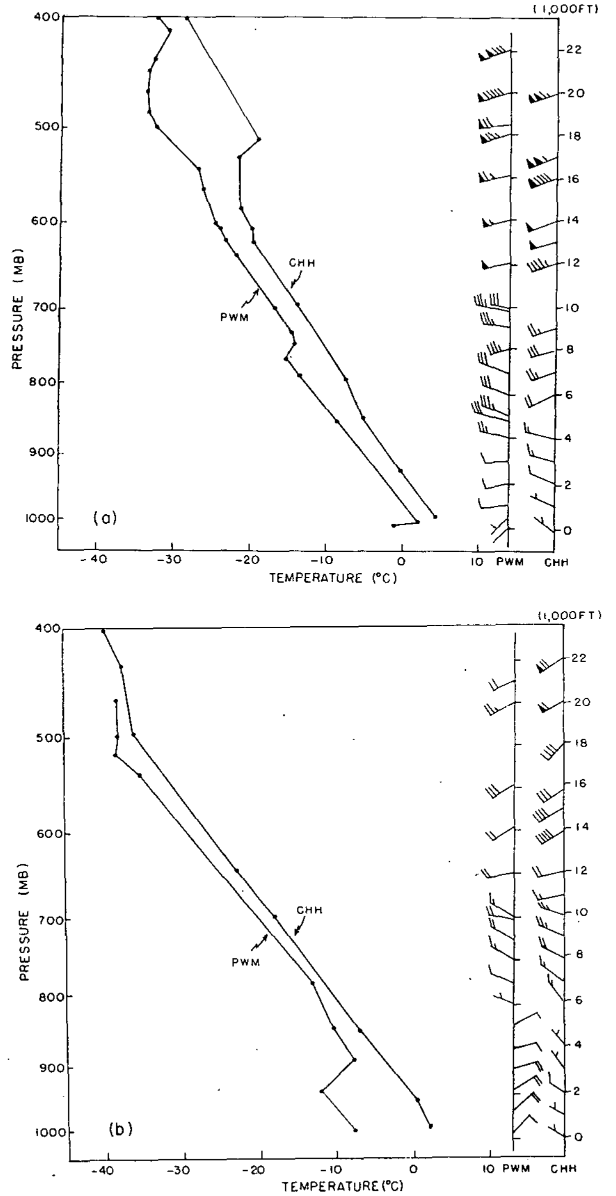

FIG. 5. Rawinsonde observations at Portland (PWM) and at Chatham (CHH), 18 December 1971, at (a) 0000 GMT and (b) 1200 GMT. Solid lines represent temperature. The wind soundings are plotted in the conventional way, with north understood to be upward.

The warmest observed value of θ_w was 0.5C at the surface in the 1200 GMT Chatham sounding. Undilute ascent of this air to 500 mb would result in a temperature of −40.5C, a value yielding negative thermal buoyancy even for the environment simultaneously observed at Portland. The vertical wind shears at both stations near this level suggest a 500-mb temperature over the disturbance no colder than −38C. Rising air with θ_w of 2.5C would be neutrally buoyant in this 500-mb environment. Whereas such surface values are conceivable over the Bay, an excess over this amount would be required for active convection, and the bouyancy would in any event be lost below the 500-mb level due to mixing unless the environment were saturated. In this case, the convection would simply introduce fine-scale structure into the pattern of condensation that would have occurred anyway, and would probably not be of large dynamical importance. We conclude that deep convection was not an important factor in this storm, as it is in storms which develop in an unsaturated environment with substantial potential instability, such as severe convective storms, hurricanes, and evidently some synoptic-scale extratropical cyclones (Tracton, 1973).

This is not to say that convection was unimportant so far as precipitation is concerned. Low-level convection, in addition to surface frictional effects, seems to have been responsible for the heavy snowfall north of Gloucester between 1200 GMT and 1500 GMT. Here the particularly strong onshore flow offers a more reasonable explanation than the mesoscale disturbance itself, which lay rather far to the south.

