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A Mesoclimatological Study on Heavy Snowfall*

— A Synoptic Study on the Mesoscale Disturbances —

by

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Abstract

Based on the analyses of weather maps of scales from local through Asiatic to northern hemispheric, the author studies in this paper some mesoclimatological problems of the mesoscale disturbances observed during the period of heavy snow in the Hokuriku District. The main problems treated are as follows:—

First, the statistical characters of the so-called plain heavy snow free from mountain effect and of mountain heavy snow are examined. According to the statistics on the frequency of heavy snowfalls for 9 winters from 1953 to 1961, mountain heavy snow is the most frequent, accounting for more than half of the total occurrences. On the contrary, the frequency of plain snow is comparatively low, as the mean occurrence of plain snow is only 2.5 days during one winter season. Plain heavy snow is mainly related to the bulge of isobars on the weather chart in which a cold vortex is located over the Japan Sea. Especially it seems that, under the prevalence of the bulge pressure pattern, there occur heavy snow and rainfall, thunderstorms and gusts with the passing of a mesoscale disturbance, throughout the year. Therefore this pressure pattern has great importance in forecasting severe storms around the Japan Sea side of the Japanese mainland.

Secondly are studied the characteristic pressure patterns on a broader scale during the period of the formation and development of mesoscale disturbances in plain heavy snow. Such a pressure pattern on a broader scale on northern hemispheric 500 mb charts is characterized by a cut-off High which stagnates over the area extending from Alaska to Kamchatka and by a ridge along approximately 90°E corresponding to cut-off cold Low over the Far East. On Asiatic 500 mb charts, plain heavy snow sometimes falls when

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the trough is situated west of 140°E, the cold vortex from the high-latitude zone is located over the Japan Sea, and the regional zonal index is below about 10 m/s. On the contrary, mountain heavy snow falls when the trough is situated east of 140°E, the cold vortex is located in the high-latitude zone, and the regional zonal index exceeds 14 m/s.

Thirdly, 11 examples of plain heavy snow in relation to mesoscale disturbances are analyzed in more detail using the synoptic and radar data, and these examples are classified into 4 types on the basis of synoptic analysis. (1) Snow accompanied by the pre-frontal squall line or cold front corresponding to a Japan Sea cyclone. It is seen that a sudden pressure change (0.7-1.0 mb), wind gusts (23 m/s), bursts of snowfall intensity (3.0-7.6 mm/hr) and maximum surface wind convergence (-6×10^{-4} sec^{-1}) are most frequently recorded on the arrival of a mesoscale disturbance known as "pre-frontal squall line" preceding the cold front. (2) Snow accompanying the local convergence line, the so-called "Hokuriku-Front". When the upper cold vortex is located over the Japan Sea, the southerly wind prevails towards the sea off the coast, while over the sea off the coast prevails the northwest monsoon and along the coast the westerly winds from the San'in District. Therefore, between the three currents, a zone of convergence is formed along the coast of the Hokuriku District and brings plain snow. (3) Snow accompanying a the smaller cyclone. When the cold vortex is situated over the Japan Sea, a smaller cyclone is formed and frequently develops along the strong convergence line in the coastal region as a result of low-level convergence and high-level divergence. Furthermore, another smaller cyclone is sometimes formed and develops in the western part of the Japan Sea when the cold vortex or trough migrates towards the Korea from the high-latitude zone. Such a cyclone is considered to be related to baroclinic instability. It is found that many severe snow storms, that is to say, those having strong intensity of snowfall (22 mm/3 hr), maximum wind speed (20 m/s), thunder and lightning, are associated with the passing of these smaller cyclones over the coastal region. The horizontal scale, the lifetime and moving velocity of these cyclones are about 100-300 km, 5-20 hr and 20-50 km/hr, respectively. (4) Snow in a vortical mesoscale disturbance. The author found out that radar observations during the period of heavy snowfall frequently show remarkable spiral echoes corresponding to vortical disturbances. They are usually formed and develop off the coast, move across the plain, disappear in the mountainous region, and strong snowfall (i.e. 4.0 mm/hr) concentrated in a small area sometimes takes place along the tracks of these disturbances. Many vortical disturbances have been observed mainly in the orographical convergence areas such as the Tango and Noto peninsulas, especially combined with a low-level convergence. These disturbances are characterized by a horizontal scale of 50-100 km, a lifetime less than several hours and convergence of 10^{-4} sec^{-1}.

Lastly, the radar analyses of snowfall, especially the characteristics of line echoes (snowbands) during the period of heavy snowfall are investigated. The line echoes with 30-50 Km spacings and 10-20 Km wide are lined up in the direction of NW-SE and W-E, the former for mountain snow, the latter for plain snow. The locations of line echoes are restricted geographically and their orientations elongate statistically in the direction of the wind shear between 1000 and 500 mb levels. If, however, the shear is small, then the echo pattern appears to be rather chaotic and in disorder. On the other hand, the spacing of line echoes widens with the increasing height of the inversion layer. Furthermore, it is found that the areas of radar echoes are not always in good agreement with the actual snowfall areas. That is to say, in some cases an echo area coincides closely with a snowfall area, but in others a big gap is observed between the two areas. This seems to be related to the vertical distribution of upper winds and the velocity of snowflakes falling from their formation layer.

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Introduction

According to the report (MIYAZAWA, 1960) on the Hokuriku Front which brings heavy snowfall, the first contributor was M. ISHIDA (1908) who concluded that "the heavy snowfalls in this district were due to the orographical effect and the major cyclone passing across the Japan Sea." During the nearly sixty years since then, there have been many attempts made to elucidate the mechanism of snowfall, mainly by the weather forecasters in the Hokuriku District, with more or less enthusiasm corresponding to the amount of snowfall. Indeed, studies of heavy snowfall are apt to become active in years of heavy snow: there have been a great number of studies based on the heavy snowfalls in January 1945, December 1957, December 1960, January 1961, and January 1963 after World War II. Especially during the last 5 years, an observation project has been organized in the Hokuriku District to study and elucidate the mechanism of heavy snowfalls by means of the airplane, observational ship, and radar, the Meteorological Research Institute taking a leading part.

The author, engaged in the practical forecasting of snowfall, has been studying the mechanism of heavy snowfalls in the Hokuriku and the Shin-etsu Border District for about twenty years since 1948. The following paragraphs summarize the results of the major researches carried out by the author, compared with those obtained by the recent Heavy Snow Storm Project Observation.

(1) The snowfall amount observed locally in the mountainous region of the Shin-etsu Border District was analyzed with reference to the aerological data obtained at Wajima, and the snowfalls were classified into two types: those due to monsoon and those due to minor cyclones. The former become larger in proportion to the thickness of the inversion layer appearing in the lower layers at Wajima. On the other hand, it was observed that the latter were proportionate to the mixing ratio at the 2.5 km height (MIYAZAWA, 1949). According to the results of the recent observation project, under the influence of the prevailing northwest monsoon the ascent curve at Wajima shows that an inversion layer always exists in the lower layers and becomes higher when the cumulus convection becomes active by the inflow of upper cold air. That is to say, it has been reconfirmed that the layer from the inversion level to the sea-level is close to the dry adiabatic lapse rate and that the higher the inversion level, the heavier is the snowfall (MATSUMOTO *et al.*, 1966).

(2) According to the snowfall statistics observed in the Nagano District, abund-

ant snowfalls are apt to occur from night to early morning. That is to say, a harmonic analysis of the frequency curve for each hour of abundant snowfall shows that sharp peaks of frequency can be seen at 5–9 A.M. and 21–22 P.M., while sharp falls at 16 P.M. and 2 A.M. This is considered to be caused by the atmospheric instability due to radiation cooling at the top of the cloud layer with the increase of vertical wind shear at the basin (MIYAZAWA, 1957). Recently similar statistical results have been obtained in Hokkaido (OKABAYASHI, 1966).

(3) The heavy snowfall that occurred along the coast in the Hokuriku District from 29th to 31st December, 1957, has led the present writer to a re-examination of the so-called "Hokuriku Front" and an over-all discussion of the problem (MIYAZAWA, 1960). The main results of this discussion are that the upper cold cyclone occurring over the Japan Sea greatly influences the atmospheric stability in the Hokuriku District; that a heavy snow falls as the result of the release of convective atmospheric instability, and that an analysis of the local weather map indicates that the smaller surface disturbances and cyclone appearing in the vicinity of a cold vortex determine the time and place of heavy snowfall. This work is the first attempt at analysis of heavy snowfall consistently carried out on a meso- to hemispheric scale using dynamical quantities such as divergence and vorticity (MIYAZAWA, 1960).

(4) The method of mesoanalysis, which has been used in the studies of thunderstorm and rainfall concentrated in a small area in the summer season, is applied, for the first time, to the analysis of heavy snowfall in the winter season, and the peculiar aspects are studied of plain snow accompanying the prefrontal squall line in advance of the cold front of the cyclones over the Japan Sea (MIYAZAWA, 1961).

(5) Using the data on the plain-snow-type heavy snowfall (plain heavy snow) at the end of December 1960, the possibility of forecasting plain snow is discussed (MIYAZAWA, 1962). Since plain snow falls when the cut-off cold vortex at 500 mb level is situated over the Japan Sea, while mountain snow takes place when it is situated either at higher latitudes or off the east coast of the Japanese mainland, it is possible to predict plain snow or mountain snow by tracing the cold vortex from the higher latitudes. Through an analysis of the relationship between heavy snowfalls and predictors such as upper air temperature, convective instability, stability index, mixing ratio, and saturation degree, it is also found out that the upper air temperature is most closely connected with heavy snowfall: when the temperature is below −35°C, plain snow falls; when below −32°C, common heavy snow falls, at 500 mb level at Wajima. In addition, the finding and tracing of the convergence area of surface wind and smaller cyclones observed in the local weather map and of isallobaric cyclones in isallobaric analysis will be valuable for the forecasting of the movement of the heavy snowfall area. A comparison between the observed value and the one calculated by the snowfall amount due to the orographic and dynamic vertical velocity and the release of instability shows on many occasions that the calculated value is lower than the observed one, though both have a general tendency to agree with each other.

(6) The modification of the air-mass reaching the Hokuriku District from the Continent is discussed, and the total amount of heat and evaporation supplied from the warm sea current during the period of heavy snowfall is found to be more than 2000 ly/day by using Jacob's formula (MIYAZAWA, 1964).

(7) In January 1963, when a heavy snow fell, radar was set up at Mt. Yahiko for the first time on the coast of the Japan Sea, and the first radar analysis on snowfall phenomena was carried out by the author (MIYAZAWA, 1965). As a result, the author found that the line echo (snowband) was lined up along the convergence line (Hokuriku Front) of the coast and that a snowfall distribution of a belt shape was brought forth by the eastward movement of the echo cell. Furthermore, studies were made of the relationship between echo area and snowfall area, as well as the state of the appearance and geographical surroundings of the line echo in the winter monsoon.

(8) Recently, the author found out an interesting and remarkable fact in the observed data of the two radar stations at Mt. Yahiko and Tōjinbo in the Hokuriku District: during the period of heavy rainfall and snowfall concentrated in a small area, small vortical disturbances similar to a midget-typhoon with spiral radar echoes have often been formed and developed off the coast of the Hokuriki District and brought forth abundant rain and snow in moving from sea to inland (MIYAZAWA, 1965, 1967). In the days when there were no radar stations, the mesoscale disturbances were considered vaguely as smaller cyclones or disturbances, but now that radar observation is available it is possible to describe them by seeing them with our eyes.

Among the result stated above, those after 1965 have been obtained in close connection with the studies of S. Matsumoto and his collaborators (MATSUMOTO *et al.*, 1967), who made synoptic and theoretical studies of the disturbances during the Heavy Snow Storm Project Observation carried out in the five winters from 1963 to 1967. On the other hand, the author has studied 11 cases of heavy snowfall, observed in the ten winter seasons of 1957 to 1966, in order to make in more detail the synoptic and radar analysis of these mesoscale disturbances.

For practical analysis, the author has collected and classified those concrete cases pertaining to mesoscale disturbances observed during the period of heavy snowfall which have many problematic points. The author has also clarified the synoptic and geographical aspects of the disturbances through the analysis of snow cloud by means of radar. The main results of these studies will be presented in detail in the following chapters.

1. Statistical characters of heavy snowfall

1.1 Frequent occurrence of heavy snowfall

A snowfall over 30 cm in daily snow depth in the Hokuriku District is defined "heavy." In Niigata Prefecture, when the center of the snow depth contour lines of more than 30 cm on the daily snow depth map is situated at the coast or the plain including Sado Island, the type of snowfall is called "Sato Yuki", which may be rendered into English by "plain snow". On the other hand, when the center lies near or in the mountains, we speak of "Yama Yuki", literally "mountain snow". No definition of plain and mountain snow has yet won universal recognition. In his survey of snowfall in Toyama Prefecture, K. FUKUDA (1961) defined mountain snow as heavy snow whose amount is great on the north to west slope of the mountains 3,000 m above sea level and smaller over the coast, and defined plain snow as heavy snow whose amount is great both on the coast and the mountainous region. On the other hand, K. FUKAISHI (1961) studied the types of snowfall distribution in Niigata Prefecture and defined mountain snow and plain snow as, respectively, heavy snow whose daily maximum snow depth

exists in the mountainous region and in the plain near the coast. He pointed out the existence of middle-type snow which can not be classified as either of the two mentioned above.

Since there is no quantitative method for defining the boundary line between the mountainous region, the piedmont district, and the plain and coastal area, and the durations of snowfall under consideration are different by researchers, such classification of the types of snowfall distribution is rather subjective. Therefore, in this report, to obtain an objective classification, the following method for defining the boundary was adopted from an etiological point of view.

It would be reasonable to assume that the mountainous region is an area where the theoretically expected orographic snowfall amount in 24 hours is estimated to be more than 25 cm. Practically, assuming the wind directions to be 280°~340°, the dew point temperature −2°C and the wind speed 15 m/s, the orographical daily precipitation was calculated using the grid distance d=15 km (SAITO, 1957). Thus the boundary line between mountainous region and plain is defined as the envelopes of areas where the orographic daily precipitation is more than 12 mm, i.e., 24 cm in snowfall amount assuming snow density to be 0.05 gr/cm^3.

In Fig. 1 is presented the boundary line as compared with the boundary line which is the contour line of 200 m above sea level used in routine work. The two lines coincide with each other rather well except in southern Niigata Prefecture. The disagreement between these lines near Takada shows the predominance of flat mountains where the orographical effect is small. The contour line of 200 m above sea level also is the geographical boundary line between the plain and the mountainous region.

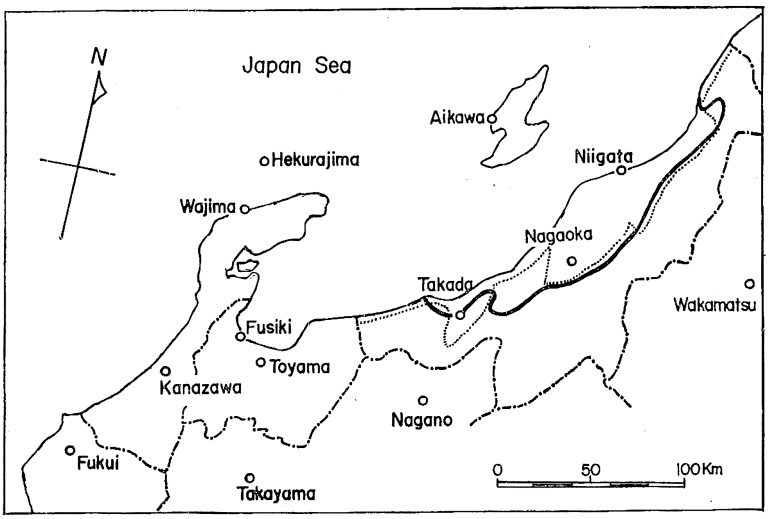


Fig. 1. Distribution of main stations in the Hokuriku District, boundary of prefectures (chain line) and boundary between plain and mountainous region (thick line). Dotted line shows contour of 200 m above sea level.

Next, the types of heavy snowfall distribution in Niigata Prefecture during four winters for December 1957 to March 1961, were classified into "mountain snow (Y)"—heavy snowfall in the mountainous region, "plain snow (S)"—heavy snowfall in the plain including the coast, and "mixed-type snow" (M)—heavy snowfall both in the mountainous region and plain, using the method mentioned above. The result is presented in Table 1. The frequency of plain snow including the mixed-type is rather small, being only about 20% (22 cases) of the total cases of heavy snow. On the contrary, mountain snow is more frequent and exceeds half of the total cases. Furthermore, it will be seen that the average occurrence of plain snow alone is only 2.5 days at most in one winter season though its occurrence shows wide fluctuation each year, but the disasters due to plain snow are always enormous, because industries and population are concentrated in the plain and coastal area. Therefore, we can not disregard plain snow. K. FUKAISHI (1963) obtained similar statistical results on the heavy snow in Niigata Prefecture during 5 winters from 1953 to 1957, according to which the average frequency of plain snow is about 9% (10 cases) of the total cases of heavy snow (118 cases). Here, heavy snow was defined as snow falling at the rate of more than 20 cm in 24 hours and observed at more than five stations.

Table 1. Frequency of types of heavy snowfall in Niigata Prefecture during December 1957—March 1961 (unit: day).

Y: Heavy snowfall in the mountainous region called "Yama Yuki".
S: Heavy snowfall in the plain called "Sato Yuki".
M: Heavy snowfall in the plain and the mountainous region.

Type \ Month	Dec. 1957–Mar. 1958	Dec. 1958–Mar. 1959	Dec. 1959–Mar. 1960	Nov. 1960–Mar. 1961	Total	Mean
Y	27	13	23	26	89	22
S	4	0	0	6	10	3
M	0	3	3	6	12	3
Total	31	16	26	38	111	28

1.2 Classification of heavy snowfall related to surface pressure pattern

The classification of heavy snowfall in relation to the surface pressure pattern was studied statistically. The pressure pattern for mountain snow is the so-called "West-High East-Low" under the prevailing NW-monsoon, but the pattern for plain snow cannot be classified with it. The relation between heavy snowfall and surface pressure pattern is shown in Table 2. Here, the number of cases of plain snow including the mixed-type snow is 22, based on Table 1. In Table 2, the size of the area of heavy snow is indicated by the percentage ratio of the number of stations where the daily snowfall amount is more than 30 cm to the number of the total stations (54 stations). That is to say, when the value of the percentage rate is "$\geqq$10%", it is taken to be heavy snow of a large size and when "<10%", of a small size. Synoptic pressure patterns of plain snow are roughly shown in Fig. 2. The common pressure pattern for plain snow is the type in which the isobars over the Japan Sea are curved cyclonically and the anticyclone from the Continent extends southwards, frequently covering the seas of south the Japanese mainland (type A, B). Especially, an extensive plain snow is apt to occur when a trough and a rather small cyclone exist over the Japan Sea

Table 2. Frequency of synoptic pressure patterns for heavy snowfall in the plain (1957～1961).

Scale of heavy snowfall is shown by the ratio of the number of stations where 30 cm or more of snowfall was observed in 24 hours to the number of total station.

Type	Pressure pattern / Scale	A	B	C	D
S	≧10%	3	0	1	0
	<10%	1	2	2	1
M	≧10%	1	1	8	1
	<10%	1	0	0	0

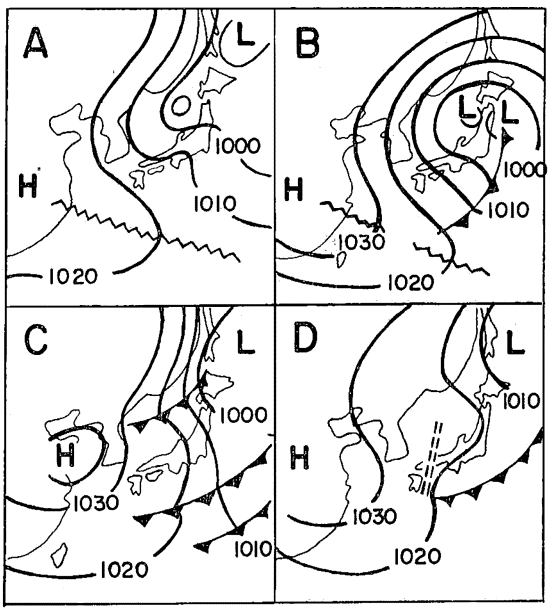


Fig. 2. Types of surface synoptic patterns for Sato Yuki or heavy snowfall in the plain.
A; cyclonic curvature of surface isobars around the Japan Sea (occasionally accompanied by a smaller cyclone). This type is called "Fukuro-type".
B; development of a low stagnating at the western part of Hokkaido.
C; passage of the cold front.
D; trough or low passing through the inland part of Japan.

(type A), and the snow of the mixed type is caused by the passage of a squall line or cold front (type C). Thus, the appropriate name for the pressure pattern in which the isbars wrap up the Japan Sea (type A above) will be called "Fukuro-type", a name coined by the author (FUKURO is the Japanese word for a bag). It was recently found that the pressure pattern of "Fukuro-type" is caused by the upper cold air invading

into the Japan Sea, and the smaller cyclone over the Japan Sea or the cyclone at the western part of Hokkaido corresponds to the upper cold vortex. Therefore, the pressure pattern of "Fukuro-type" plays an important role in the formation of mesoscale disturbances like the gust, thunder and heavy snowfall, etc.

2. Broader-scale analysis of heavy snowfall

Since mesoscale phenomena are closely connected with those of a broader scale, we may reasonably presume the characteristic features of a broader scale which are suitable for the formation and development of mesoscale disturbances which bring forth abundant snowfall. As a preliminary to the discussion of mesoscale phenomena concerning plain snow, the remarkable plain snows for December 1957, December 1960 and January 1963 were studied based on analyses of northern hemispheric and Asiatic scales. Main results are summarized as follows:

(1) Ridge stretching NEwards along 90°E in Central Asia.
(2) Cut-off high stretching from Alaska to the Kamchatka Peninsula.
(3) Low index zonal circulation.
(4) Remarkable anticyclone in the mid-stratosphere around the Far East.
(5) Upper trough located west of 140°E.

2.1 Analysis of the northern hemispheric 500 and 30 mb charts

Using the northern hemispheric monthy and 5-day mean 500 mb height and anomaly charts, the characteristic features of broader-scale pattern for the heavy and light snowfall were studied. As shown in Fig. 3(a), (b), for the monthly mean 500 mb height and anomaly charts on January 1963 which is well known for an unprecedent heavy snowfall, the troughs of wave number 3 are predominant and their positions are located at the Far East, the eastern part of North America and Europe, the ridges stretching along 90°E of Central Asia and from Alaska to the Kamchatka Peninsula. On the other hand, a strong blocking high is built up near Iceland along 10°W. On the anomaly chart the same remarkable characters are also seen; that is to say, the negative area in the anomaly chart, which shows −150 mb near Japan, corresponding to the trough near the Far East, covers the area from Japan to the Central Pacific, and the positive area has +100 mb at Central Asia and +200 mb near Alaska, a belt-shaped positive area to the north of Japan connecting these positives. It is concluded from the above that the characteristic features of the mean 500 mb chart for the plain heavy snow in January 1963 are as follows: (1) the low area located northwest of the Sea of Okhotsk (60°N, 135°E) in an ordinary year is displaced southwards toward Hokkaido and its neighbourhood, (2) the trough is intensified in the western part of the Japan Sea, (3) a typical low index circulation is seen owing the development of a ridge at Central Asia and from the Gulf of Alaska to the Sea of Okhotsk passing the Aleutian Islands.

