Heavy Snowfall by Orography and Wind Shift in Cold Front Crossing Korean Eastern Coast

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Abstract

Using a 3D-non-hydrostatic, numerical Weather Research & Forecasting Model (WRF) version 2.2 with FNL initial data to the model, a numerical simulation of heavy snowfall caused vast economical loss from destruction of houses and traffic interruption at Gangneung city in the coastal region of Korea has been undertaken from 00 UTC, January 13 through 12 UTC, January 15, 2003. Before snowfall occurrence in the coastal region on January 13, a northwesterly wind of 3 to 6 m/s prevailed in the study area before cold front passage under the influence of a high pressure system over northeastern China north of the Korean peninsula and a low pressure centered over the northeastern part of Japan. When snowfall occurred in Gangneung, the prevailing synoptic scale northwesterly wind changed to a north or north northeasterly wind at greater than 5 m/s on the coast and greater than 10m/s over the open sea after cold front passage. The northeast to northerly onshore wind became an upslope wind in combining with the sea-valley wind and was directed toward the top of Mt. Taegulyang (alt. 896 m) located west of the city. This upslope wind lifted moisture transported from the eastern sea along the eastern slope of the mountain toward the top and resulted in condensation into cloud consisting of liquid water or snow flakes. Simultaneously, cold northwesterly winds from north-western China moved down along the eastern slope of the mountain toward Gangneung and prevented further intrusion of the easterly upslope wind. This forced moisture to rise toward the mountain top and western basin, resulting in the formation of a thick layer of cloud from a height of 50 m to 2.8 km from the western basin of the mountain eastward towards the open sea. The cloud base along the eastern slope and at 50 m height over the city was below 0^0C in ambient air temperature and -8^0C at a height of 900m near the top of the mountain and consisted of both super saturated water droplets and ice particles. As a result, a maximum rainfall (snowfall) amount of 149 mm/3hr (19.8 cm) with accumulated snow amount of 36.8 cm was recorded in Gangneung. A rain band was located in the same area as a band of snowfall and directly coincided with the area of relative humidity greater than 95 %. Areas of total cloud mixing ratio greater than 0.01 g/kg and relative humidity greater than 95 % in vertical profiles closely matched cloud areas on GMS-IR satellite imagery and also on radar images. The proportion of snowfall to rainfall was approximately 1 to 10. Under the influence of a north-westerly wind parallel to the coast, moisture advection became very weak, resulting in either a small amount of snow or none at all on the coast.

Keywords: Numerical prediction, Snowfall, Precipitation, WRF model, FNL data, GOES-IR satellite images, Radar echo image, Relative humidity, Mixing ratio

Introduction

It has been known that cloud physics associated with snowfall and winter rainfall are basically similar .The primary difference between rain and snow is how much cooling of rain droplets is necessary to form snowflakes[1]. Fu and Fletcher[2], Li and Yanai[3], Mooley and Parthasarathy[4] and Yang and Lau[5] explained the impact of SST variability and land-sea thermal contrast and land surface processes associated with Asian summer monsoon rainfall. Dey et al[6], Dickson[7], Hahn and Shukla[8], Ropelewski et al[9], Khandekar[10], Yanai and Li[11], Parthasarathy et al[12], Parthasarathy and Yang[13], Sankar-Rao et al[14] and Yang[15] explained the relationship between Asian summer monsoon rainfall and ENSO and also Eurasian snow cover. Yang and Xu[16] determined a linkage between Eurasian winter snow cover and, regional Chinese summer rainfall and Morinaga and Yasunari[17] explained the interactions between the snow cover and the atmospheric circulation in the northern hemisphere. Chang and Foster[18] and Chang et al[19, 20] estimated Northern Hemisphere snow volume using satellite sensors.

In the mountainous coastal region of Korea, mesoscale snowfall and rainfall are directly affected by moisture advection from the sea, by a thermally developed wind system and condensation due to the orographic effect of the mountainous terrain[21, 22]. James and Houze[23] concluded that the modification of precipitation occurs by coastal orography in storms crossing northern California and Market and Cissell[24] explained the formation of a sharp snow gradient in a mid-western heavy snow event. Waldstreicher[25] explained the ocean effect on a snowstorm that produced one foot of snow from a 3000 ft cloud. In recent years, frequent heavy snowfall events have been found in the eastern mountainous coastal region of the Korean peninsula. Heo et al[26] and Jung et al[27] carried out a numerical study on dynamical and thermodynamical characteristics associated with a heavy snowfall event over the Korean peninsula. Choi[28] explained that snowfall can occur by condensation of moist air parcels through a large amount of both evaporation of water particles from the warm sea surface into the colder atmosphere.

It may be possible to categorize two synoptic atmospheric pressure patterns, which can induce heavy snowfall in the eastern coastal region of Korean peninsula in winter according to Choi[28], Chung et al[29], Ham and Jang[30] and Kim et al[31]. Category 1 is high pressure system in northern China and low-pressure system in the South Sea of Korea producing easterly wind; Category 2 is high pressure system in the north of China extending southwards (i.e. high pressure in the west of Korea) and low pressure covering the whole of the eastern Korean peninsula in the wake of the rapid passage of a trough or cold front which has passed over the East Sea. This induces strong north to northeasterly winds from the East Sea into the coastal basin and mountain region.

The main purpose of this study is to predict the precursor conditions of a winter snowfall event, in order to prevent from vast economical loss from the destruction of houses and traffic interruption on the road with thick coverage of snow at least for one week in Gangneung coastal city in Korea, by considering the case of category 2, using the 3D-Weather Research & Forecasting model (WRF) version 2.2, GOES-IR satellite images supported by the Japan Meteorological Agency (JMA) and radar images from six radars established by Korean Meteorological Administration (KMA) and to reveal the driving mechanism that caused the snow to fall over the mountainous coastal region.

Numerical Method and Input Data

For the generation of snowfall precipitation at Gangneung city (37^{0}45N, 128^{0}54E) in the eastern mountainous coastal region of Korea, the three-dimensional, grid point WRF model version 2.2, employing a terrain following coordinate system, was adopted for 60 hours numerical simulation from 00 UTC (09 LST), January 13 through 12 UTC (LST = 9h + UTC; 21 LST), January 15, 2003 (Fig.1). One way, triple nesting was performed using a horizontal grid spacing of 27 km covering a 91 x 91 grid square in the coarse mesh domain and a 9 km interval also covering a 91 x 91 grid square in the second domain. The third and final nesting consisted of a 3 km horizontal grid spacing again on a 91 x 91 grid square. NCEP/NCAR reanalysis FNL (1.0^{0} x 1.0^{0}) data were used for meteorological input to the model and were vertically interpolated onto 36 levels with sequentially larger intervals increasing with height from the surface to the upper boundary level.