It is instructive, however, to inquire whether the mesoscale circulation as represented in Fig. 4 could have produced the snowstorm northeast of Boston without an appeal to cumuliform *deus ex machina*. Between 0600 GMT and 0900 GMT, convergence over a 100-n mi^2 area between the Boston Light Vessel, Logan Airport, and Gloucester was about 50×10^{-5} sec^{-1}. Humidities observed in the soundings shown in Fig. 5 indicate a top of all cloudiness at about 500 mb. Therefore, we assume a parabolic profile of $\omega=dp/dt$, vanishing at 1000 mb and at 500 mb. If this profile of vertical motion is presumed to act on a saturated air column with temperature profile as observed at Chatham at 1200 GMT, and if it is assumed that the condensation and precipitation rates are equal, the rate is calculated to be 0.27 inches hr^{-1}. With the usual assumption that the density of snow is one-tenth the density of water, a foot of snow would then fall in about $4\frac{1}{2}$ hr. The result depends linearly on the specified surface divergence, and it is necessary to ask whether our value is dynamically credible. If we assume that the individual rate of change of vorticity is given by the product of absolute vorticity and convergence, then the time required to double the absolute vorticity is given by $T=0.693/(-\mathbf{V}\cdot\mathbf{V})$. For a convergence value of 50×10^{-5} sec^{-1}, the doubling time is about 0.4 hr. This time seems short, but may be realistic since the flow is crossing this region from east into the small, intensifying system. A somewhat longer time would result, moreover, if account were taken of surface friction, which must destroy a portion of the vorticity created by the convergence.

Even granting the numerous sources of uncertainty, one could hardly have arrived at more agreeable results, and an appeal to cumulus activity is not necessary. Convection within the saturated mesoscale updraft area, of course, may well have produced inhomogeneities in rate and irregularities in distribution, but we have no specific information concerning these aspects.

In this case, the environment on the whole was evidently stable but the stability was small for saturated air. Since Sumner (1950), among numerous others, has shown the importance of small stability for the growth of small-scale disturbances, it may be no coincidence that the mesoscale development occurred only when the upper-level baroclinic zone had moved so that the New England coastal region lay beneath cold middle-tropospheric air, and only where the surface layers were being warmed by the sea surface.

The limited vertical extent of the lower baroclinic zone may also have favored small-scale cyclogenesis. Eady (1949) has provided theoretical evidence of an association between small vertical extent and small horizontal scale of disturbances, and Sanders (1969) has described mesoscale development in New England in a case in which substantial low-level baroclinicity vanished at 700 mb.

4. The influence of heat transfer

The development of the mesoscale cyclone over the relatively warm waters of Massachusetts Bay strongly suggests the importance of dynamical forcing by sensible heat transfer from the sea surface. Since much of the water vapor simultaneously transferred into the atmosphere apparently condensed and precipitated more or less locally, latent heat transfer also probably constituted an important local forcing. Quasi-geostrophic theory (e.g., as in Petterssen, 1956, p. 324) indicates local generation of cyclonic vorticity at the surface if the Laplacian of diabatic heating is negative, as it would be in winter where relatively warm water is partially or entirely surrounded by land. There is abundant evidence (e.g., Petterssen, 1956, p. 267) of high frequency of synoptic-scale cyclogenesis in such geographic areas. Massachusetts Bay can be regarded as a mesoscale water body partially surrounded by land; hence mesoscale cyclogenesis in winter would be expected here rather than over nearby land.

The particular site of this cyclogenesis, at the very mouth of Boston Harbor, led us to consider whether particularly warm water might be present here. Indeed it is, at least at times. Inquiry disclosed that warm water discharge from power plants was the largest heat source, though there was some contribution from sewerage outfalls. From data provided by the Boston Edison Company we determined that during the 12-hour period prior to 0600 GMT of the 18th, the approximate time of the initiation of cyclogenesis, 6.6×10^8 gallons (25×10^5 m^3) of water were discharged into Boston Harbor, at a mean temperature of 63F. This discharge was unusually large and unusually warm, the average values being 5.7×10^5 m^3 at 55F.

We attempted to assess the meteorological consequences of this discharge. We obtained from Mollo-Christensen[3] the estimate that at least three-quarters of the excess heat content (relative to the ambient local sea temperature of 45F) would be transferred into the atmosphere. It is difficult to estimate the area over which this transfer would take place. The harbor is actively flushed by tidal currents, yet no short-term effect was detected in the sea-surface temperatures reported by the Boston Light Vessel, a mere 14 km from the mouth of the harbor. We therefore assumed that the heat was transferred into the atmosphere during the 12-hour period over an area of 100 km^2. The corresponding flux is at the rate of 0.026 cal cm^{-2} min^{-1}, only about 2% of the value found by Petterssen *et al.* (1962) over the North Atlantic in cold-air outbreaks accompanying synoptic-scale cyclogenesis. The latter flux is unquestionably important, yet our value, while much smaller, cannot be completely dismissed as locally unimportant.