Next,in Fig. 4(a, b) are shown similar charts for January 1964 which is known for its record-breaking light snowfall and abnormal warm winter. In the charts the troughs of wave number 3 are found around the polar cyclone to the north of the Taimyr Peninsula, but their positions are displaced eastward as compared with the preceding year; that is to say, a trough stretches from the Arctic Ocean to the sea east of the Japanese mainland passing the Kamchatka Peninsula, and the negative area corresponding

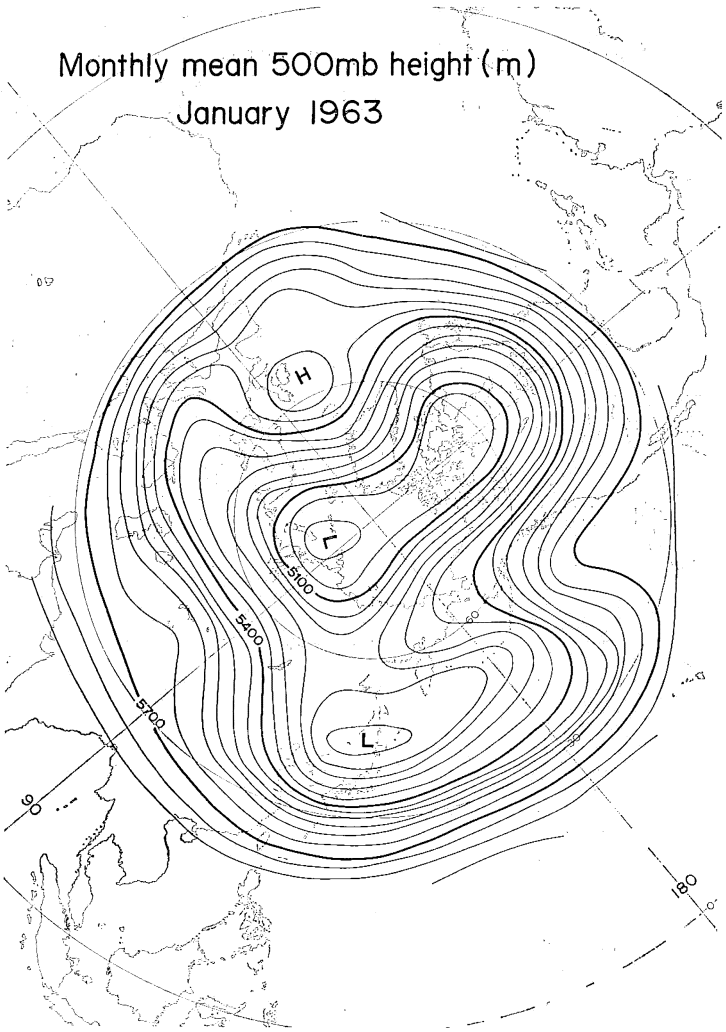


Fig. 3(a). Monthly mean 500 mb height, 1-30 January 1963.

to the trough in the anomaly chart covers a wide area around northern Kamchatka including the Aleutian Islands, Alaska and the northern Pacific. This shows a marked contrast to the situation of the preceding year (1963), when the positive area was situated in the same area. On the other hand, a positive area is located in middle latitudes contrary to the preceding year, a ridge has developed in the Far East near Lake Baikal (105°E) and a remarkable positive area centering at Manchuria covers Japan, thus the positive area covering a wide area from the eastern Asiatic Continent to the Pacific Ocean.

From the above, it is concluded that the characteristic features of the mean 500 mb chart for light snow and warm winter are as follows: there is a high pressure tendency at the surface and 500 mb level at 30°, 40°N, the positive area stretching from Manchuria over Japan to the eastern part of the Pacific Ocean, and the negative area

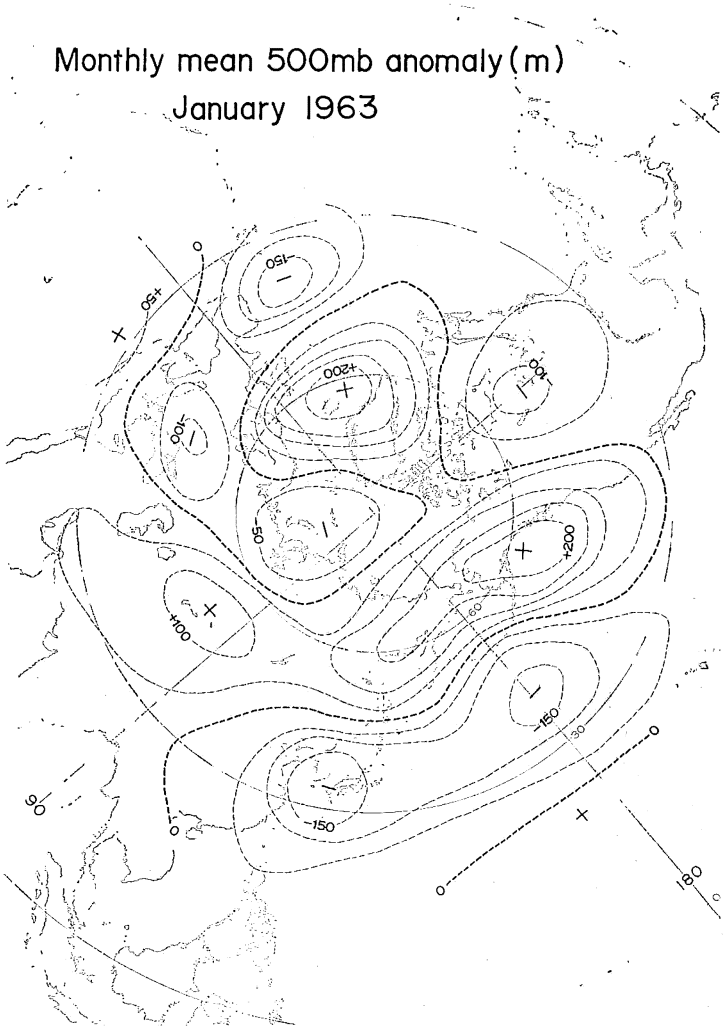


Fig. 3(b). Monthly mean 500 mb height anomaly (m), 1-30 January 1963.

located over Alaska and the Aleutian Islands.

Since similar features are found also on the 5-day mean 500 mb charts during the period of plain heavy snow in January 1963 and at the end of December 1960, it is concluded that the pressure patterns on a broader scale for plain heavy snow are characterized by a cut-off high which stagnates over the area stretching from Alaska to Kamchatka, a cold low around Hokkaido, a ridge stretching NEwards from 90°E of Central Asia, a low index circulation, etc.

Furthermore, these characteristic features of the height and temperature fields were studied using the stratospheric 30 mb chart of the northern hemisphere published in West Germany. Comparing the 30 mb chart in Fig. 5 with the 500 mb chart in Fig.

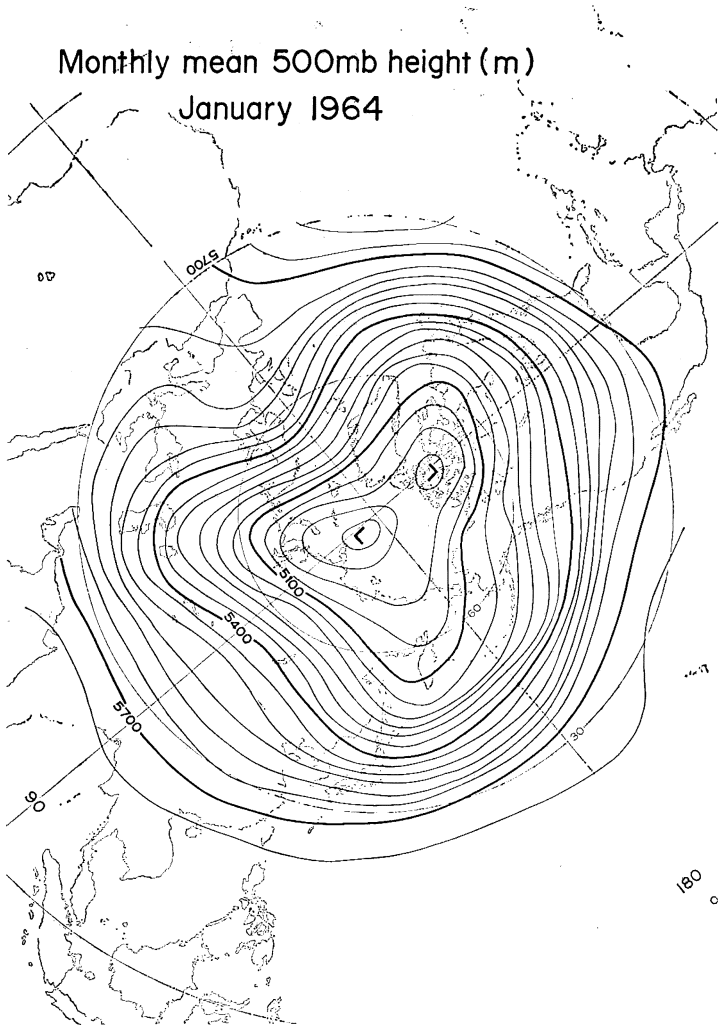


Fig. 4(a). Same as Fig. 3(a), but for 1-30 January 1964.

22, for the heavy snowfall of January 23, 1963, we recognize that the cold low (−43°C near the center) around Hokkaido at 500 mb corresponds to the warm high (−40°C near the center) over the Aleutian Islands at the mid-stratosphere, 30 mb. That is to say, the cold low at the troposphere corresponds to the warm subtropical high at the mid-stratosphere (the subtropical high for 1962, a year of light snow, is located at 180°E). Further, since the ridge is located around Japan, a long wave of number 2 is predominant, the subtropical jet disappears and the polar night jet is intensified, in contrast to the situation in January 1962.

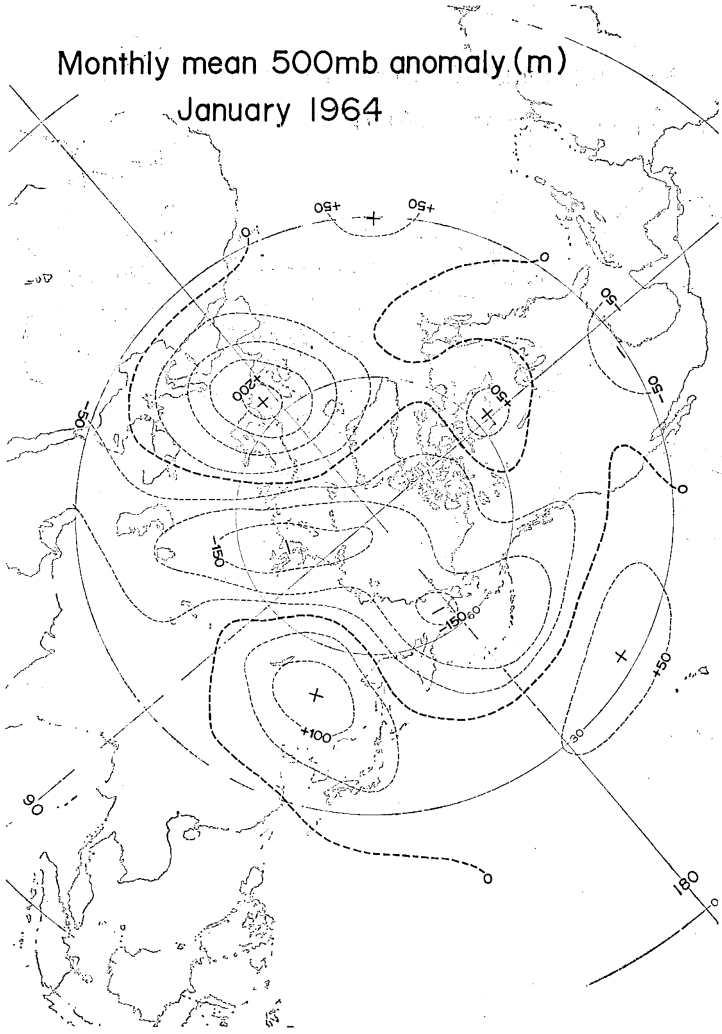


Fig. 4(b). Same as Fig. 3(b), but for 1-30 January 1964.

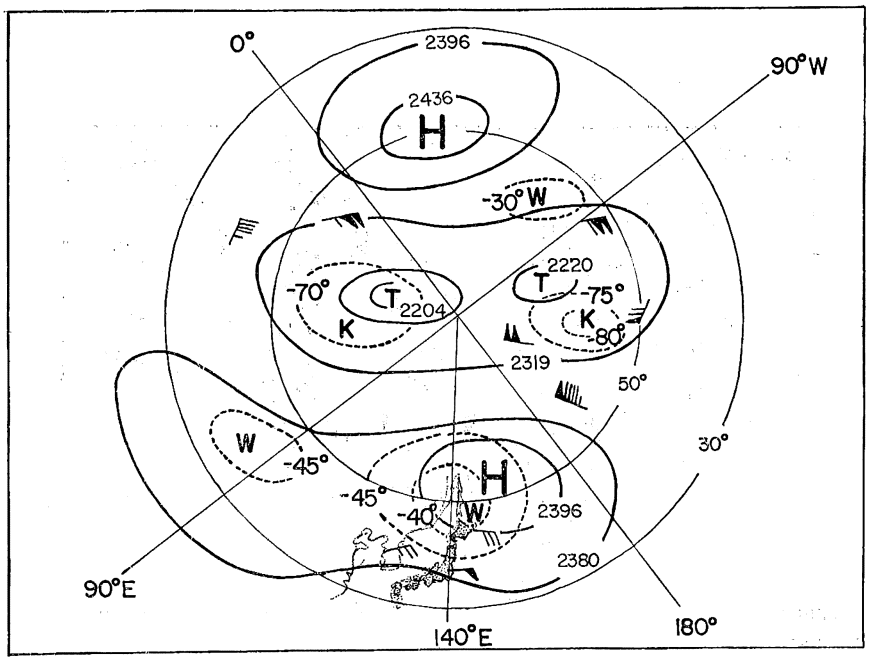


Fig. 5. 30 mb chart, 2100 JST 23 January 1963.

2.2 *Flow pattern on the 500 mb chart around the Far East*

(1) *Analysis of the* 500 *mb chart* Shifting our point of view from hemispheric to Asiatic (90-180°E), we shall study more in detail the Asiatic 500 mb chart for heavy snowfalls. The representative 500 mb and surface weather charts in the cases of mountain and plain snow for the winter of 1960-1961 are presented in Figs. 6, 7

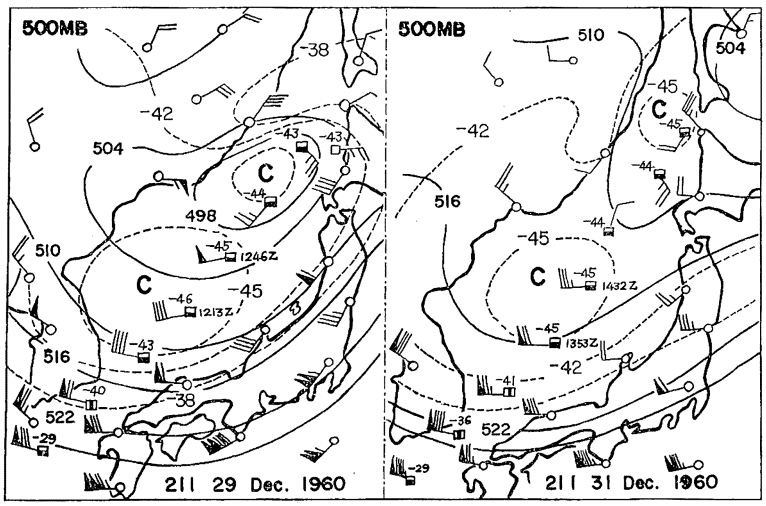


Fig. 6. 500 mb charts, 2100 JST 29 and 31 December 1960 (heavy snowfall in the plain).

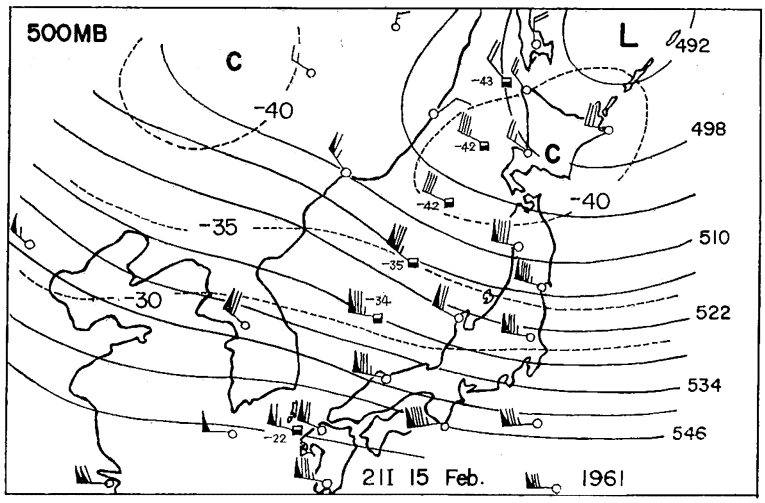


Fig. 7. 500 mb chart, 2100 JST 15 February 1961 (heavy snowfall in the mountainous region).

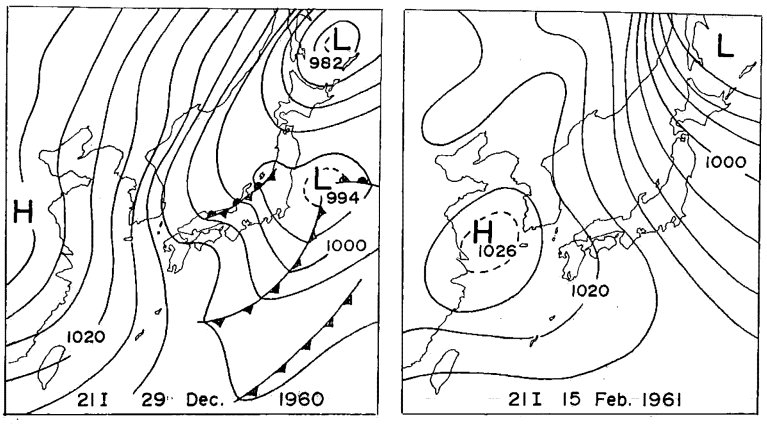


Fig. 8. Surface weather maps, 2100 JST 29 December 1960 and 2100 JST 15 February 1961.

and 8, respectively. The most striking features in the synoptic pattern are the following: the location of the cold vortex and flow pattern around the Japan Sea and Japanese mainland for the plain snow is widely different from that for the mountain snow. When heavy snow falls in the plain, the surface pressure pattern is "Fukuro-type", the pressure gradient weakens and an upper cut-off cold vortex locates over the Japan Sea. Analyzing the cold vortex in detail by using the observed data obtained from the RECON. flight of the US Air Force, we can often separate a cold vortex into more than two smaller ones by which the snowfall area is controlled. The rea-

sons why heavy snow falls in a district east or southeast of a cold vortex are the following. The strong vertical wind shear caused by the prevalence of the NW wind at a lower level and SW wind at an upper level works in combination with the thermal wind, orographic convergence and remarkable instability of the air column caused by an upper cold vortex, to form a remarkable convergence line along the coastal line, and mesoscale disturbances such as gust, thunder and plain snow are observed along this line. On the other hand, when heavy snow falls in the mountainous region, the upper trough is located east of the Japanese mainland and the center of the cold air near Hokkaido or at higher latitudes. Then NW wind prevails both in the lower and the upper layers over the Japan Sea, and this is probably responsible for the mountain snow which is due to an upward motion caused by the orographic effect of mountains.

(2) *Analysis of the zonal index* The flow pattern in the Far East (zonal index) for heavy snowfall was studied using the values for the zonal index quantitatively. Fig. 9 shows the daily variations of the 5-day running mean value of the regional zonal index in the Far East (35~55°N, 100°E~170°W) and its normal values for 1962 to 1964. The results of analysis may be summarized as follows:

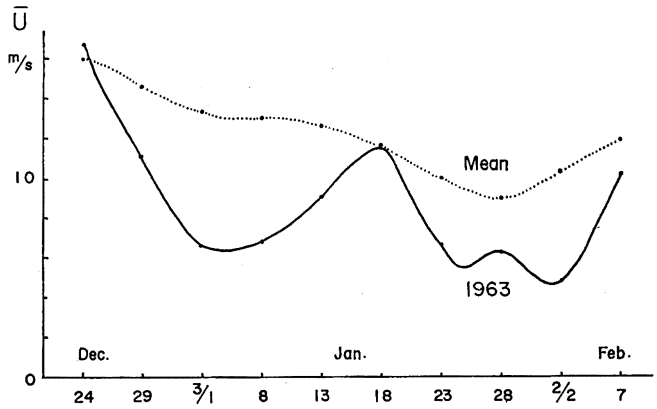


Fig. 9. Daily variations of the regional zonal index in the Far East. Solid line: December 1962-February 1963. Dotted line: mean value (1962-1964).

i) The index dropped suddenly after 24 December, with its minimum on 5 January, and then turned upward, came back to its normal value about 18 January.
ii) The index dropped again after 19 January, with its minima on 24 and 31 January.

Corresponding to the change of the index, the distribution of snowfall in the Hokuriku District varied systematically. That is to say, from 13 to 21 Jan., when the value of the zonal index was large, mountain snow fell and on 3, 22 to 26, and 30 to 31, when it was small, plain snow or mixed-type snow fell. Thus it is noted that, in January 1963, an abnormally low index prevailed and the zonal index was much lower than in the normal year.

Next, in Fig. 10 is shown the relation between the regional zonal index in the Far

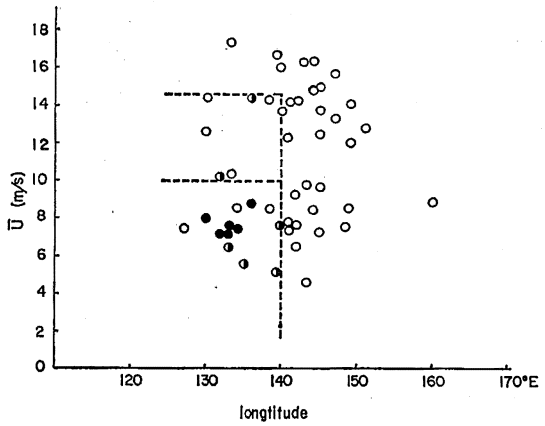


Fig. 10. Relation between the regional zonal index in the Far East (Ū) and position of the upper trough at 500 mb (longitude) for types of heavy snowfall (1961-1963). Symbols ○, ● and ◑ show the cases of heavy snowfall in the mountainous region, the plain, and both mountainous region and plain, respectively.

East (35~55°N, 100°E~170°W) and the position of the upper trough at 500 mb along 40°N latitude for the types of heavy snowfall of the two winters from 1961 to 1963. For data we took up those heavy snowfall days on which 30 cm or more of snowfall was observed in 24 hours at more than 8% of all the stations in Niigata Prefecture during the above two winters. They were classified by the method described in Paragraph 1. 2. Summarizing the results in Fig. 10 and the previous report (MIYAZAWA, 1962), we conclude that the snow of the mixed type is apt to occur when the trough is located west of 140°E, the cold vortex from high latitudes over the Japan Sea and the regional zonal index is below about 14 m/s, while under similar circumstances plain snow is likely to come with the zonal index below about 10 m/s (meandering type of westerlies). The mountain heavy snow falls when the trough is situated east of 140°E, the cold vortex in high latitudes and the regional zonal index exceeds 14 m/s (zonal type of westerlies).