For the heat and moist budgets in the atmospheric boundary layer, the WSM 6 scheme was used for microphysical processes and the YSU PBL scheme for the planetary boundary layer. The Kain-Fritsch (new Eta) for cumulus parameterization, the five thermal diffusion model for land surface and the RRTM long wave radiation scheme and dudhia short wave radiation schemes were used. When snowfall occurs, there is also rainfall and 3 hr accumulated snowfall was treated as a mixed phase of both ice and water. Hourly archived wind, air temperature, relative humidity, cloud, snowfall and rainfall amounts by the Gangwon Meteorological Office were used for the verification of numerical results of the meteorological elements in addition to GMS-IR satellite and radar images archived by the Korea Meteorological Administration.

Results and Discussion

Precursor of coastal snowfall

a) Synoptic analysis: Prior to the snowfall event between 2100 LST, January 13 to 0600 LST, January 14, a high pressure with central pressure 1039 hPa was located in northwest China (Xinjang and Yuigure regions) and another center of 1040 hPa was located over northeastern China (Dongbei region). This area of high pressure affected the weather over the whole of the Korean peninsula. A low pressure center was located between the northeast of Saharin and the southwest of the Kamchatka peninsula, Russia (Figs. 2a and b). However, this low pressure system did not affect weather directly over the Korean peninsula.

Although these pressure patterns can generate northeasterly winds over northern Korea and northwesterly winds over southern Korea, especially in Gangneung city (circle on Fig. 2a), the observed wind direction and speed at Gangneung city just before cold front passing the city was northwesterly at 2.3 m/s to 4.1 m/s (2.3 m/s to 6.4 m/s at Mt. Taegulyang at an altitude of 865 m height to the west) with a directional range from 260^{0} to 290^{0}. The numerically simulated surface wind was also northwesterly. As the surface north-westerly wind near and at the northwesterly wind at 1.5 km height above Gangneung city prevailed, moisture was prevented from being transported from the sea into Gangneung city. Even though some available moisture was transported into the mountain basin to the west of the city and over the coastal sea in the east (Figs. 2c and d), no snowfall occurred over the city. Thus, only a small area of cloud was apparent on the GMS-IR satellite image at 2100 LST, January 13, and no rain rate was detected on radar images that covered the whole of the Korean peninsula. At 0300 LST, January 14, clouds neither formed on the mountain side, coastal basin and sea, nor was there snowfall in Gangneung city. On the other hand, cloud was detected over the open sea about 50 to 100 km away from the coast and weak radar intensities revealed a small rainfall amount in figs. 2d and 3d.

b) Numerical simulation of wind, relativity humidity, precipitation and mixing ratio: Prior to the snowfall event in the study area, the numerical simulation results in the fine-mesh domain show that a northeasterly wind prevails at 10 m height above sea level over the coastal sea at 2100 LST, January 13 and 0300 LST, January 14 and a northwest to westerly wind is affecting Gangneung city and surrounding area to the west (Fig. 3a). As this northwesterly wind is still directing dry and cold air toward the coast and simultaneously there is a northwesterly wind parallel to the coastline both close to the coast and over the open sea, there is insufficient moisture advection from sea over the coast that is required to form snowfall.

As in fig. 3a, a northwesterly wind greater than 6 m/s prevailed parallel to the coastline over the sea surface of the East Sea. This wind directed a dry, cold air mass from the inland toward the coastal sea, passing through Gangneung city and caused a dry atmosphere with relative humidity (RH) less than 60 % as shown in fig. 3b. At this time, both the numerical simulation results and observations of wind, air temperature, RH at 10 m height and precipitation amount for 3 hours over Gangneung city are approximately 4 m/s and 3.8 m/s, 7^0C and 8.7^0C, 50 % and 48 %, 0 mm and 0 mm respectively (Fig. 3c). The vertical profile of mixing ratio inside cloud was 0 g/kg at 10 m over the city (Fig. 3d), indicating that the supply of water vapor provided by the northwesterly wind was insufficient for the formation of rain and snow.

At 0300 LST, January 14, on the other hand, a northeasterly wind over the northern part of the coastal sea in the fine-mesh domain had strengthened to greater than 10 m/s and a northwesterly wind over the southern part of the sea almost parallel to the coastline had intensified to 8 to 10 m/s. Thus, the northwesterly surface wind near Gangneung city prevented moisture advection from the sea over Gangneung city. This means that the dry , cold air mass in the northwesterly wind was responsible for causing low relative humidity (simulated value less than 53.3 %; observed value 48 %), and no rain or snow. This is verified by the observed data record and both satellite and radar images as at 2100 LST, January 13.

Snowfall over the coast

a) Synoptic situation with high pressure in west and low pressure in east of Korea: At the start of the snowfall event, 0900 LST, January 14, a sea-level pressure (SLP) high pressure with central value of 1040 hPa and contour value of 1729 m at 850 hPa was located near Beijing in China and covered the whole of the Korean peninsula (Fig. 4a and b). A low center at this time was located near the southern Kamchatka peninsula in Russia. With a high pressure in the west and a low pressure in the east of the Korean peninsula the Korean weather is influenced by this pressure pattern (Fig. 4c & d).

The cold front at 0900 LST had already passed through Gangneung as evidenced by the pressure pattern shown in fig. 4a. The wind strengthened to more than 3 m/s and the previous northwesterly changed to a northeasterly wind. Through the day, the wind became northerly, that is, perpendicular to the coastline near Gangneung city. This synoptic scale northerly wind could move further upslope under the influence of the sea and valley breezes generated by thermal heating of the ground and reach the top of the mountain to the west of the city (Figs 1 and 4a). Even with northerly and northeasterly at 10 m height above the sea level over the coastal basin and coastal sea, a northwesterly wind persisted in further inland and on the mountain side since this northwesterly wind prevented the north to northeasterly wind reaching the mountain top.