If this heat were used solely to warm the overlying volume of air to a depth of 100 m, the resulting rate of temperature increase would be 0.66C hr^{-1}, again a value that is neither large nor entirely trivial. Rough estimates of the horizontal advective rate of change at the surface accompanying the mesoscale cyclone, for example, is not an order of magnitude larger.

If this heat were somehow converted entirely to kinetic energy of mesoscale motions over the volume of the cyclone with, say, a horizontal cross section of 1200 km^2 extending from the surface to the 500-mb level, then the 12-hour heating would generate a wind of 5 m sec^{-1}. If, with some attempt at realism, one attributed a 4% efficiency to the process, the resulting wind would be 1 m sec^{-1}, again neither large enough to be exciting nor small enough to be forgotten.

It seems clear that the anthropogenic heat source cannot have been the primary cause of the cyclogenesis. Indeed we have argued for an interpretation in terms of small-scale shallow baroclinic instability. In this instance, however, the structure of the atmosphere by chance might have been ripe for extraordinary response to a small perturbation; and the discharged melange of warm water and sewerage by chance was unusually large. We cannot entirely put aside the suspicion that the origin of this storm may have been singularly revolting.

5. Concluding remarks

We feel that this storm had only limited similarity to the well-known phenomenon of the Great Lakes snowstorm, as recently discribed, for example, by Eichenlaub and Garrett (1972) and by Sykes (1972). The Lakes storm, though perhaps comparable in scale, appears to be more essentially convective in character. The temperature difference between surface air and lake water seems to be larger than in our case, and there does not

[3] Professor E. Mollo-Christensen, M. I. T.; private communication.

seem to be as substantial a perturbation in the mesoscale wind and pressure fields as we have described. Release of latent heat is generally regarded as the dominant forcing mechanism and little attention has been given to conventional baroclinic effects. Although Kaplan and Paine (1973) have pointed to the importance of associated synoptic-scale troughs, they are regarded as a mechanism for organizing the low-level convective fluxes over the Lakes so as to produce the intense local snowstorms. Convective snowstorms in fact often occur along exposed lee shores of the New England coastline in circumstances similar to those which produce the Great Lakes storms; and indeed the snowfall in our case northwest of Gloucester between 1200 GMT and 1500 GMT was probably of this type. The heavy snow between Revere and Gloucester, however, cannot be accounted for on this basis.

The baroclinic "polar low" storm appears to be more frequent in the United Kingdom than in the eastern United States, though the storm of 18 December 1971 was not without parallel. Pierce (1968), for example, has described a similar instance in November 1967. The relative rarity of the phenomenon here is not difficult to understand: a persistent weather type in the United Kingdom is one which a major tropospheric ridge lies over the eastern Atlantic Ocean while a major trough is found over western Europe. The polar low develops in the northwesterly flow between these two features, over a relatively warm sea surface. With a comparable large-scale circulation pattern in North America, comparable cyclogenesis would not be anticipated because a cold winter continent lies to the northwest of New Ehgland. The polar low here can develop only right on our doorstep, so to speak, and evidently only under a seldom-met combination of circumstances.

In summary, we have described a mesoscale storm which produced a foot of snow in parts of coastal New England. The behavior of the storm was consistent with qualitative inferences drawn from quasi-geostrophic theory, indicating that the advections of temperature and vorticity were dominant physical mechanisms, as they are in synoptic-scale baroclinic disturbances. The direct effect of heat transfer into the atmosphere from the relatively warm waters of Massachusetts and Cape Cod Bays was to determine the location of cyclogenesis. The transfer had further indirect consequences, maintaining a small hydrostatic stability over the area and a shallow zone of strong baroclinicity between land and sea, both necessary circumstances for cyclogenesis on a small scale. There is a remote possibility that a significant part of the heat transfer may have been anthropogenic.

Acknowledgements. The authors are grateful to Commander W. E. Smith and W/O R. Warbutton, U. S. Coast Guard, for patient and valuable assistance in data acquisition, and to Mr. M. J. Feldman of the Boston Edison Company for generously making available to us the data on effluents. The work was supported by the National Science Foundation under Grant GA-27908X, and one of the authors was the recipient of an NSF Fellowship.

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