In other words plain snow is apt to occur when the meandering of westerlies is large and the cold vortex from high latitudes comes over the Japan Sea corresponding to the low index of westerlies, while we are likely to have mountain snow when the cold vortex lies over the sea east of the Japanese mainland or in high latitudes and the zonal westerlies are strong.

3. Mesoanalyses of snowfall accompanying the passage of a cold front and prefrontal squall line

3.1 Analysis of plain snow accompanying the passage of the prefrontal squall line (example 1)

(1) *Data* For the period from December 1959 to February 1960, 10 cases of remarkable phenomena such as gust, intense snowfall and thunder were observed in the northern Hokuriku District just before the northwesterly monsoon started. Inspecting the case of 26 January more in detail, we found that the intense snowfall

with thunder (Sato Yuki) in a small section of the plain and coast was preceded by the passage of a prefrontal squall line in advance of the cold front. That is to say, heavy snowfall is sometimes observed just before the cold front arrives. Thus, we know that the violent convection in winter like heavy snowfall is similar in scale to such phenomena as thunder and heavy rainfall in summer, and it could hardly be detected by the current synoptic scale observation network, since the average weather station spacing is something over 50 km. To fill in the gaps in the regular observational net-

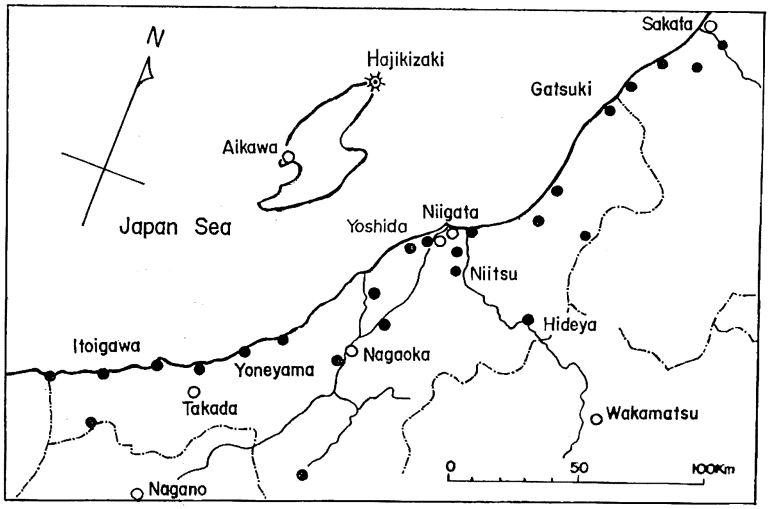


Fig. 11. Distribution of weather stations in the northern Hokuriku District. Black and white circles indicate railway stations equipped with anemographs and weather stations, respectively. Lighthouse is shown by symbol "☼".

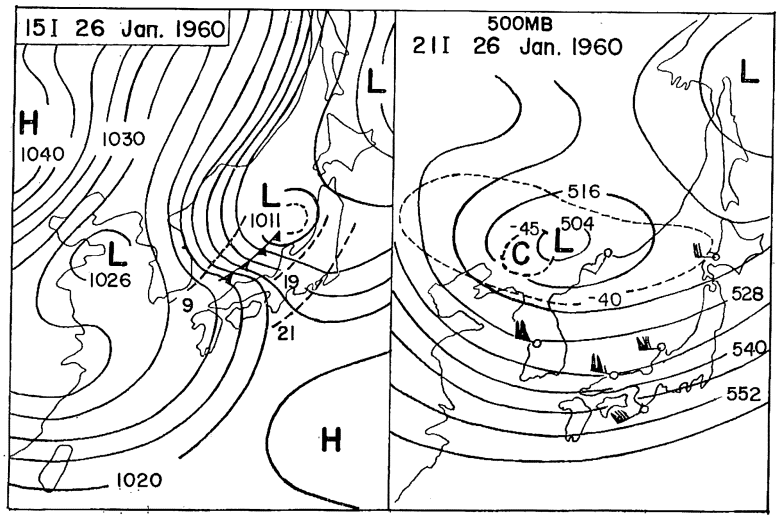


Fig. 12. Left; surface weather map, 1500 JST 26 January 1960. Broken lines show the successive positions of the cold front. Right; 500 mb chart, 2100 JST 26 January 1960.

work, the anemograph recordings at 25 railway stations in Niigata Prefecture as well as the data obtained on patrol ships were made use of as auxiliary data for mesoanalysis. Fig. 11 shows the distribution of the observational stations, Fig. 12 the surface weather map and the 500 mb chart.

(2) *Mesoanalysis* Based upon analyses of the weather chart, we can say that the abundant snowfall seems to be caused by the instability of the atmospheric layers due to the cold vortex at 500 mb located over the northern Japan Sea and by the passage of the cold front, but it is necessary to bear in mind that the intense snowfall occurs before the passing of the cold front. The changes in weather elements observed at the selected stations before the passing of the cold front may be summarized as follows. Fig. 13 shows the typical cases of the change in weather elements at Niigata and Yoshida.

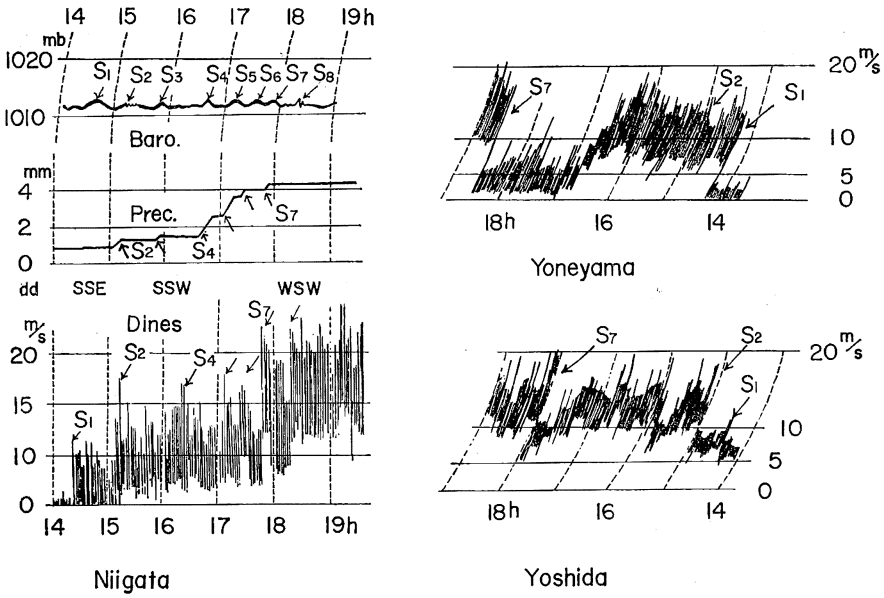


Fig. 13. Variations of surface pressure, precipitation, wind speed before the passing of a cold front at Niigata (left side), and wind speeds at Yoneyama and Yoshida (right side), 26 January 1960.

(i) Eight sharp pressure rises, S_1, ... S_8, are recognized, and the amplitudes of pressure changes are about 1.0 mb and the variation of pressure coincides well with that of snowfall intensity.

(ii) The variation of pressure also coincides well with that of instantaneous wind, and S_1, ... , S_8 indicate the points where the winds suddenly begin to blow.

(iii) Though this does not appear in the figure, the temperature either rises or drops with the pressure change. When it will rise and when drop can not be simply formulated.

(iv) A violent phenomenon such as the thunderstorm often accompanies pressure rise.

It is concluded that these sudden changes in weather elements were produced by the prefrontal squall line because they were observed before the passage of the cold front through the plain at about 1930 JST. The surface meso-map in Fig. 14 was made by using such a conversion of the time section of meteorological elements into the

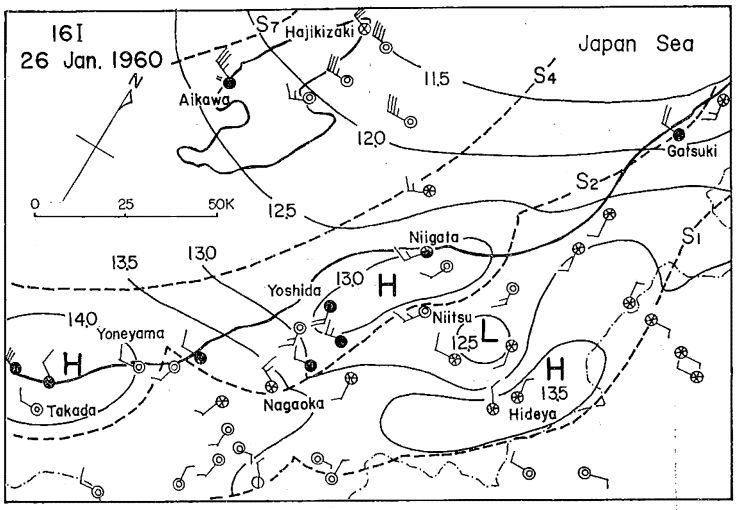


Fig. 14. Surface meso-map for 1600 JST 26 January 1960. Prefrontal squall lines are shown by broken lines.

space section in the direction of the disturbance movement. The phase speed of the prefrontal squall line is estimated to be 45 km/hr over the sea, and its speed decreases to 20 km/hr inland. The mesoscale highs, low and the arc-shaped prefrontal squall lines run around the separated mesoscale highs and are seen also in the meso-map. The maximum value of the convergence along the squall lines was of the order of -6×10^{-4} sec^{-1} and the snowfall amounts of 30 cm in 8 hours were recorded during the passage of the squall lines. This is an example of plain snow accompanying a prefrontal squall line in advance of the cold front. Further detailed discussions based on radar and ship data will be made in the following paragraph.

3.2 Analysis of streaked distribution of precipitation accompanying the passage of a prefrontal squall line and cold front (example 2)

(1) *Data* On December 6, 1964, a streaked distribution of precipitation was observed in association with the passage of prefrontal squall lines and cold fronts accompanying the cyclone over the Japan Sea, as shown in Figs. 15, 16. Since the air temperature was rather high, the precipitation changed to rain in the coastal area, but the synoptic structure on this day might have shown the characteristic situations of heavy snowfall both in the plain and mountains if the temperature had been lower. Since the observation ship "Seifumaru" at about 300 km off the shore of the Hokuriku District and the radar continuous observation at Mt. Yahiko were available for this case study, the relations between the squall line and the cold front were analyzed.

(2) *Mesoanalysis* T. FUJITA (1959) concluded that the cold dome, mesohigh, results

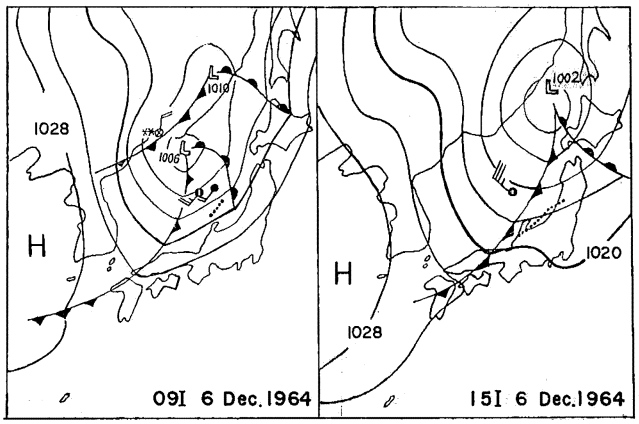


Fig. 15. Surface weather maps for 0900 JST and 1500 JST 6 December 1964. Dotted lines show prefrontal squall lines.

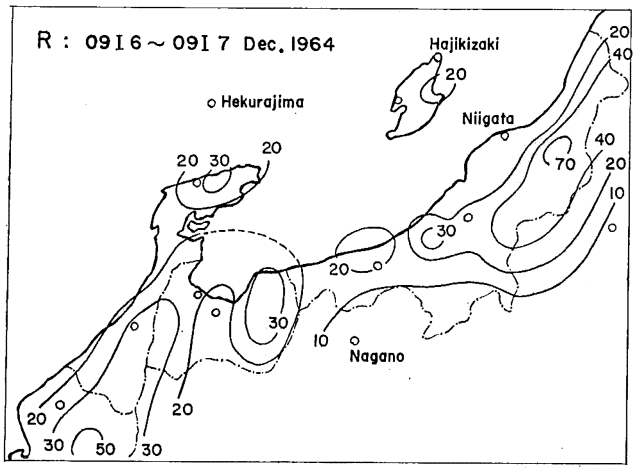


Fig. 16. Distribution of rainfall amounts (mm) from 0900 JST 6 to 0900 JST 7 December 1964.

from the cooling caused by evaporation from the falling raindrops wet adiabatically in the subcloud layer which is nearly dry adiabatic. As the squall line is a phenomenon within a single air mass, pseudo-wet-bulb potential temperature θ_{sw} is considered to conserve even if a temperature fall takes place. The remarkable change of θ_{sw} is caused by the passage of a cold front and, therefore, in order to discriminate the prefrontal squall line from the cold front, an analysis of θ_{sw} was performed (TATEHIRA *et al.*, 1963). A typical example of the change of meteorological elements at Wajima is presented in Fig. 17. A remarkable temperature drop accompanies the passage of squall line S_2, but θ_{sw} is conserved. On the other hand θ_{sw} changes remarkably when the cold front C_1 passes over there. Intense rain, gust and pressure rise (+1.0 mb) are observed when lines S_2, C_1 pass over, and a sudden temperature drop results from the cooling caused by evaporation from the falling raindrops. Thus the changes of surface meteorological elements around the Hokuriku District were analyzed in detail, and squall

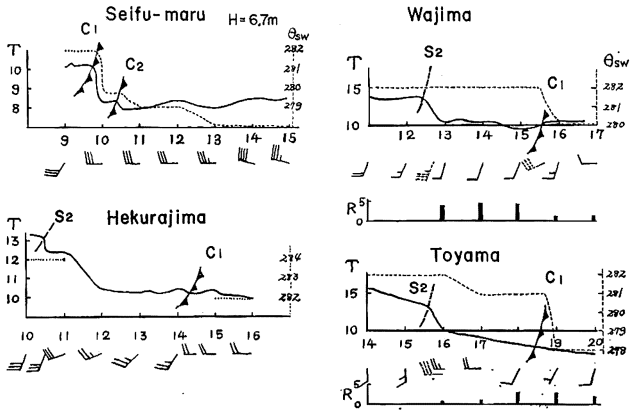


Fig. 17. Changes of surface meteorological elements corresponding to the passage of a cold front and a prefrontal squall line.
Full line: temperature.
Dotted line: pseudo-wet-bulb potential temperature.
R: rainfall amount (mm).

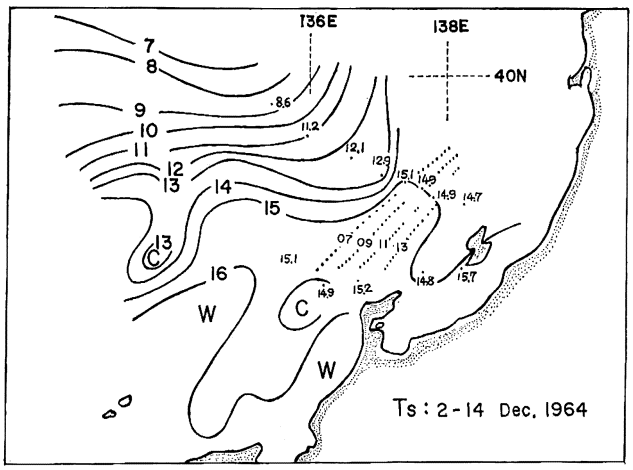


Fig. 18. The distribution of sea surface temperature (°C) observed from 2 to 14 December 1964. Dotted lines indicate the successive positions of prefrontal squall line S_2.

lines S_1, S_2 and cold fronts C_1, C_2 were detected. Squall line S_2 was formed over the Tsushima warm sea current, on the warm-air side of the cyclone, about 300 km from the cold front C_1, and moved SEwards as shown in Fig. 18. Squall line S_1 was originated to the north of Sado Island in advance of line S_2 and passed north of Niigata Prefecture, independent of line S_2. Cold front C_2 is considered to be the secondary front in the rear of line C_1. Fig. 19 is the radar photograph representing the relation between squall lines S_1, S_2 and cold front C_1. The squall lines and cold front are seen to slow down their speeds as they approach the coast from the sea, and their speeds were estimated as 20~30 km/hr in the Hokuriku District, and then they accelerated up to 40~50 km/hr at the Pacific side of the Japanese mainland. It was possible to track them 100 km inland from the coast.

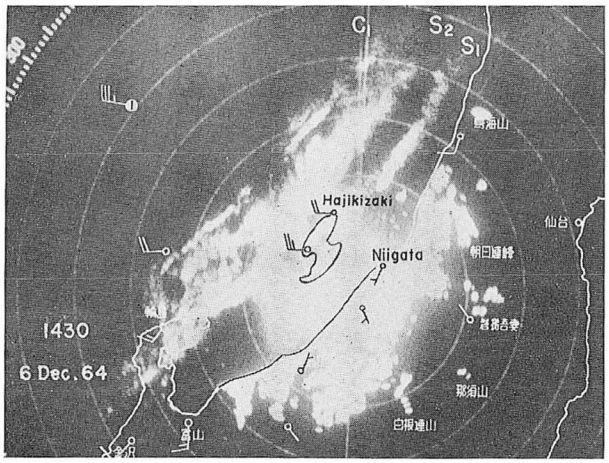


Fig. 19. PPI radar scope photograph at Mt. Yahiko at 1430 JST 6 December 1964. Range marks are 50 km.

Next, by tracking one of the radar echoes representing the smaller disturbances which make up of the squall line, the relations between the height of the echo top as an indicator of the development of disturbance systems (S_1, S_2) and the distance from the coastal line of the Hokuriku District, were studied and shown Fig. 20. It is found that fluctuations with a period of 3 hours are easily recognized on development of the dis-

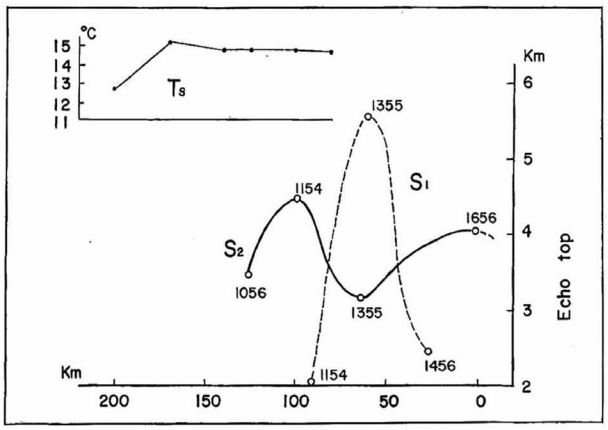


Fig. 20. Relation between radar echo top height as an indicator of development of disturbance system (S_1, S_2) and distance from the coastal line of the Hokuriku District. T_s indicates sea surface temperature.

turbance, and the intensities of meteorological phenomena such as gust, pressure and temperature caused by the disturbance are dependent on the development stages of the disturbance. For instance, the disturbance in system S_1 arrived at its mature stage over the sea 50 km off the shore of the northern Hokuriku District, and fell into decay at the coastal area. Consequently, at Hajikizaki a remarkable temperature drop of 3°C,

and at Niigata and Sakata a weak temperature rise of 1°C without precipitation were observed. On the other hand, the disturbance in system S_2 passing the Noto peninsula brought a remarkable temperature drop of 3°C and intense rainfall of 7.6 mm/hr at Wajima, and then temperature drops of 2~3°C and intense rainfall of 5~7 mm/hr were observed over the whole Hokuriku District because of the recovery of disturbance activity. Thus it could be suggested that temperature drop and pressure rise result from the cooling caused by evaporation from the falling raindrops by a wet adiabatic lapse rate at the mature stage, while temperature rise result from a downward air current by a dry adiabatic lapse rate at the decay stage.

Thus the meteorological phenomena caused by a cold front and a prefrontal squall line show marked local variation, and this seems to be due to the smallness of the area under their control, the different stages of their development, and the shortness of their lifetime. In other words, a cold front can not be analyzed simply while a monsoon is prevailing.

4. Mesoanalyses of snowfall accompanying the convergence line, the so-called "Hokuriku Front"

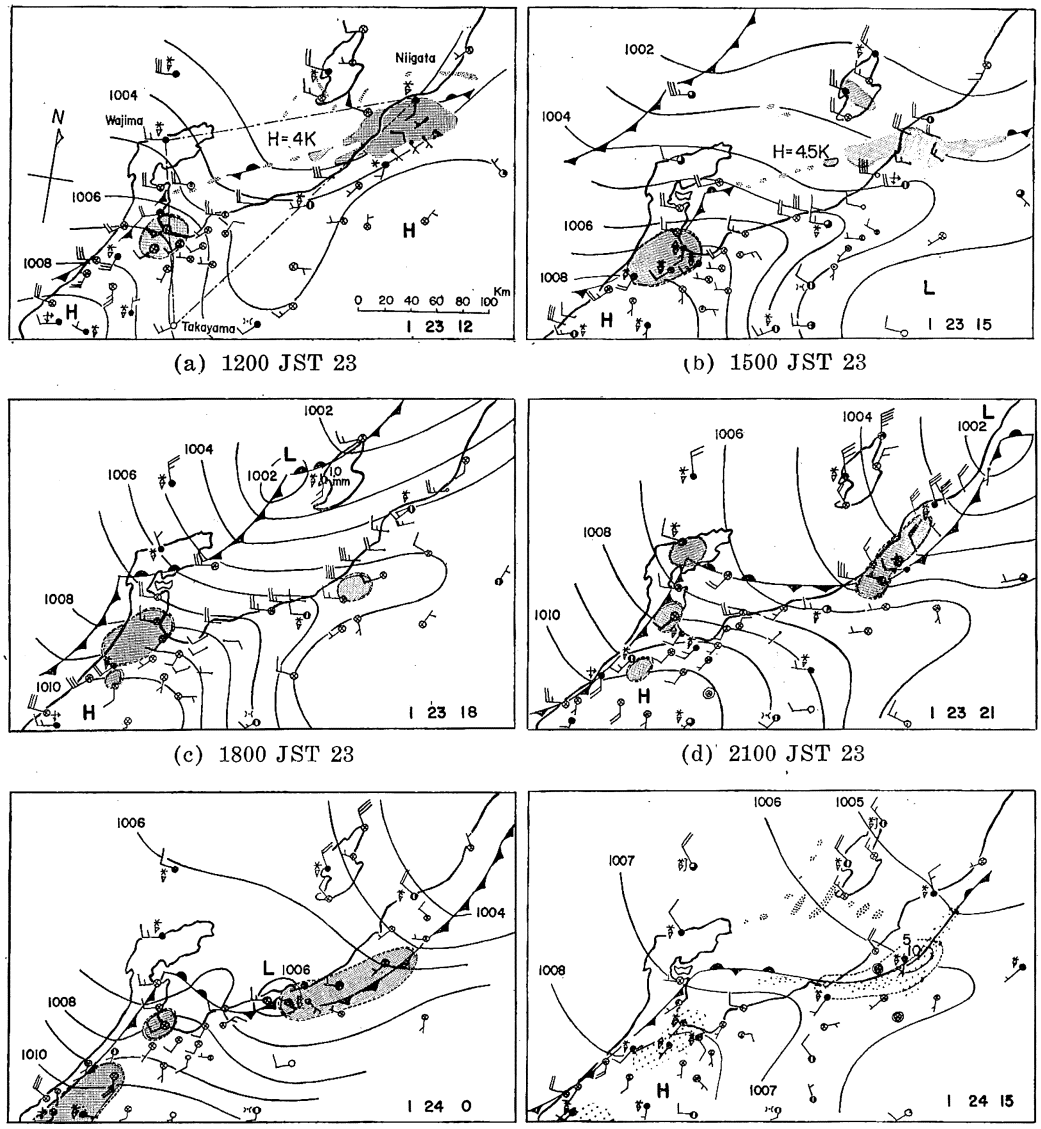
Because of the fact that the Hokuriku District is located on the Japan Sea side of the central Japanese mainland which has an arc-shaped configuration, air currents of various directions are liable to converge in this district (YOSHINO, 1961). The surface wind analysis for the Hokuriku District at the time of heavy snowfalls are as follows: (1) northwesterly wind from the Japan Sea to the coast, (2) westerly wind from the San'in District, (3) southerly wind from the mountains inland to the coastal area. These three wind systems contribute to the convergence of air currents at this district, and a local front called "Hokuriku Front" is formed along the coastal line and brings plain snow.