The north to northeasterly upslope wind is confined to the top of the mountain west of the city. Since a strong northerly or easterly upslope wind perpendicular to the coastline can continuously transport a large amount of moisture from the East Sea over the coastal inland and towards the top of the mountain west of Gangneung city, persistent formation of cloud due to the orographic effect of upslope moisture transport can also occur. As a north-westerly wind in the western basin of the mountain meets the easterly upslope wind near the top of the mountain, moisture advection is limited to near the top of the mountain and the cloud area near the mountain top extends toward the east over the coast in addition to spreading down the eastern slope of the mountain. The thick cloud layer caused heavy snowfall over both the coastal area and sea (figs. 5 and 9). In fig. 5b and d, radar images indicating rain rate at six KMA radars show precipitation occurring at Gangneung city at 0900 LST and 1500 LST. Thus, as rain droplets in below 0^0C ambient air temperature should contain both super-cooled water droplets and ice crystals, snowfall is also observed at each time.

b) Numerical simulation of wind, relative humidity, precipitation and mixing ratio: Figs. 6a and 6b show the numerically simulated northeasterly wind at 0900 LST and the northerly wind perpendicular to the Gangneung coastline at 1500 LST, which closely match the observed wind speed and direction. From 0900 LST until 2100 LST, the observed wind direction at Gangneung city is in the range 340^0 to 020^0 and with wind speed in the range 0 m/s to 5.4 m/s. At 0900 LST the wind speed is 3.6 m/s and 2.8 m/s at 1500 LST, indicating decreased wind speed toward the evening. The stronger is the wind, the more moisture can be transported from the sea inland. On the other hand, the wind speed over the coast and adjacent sea is greater than 8 m/s and over the open sea it is greater than 10 m/s, even reaching 14 m/s in parts. Even though this strong marine wind greater than 10 m/s is directed toward the coast as shown in fig. 6a and b, the larger surface roughness of the land surface and the mountain barrier to the west of the city than the sea surface, can cause a reduction in marine wind speed, as shown by values of less than 6 m/s over the coastal inland.

From vertical profiles of wind, air temperature, relative humidity and cloud mixing ratio in fig. 9, the process by which cloud forms is clear. Moisture that is transported by the northeasterly and northerly onshore wind should cool during its ascent toward the mountain top and become saturated. The saturated water vapor forms a large area of stratocumulus cloud near the right-hand side of the mountain top under the influence of the westerly wind on the western side of the mountain that meets the easterly upslope wind near the top of the mountain. Gradually, 100 % relative humidity area due to the persistent northerly onshore wind also extended vertically and horizontally, making the cloud area to become larger. The cloud developed up to 2.6 km height over the mountain and extended over the sea by 0900 LST. From the vertical profiles of relative humidity (%) (Fig. 9a and b) and total cloud mixing ratio (g/kg) (Fig. 9c and d), which represent cloud water content, stratocumulus cloud develops due to the persistent moisture advection from the sea by the upslope northerly wind and continuously accumulates into a large area of cloud both near the top of the mountain and along its eastern slope. The cloud base lowers toward the ground from 0900 LST, January 14 until 1200 LST. Thus, the cloud base lowers until finally it reaches less than 50 m above the ground over Gangneung city, especially around 0900 LST, January 14 and persists until 1200 LST.

As shown in figs. 6a, 8a, 8c, 9a, 9c, after 1200 LST, moisture advection extends further inland and moisture in the vertical spreads out under the increase in atmospheric boundary layer depth from 3.3 km at 0900 LST to 3.5 km at 1500 LST. Thus, the cloud base rises to about 500 m height above the ground and even to 1 km over the open sea. A line below 0 °C ambient air temperature on the vertical profile is very close to the ground at approximately 50 m height, where the cloud base is located at 0900 LST and the air temperature near the mountain top is - 8°C. This implies that the temperature of cloud droplets is lower than 0 °C and that heavy snowfall could be easily produced from the thick cloud layer. Generally, if cloud droplets descend toward the ground with the ambient air temperature greater than 0 °C, precipitation becomes rain. As the cloud droplets in the ice phase approach the city surface, snow is changed into rain, through the process of ice crystals melting in an air temperature greater than 0 °C. When the distance between the cloud base and the ground is very small, snow crystals remain and snow still occurs. When the distance between cloud base and ground is large, snow changes to rain.

As the air temperature near the cloud base was below 0 °C at 0900 LST and below – 6 °C at 1500 LST, January 14, precipitation falling from the cloud base toward the city surface should be minute ice crystals and precipitation reaching the ground when the air temperature is 0.8 °C, might still be unmelted snow combined with rain droplets, that is, sleet. Gangneung city at 0900 LST had accumulated more snow amounting to 2.2 cm, which corresponds to a rainfall amount of 1.6 mm and at 1500 LST a further 11.0 cm of snow had registered, which corresponds to a rainfall amount of 7.4 mm. However, Gangwon Regional Meteorological Administration (GRMA) in Gangneung city and Taegulyang Meteorological Office near the top of the mountain to the west of the city reported snowfall at the same time and at Gangneung city it was snow only with no rain.

The city had a maximum snowfall amount of 19.8 cm as the area of 100% relative humidity area near the ground increased from 0900 LST to 1200 LST (Figs. 8a, 8b, 8c, 8d). Snowfall (rainfall) amounts observed at Gangneung city were 2.2 cm (1.6 mm) at 0900 LST, 19.8 cm (14.9 mm) at 1200 LST, 11.0 cm (7.4 mm) at 1500 LST, 2.0 cm (1.1 mm) at 1800 LST and 1.7 cm (1.5 mm) at 2100 LST. Snow continued to fall until 2100 LST, January 14 when after this time, no snow fell on the coast. Generally, it can be seen that the area of 100% relative humidity near the ground according to the vertical profiles of wind, relative humidity and air temperature in Fig. 8a and b, coincide with the area of cloud formation when comparing total cloud mixing ratio in fig. 9c and d. Even though the cloud base was below 0 °C, cloud droplets were ice crystals. The chances of droplets reaching the ground are less as snow depends upon no melting of ice crystals when the fall distance to the ground is small.

End of snowfall

a) Synoptic situation: As the northerly wind speed decreased from 1.9 m/s at 1800 LST to 0 m/s at 2100 LST, moisture advection from the sea to the land also decreased, thereby reducing cloud formation and leaving little or no cloud over the inland areas such as Gangneung city. After 2100 LST, January 14 until 0000 LST, January 15, the snowfall band (or rainfall band) gradually moved from the coastal inland toward the adjacent sea. The moderate northeasterly and northerly wind prevailed during the snowfall period and gradually changed into a very weak northerly wind at less than 0.2 m/s to 0 m/s. As the onshore wind disappeared at the coast, the offshore westerly wind directed from the mountain toward the coast remained weak. Thus, with this wind pattern it is very difficult for moisture advection from the sea over the coast.

After midnight until 0300 LST, January 15, the observed northerly wind became a stronger westerly wind in the range 0 m/s to 4.2 m/s, which provided only a limited amount of moisture transport from the inland basin toward the coast (Fig. 6a). As a result, cloud formation was also limited over the adjacent sea and no snowfall occurred in the city. This implies that the westerly wind can transport only dry, cold air masses from the inland area towards the city. That is, there is no moisture advection from sea and no cloud or snowfall results in the study area (Figs. 6b, 10b, 10c and 10d). The cloud formed previously should diminish with cloud base increasing in height to about 1 km above the coastal sea. The calculated wind at 0300 LST was 300° at 5 m/s, indicating a discrepancy of 30° with the observed wind direction.

Even if northwesterly wind coming from northern China cooled air parcels, generally, air parcels in winter with small moisture content could not become saturated and hence no snowfall could occur in the coastal region. As this northwesterly wind did not provide sufficient moisture advection toward the coast, the calculated value of precipitation compared to the observed value of zero resulted in a large difference. This difference is probably due to an increase or reduction of moisture as modified by the model or by one or two hours faster movement of the snowfall band (or rainfall band) toward the coast as calculated by the model compared to the observed movement and especially at 2100 LST, January 14. Even if a partial discrepancy between the calculated and observed rainfall amounts still existed, the occurrence time of snowfall (rainfall) by the model is the same as the observed and the general tendency of the calculated rainfall amount matched well with the observed tendency.

Comparison of precipitation and snowfall: After 56 hours of numerical simulation with FNL meteorological data sets, results of winter rain and snowfall amounts were compared with rain and snowfall amounts measured at Gangwon Regional Meteorological Administration in Gangneung city, Korea. The general tendency of calculated rainfall amounts matched well with those of the observed, except for two cases where there was some discrepancy owing to one hour earlier or later occurrence of the snowfall event (Table 1).

Conclusion

During a snowfall event that caused vast economical loss from destruction of houses and traffic interruption on the road with heavy coverage of snow at least for two weeks or sometimes three weeks in Gangneung coastal city in Korea, a northeast and easterly wind perpendicular to the coastline developed due to a high pressure system located over the west of the Korean peninsula and a low pressure in the east. This onshore wind transported a large amount of moisture from the sea to the inland basin and further toward the top of the mountain which lies to the west of Gangneung city. The uplifted moisture became saturated, resulting in the formation of both ice and rain droplets inside low level cloud such as stratocumulus. This process gradually caused the cloud to thicken and the ambient air temperature of below 0 °C at the cloud base resulted in snow falling from there. With the ambient air temperature below 0 °C near the cloud base, water droplets falling from the stratocumulus cloud were in the ice phase in the form of snow flakes. The band of snow (or rainfall band) near the ground directly coincided with the area of relative humidity greater than 95 %. However, as the low clouds spread out from the western basin of the mountain over the mountain top and extended toward the ground over the coastal area in the east, snow changed into rain due to the air temperature being greater than 0 °C. The distance from the cloud base to the ground was less than 50 m which enabled the falling precipitation particles to remain in the ice phase as snow and snowfall occurred over the coastal basin.

As the northeasterly wind gradually changed into a very weak north or northwesterly over the coastal sea just prior to the snowfall stopping in the evening, moisture advection from the coastal sea to the inland area became weaker and finally stopped also resulting in the movement of the snowfall band to the coast and finally led to the cessation of snowfall in Gangneung city. Through this research result, it may be easy to predict heavy snowfall event in advance, which has frequently caused vast economical loss and traffic interruption for a long period in both Gangneung city and mountain area and to prevent winter snowfall disaster.