Many mesoscale disturbances caused by the horizontal convergence along the local front are observed. Mesoanalysis of snowfalls accompanying the surface wind convergence will be discussed in the following examples:

4.1 Analysis of plain snow over an extensive area (example 3, heavy snowfall for January 1963)

(1) *Analysis based on the surface meso-map* For the period from 1200 JST 23 to 1500 JST 24 January, 1963, 3-hourly surface meso-maps are shown in Fig. 21-(a)-(f). As is shown in Fig. 22, the cold vortex invaded over the Japan Sea from southern Manchuria on the afternoon of 22 and passed across the Tsugaru strait on the morning of 25. From 22 to 25 the air column over the Hokuriku District, which located on the south side of the cold vortex, became extremely unstable in stratification and brought the most tremendous heavy snowfall in this period. The chief cause of this heavy snowfall was the persistent stagnation and fluctuation of the local front, but from a synoptic point of view the superposition of the following three sources may be pointed out.

(i) *Snowfall accompanying the convergence line* As is shown in Fig. 21 a, b, f, three wind systems, southerly from inland, westerly from the San'in District to the coastal line of the Hokuriku District and northwesterly from the sea, converge to a line along the coastal line and bring snowfall due to horizontal convergence. Radar echo cells



(a) 1200 JST 23 (b) 1500 JST 23

(c) 1800 JST 23 (d) 2100 JST 23

(e) 0000 JST 24 (f) 1500 JST 24

Fig. 21. Surface meso-map, 23-24 January 1963. The radar echo groups are stippled and stippled areas enclosed with broken line indicate 3-hourly precipitation exceeding 3 mm. The area of the triangle within chain lines, for which divergence is computed, is 13,600 km^2.

representing smaller disturbances are lined up along the convergence line. The echo height is 4.0~5.3 km, warm air flows into the southern side of the line echo and the partial strong wind speed near the echo cell, which amounts to 50 knots and is more than that of the geostrophic and gradient wind, points to the existence of an active convective cloud as an one of the smaller mesoscale disturbances. The individual echo cells

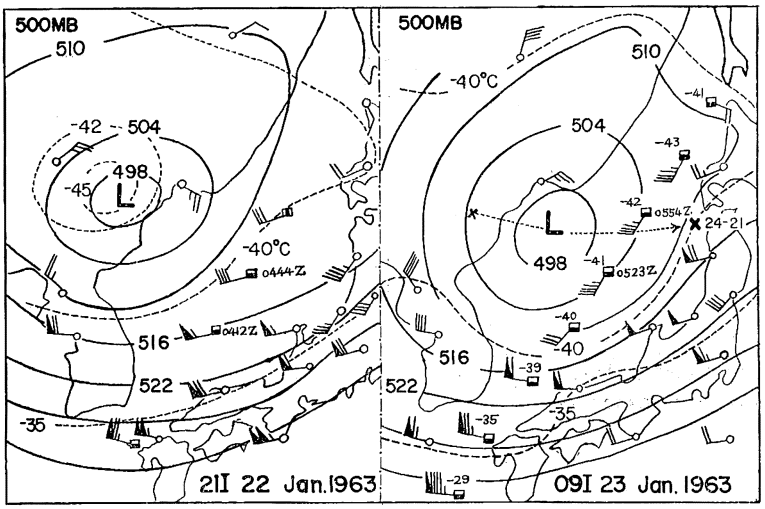


Fig. 22. 500 mb charts, 2100 JST 22 and 0900 JST 23 January 1963.

in the line echo diffuse and bring snowfall as they move inland from the sea. Discussions on the relation between the distribution of the radar line echo and the corresponding weather and snowfall amount will be made in Paragraph 7. In Fig. 21 f, the convergence line shifted southward passing Nagaoka and an intense snowfall was observed at Nagaoka near the center of line echoes. It amounted to 11.0 mm/3hr which is a considerably large value for plain snow.

(ii) *Snowfall accompanying the smaller cyclone formed along the convergence line* As is shown in Fig. 21 e, the smaller cyclone which developed rapidly along the convergence line is located at Takada, and an intense snowfall is observed in advance of the cyclone. As the result of intense horizontal convergence, a smaller disturbance grows up into a smaller cyclone and the area of intense snowfall moves successively along the track of the cyclone.

(iii) *Snowfall accompanying the cold front* The snowfalls accompanying the cold front moving southwards from the sea are presented in Fig. 21 c, d. Surface analysis shows that the cold front from the sea takes the place of the stagnant convergence line. Without observed data by radar and ship the cold front can scarcely be detected. At about 2000 JST 23, the Niigata district had a heavy snow storm associated with the passage of the cold front and the heavy snowfall of January 1963 started. It is necessary to bear in mind that the passage of a fresh cold front accompanied by a snow storm plays the role of a trigger to the sudden outbreak of an extensive and heavy plain snow and the conversion from mountain to plain snow as in the case of December 29, 1960, discribed in Paragraph 5.1.

(2) *Mesoanalysis* Since the actual observation field is composed of the basic and the mesoscale fields, we can isolate mesoscale disturbances by taking the deviation of observed data from the basic field. Deviations of temperature and pressure are obtained by subtraction of scalor, those of wind by subtraction of vector. Here the basic field is assumed to be a 6-days mean field for the period 20~25 January. The deviations of pressure, temperature and wind fields obtained by this method every 3 hours from 1200

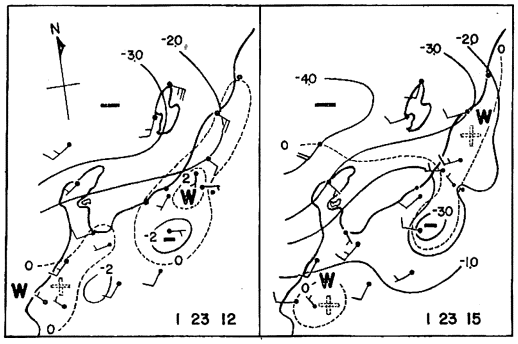


Fig. 23(a). Mesoscale disturbances for 1200 and 1500 JST 23 January 1963. Solid, dotted lines and arrows show deviation of pressure, temperature and wind vectors from 6-day mean, respectively.

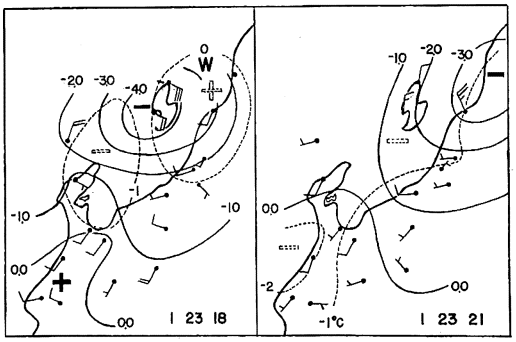


Fig. 23(b). Same as Fig. 23(a), but for 1800, 2100 JST 23 January 1963.

to 2100 JST 23, 1963, are presented in Fig. 23. On the other hand, S. MATSUMOTO and K. NINOMIYA (1967) showed that a mesoscale disturbance could be separated by anomaly analysis using a 2.5-hour running mean on the time series at 30 min. intervals in order to eliminate the semidiurnal change of pressure. The method described above is similar to Matsumoto's in using the deviation.

The results of mesoanalysis are summarized as follows:

(i) Southerly warm air flows into the south side of the convergence line and a snowfall area is recognized in advance of warm air.

(ii) The pressure fall and cyclonic wind system due to the approach of the cold front is analyzed. The smaller cyclone whose scale is about 200 km is accompanied by cold advection in rear and warm advection in advance of the front, and moves towards SE with a speed of 40 km/hr. The features of this smaller cyclone is in large measure similar to a cyclone system on a synoptic scale.

Next, the convergence was calculated by using the aerological data for the triangle formed by Wajima, Niigata and Takayama (see Fig. 21(a) for locations), special aerological observations fortunately being carried on at that time at Niigata and Takayama in addition to the regular ones at Wajima. The area thus covered is 1.36×10^4 km^2, which is about one fourth of the routine network and is suitable for the discussion of mesoscale disturbances formed at the convergence area in the coastal region of the Hokuriku District. In Fig. 24 the time change of vertical convergence is compared with the 6-hour precipitation averaged over 4 stations, Wajima, Niigata, Takayama, and Toyama and with the precipitation at Toyama. Furthermore, the tropopause, cold dome and convective instability layer are shown in the figure. The results of upper measoanalysis are summarized as follows:

(i) The convergence line, Hokuriku Front, is likely to be formed under a condition of intense lower convergence provided by the cold vortex coming over the warm Japan Sea surface. The maximum value of convergence at the lower level is about -2×10^{-4} sec^{-1} and this occurs when the cold vortex has just passed the northern Japan Sea (see Fig. 22).

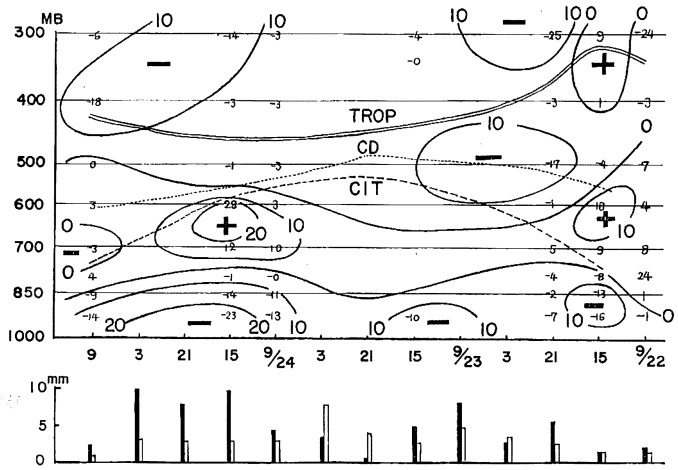


Fig. 24. Time section of divergence (10^{-5} sec^{-1}), precipitation (mm per 6 hours) at Toyama (black bars) and mean precipitation in the area (Wajima-Niigata-Takada-Toyama, white bars) from 22 to 23 January 1963. Convective instability layer, tropopause and cold dome are shown by CIT (broken line), TROP (double line) and CD (dotted line), respectively.

(ii) The existence of mesoscale convective systems is obviously recognized, with a convergence field in the lower layer and a divergence field in the upper layer, the boundary being at 2–3 km height, and the larger the lower convergence, the larger the upper divergence. These convective systems appear in the cold air inside of the cold dome and are accompanied by the fall of tropopause height and increase of convective instability.

(iii) The convergence in the lower layer and average precipitation are closely interrelated. It must be pointed out particularly that the convergence has a good relationship with the amount of precipitation at Toyama.

4.2 Analysis of plain snow over a wide area (example 4; January 1966)

On January 22 to 23, 1966, a heavy plain snowfall occurred over the whole of the Hokuriku District. The maximum snowfall intensity, 105 cm/day, was observed at Takada where sufferings from the tremendous snow were great. It is clearly seen that the Hokuriku District lies south of the cold vortex, where the stratification is unstable, the surface pressure patterns is "Fukuro-type" and a convergence line is apt to be formed (see Fig. 35). As is seen in Fig. 25, three wind systems, northwesterly from the sea, westerly from the San'in, southerly from inland, converge because of the special configuration of the Hokuriku District. Based on the composite radar echoes observed at Mt. Yahiko and Tōjinbo, the echoes are lined up along the convergence line of surface winds and closely correspond to the banded area of snowfall. Particularly, intense snowfall, 13.9 mm in 3 hours, was observed at Takada which is the center of the echo area. More detailed discussion on the relation between the distribution of snowfall amount in 1 hour and the radar echo area for it will be made in paragraph 7.3.

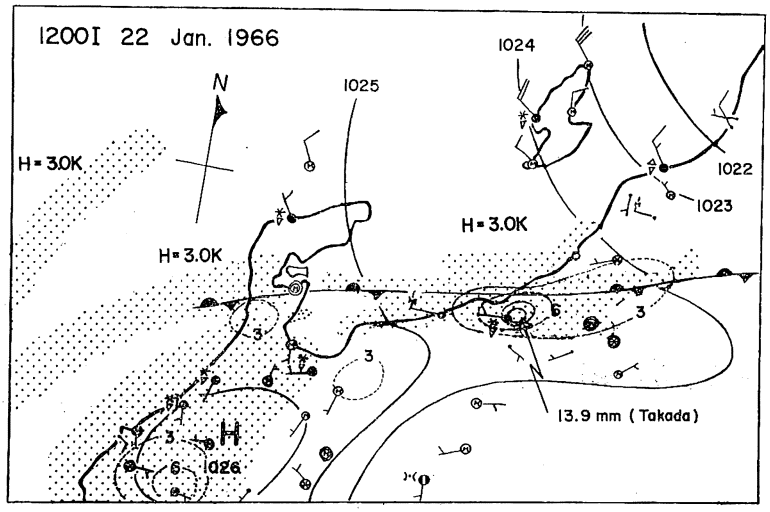


Fig. 25. The composite radar map obtained at Mt. Yahiko and Tōjinbo stations for 1200 JST 22 January 1966. Radar echoes were observed in the stippled areas and dotted lines are isohyets, the numerals indicating the 3-hourly precipitation (in mm).

4.3 Analysis of plain snow at a local area (example 5)

The plain snow at a local area is sometimes observed along the coastal line under a stable air stratification without the invading of a cold vortex. As is shown in Fig. 26, a prevailing northwesterly monsoon is beginning to recede, the anticyclone is on its eastward way from the Continent and cold vortex at 500 mb level is located in high latitudes near Sakhalin, and the air stratification is rather stable. Under this synoptic situation, two wind systems, southerly wind from the anticyclone over the

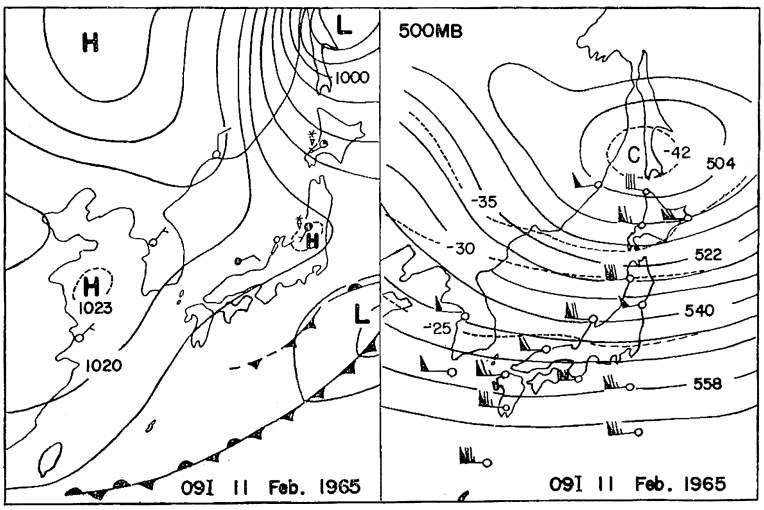


Fig. 26. Surface weather map (left) and 500 mb chart (right) for 0900 JST 11 February 1965.

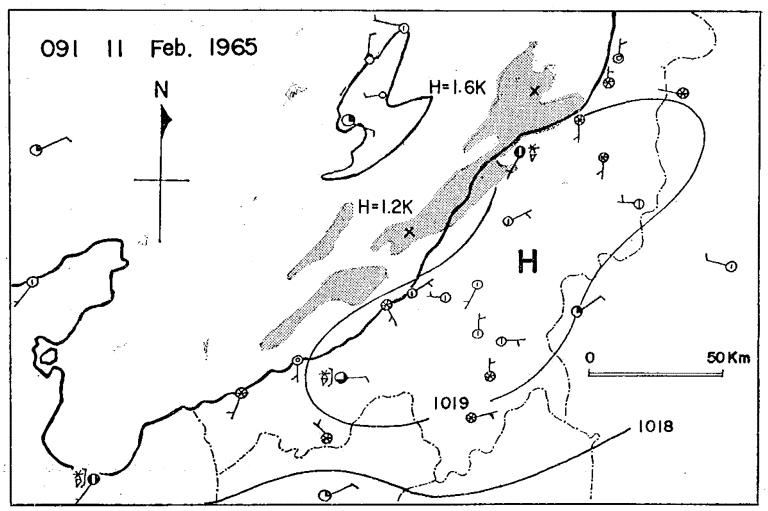


Fig. 27. Surface meso-map for 0900 JST 11 January 1965. Radar echo groups are stippled.

inland region, northerly wind from the sea, converge along the coastal line and bring about plain snow. Fig. 27 shows the surface meso-map and distribution of radar echo. The striking fact is that the radar echoes are lined up in streaks along the coastal line, and the echo height, 1.2–1.6 km, is comparatively low because of the stable layer. It should be pointed out from experience that plain snow of this kind often gains in intensity from night to early morning, weakening in the daytime, and that the snowfall reaches several centimeters.

5. Mesoanalyses of snowfall accompanying the smaller cyclone

In connection with the heavy snowfall of December 1957, the author pointed out, for the first time, that we have heavy plain snow in the Hokuriku District when the upper air temperature is abnormally low and the smaller cyclone or disturbance passes over the Hokuriku District. Later, the results of snowfall analysis on December 1960 and January 1963 indicated that finding out and tracking the smaller cyclone and disturbance is valuable for the forecasting of heavy snowfall. The recent developments of radar observation in the Hokuriku District have revealed some interesting features; that is to say, we may visualize one of the smaller cyclones as a vortical echo on radar scope. Summarizing the results of studies, it is suggested that the smaller cyclones which bring forth abundant snowfall are formed synoptically in the following four cases:

(1) as a developing frontal wave accompanying the cold front moving southwards across the Japan Sea (Fig. 21–(c), example 3 for January 23, 1963).

(2) in the intense lower convergence area under an unstable stratified condition around the center of a cold vortex over the Japan Sea (Fig. 21–(e), example 3 for January 23, 1963 and Fig. 28, example 6 for December 31, 1960).

(3) in the intense surface wind convergence area at the beginning of intense NW-

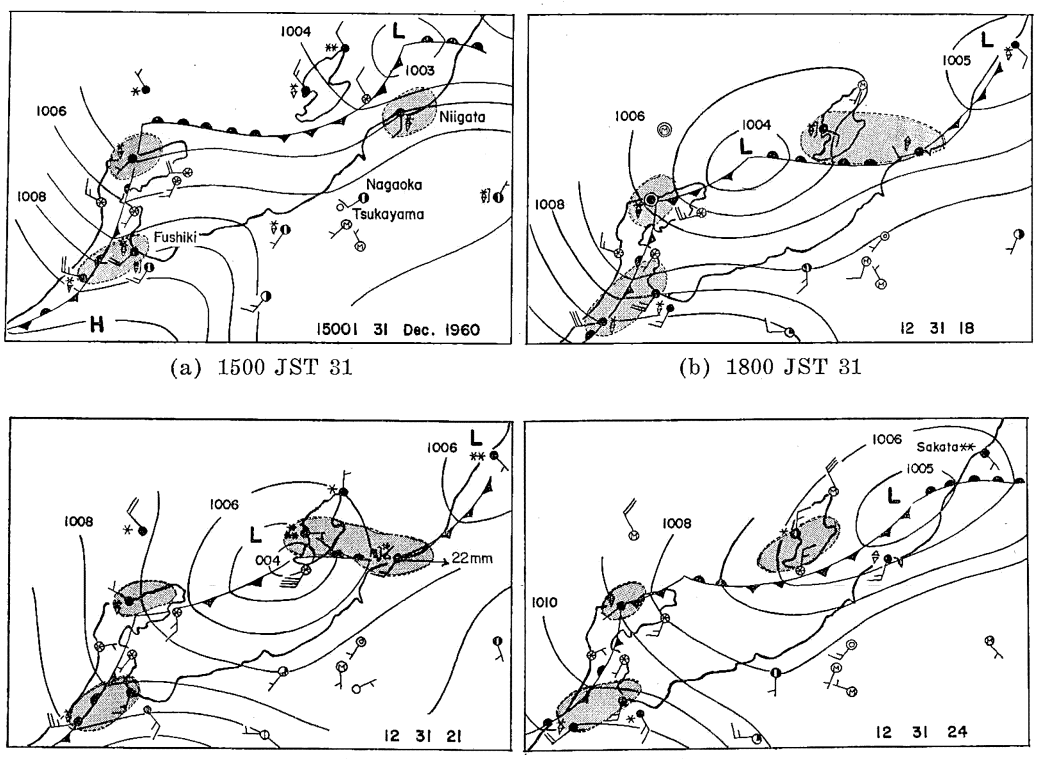
monsoon prevalence (Fig. 32, example 9 for February 3, 1965).

(4) in advance of a cold vortex or upper trough which has moved from the Continent into the western part of the Japan Sea under a situation of baroclinic instability and across the Hokuriku District (Fig. 29, example 7 for January 23 1966 and Fig. 31, example 8 for January 15, 1967).

As the case (1) has already been described in Paragraph 4.1, the cases (2), (4) will be discussed in the following paragraphs and the case (3) in Paragraph 6.2.

5.1 Analysis of snowfall accompanying the smaller cyclone developed in a coastal convergence area (example 6)

From December 29, 1960 to January 1, 1961, recordbreaking heavy snowfalls were observed: 175 cm in 24 hours at Tsukayama, 125 cm at Nagaoka in Niigata Prefecture from 30 to 31 December, and 62 cm in 24 hours at Niigata City, 89 cm at Fushiki from 31 December to 1 January. Fig. 28 shows a series of surface meso-



(a) 1500 JST 31 (b) 1800 JST 31

(c) 2100 JST 31 (d) 2400 JST 31

Fig. 28. Surface meso-map for 31 December 1960. Stipple areas indicate 3-hourly precipitation exceeding 3 mm.

maps during this period; the 500 mb chart has already been shown in Fig. 6. The remarkable convergence and unstable area caused by the cold vortex, the bulge pattern of isobars, were formed along the coastal line of the Hokuriku District which

lay on the SE side of the upper cold vortex. Under this synoptic condition, a smaller cyclone was formed near the Noto peninsula, moved to northern Niigata Prefecture passing over Sado Island. The main results of mesoanalysis are summarized as follows:

(1) The coastal region always coincides with the area of surface wind convergence throughout the winter season, but when the smaller cyclone is formed and developed, the convergence increases. Namely, the smaller cyclone was found to develop only in the mesoscale convergence zone of the order of -1×10^{-4} sec^{-1} by using the quadrangle network formed by Wajima, Aikawa, Niigata and Takada.

(2) A smaller cyclone forms in the convergence area, and moves eastwards passing around the Noto Peninsula and Sado Island with the velocity of about 20 km hr^{-1} which is in good agreement with the wind speed at 700 mb level observed by airplane over the sea off Sakata.

(3) Around Sado Island, in the vicinity of the cyclone, an intense snow storm with a wind speed of 20 m/s and a snowfall intensity of 22 mm/3 hr with thunder at Niigata City was recorded on its arrival. These observational facts suggest the severity of this mesoscale disturbance. The existence of strong wind caused by the disturbance mentioned here is similar to the example in Fig. 21(a).

(4) The scale of the cyclone are about 200 km in maximum diameter of its circular isobar and its lifetime about several hours.

5.2 Analyses of snowfall accompanying the smaller cyclone that appeared in advance of an upper cold vortex or trough (examples 7, 8)

When the cold vortex or cold tongue located at Lake Baikal or the upper Lena River moves southwards and arrives at the northern Korea Peninsula or the northern Yellow Sea, a smaller cyclone sometimes forms at the western part of the Japan Sea, on the leeside of the trough. The analytical fact that the cyclone develops on the forward side of a cold vortex or cold tongue, is fully explained theoretically: as is well known, on the forward side of a cold vortex, the upward air current predominates because of advection of vorticity and thermal vorticity. In this case the smaller cyclone is found 500–1,000 km downstream from the position of the trough or the center of the cold vortex. On the other hand the smaller cyclone mentioned in the previous paragraph is observed inside or at the center of the cold vortex where the downward air current is predominant and its lifetime and horizontal scale are smaller than those of the cyclone analyzed in this paragraph. Therefore, a new theory seems to be necessary.

In Fig. 29 (left), when the isothermal of −40°C surrounding the cold vortex at 500 mb level from the Lena River arrived at the northern Korea Peninsula on January 23, 1966, a smaller cyclone was originated in the western part of the Japan Sea, about 450 km downstream from the vortex, and moved to the southern Tōhoku District with a speed of about 40 km/hr. Surface meso-maps when the smaller cyclone was formed and passed across the Hokuriku District are shown in Fig. 29 (right). The scale of the cyclone and its lifetime are about 300 km and 18 hours respectively, and the cyclone dissipated at the southern Tōhoku District. Therefore, without the observed data afforded by ships the smaller cyclone could scarcely be detected. The

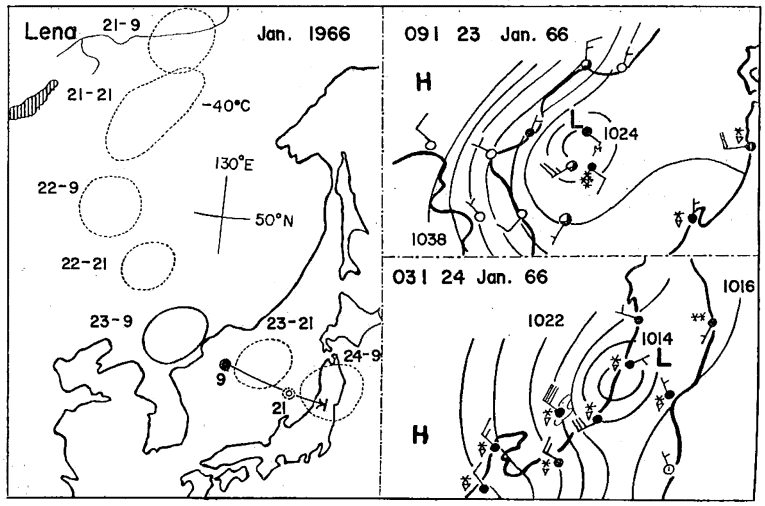


Fig. 29. Left; successive positions of the cold vortex surrounded by −40°C isotherm at 500 mb, 21-24 January 1966. Right; surface meso-maps, 0900 JST 23 and 0300 JST 24 January 1966.

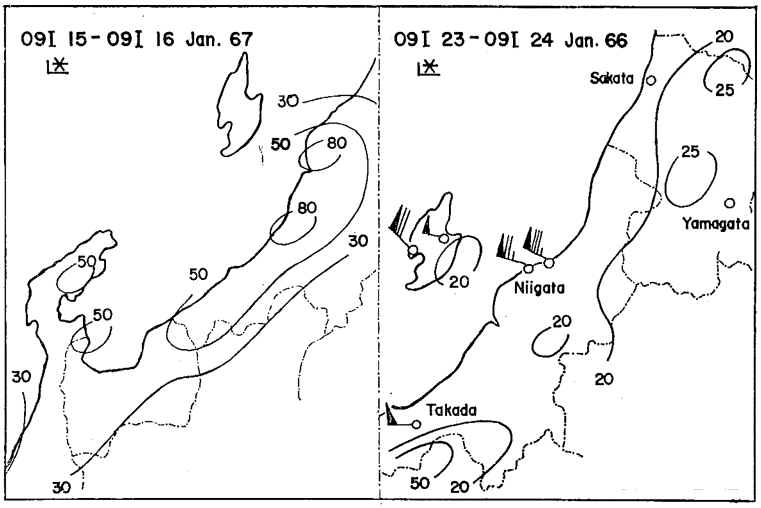


Fig. 30. Left; distribution of snowfall amount (cm) from 0900 JST 15 to 0900 JST 16 January 1967. Right; distribution of snowfall amount (cm) and maximum instantaneous wind speed (knot) from 0900 JST 23 to 0900 JST 24 January 1966.

snowfall intensity and the instantaneous wind velocity along the path of the cyclone were very large, as shown in Fig. 30 (right), although the daily snowfall amount was not remarkable (example 7).

In Fig. 31 (left), we see that, when the isothermal of −40°C surrounding the cold tongue at 500 mb from the Lake Baikal arrived at the northern China on January 15, 1967, a smaller cyclone was formed at the western part of the Japan Sea, about 1,000 km downstream from the tongue, moved toward ESE with a speed of

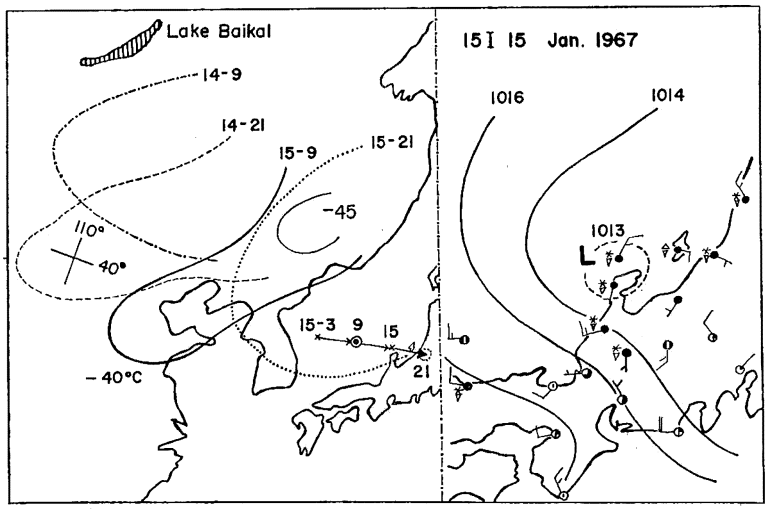


Fig. 31. Same as Fig. 29, but for the period from 14 to 15 January 1967.

46 km/hr and invaded the Hokuriku District. The cyclone presented here is of so small a scale that it could hardly be detected without the observational data afforded by ships at the beginning of its formation, but it was possible to catch the cyclone by pressure fall by isallobaric analysis. The diameter and lifetime are about 300 km and 18 hours, respectively, and the smaller cyclone passed through central Niigata Prefecture and brought remarkable plain snow in the Hokuriku District, shown by the surface meso-map in Fig. 31 (right), with the distribution of snowfall amount as in Fig. 30 (left).

6. Mesoanalyses of snowfall accompanying the vortical disturbance

6.1 Existence of vortical disturbance

It has been pointed out above that heavy snowfall in the plain area of the Hokuriku District is caused by the successive passage of mesoscale disturbances or smaller surface cyclones in the vicinity of a cold vortex center. Recently, the author found out an interesting and remarkable fact that, during the period of heavy snowfall, vortical disturbances like midget-typhoons with spiral radar echoes have often been formed and developed over the sea off the Hokuriku District, which could be tracked inland from the sea and brought considerable amounts of precipitation. It has been confirmed too by the newly-established radar at Tōjinbo that these disturbances are actually formed and contribute greatly to the making of a heavy snowfall (FUJIWARA, 1967). These small disturbances, which usually accompany a definite cyclonic pressure pattern, should be called "mesocyclones", since their horizontal dimensions are one order of magnitude smaller than those of ordinary typhoons, which have a diameter of several hundred kilometers, and larger than those of tornadoes, whose diameter is several hundred meters. In this report is presented the mesoscale study of snowfall accompanying such vortical disturbances.

6.2 Actual examples of vortical disturbance (examples 9–11)

(1) *February 2–3, 1965 (example 9)* On February 2–3, 1965, the plain and mountainous regions in Niigata Prefecture had the heaviest snowfall of the winter season of the year. As shown in Fig. 32 (left), a well-developed monsoon prevails over the Hokuriku District, and the surface pressure field shows a typical wintertype distribution, but in the surface meso-map in the same figure (right) we find that a rotat-

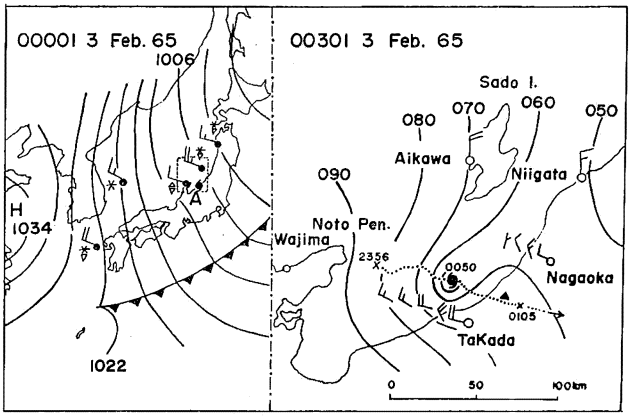


Fig. 32. Surface weather map for 0000 JST 3 February 1965 (left) and surface meso-map in area A for 0030 JST 3 February 1965 (right). The center of vortical disturbance is shown by the symbol ⊛.

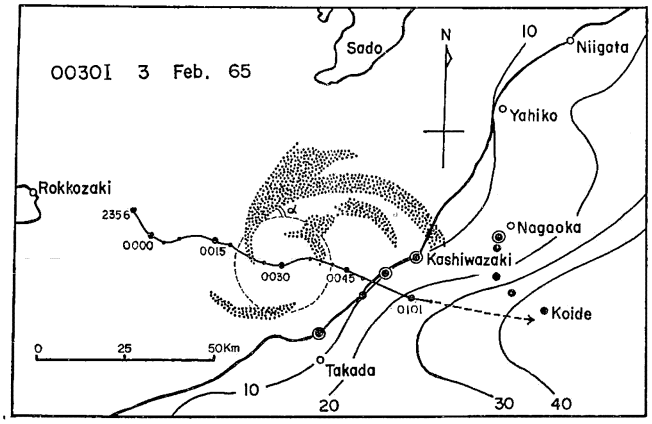


Fig. 33. Distribution of snowfall amount (cm) from 1600 JST 2 to 0800 JST 3 and spiral radar echo (shaded area) at 0030 JST 3 February 1965. The center of the vortical disturbance moved along the line with an arrow. Black circles indicate railway stations equipped with automatic recording instruments. The crossing angle α is defined by the angle at which the spiral band intersects any circle (dotted line) having its center at the disturbance center.

ing disturbance lurks in the coastal area. This vortical mesoscale disturbance was formed on the sea off the Noto peninsula, moved SEwards and arrived in the southern part of Niigata Prefecture as shown in Fig. 33. The distribution of the snowfall amount was the mountain-snow type and the zone of largest snowfall amount was along the track of the disturbance, extending from Kashiwazaki to Koide, but we can not, for lack of data, make sure whether this was due to the disturbance. The radar echo associated with the vortical disturbance had a well-defined spiral-like appearance similar to that of a typhoon, and persisted for 1.5 hours until it decayed over the mountain area of Niigata Prefecture. In this example, the diameter of the "eye" was about 20 km and the horizontal scale of this disturbance was about 80 km in diameter.

(2) *February 1, 1963 (example 10)* A vortical disturbance was formed in the warm sector of the cyclone over the Japan Sea. The surface weather map is shown in Fig. 34 (left), the vortical disturbance with spiral echoes and the distribution of snowfall amounts in Fig. 34 (right). In this example, there is little doubt about

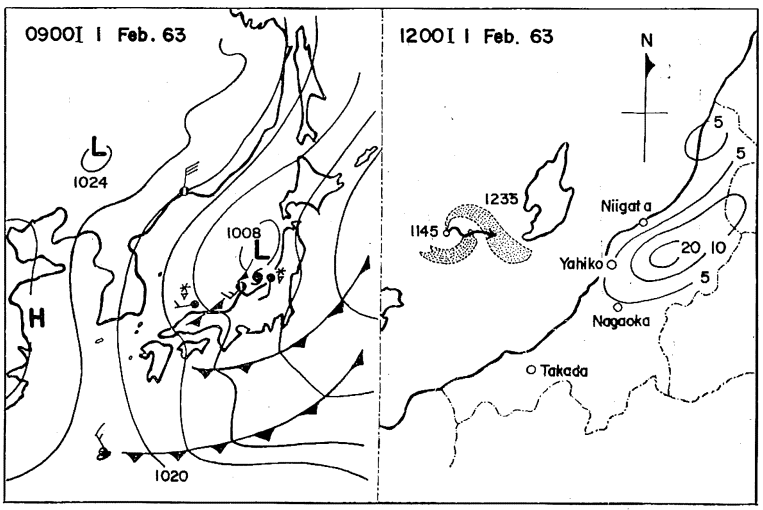


Fig. 34. Left; surface weather map for 0900 JST 1 February 1963. Right; distribution of snowfall amount (cm) from 0800 to 1600 JST 1 and spiral radar echo (shaded area) at 1200 JST 1 February 1963.

the occurrence of snowfall concentrated in a small area corresponding to the passage of the vortical disturbance, though lack of continuous radar data precludes any judgment concerning this latter's contribution in the snowfall. But we can find out a typical vortical disturbance with a diameter of about 60 km in horizontal scale and an eye of 10 km diameter over the sea in the vicinity of the Noto peninsula and Sado Island.

(3) *January 22, 1966 (example 11)* On January 22, 1966, the plain region in the Hokuriku District had a heavy snowfall. Especially, the small area around Takada City, Niigata Prefecture, had a record-breaking local snowfall as shown in Fig 46. In Fig. 35 are presented the surface weather map and the 500 mb chart, and the

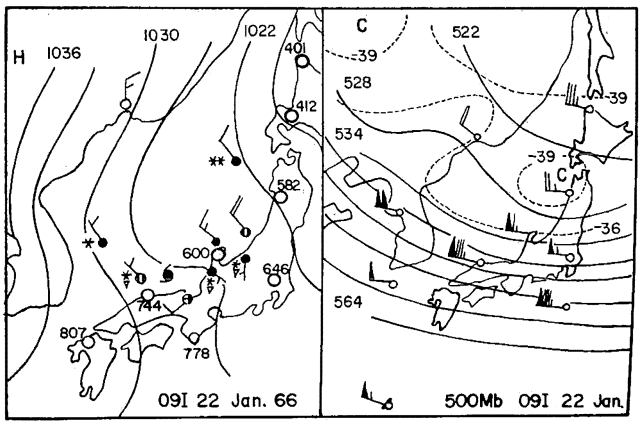


Fig. 35. Surface and 500 mb weather maps, 0900 JST 22 January 1966.

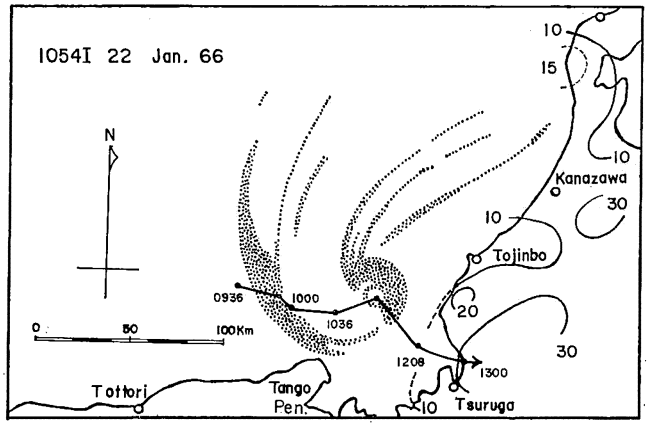


Fig. 36. Distribution of snowfall amount (cm) from 0900 JST 22 to 0900 JST 23 January and spiral radar echo (shaded area) at 1054 JST 22 January 1966.

Fukuro-type barometric distribution (see Section 1.2 above) and the existence of an upper cold vortex over the Sea of Japan lead one to expect a heavy snowfall in the plains of the Hokuriku District. Under this situation, by radar observations at Mt. Yahiko and Tōjinbo we found a number of vortical disturbances, as shown in Fig. 46. We show in Fig. 36 a typical one of them which was formed over the sea off the Tango peninsula, moved ESEwards and passed through the northern part of Tsuruga City. A remarkable fact is that a sudden pressure fall, change in the surface wind direction and burst of snowfall intensity were observed on its arrival. The scale of the spiral echo, about 100 km in diameter, is somewhat larger than those observed in the winters of 1963 and 1965 mentioned in the previous two examples. The lifetime seems to be about 4 hours, which is longer than the other examples.

(4) *Other examples* In addition to the three examples mentioned above, there are many vortical disturbances observed at Mt. Yahiko and Tōjinbo during the five win-

ters from 1963 to 1967, and some studies on these disturbances have been reported already (FUJIWARA, TATEHIRA and YANAGISAWA, 1967). Summarizing as to the vortical disturbances observed up to the present, the author would like to classify the pressure patterns responsible for the disturbances into the following three types:

(i) *Under intense NW-monsoon prevalence immediately after a cold front passage*
0030 JST 3 February 1965 (sea in the vicinity of Noto and Sado)
1009 JST 1 December 1965 (sea off Fukui)
0315 JST 5 February 1966 (sea off Fukui)

(ii) *At the end of NW-monsoon prevalence or under the pressure pattern of "Fukuro-type"*
1812 JST 18 January 1966 (sea off the Tango peninsula)
0330 JST 21 January 1966 (sea off the Tango peninsula)
1054 JST 22 January 1966 (sea off the Tango peninsula)
1611 JST 22 January 1966 (western sea off the Noto peninsula)

(iii) *In the "warm sector" of a cyclone over the Japan Sea*
1200 JST 1 February 1963 (sea in the vicinity of Noto and Sado)

In sum, the disturbance seems to be formed in geographically limited areas such as the sea off Tango, or the sea between the Noto peninsula and Sado Island. From this we suspect that the necessary condition for the formation of such disturbances is a strong lower convergence which is caused by the combination of topographical and synoptic effects.

Figs. 37, 38 and 39 are radar photographs of the examples described above. We can easily find the rotating character of the vortical disturbances by 16-mm movies of the radar echoes taken at Mt. Yahiko (647 m above sea level) and Tōjinbo (105 m above sea level).

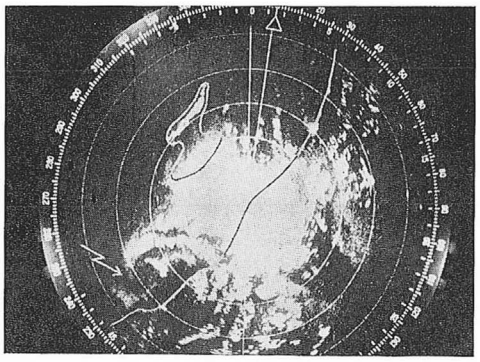


Fig. 37. PPI radar scope photograph at Mt. Yahiko at 0030 JST 3 February 1965. Range marks are 20 km.

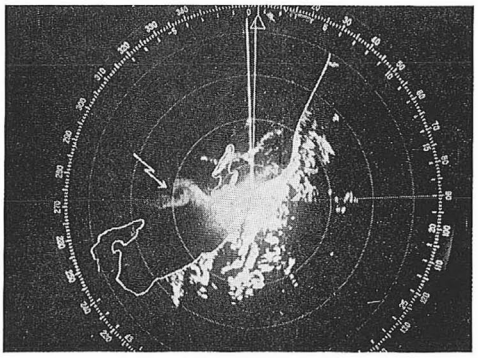


Fig. 38. Same as Fig. 37, but for 1200 JST 1 February 1963. Range marks are 50 km.

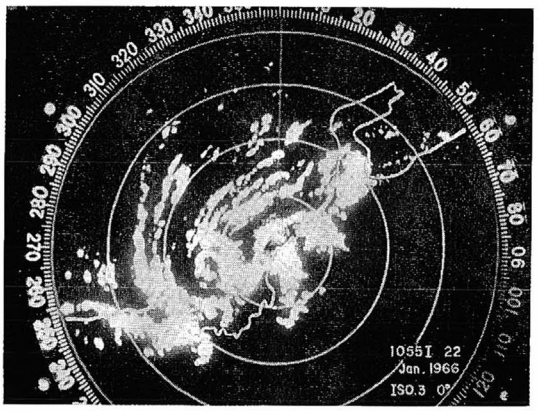


Fig. 39. PPI radar scope photograph at Tōjinbo at 1055 JST 22 January 1966. Range marks are 50 km.

6.3 Meso- and radar analysis of vortical disturbances

On February 2–3, 1965 (example 9) and January 22, 1966 (example 11), we successfully obtained a series of radar pictures of the formation and subsequent development of vortical disturbances in the Hokuriku District. These will be subjected to detailed analysis.

(1) *Movement of the center of disturbance* As shown in the examples, the tracks of the vortical disturbances makes an apparent sinusoidal oscillation around the mean path. This feature is very similar to that of an ordinary typhoon. The movement of the center of vortical disturbance is quite complicated compared with that of the ordinary snow echo cell. The former is characterized by a rotating component and the latter by straight translation.

The center of logarithmic spiral or the geometrical center of the echo was applied in determining the center of the disturbances. The crossing angle α, defined by the angle at which the band intersects any circle having its center at the disturbance center, was estimated to be about 30° for the example 9 (Fig. 33), and 42° for the example 11 (Fig. 36). These angles were larger than that of an ordinary typhoon, whose angle is usually 10–20° (Observation Division of J.M.A., 1966). It is thus to be noted that the large crossing angle of the spiral band of vortical disturbance is an important feature. T. FUJITA (1963) shows that an important feature of the precipitation bands of a mesocyclone is its extremely large crossing angle, 45–60°. He considers it due to the difference in internal structure between mesocyclones and small hurricanes.

By use of a series of radar pictures of the example 9, as shown in Fig. 40, the development and dissipation of vortical disturbance was investigated. The existence of vortical disturbance was first seen as a fingered echo curling around the circulation center. To the north of the path of the disturbance, a spiral echo developed gradually and then it became indistinct and hardly detectable as it moved from the sea to the mountainous region. It was found that the two disturbances shown in Fig. 33 and 36 moved along in a direction about 25° and 10° to the right of the

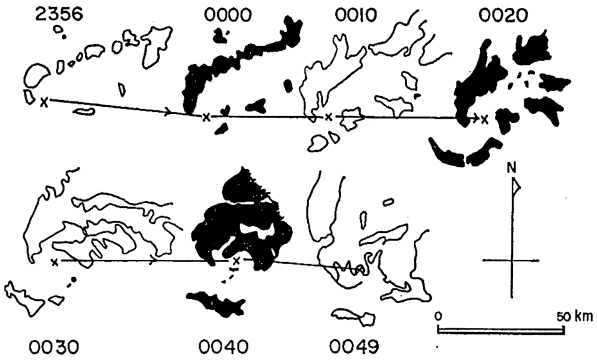


Fig. 40. Development and change in the spiral echo of vortical disturbance on 2-3 February 1965.

direction of the 700 mb wind at the nearby rawinsonde stations Wajima and Yonago, and the moving velocities were estimated to be 80 km/hr and 60 km/hr, respectively. These are in good agreement with the 700 mb wind speed at Wajima and the 2.7 km-level wind speed at Yonago, both of which are equivalent to that at the echo top, about 3,000 m. It is concluded that the disturbance moves in the direction about 10–20° to the right of the 700 mb wind direction with a velocity equivalent to the 700 mb wind in the vicinity of the disturbance.