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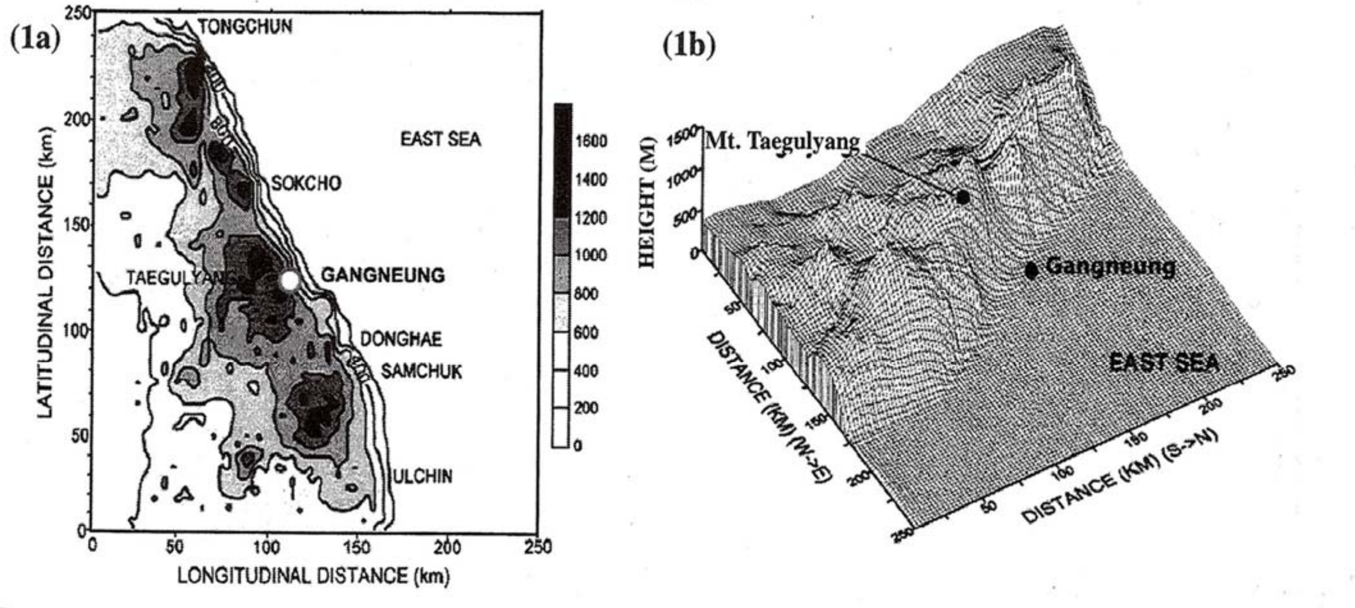
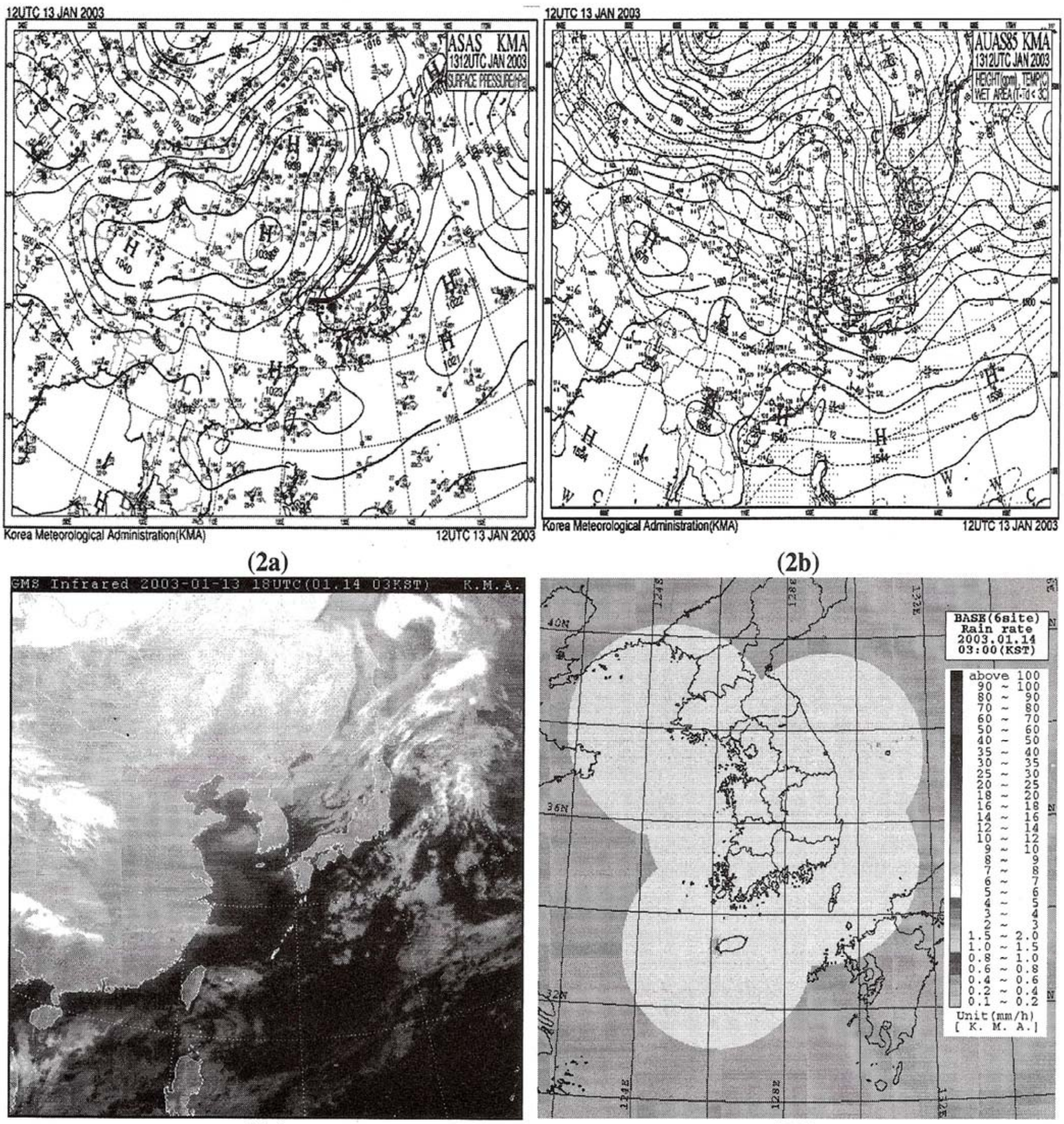


Fig. 1. (a) 2D - and (b) 3D - maps of study area near Gangneung city ($37^{0}45N$, $128^{0}54E$), in eastern Korea highlighting topography surrounding Gangneung (horizontal resolution 5 km). Gangneung city and Mt. Taegulyang are 20 and 860 m above mean sea level respectively. Actual north is in 90° left from topographical north in figure. Gangwon Meteorological Administration is located near the central part of Gangneung city.



(2a) (2b)

(2c) (2d)

Fig. 2. (a) Surface weather chart, (b) 850 hPa chart, (c) GMS-IR satellite images and (d) Radar images indicating rain rate at six radars established by Korean Meteorological Administration at 2100 LST (1200 UTC), January 13, 2003. Thick curve line in (a) and cycle in (a) ~ (d) denote cold front and Gangneung city. High pressure center in northwestern China and low pressure center in the northeast side of Saharin island, Russia produced northwesterly wind near the surface and at 1.5 km height above Gangneung city prevailed and a little moisture transported from the sea to the city caused cloud to form over both the mountain basin to the west of the city and over the coastal sea in the east but no snow resulted over the city

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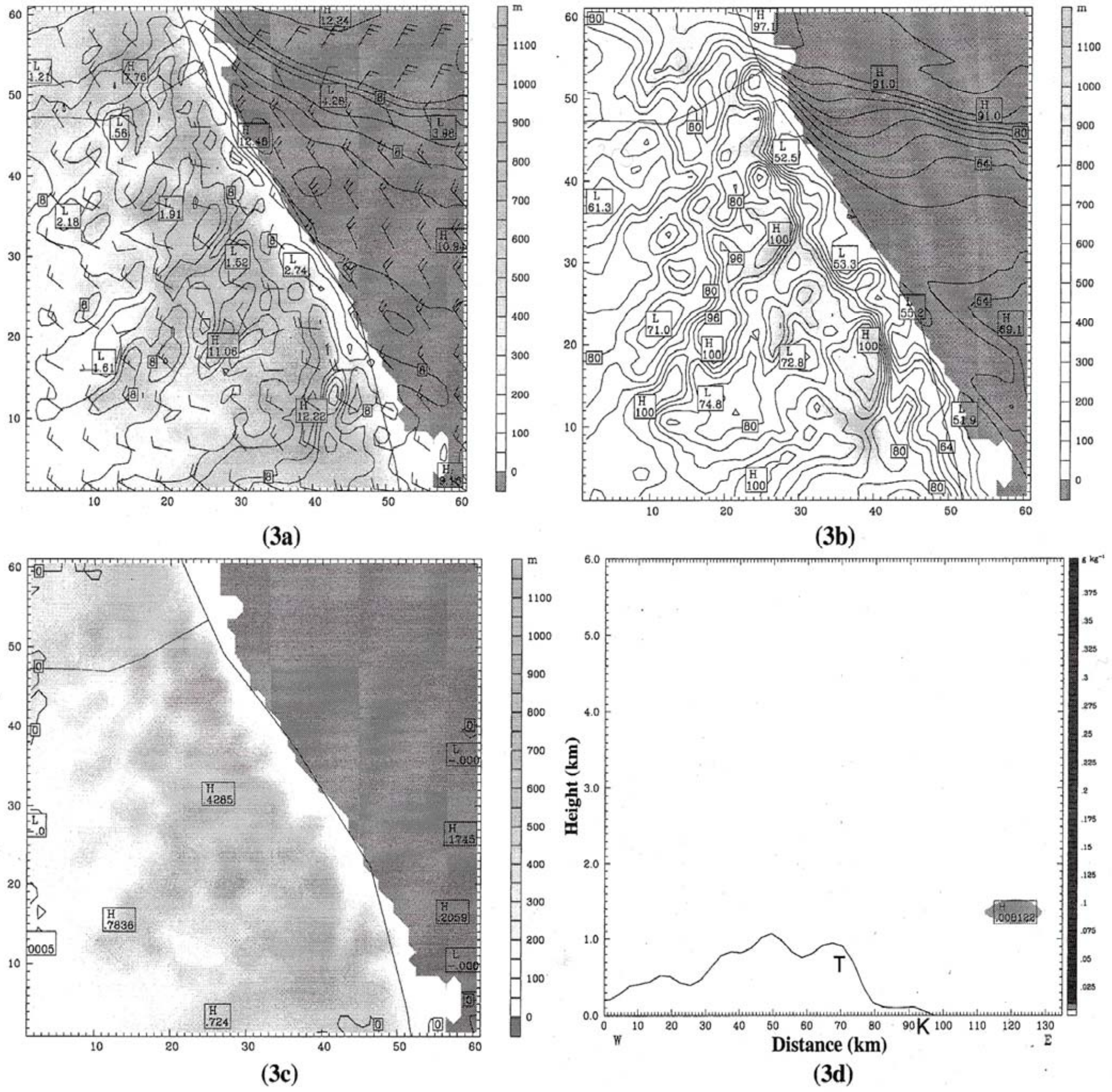

(3a) (3b)

(3c) (3d)

Fig. 3. (a) Surface wind (m/s), (b) Relative humidity (%), (c) Total precipitation amount in the past 3 hours and (d) Vertical profiles of total cloud mixing ratio (g/kg) on a straight line from T (Mt. Taegulyang) to K (Gangneung city) in fig. 3c at 2100LST, January 13, 2003.. Northwesterly and westerly were in the inland of Gangneung city. North-westerly winds parallel to the coastline over both the coast and open sea do not allow sufficient moisture advection from the sea over the land area to form sufficient cloud and then snowfall. RH is very low at less than 60 % near the Gangneung surface, but small amounts of precipitation are near Mt. Taegulyang and over the offshore.

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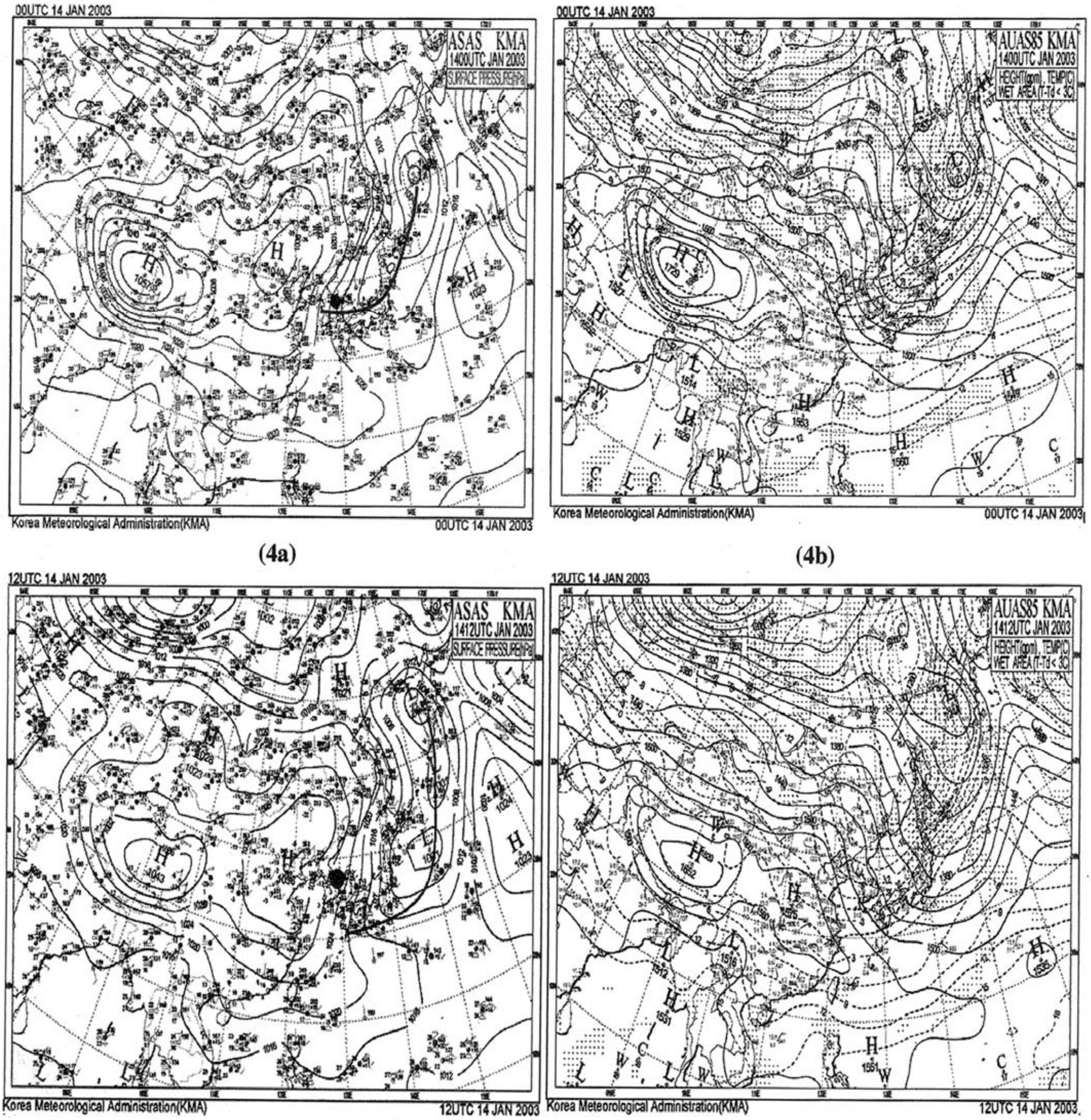