The vortical disturbance may be formed over the sea off the coastal region, and then moves inland and gradually dissipates over the mountainous region because of the surface friction. The lifetime, the time from formation to dissipation of a disturbance seems to be within several hours. This value is much larger than the mean lifetime of a thunderstorm cell which is less than 1 hr (FUJITA, 1963). The

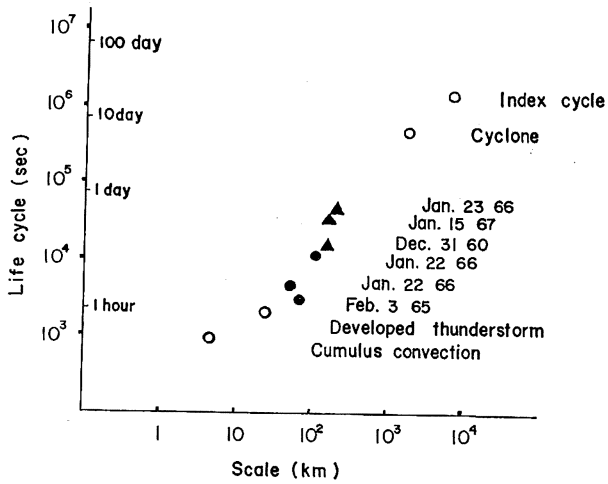


Fig. 41. Relation between the life cycles and horizontal scales of synoptic disturbances ranging from cumulus convection to index cycle. Symbols ● and ▲ show cases of vortical disturbances and smaller cyclone, respectively.

relations between life cycles and horizontal scales of synoptic disturbances ranging from cumulus convection to index cycle are shown in Fig. 41 (MATSUMOTO, 1967). Plotting in the figure the characteristic dimensions of the smaller cyclone and vortical disturbance studied in the previous paragraphs, we can easily recognize a linear relation among them. Thus the mesoscale disturbances associated with heavy snowfall is characterized by a diameter of 50 to 300 km and lifetime of less than 20 hours, and vortical mesoscale disturbances, in particular, by a diameter of 50 to 100 km and lifetime of less than several hours.

(2) *Mesoanalysis of disturbances*

(i) *Example of February 2–3, 1965 (example 9)* As the observation network in the coastal region of the Hokuriku District is very sparse, we rarely get a chance of closely tracking the process of a vortical mesoscale disturbance with a diameter of about 50 km. On February 2–3, 1965, fortunately, the data of a relatively dense network was obtained in the coastal region by adding to the regular network 9 railway stations equipped with automatic recording instruments, such as anemographs and barographs. In Fig. 33 is shown the distribution of the observing stations in the area under consideration.

Time sections of surface weather elements observed at Kashiwazaki and Takada during the passage of the vortical disturbance are given in Fig. 42. The disturbance passed near Kashiwazaki. A rather weak wind was observed at Kashiwazaki, which lasted for about 20 minutes around the time when the minimum surface pressure was observed, 0100 JST February 3. It seems reasonable to suppose that there was a rather weak wind near the center and a strong wind at a distance of about 25 km from the center, if a steady movement of the disturbance is assumed. This feature is quite similar to that of the typhoon wind field and coincides with the relation between v_θ and r estimated by the moving velocity of an echo shown in the following paragraph. The changes in weather elements obtained at the selected stations with the passage of the vortical disturbance may be summarized as follows. The intensity of snowfall was 2 mm/hour in Nagaoka, maximum instantaneous wind speed 20–22 m/s in the coastal area and 15 m/s inland. The barographs indicate the distinct

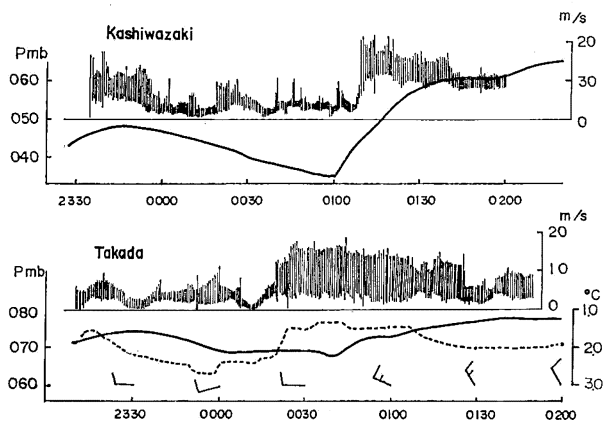


Fig. 42. Variation of wind speed, surface pressure (full line) and temperature (dotted line) at Kashiwazaki and Takada, 2-3 February 1965. Long barb: 10 kts, short barb: 5 kts.

dip-then-rise pattern of 2.0–1.3 mb difference in the coastal area and mountainous region such as Koide. On the other hand, radar failed in tracking of the disturbance as soon as it entered the mountainous region near Kashiwazaki. Therefore, only the barograph observations at railway stations were available to track it to the mountainous region near Koide (Fig. 33).

A surface meso-map was made and shown Fig. 32 (right) by converting the time sections at the available observations into space sections. We see in the figure that the disturbance lurks behind the isobars which run in the direction of NW to SE.

(ii) *Example of January 22, 1966 (example 11)* Next, let us look at the detailed structure of the typical disturbance which passed the northern part of Tsuruga City, shown in Fig. 43, using the hourly observed data in Fukui and Ishikawa Prefectures. Fig. 44 shows the horizontal cross-section along the chain line in Fig. 43, perpendicular to the track of the disturbance, and the hourly meteorological elements

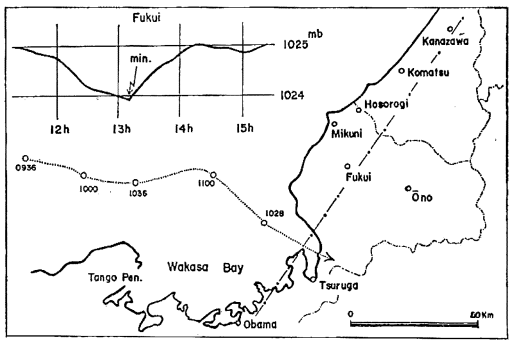


Fig. 43. Track of vortical disturbance and variation of surface pressure at Fukui, 22 January 1966.

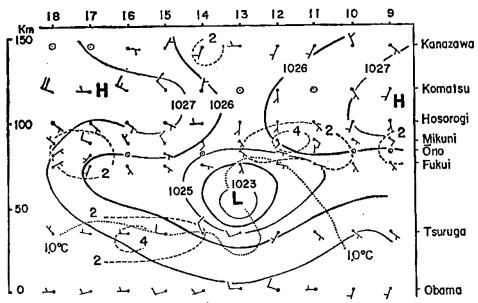


Fig. 44. Hourly variation of meteorological elements corresponding to the passage of vortical disturbance, 22 January 1966. Broken and dotted lines show hourly amount of snowfall (mm) and isotherm (1.0°C), respectively.

at the stations are projected on the chain line. It is noticeable that areas of intense snowfall, 4 mm/hour, appear both in the front and the rear of the disturbance, warm air flows into the front and cold air into the rear of it. The structure of disturbance, which is on a small horizontal scale, about 80 km in the direction of S to N, is pretty similar to one on a synoptic scale. The variation of the barograph at Fukui caused by the disturbance is also presented in Fig. 43 (upper). The amplitude of pressure change is about 1.2 mb, which is far smaller than that of a synoptic-scale phenomenon, which is several tens of milibars.

On this day, an other vortical disturbance moved eastwards passing across the Noto peninsula and the variation of meteorological elements corresponding to the passage of the disturbance is shown in Fig. 45. Since the disturbance was of a rather small scale, which was about 60 km, the variation of elements was small. But abundant snowfall amounts of 1.2 mm in 10-min. at Wajima, 1.0 mm in 10-min. and a

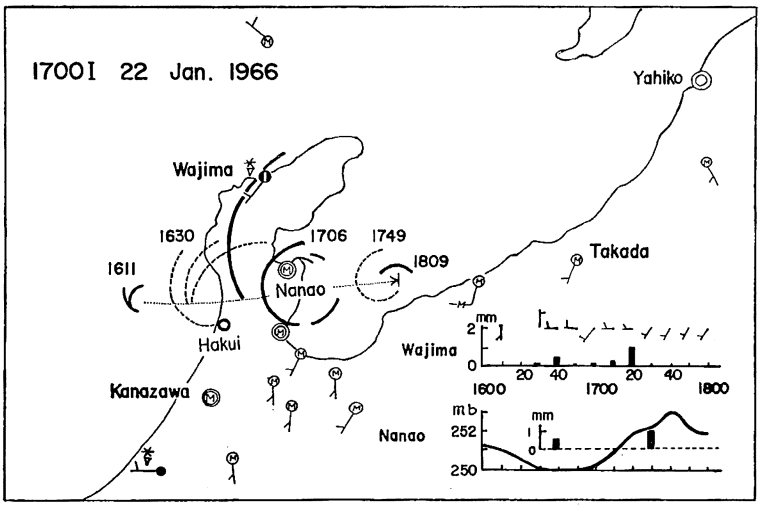


Fig. 45. Variation of meteorological elements corresponding to the passage of vortical disturbance, 22 January 1966.

pressure drop of 2 mb at Nanao and Hakui, were recorded on its arrival. The disturbance was formed to the west of the Noto peninsula, was at its height of development at the peninsula and dissipated at Toyama Bay. The lifetime seems to have been about 2 hours.

Furthermore, as one of the Heavy Snow Storm Project Observations, the distribution of the sea surface temperature was obtained and given in Fig. 46. The most noticeable feature of it is that the vortical disturbance seems to have been formed at an area where contour lines of sea surface temperature are crowded or

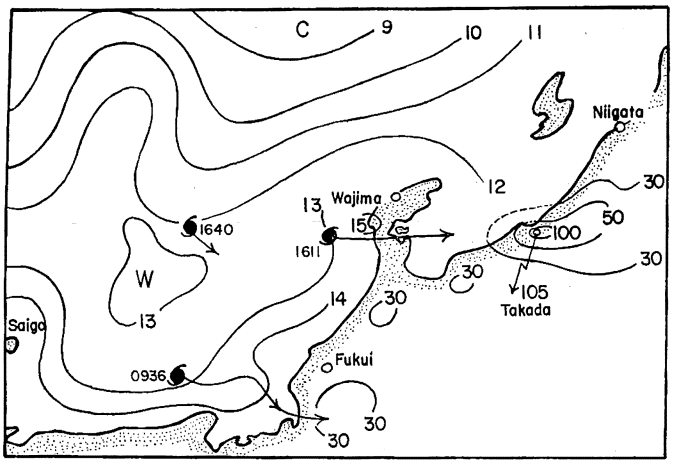


Fig. 46. The distribution of sea surface temperature (°C) observed from 14 to 27 January 1966. Arrows show the movement of vortical disturbance at 22 January 1966. The snowfall amount (cm) in the Hokuriku District observed from 0900 JST 22 to 0900 JST 23 is also shown.

over a warm sea current where vapour and sensible heat are freely supplied. This observed fact needs to be confirmed by further data in future.

6.4 Dynamical analysis of vortical disturbance

When we treat of a physical magnitude such as circulation around the center of a vortical mesoscale disturbance, it is difficult to estimate the wind field around the disturbance because of absence of observed data. It is well known that the movements of individual radar echoes are in good agreement with the upper winds at the same level (TATEHIRA, 1961). In the present analysis the upper winds were estimated from the movement of radar echoes. In the example of February 3, 1965 (Fig. 37) with 1.5 degrees of elevation angle, the height of the radar beam is 2.4 km at a place 60 km distant from the radar site. Therefore, it would be reasonable to assume that the height of the upper wind is about 2 km in both of the examples of February 3, 1965 and January 22, 1966 (Fig. 39). Fig. 47 shows the relative cyclonic circulation around the center of disturbance obtained by subtracting the

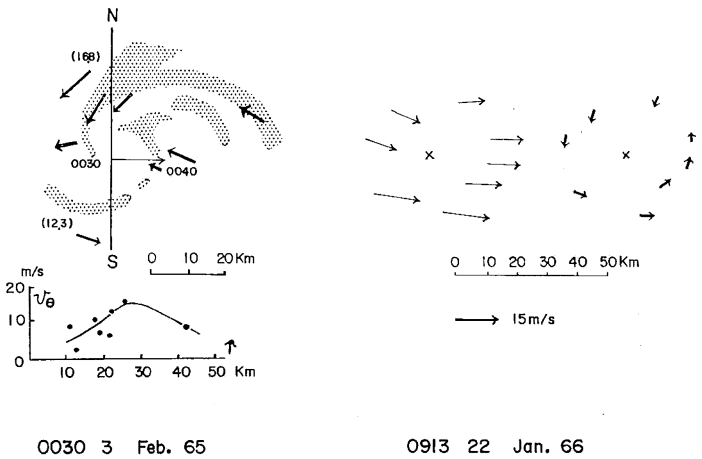


Fig. 47. Cyclonic wind relative to the movement of the center of vortical disturbance and relation between tangential speed of the circulating parcel and radius. Thick arrows, numbers in parenthese and shaded areas indicate wind vectors, wind speeds (m/s) and spiral band, respectively.

moving velocity of the system of disturbance from the actual movement of the echo. The relation between the tangential speed v_θ and the radius from center r is shown in the lower part of the figure. The tangential speed of the air circling around the center has its maximum value at a distance of 25 km and a rather weak wind speed is obtained near the center. These facts are in good agreement with the result of mesoanalysis mentioned in the foregoing section, although they were derived from wind fields of different levels—surface and upper.

From the wind data estimated around the vortex given in Fig. 47 (left), the distributions of velocity divergence and vorticity at 7.5 km grid points were calculated by applying interpolation of the wind data and assuming a weak wind near the center as shown Fig. 48. It is interesting to see that the spiral bands correspond to the

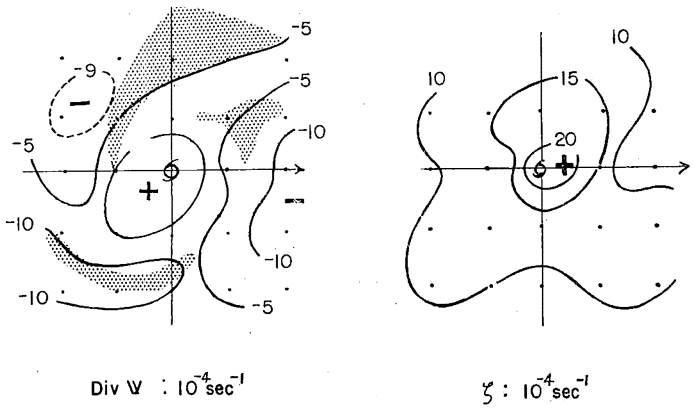


Fig. 48. Distribution of divergence (left), vorticity (right) around vortical disturbance in 10^{-4} sec^{-1}, 0030 JST 3 February 1965. Shaded areas indicate spiral bands.

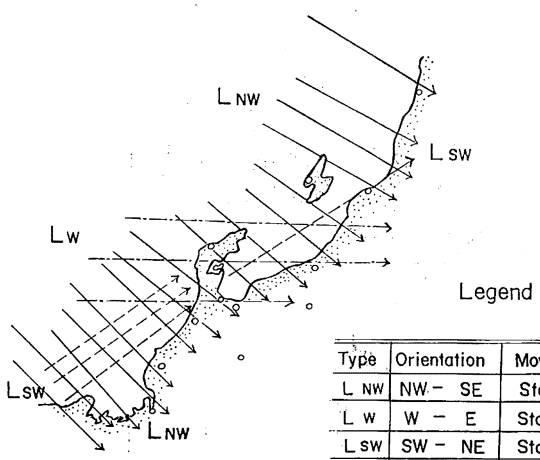
convergence zones qualitatively. The value of vorticity is of the order of 10^{-3} sec^{-1}, one order larger than that of convergence, which is 10^{-4} sec^{-1}. The convergence estimated here accompanied by an intense ascending air current, which is more than several tens of centimeters per second and brings forth with it a considerable amount of precipitation. Thus these values are typical of the mesoscale disturbance in heavy snowfalls in the Hokuriku District.

Using the values of convergence for February 3, 1965, the intensity of snowfall can be estimated. That is to say, the mean value of convergence at 2 km level was assumed to be -5×10^{-4} sec^{-1} based on Fig. 48, and the convergence to have a linear decrease with height up to the level of non-divergence which is at 3 km level. As can be seen from the vertical distribution of convergence for the formative stage of a mesoscale disturbance in heavy snowfall in the Hokuriku District shown in Fig. 24 and from the result obtained by S. MATSUMOTO (1967), the assumption can be accepted to be quite realistic. Under this circumstance, the intensities of precipitation were estimated by using the so-called condensation function F and the values of the upward air current derived from convergences at each level. Then the estimated snowfall intensity will be about 2 mm in 10-min. If a place is affected by a disturbance for 30 min., the snowfall amount at the place is estimated to be 6 mm. Although the amount thus obtained may not be so large, this will be enough to suggest the existence of a close relation between the passage of such disturbances and the variations in the intensity of short-time and locally limited snowfall, and also to establish the possibility of their successive passages causing heavy snowfall cumulatively.

7. Radar analysis of snowfall

7.1 Characteristics of the radar echo pattern under winter monsoon prevalence

The distributions of radar echoes in the Hokuriku District in connection with monsoon prevalence in winter have been checked and analyzed. And the following three distribution patterns have been identified: (1) Chaotic and at random (R), (2) Line-shaped (L), (3) Vortical and ring-shaped (V).



Legend

Type	Orientation	Movement	Place of snowfall
L NW	NW - SE	Stationary	Mountain
L W	W - E	Stationary	Plain
L SW	SW - NE	Stationary	Plain
L'SW	SW - NE	SE - ward	P. & M.

Fig. 49. Schematic model showing the pattern of radar echoes during winter monsoon in the Hokuriku District.

We classify the line echoes by orientation, moving direction and snowfall distribution, and show them schematically in Fig. 49. It is to be clearly noticed that a certain band structure of echo arrangemnt predominates in connection with a certain distribution type of snowfall.

The sequence of appearance of various echo patterns in one period of monsoon prevalence is often, though not always, as follows:

$C \longrightarrow L'_{SW} \longrightarrow (V) \longrightarrow R \longrightarrow L_{NW} \longrightarrow L_W,\ L_{SW} \longrightarrow (V)$; east of the Noto peninsula

$C \longrightarrow L'_{SW} \longrightarrow (V) \longrightarrow R \longrightarrow L_{NW},\ L_W,\ L_{SW} \longrightarrow (V)$; west of the Noto peninsula,

where, C denotes a plain echo connected with a cyclone, L'_{SW} a progressive line echo directed from SW to NE, L_{NW} one directed from NW to SE, L_W one directed from W to E and L_{SW} one directed from SW to NE. V, which denotes a vortex-shaped echo, is put in parentheses because of the rarity of its appearance.

7.2 Characteristic of the radar line echo

(1) *Line echo stretching from NW to SE* The representative radar echoes lined up in the direction of NW to SE when the north westerly monsoon predominates and mountain snow falls, are shown in Fig. 50 (upper). It is a composite tracing, obtained from the films of radar echoes at the radar observatories at Mt. Yahiko and Tōjinbo. It is seen that groups of small echoes appear in lines spaced 30 km apart one from the next, 10 km wide and 2.4-5.1 km high, and they seem to run approximately along the direction of the wind at 850 mb. Taking similar line echoes for January 1966 on the radar map, we obtained the geographical distributions of line echoes for the particular case when the NW monsoon predominates over the Japan sea side and show them in Fig. 51. As T. SEKIGUCHI (1961) pointed out, line echoes are distributed within a geographically limited area in the case of a typhoon, and likewise under NW monsoon prevalence there are certain areas which presumably provide favorable geographical conditions for the arrangement of line echoes. Thus the prevalence of line echoes passing Sado Island and the Noto peninsula can undoubtedly

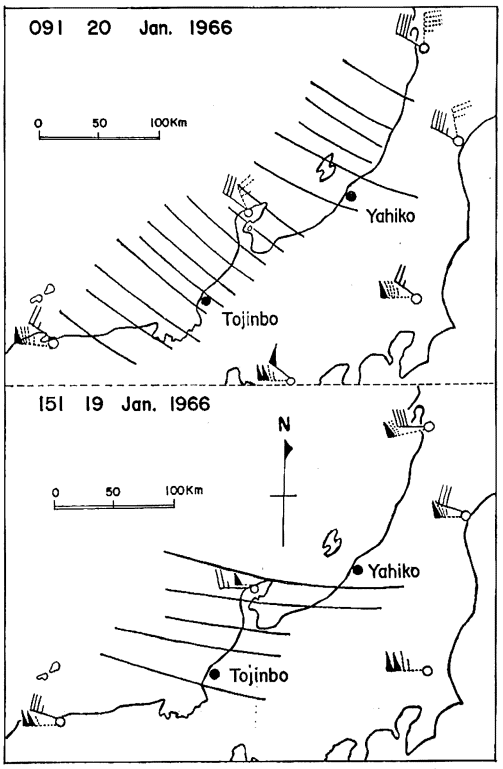


Fig. 50. Upper; composite chart of sketch of radar line echoes when NW monsoon prevailed, 0900 JST 20 January 1966 (heavy snowfall in the mountainous region). Lower; same as upper, but when NW monsoon weakened, 1500 JST 19 January 1966 (heavy snowfall in the plain).
Dotted barb: wind at 500 mb (knots).
Full barb: wind at 850 mb (knots).

be explained by orographic effects and is analogous to the formation of two vortical filaments trailing from both ends of airplane wings (MATSUMOTO, 1967), but the prevalence of line echoes over the sea off Yamagata Prefecture can not be explained in the same way. This latter must, probably, be attributed to the active convection in an air flow heated from below. In this case the spacings of the line echoes stretching NW to SE are 20-50 km; and they extend from the sea off the Hokuriku District to the Pacific side of Japan through the narrow gorges and the transverse valleys in the back-bone mountains of the Japanese mainland and disappear at a distance of 30-50 km from the watershed. For instance, the line echoes stretching from the vicinity of Niigata City to SEwards run along the Agano River, go over the watershed and disappear near Aizuwakamatsu. E. FUKUI (1966) pointed out already that the climatic boundary line for the winter season dividing the Japan Sea side and the Pacific side of Japan should be drawn somewhat — say 30-50 km — east of the backbone range. This statement of E. FUKUI's well agrees with what we have observed about radar echoes invading to the Pacific side.