(4a)

(4b)

(4c)

(4d)

Fig. 4. (a) Surface weather chart, (b) 850 hPa chart at 0900 LST (0000 UTC), January 14, 2003, (c) surface weather chart and (d) 850 hPa chart at 1500 LST (0600 UTC), January 14. Thick curve line and cycle denote cold front and Gangneung city. As cold front passed by Gangneung area, wind direction changed from northwesterly to northerly and north-easterly. Northerly and northeasterly winds at Gangneung basin and coastal sea allowed much moisture advection from the sea over the coast and resulted in snowfall there.

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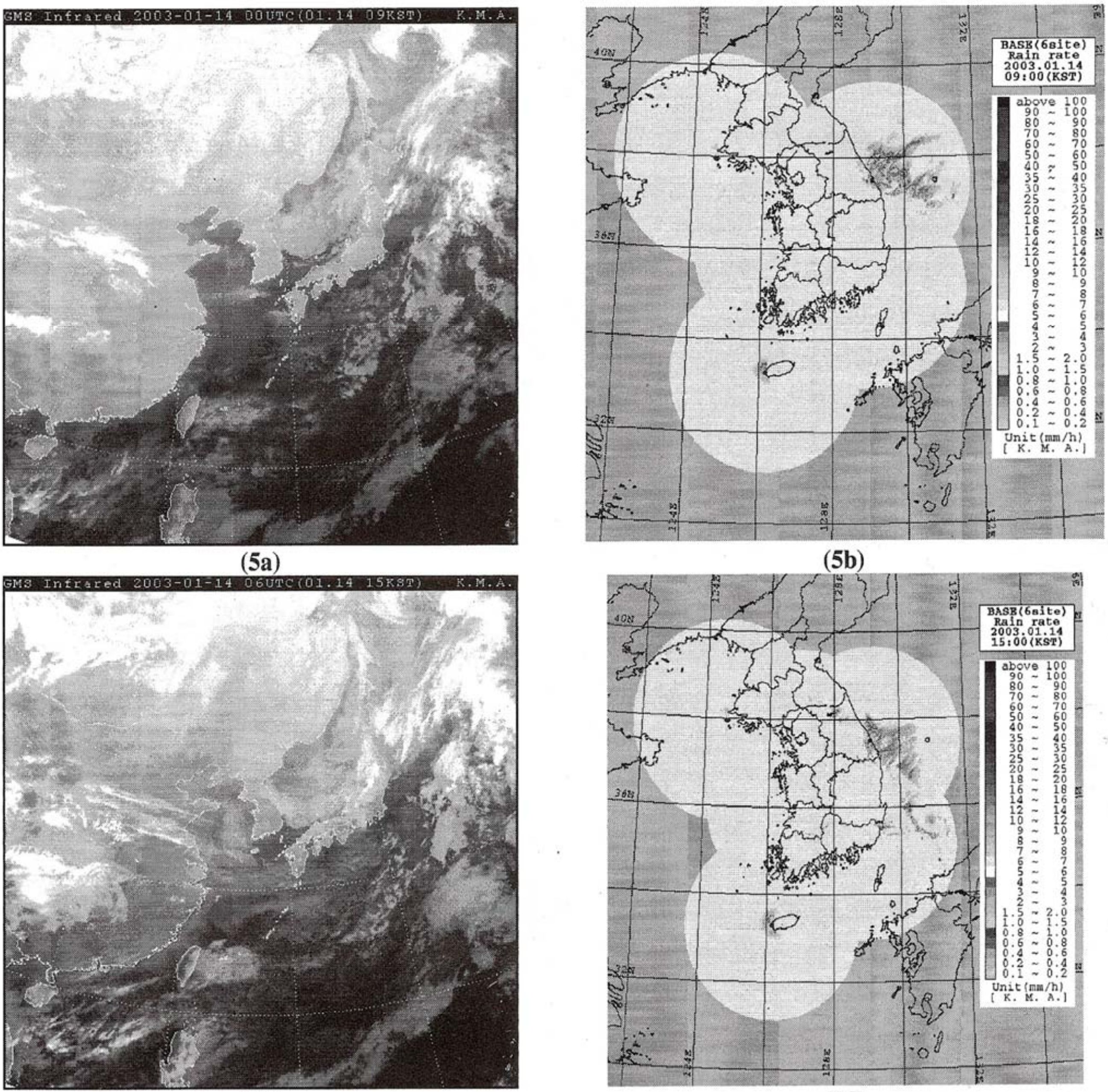