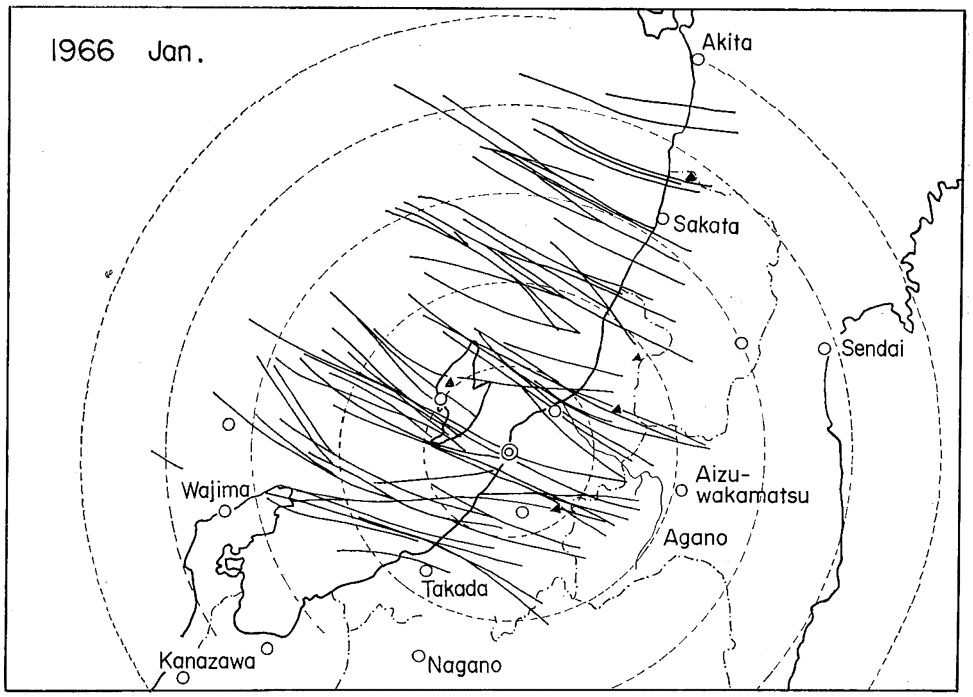


Fig. 51. Geographical distribution of radar line echoes relating to snowfall in the mountainous region, January 1966. The orientations of line echoes are from NW to SE.

(2) *Line echoes stretching from W to E and SW to NE* The representative radar echoes lined up in the direction of W to E or SW to NE when the synoptic situation is at the end of monsoon prevalence or "Fukuro-type," are shown in Fig. 50 (lower). It is seen that the echoes are lined up in bands stretching from the sea 150 km off the Noto peninsula over Toyama Bay to the plain and mountainous region in Niigata Prefecture, with 30-50 km spacings, 10-20 km wide and 5.1-5.9 km high, and they are nearly parallel to the wind direction at 850 mb or 500 mb level. With a slight variation of wind direction the orientation of line echoes changes from W-E to SW-NE. Therefore, the orientation of line echoes undoubtedly plays a very important role in the determination of the heavy snowfall area. The orientations and distributions of similar remarkable line echoes for 12 cases during the period of the Heavy Snow Storm Project Observation carried out in January from 1964 to 1966, is shown in Fig. 52. In the figure, the line echoes are seen to be concentrated in specific areas: one of the line echo systems extends from Toyama Bay inland into Niigata Prefecture passing north of Takada City and the plain between Mt. Myōkō-san and Yoneyama, and another one extends eastwards between Mt. Yoneyama and Yahiko. It is suggested that the upper wind related to the location of the cold vortex is responsible for the existence of two different line echo systems, as will be discussed in the following section. Usually line echoes stagnate, but individual echo cells move along the line echo which is made of these cells, repeating appearance and disappearance, and bring heavy snow or gust of wind over plain and mountain area. The width of a line echo is about 20 km over the sea and tends to increase up to 30-50 km and be diffused over land.

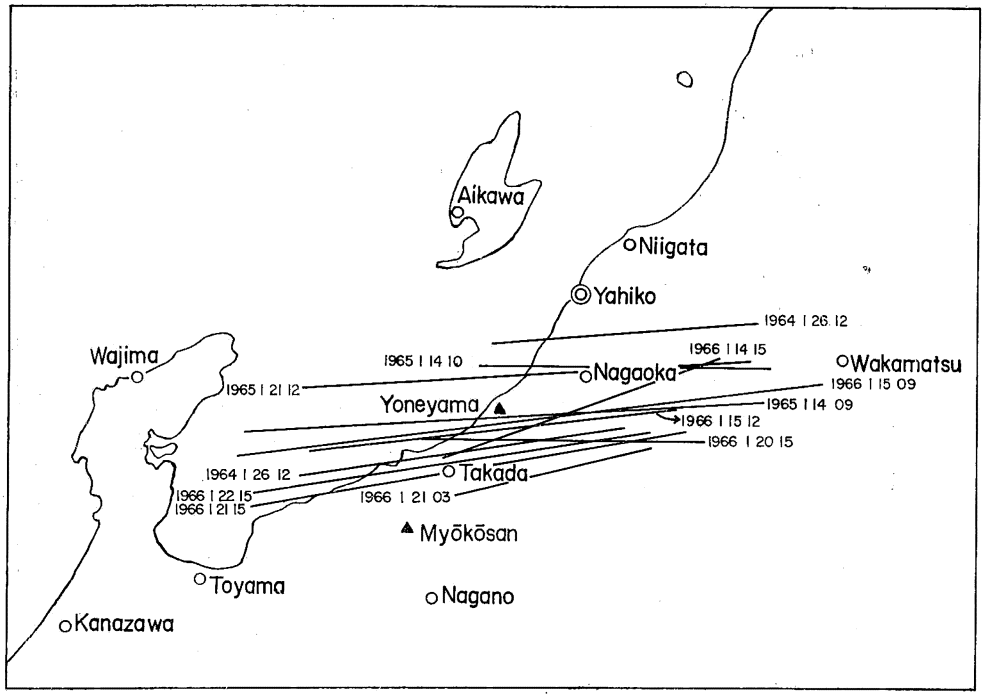


Fig. 52. Same as Fig. 51, but for snowfall in the plain, January 1964, 1965 and 1966. The orientations of line echoes are from W to E and or SW to NE.

A line echo stretching from W to E or from SW to NE has larger values of width and height than one stretching from NW to SE, and this fact suggests that the former has a more intense convective activity than the latter. As described in Chapter 3, moving echoes with orientation SW-NE appear with the passage of a cold front or a squall line, and successive invasions of line echoes from the sea bring forth snowfall on the land irrespective of whether it is plains or mountainuous region.

(3) *Relation between the appearance of line echoes and atmospheric stratification*
J. S. MALKUS (1963) stated that the orientation of cloud is associated with the wind shear between the convective cloud layer and the upper boundary layer over the tropical sea; R. TATEHIRA (1963) showed that the line echo formed by a cold front seems to be parallel to the wind shear between 850 mb and 700 mb levels. From a similar point of view, the author investigated the relation between the orientation of line echoes that appeared over the sea north of the Noto peninsula in winter and the orientation of wind shear among the adjacent layers at Wajima, using the data of 27 cases of line echo appearance from December 1963 to March 1964. Table 3 shows the mean angle (in deg.) between the orientation of the line echo (snowband) and the direction of wind shear vector between two isobaric surfaces. The positive and negative signs show that line echoes incline to the right and left, respectively, of the shear vectors, and the numeral within the frame shows a rather small angle (in deg.). Consequently, the orientation of line echoes seems to be governed by the upper wind shear at 1000-500 mb or 850-500 mb level. In general, the lower wind direction (1000, 850 mb) is NW for mountain snow and W or SW for plain snow,

Table 3. Mean angle (in deg.) between the orientation of snowband and the direction of wind shear vector between two isobaric surfaces. Positive (negative) sign shows that snowbands incline to the right (left) of the shear vectors.

Isobaric surface (mb)	850	700	600	500
1000	+75 (7) −64(20)	+13 (6) −46(21)	+10 (5) −41(21)	+ 8 (3) −27(24)
850		+33 (8) −38(19)	+45 (6) −39(21)	+16 (6) −28(21)
700			+45 (9) −60(18)	+30 (9) −32(18)

and the upper wind direction (500 mb) is NW for the former and SW for the latter case. Thus, it might be concluded that the line echoes for mountain snow are stretched from NW to SW, and for plain snow from SW to NE or from W to E, and in brief, the line echoes are nearly always parallel to the direction of wind at 1000 or 850 mb level.

By the research using the data of 13 cases of line echoes which appeared over the sea west of the Noto peninsula, observed by Tōjinbo radar, it was statistically concluded that the orientation of line echoes coincide most closely with the wind direction at 850 mb level or with the direction of the wind shear at 850-500 mb level, and the individual echo cell constituents of a line echo move along with the upper wind at 2-4 km level east of, and at 850 mb level west of, the Noto peninsula (NAKAMURA, 1966).

Next, the relations between the appearance of line echoes and the character of atmospheric stratification are exermined.

In the period 19-21, January 1966, a 3-hourly aerological observation project was carried out at Wajima. Fig. 53 shows the vertical time section which is made using the data obtained by this project and the characteristic echo patterns in this period. The continental polar air mass was flowing out over the Japan Sea under a winter monsoon situation, and a remarkable inversion layer was observed. Below the inversion layer was seen active cumulus convection with heat supply from the sea surface, but above the layer, humidity was extremely low.

Thus the inversion works as a lid on cumulus convection, and the mesoscale undulation of an inversion layer is closely related to cumulus convection, i.e., where a group of active cumuli and an abundant snowfall are observed, the inversion layer occurs at a high level. As a matter of the fact, the snowfall amounts were estimated to be 30 cm on the mountains, 5 cm on the plain in the day-time of 20 January, and then 50 cm on the mountains, 20 cm on the plain in the night of this day. The kinds of echo and the orientation and space of line echoes are shown at the bottom of Fig. 53. From these we can conclude that the following general tendencies are to be recognized:

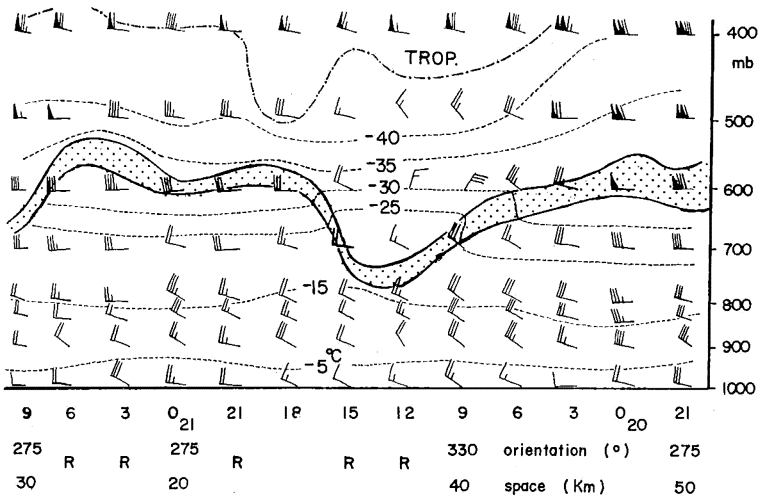


Fig. 53. The vertical time section at Wajima, 19-21 January 1966. Dotted and chain lines show isotherms labelled in °C, and tropopause, respectively. The stable boundary is stippled. Numerals at the bottom indicate the orientation and space of radar line echoes. R shows the case of random distribution of echoes.

(i) As the shear grows large, line echoes which are parallel with the shear or lower wind tend to appear.

(ii) As the shear becomes small, random echoes appear. It is probably due to the growth of Bénard's cellular convective clouds (BÉNARD, 1900).

(iii) There is a certain relation, which is difficult to define, between the height of

Table 4. The character of cloud and radar bands over the Japan Sea.

Name	Date	Classification	Orientation	Space	Wind parallel to bands
K. Higuchi (1963)	1960 1962	cloud (airplane)	NW—SE W—E	30 km	surface isobar
T. Asai (1966)	1966. 2.3	cloud (airplane)	WNW—ESE	20	mean wind dir. in the cloud layer
K. Ninomiya (1966)	1962. 2.11	cloud (satellite)		70—100	wind dir. at 850 mb
S. Miyazawa (1964)	1963. 12.1	radar	NW—SE W—E	20 50	vertical wind shear (1000, 850-500 mb)
R. Fujiwara M. Nakamura (1966)	1966. 1	radar	W—E SW—NE	25, 50 10—15	wind at 850 mb or vertical wind shear (850-500 mb)
J.S. Malkus (1963)	1957. 7—8	cloud (airplane)		68—80	
J. Kuettner (1959)		cloud		5—10	mean wind dir. in the cloud layer

the inversion layer and line echoes. As the layer becomes higher (the height of the cloud consequently becomes higher) the space between line echoes becomes wider.

Recently, there have been published a number of reports on the orientation of cloud bands and radar bands, and on the space between them. Table 4 lists the reports which treat the problem of snowfall in the Hokuriku District. Since the scale of the phenomena investigated varies according to the observing means, as radar, airplanes and meteorological satellites, the numerical values of their space and orientation can not be discussed en bloc.

7.3 Correspondence of an echo area with a snowfall area

It is necessary, from the stand point of weather forecast practice or of cloud physics, to know how an echo area corresponds with a snowfall area. But there are many problems yet unsolved. Here, the author presents only some cases of correspondence of an echo area observed at Mt. Yahiko with a snowfall area. In order to study the relations between a radar echo and a corresponding snowfall area, it is

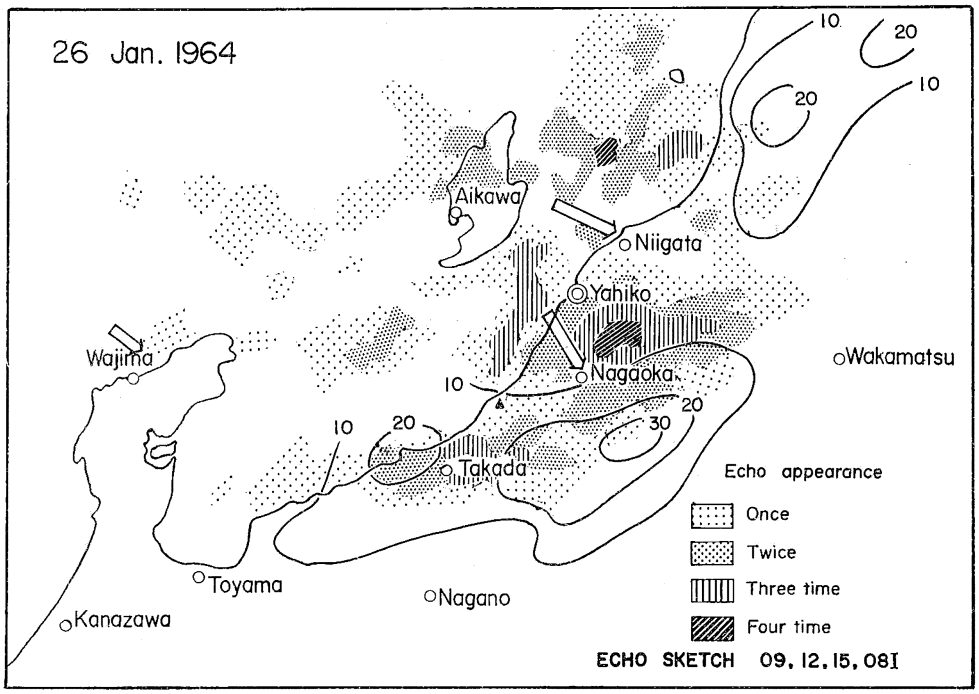


Fig. 54(a). Relation between the distribution of daily snowfall amount (cm) and that of the composite echo area obtained in 24 hours for January 26, 1964. This example shows that the two areas do not agree with each other. The thin, and thick stipples and light and heavy hatches show the areas where the echo appeared once, twice, three and four times on the composite echo map, respectively. The double arrows indicate the horizontal distance and direction of drifting of snowflakes from echo top to ground.

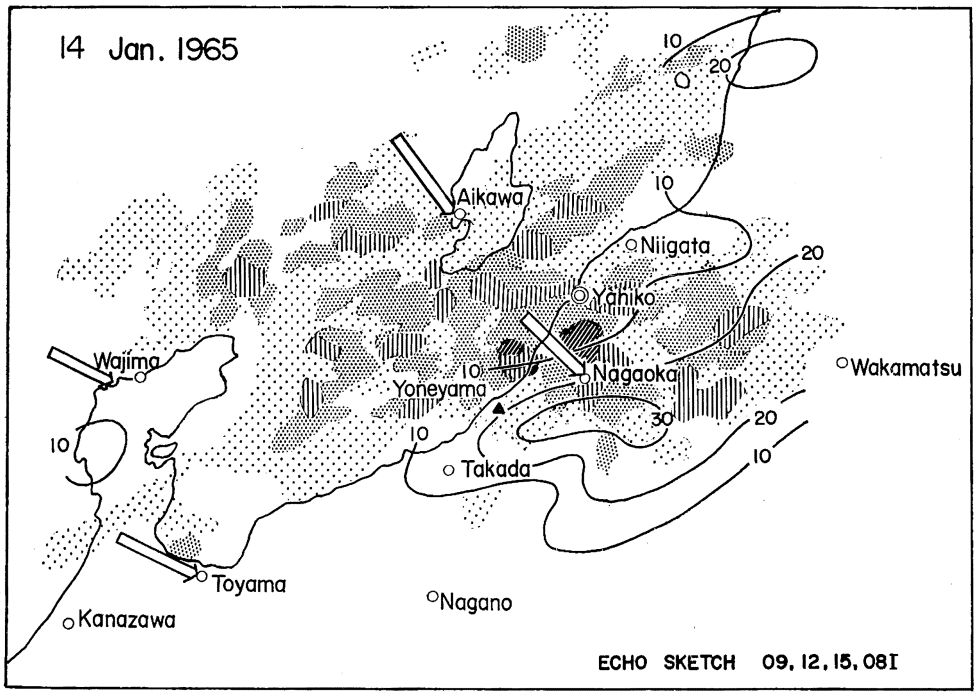


Fig. 54(b). Same as (a), but for January 14, 1965.

necessary to understand the detectability of mountain radar. The echoes observed by mountain radar such as Yahiko-radar are seriously influenced by ground echoes and the screen effect of topography, and it should be born in mind that the height of the lower limit of a detectable echo differs considerably from area to area.

An echo area does not always coincide with a snowfall area; that is, though in some cases an echo area coincides closely with a snowfall area, in others a wide gap is observed between the two. The gap seems to be related with the vertical distribution of upper wind and the falling velocity of snowflakes from their formation layer. In general, as an echo cell moves and its intensity changes every moment, it is necessary to compare them within an appropriate time interval if we are to examine their correspondence. In this report, considering the availability of data, the author made the comparison as followings:

(a) to compare a composite echo map composed of successive four or six radar sketches in 24 hours from 9 o'clock with the snowfall amount (mm) map of the same period
(b) to compare a composite map of two radar sketches in an hour with the snowfall amount (mm) map for the same one hour
(c) to compare an instantaneous echo map with a snowfall intensity map at the same time

(i) *Relations between the distribution of daily snowfall amount and the composite echo area obtained in the same 24-hours* The relations between the distribution of

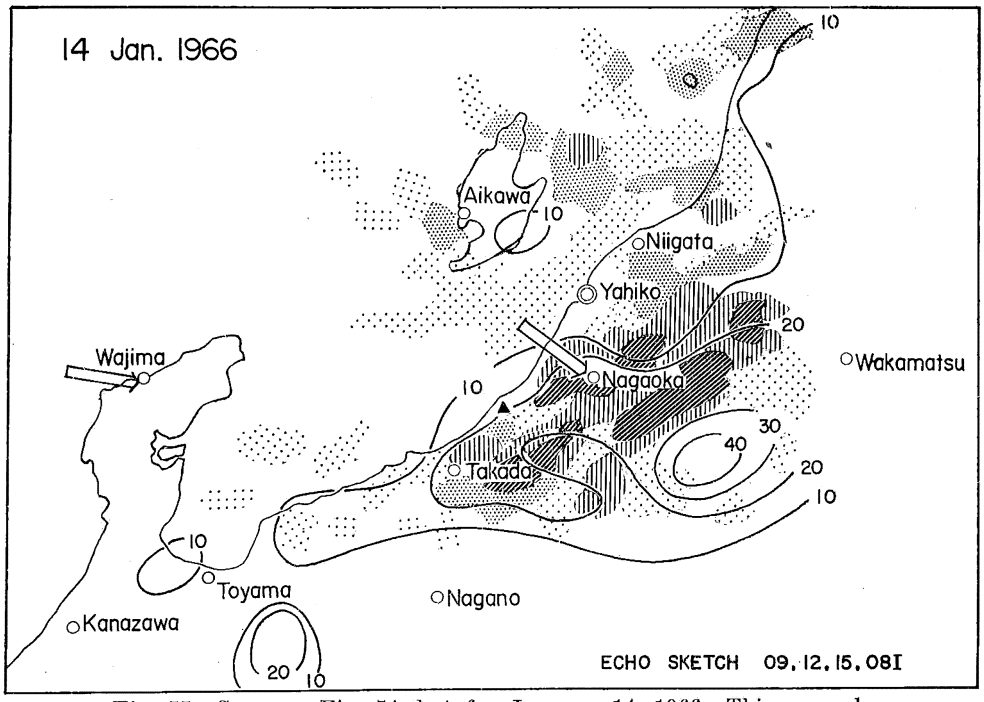


Fig. 55. Same as Fig. 54, but for January 14, 1966. This example shows that the two areas are in pretty good agreement with each other.

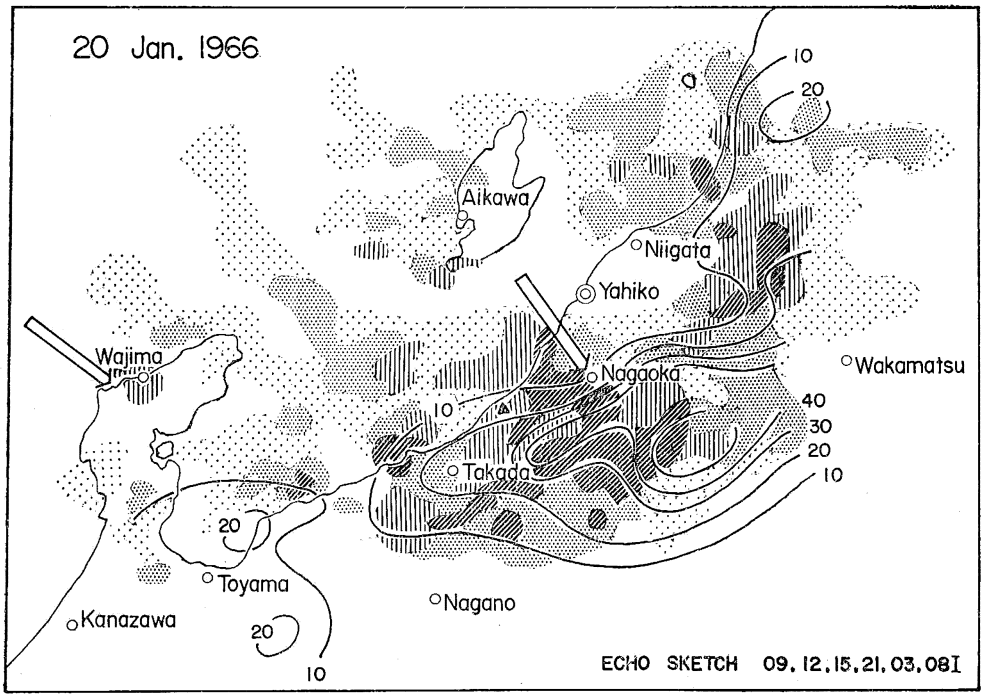


Fig. 56. Same as Fig. 54, but for January 20, 1966. This example shows that the two areas are in good agreement with each other.

daily snowfall amount and that of the composite echo obtained in the same 24 hours are presented in Figs. 54-56. In Fig. 54(a, b), a remarkable gap is seen between the snowfall and the echo area. The gap in much smaller in Fig. 55 and no gap is seen in Fig. 56. The double arrows in the figures indicate the horizontal distance and direction of the drifting of snowflakes from the echo top to the ground due to the upper wind at 850 mb level, which is equivalent to the height of the middle layer of snow cloud, assuming the falling velocity of snowflakes to be 1.5 m/s (MAGONO, 1953). The upper wind is obtained by aerological observations carried out every 3-6 hours or from the geostrophic wind. The fact that the area of heavy snowfall is located on the leeside of the overlapped echo area at a distance indicated by the arrow, suggests that the gap results from the snowflakes drifted and concentrated downstream by the upper wind.

Furthermore, it is to be noted that as seen in Fig. 54(b) the gaps are remarkable when the echo areas are located north of Mt. Yoneyama and not when they are south of Mt. Yoneyama as shown as Fig. 56. This fact is also presumably to be attributed to the predominant NW monsoon by which the snowflakes over the coastal area are carried inland.

(ii) *Relations between the distribution of hourly snowfall amount and the composite echo area obtained during 1 hour* The relations between the distribution of hourly snowfall amount and that of the composite echoes obtained during 1 hour are pre-

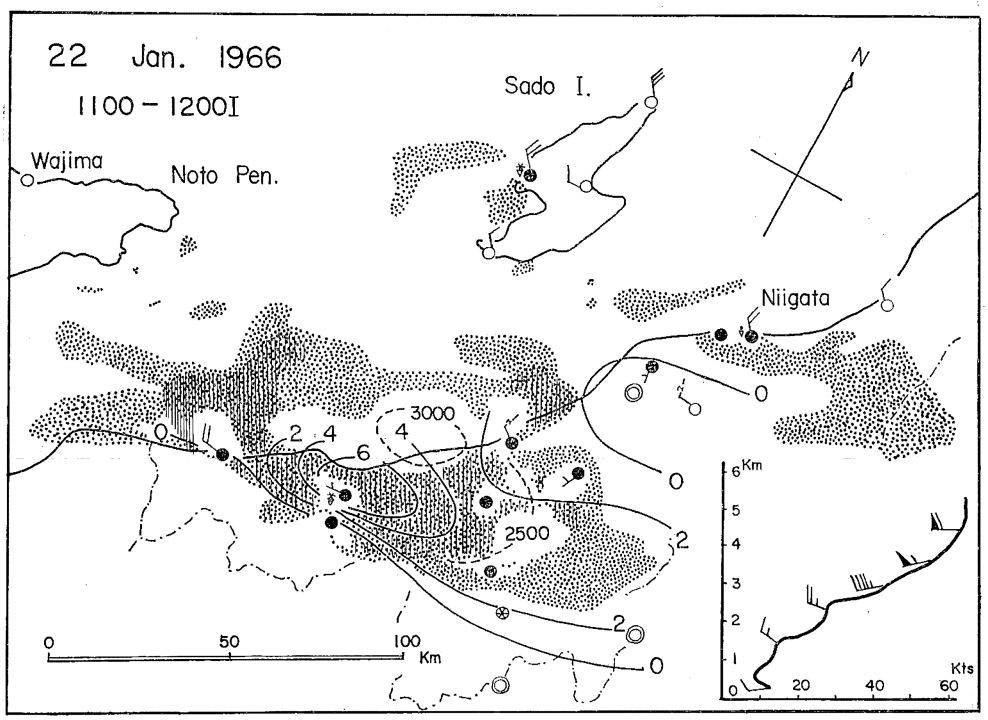


Fig. 57. Relation between the areas of composite radar echoes and snowfall amount (mm) during 1 hour for snowfall in the plain. Vertical distribution of upper wind at Wajima is also shown (lower right corner).

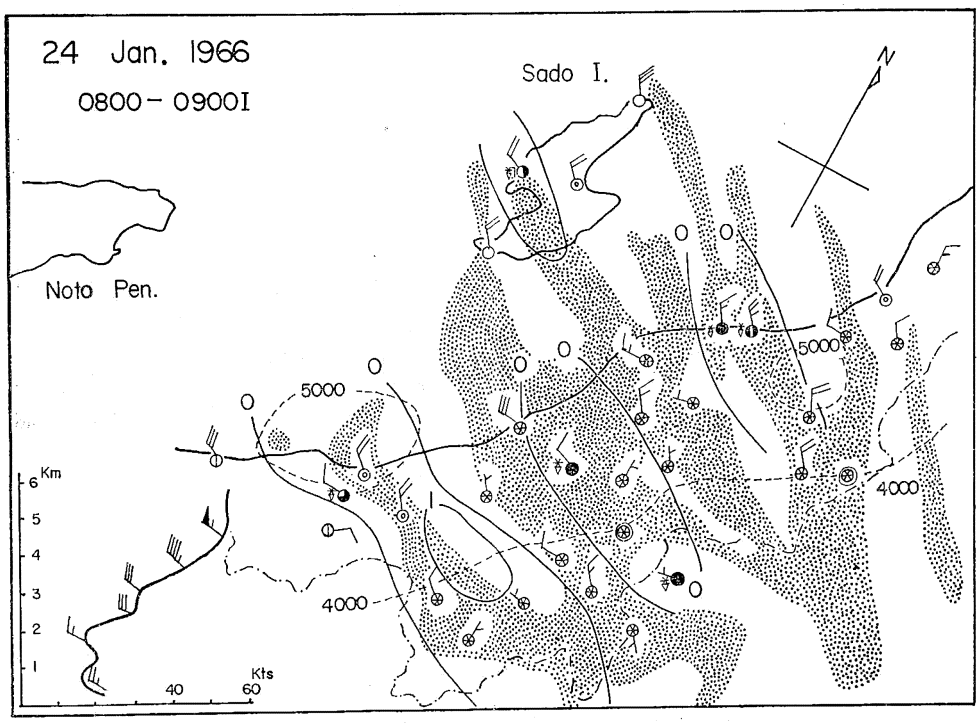


Fig. 58. Same as Fig. 57, but for snowfall in the mountainous region.

sented in Figs. 57 and 58. The echo areas in the figures are composed of two successive radar sketches during 1 hour. It is seen in the figures that the echo areas coincide well with the snowfall distributions qualitatively, but there are exceptional cases in which an echo area corresponding to the snowfall area can not be detected. (Relevant figures have been omitted). In the case of plain snow given in Fig. 57, the composite echo area is in good agreement with the snowfall area, and the maximum height of the echo top is 3,000 m at the coast where the upward air current is considered to be most intense, but the area of maximum height of the echo top is not coincident with the maximum of snowfall intensity. From the vertical wind distribution at the nearby Wajima rawinsonde station, it is clearly seen that the strong wind shear at about 3 km level, which bounds the convective layer underneath, suppresses the development of snow cloud. Since the echoes are oriented from W to E and the falling snowflakes are carried by the lower westerly wind, it is seen that the echo area fairly coincides with the areal distribution of snowfall. In the case of mountain snow given in Fig. 58, the streaked echo distribution oriented from NW to SE coincides well with the snowfall amount. The maximum height of the echo top is located at the coast and the maximum snowfall amount inland. It is thus quite resonable to suppose the effect of the spilling over of snowflakes.

(iii) *Simultaneous comparison between the distribution of echoes and of weather elements* The distribution of echoes oriented from SW to NE in plain snow and its correspondence to the weather elements and intensity of snowfall are given in Fig. 59.

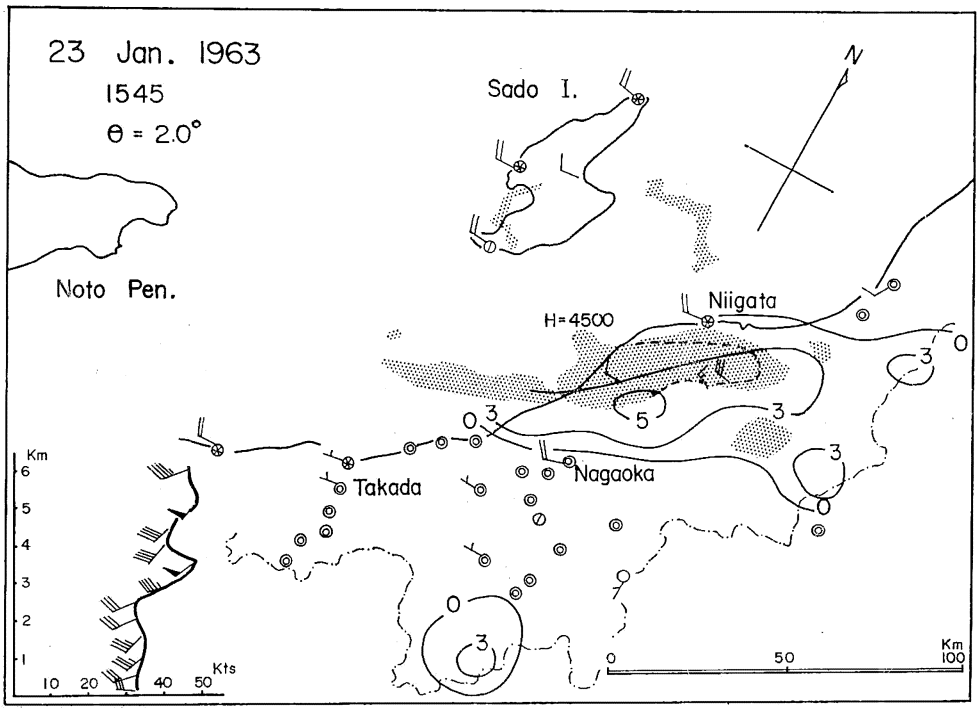


Fig. 59. Relation between the areas of radar echo and snowfall intensity at the same time. Numerals show the snowfall intensities (snowfall amount in 1 hour). Vertical distribution of upper wind at Niigata is also shown (lower left corner).

There is a time lag of 15 minutes between the two distributions, but the horizontal displacement of the echo cell is very small and its moving direction keeps itself stable during the 15 minutes. Therefore the orientation of line echoes is also unchanged during the 15 minutes. What is interesting is the fact that the area of intense snowfall appears downstream of, and runs parallel to, the line echo. The individual echoes move toward NE with a speed of 80 km/hour, which is in pretty good agreement with the upper wind at 2,900 m level observed at Niigata. On the other hand, it is inferred that the gap of about 10 km on the leeside is due to the westerly wind, 17 m/s, within a shallow layer just under 700 m level. That is to say, when the snowflakes drift down from 700 m height, with a falling velocity assumed to be 1.5 m/s, a gap of about 7 km is estimated, and in addition, the southwesterly wind above 800 m level does not exercise any important effect upon the gap, since the wind direction is parallel to the orientation of the line echoes. Furthermore, an echo area corresponding to the snowfall area in the southern part of Niigata Prefecture, where snowfall intensity is 3 cm/hr, can not be detected because of the screen effect of the mountains on radar beams.

8. Concluding remarks

In the present paper, based on analyses of local weather map scales and broader-scale analyses such as Asiastic and northern hemispheric weather maps, the author

studied some problems in the mesoscale disturbances observed during periods of heavy snow in the Hokuriku District. The main problems treated are as follows:—

(1) Statistical investigations of several questions about plain snow and mountain snow.

As to the classification of snowfall distributions into plain snow and mountain snow, there is no standard method that has won universal acceptance. Therefore the author divided Niigata Prefecture into two parts, mountainous region and plains, considering orographic effects on precipitation, and then classified the snowfall distribution types into three ones: plain snow, mountain snow and mixed-type snow. The classification was done objectively, based on where the maximum snowfall occurs, and afforded the basis for statistic investigation.

(a) According to the statistics on the frequency of heavy snowfalls for the 9 winters from 1953 to 1961, the heavy mountain snow is the most frequent and exceeds half of the total cases. On the contrary, the frequency of plain snow is comparatively low and it accounts for only about 10% of the total. The sum of cases of plain and mixed-type snow is only 20% of the total cases and the occurrence of genuine plain snow is only 2.5 days during one winter season. Here, heavy snow is defined as snow that falls more than 30 cm or 20 cm deep in 24 hours at more than 5 of the total stations.

(b) The representative surface pressure pattern in plain snow related to the mesoscale disturbance is the type "West-High East-Low" and "Fukuro-type" in which isobars are curved cyclonically. Under the prevalence of the "Fukuro-type" pressure pattern in which a cold vortex is located over the Japan Sea, there occur throughout the year heavy snow and rainfall as well as thunderstorms and gusts. Thus this pressure pattern plays an important role in the formation of mesoscale disturbances.

(2) The characteristic pressure patterns on a broader scale during the period of the formation and development of mesoscale disturbances in plain heavy snow.

The characteristic features of the broader scale related to the formation of mesoscale disturbances during the periods of abundant plain snow of December 1957, December 1960 and January 1963, are as follows:

(a) On the northern hemispheric 500 mb chart are seen a cold low over the area from the Japan Sea to northern Japan, a cut-off high which stagnates over the area extending from Alaska to Kamchatka and a ridge stretching NEwards from the Central Asia along 90°E.

(b) At mid-stratosphere, 30 mb, it is recognized that the intense subtropical high corresponds to the intense cold low of the troposphere around Japan, the hemispheric long wave of wave number 2 is predominant and the polar night jet is intensified.

(c) On the Asiatic 500 mb chart, mixed-type snow is apt to occur when the trough is located west of 140°E and the regional zonal index is below about 14 m/s, and plain snow when below about 10 m/s. That is to say, plain snow is apt to fall when the meandering of westerlies is large (low index circulation) and the cold vor-

tex from high latitudes enters over the Japan Sea, and mountain snow when the cold vortex is located over the sea east of the Japanese mainland or in high latitudes and the zonal westerlies are strong (high index circulation).

(3) More detailed analysis of 11 examples of heavy plain snow in association with mesoscale disturbances using synoptic and radar data, classification of these examples into 4 types on the basis of synoptic analysis, and clarification of the features of each disturbance.

(a) *Snow accompanying a cold front and prefrontal squall line (examples 1, 2)*

In these examples sudden pressure change (0.7-1.0 mb), wind gust (23 m/s), burst of snowfall intensity (3.0-7.6 mm/hr) and maximum surface wind convergence (-6×10^{-4} sec^{-1}) are recorded on the arrival over the Japan Sea of a few wave-shaped lines denoted as "prefrontal squall line" preceding a cold front. The cold front and squall line moving southwards over the Japan Sea correspond to the line-shaped radar echo and move with speeds of 20-50 km/hr, but they are seen to slow down their speed as they approach the coast of the Hokuriku District and then to gain speed after passing over the Hokuriku District. The changes in meteorological elements caused by the passage of these lines seem to depend on the stage of development each mesoscale disturbance is in at the time. Thus a cold front can not be analyzed simply while a monsoon is prevailing.

(b) *Snow accompanying the local convergence line called "Hokuriku front" (examples 3-5)*

When the upper cold vortex is located over the Japan Sea and the surface pressure pattern is "Fukuro-type", the air column becomes unstable in stratification. In addition, as a result of the special orographic effect in the Hokuriku District, the southerly wind prevails from inland towards the sea while over the sea prevails the northwest monsoon and along the coast the westerly wind from the San'in District. The three air currents converge in the coastal area of the Hokuriku District, bringing abundant snow (i.e., 13.9 mm/3 hours for example 4) along the convergence line. The radar echoes are lined up along the convergence line and closely related to the banded area of snowfall. The maximum value of convergence at the lower level is about -2×10^{-4} sec^{-1} while the cold vortex passes across the northern Japan Sea. We recognize a mesoscale convective system, having a convergence field in the lower layer and a divergence field in the upper layer, with the boundary of the two layers at 2-3km height, and the convergence in the lower layer and precipitation are closely interrelated (example 3). Furthermore, as a result of the convergence between southerly wind from inland and northerly wind from the sea, steady plain snow is observed locally in the rear of the migrating anticyclone without the invasion of an upper cold vortex (example 5).

(c) *Snow accompanying a smaller cyclone (examples 6-8)*

Smaller cyclones which bring forth abundant snowfall are formed in an intense lower convergence area under unstable stratified conditions around the center of a cold vortex over the Japan Sea. Another kind of smaller cyclones are formed at 500-1,000 km downstream from the position of the upper cold vortex or trough which moves into the Japan Sea from the Continent under a situation of baroclinic instability. It is found that many violent snow storms, that is to say, having a snowfall intensity of 22 mm/3 hr and a maximum wind speed of 20 m/s, together with

thunder and lightning, are associated with the passing of these smaller cyclones over the coastal region (example 6). The horizontal scale, the lifetime and the moving velocity of these cyclones are about 100-300 km, 5-20 hr and 20-50 km/hr, respectively.

(d) *Snow accompanying a vortical mesoscale disturbance (examples 9-11)*

Smaller cyclones and disturbances which bring forth abundant snow have often been recognized on the radar scope as vortical echoes with a clear spiral band and "eye" area". They are classified under the category (c), but disturbances on a smaller scale which are seen on the radar scope are defined as vortical disturbances. In the year 1965 the author found out this observational fact for the first time and recently this fact has been confirmed by other radar systems as at Tōjinbo. These disturbances are formed in such areas as the sea bounded by Noto and Sado and the sea off the Tango peninsula. As the necessary condition for their formation, we may cite the strong lower convergence which is caused by both the topographical and the synoptic effects. The moving velocity is pretty large and amounts to 60-80 km/hr. Sometimes a dip-then-rise pattern of 1.3-2.0 mb in barograph, maximum snow intensity of 4 mm/hr, average convergence of -5×10^{-4} sec^{-1} and maximum instantaneous wind speed of 20-22 m/s are recorded when the disturbance passes through. These disturbances are characterized by a horizontal scale of 50-100 km, a lifetime less than several hours and a convergence of 10^{-4} sec^{-1}, and these values are rather less than those of a smaller cyclone.

(4) Radar analyses on snowfall phenomena using the data of two radar sites, Mt. Yahiko and Tōjinbo, synoptic and geographic investigation of the characteristic features of line echoes and study of the relationships between the echo area and the snowfall area.

The characteristics of line echoes (snowband) during the period of snowfall are investigated. Line echoes at 30-50 km spacings and with a width of 10-20 km wide are lined up in the directions NW-SE and W-E, the former for mountain snow, the latter for plain snow. The locations of line echoes are restricted geographically, and this fact is explained qualitatively by the orographic effect and the characteristics of atmospheric stratification. The orientations of line echoes run statistically in the direction of the wind shear between 1000 and 500 mb levels. As the shear grows large, line echoes tend to appear. On the other hand, as the shear becomes small, random echoes appear. Further, as the inversion layer that appears in an ascent curve becomes higher the space between line echoes becomes wider, while as it comes down the space between line echoes becomes smaller. In some cases an echo area coincides closely with a snowfall area, but in others a big gap is observed between the two areas. This is quite reasonable if we consider the effect of the spilling-over of snowflakes due to the wind.

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豪雪に関する中気候学的研究

——中規模じょう乱の総観解析的研究——

宮　沢　清　治

1957年から1966年までの北陸地方の大雪例をしゅう集し，実際的解析法を研究し，豪雪時にみられる中規模じょう乱の中気候学的諸問題を北半球規模から局地的規模に至る各尺度のもとで明らかにした。その要旨は次のとおりである。

1. 地形効果に起因しない平野部に降る里雪と山間部に降る山雪，平野・山間部に降る混合型大雪を定義し，統計的に検討した。1953～1961年の9冬の大雪の出現度数をみると，山雪は大雪の全例数のうち半分以上をしめるが，純里雪は約1割，混合型を含めても約2割で，純里雪は1冬に2.5日程度起るにすぎない。里雪は主として上層寒冷渦が日本海に位置したとき現われる地上等圧線型式の袋型のときに降る。袋型気圧配置は年間を通じてみられ，豪雨雪，雷雨，突風などの中規模じょう乱の発生しやすい場として重要な意味をもつ。

2. 里雪時の中規模じょう乱の発生，発達に適合する広域場の特徴を研究した。このような広域場の特徴として北半球500 mbでは，アラスカからカムチャッカにのびる切離高気圧，極東の寒冷低気圧に対応して90° Eに沿ってのびる尾根がみられる。日本付近の対流圏の寒冷低気圧は中部成層圏（30 mb）での温暖な亜熱帯高気圧に対応している。極東500 mb天気図では，里雪は谷が140° E以西に位置して，高緯度地方からの寒冷渦が日本海に南下し，東西指数が約10 m/s以下のときに降りやすく（低指数循環），反対に山雪は谷が140° E以東に位置して，寒冷渦が日本の東海上や高緯度地方にあって東西指数が14 m/s以上のときに降りやすい（高指数循環）。

3. 中規模じょう乱による里雪現象を11例抽出し，4種類に分類し，個々のじょう乱の実態を明らかにした。

(1) 日本海低気圧に伴なう不安定線，寒冷前線による降雪。寒冷前線に先行する不安定線（Prefrontal squall line）の通過によって強雪が降ることがある。解析例では気圧急変（0.7～1.0 mb），突風（23 m/s），最大降雪強度（3.0～7.6 mm/hr），最大収束量（$-6\times10^{-4}\,\mathrm{sec}^{-1}$）が観測され，これらのじょう乱系には移動性の線状エコーが対応する。

(2) 局地的な収束線（北陸不連続線）による降雪。上層寒冷渦が日本海に位置し，気層が不安定になる

と，内陸から海上に向う南風，沿岸海上からの北西風，山陰地方から沿岸沿いに吹く西風が観測され，これらの3風系は北陸沿岸沿いに収束線を形成し，強雪をもたらす。なお上層寒冷渦を伴なわない移動性高気圧後面での南風，北風による小範囲の安定性の里雪現象がみられる。

(3) 小低気圧による降雪。上層寒冷渦が日本海に位置するとき，寒冷渦の中心や周辺で垂直不安定に基因して沿岸海域に強い収束線が形成され，これに沿って小低気圧が発生，発達することがある。さらに寒冷渦や谷が高緯度から朝鮮方面に移動してくるとき，傾圧不安定効果によって日本海西部で小低気圧が発生，発達することもある。これらの小低気圧の通過による風雪は激しく雷電を伴ない，降雪強度 22 mm/3 hr に達することがある。小低気圧の水平規模，寿命は 100～300 km，5～20 時間で移動速度は 20～50 km/hr 程度である。

(4) 中規模のうず状じょう乱による降雪。レーダー観測によって豪雪時に顕著なスパイラルバンドをもったうず状じょう乱がしばしば現われることをみいだした。これらのじょう乱は，通常沿岸海上で発生，発達し平野部を経て山間部で消滅するが，じょう乱の経路に沿ってしばしば集中強雪（例えば 4 mm/hr）が降り，気圧上昇，突風などを伴なう。丹後半島沖や能登半島付近のような地形収束のある地域で，強い下層収束の大気成層の効果が加わったときに数多く観測され，じょう乱の水平規模，寿命は 50～100 km，数時間以内で $10^{-4}\,\mathrm{sec}^{-1}$ の収束値によって特徴づけられる。

4. 降雪現象のレーダー解析を行ない，豪雪時の線状エコー（降雪帯）の特性について研究した。線状エコーは，間隔 30～50 km，幅 10～20 km で山雪時は NW—SE，里雪時は W—E の方向に配列する。線状エコーの出現位置は地理的に限定され，その走向は統計的に 1000～500 mb の風のシヤーの方向に配列するが，シヤーが小さくなるとセル状のランダムなエコーが卓越する。また線状エコーの間隔は，大気成層の逆転層の高さが増すにつれて拡大する。さらにレーダーエコー域は，実際の降雪域とは必ずしも一致しないでかなり一致する場合とずれの大きい場合がある。これらのずれは雪片が生成層から地上に落下する場合風によつて流される効果によるものと考えられる。