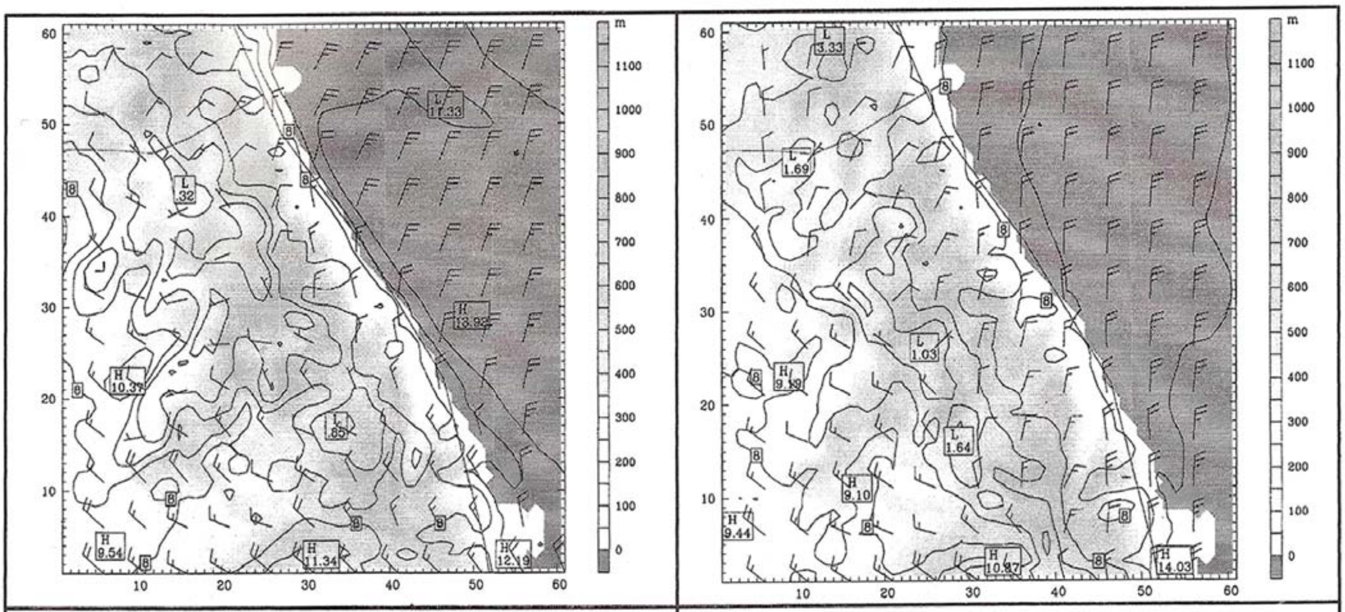
(5a) (5b)

(5c) (5d)

Fig. 5: (a) GMS-IR satellite infrared image, (b) radar image indicating rain rate at six radars established by Korean Meteorological Administration at 0900 LST (0000 UTC), January 14 and except for (a) and (b), (c) and (d) at 1500 LST (0600 UTC), January 14. Gangneung city (circle) has cloud which produces snowfall to begin at 0900 LST and ends at 2200 LST. Maximum snowfall (rainfall) amount reaches 19.8 cm (14.9mm) at 1200 LST

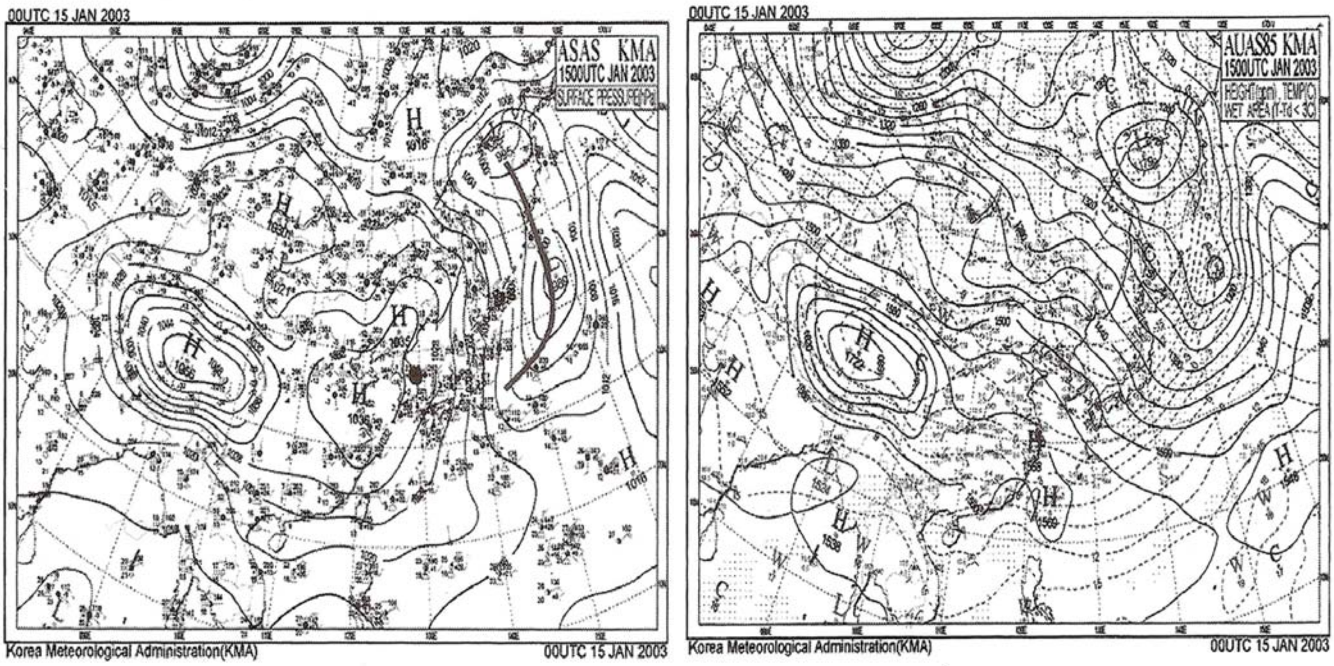
Table I
Comparison of calculated precipitation amounts (mm) to observed at Gangneung city from January 13-15, 2003. ( ) denotes snowfall amount (cm)

Date	Comparison	0900	1200	1500	1800	2100	0000
01/14	Observed	1.6	14.9	7.4	1.1	1.5	0.0
	(Snow)	(2.2)	(19.8)	(11.0)	(2.0)	(1.7)	(0.1)
	(Accumulated snow)	2.2	22.0	33.0	35.0	36.7	36.8
01/15	Calculated	5.5	15.4	7.3	1.5	0.4	0.1



(6a) (6b)

Fig. 6: (a) Surface wind (m/s) at (a) 0900LST (0000 UTC) and (b) 1500LST (0600 UTC), January 14, 2003. Cycle denotes Gangneung city. Northeasterly and northerly winds transport a large amount of moisture from the sea toward the mountain top west of the city and snowfall amounts reach 2.2 cm at 0900 LST and 11 cm at 1500 LST.



(7a) (7b)

Fig. 7: (a) Surface weather charts and (b) 850 hPa chart at 0900 LST (0000 UTC), January 15 (0000 UTC, January 15), 2003. Thick curve line and cycle denote cold front and Gangneung city. Wind direction was shifted from northerly wind into northwesterly wind from 0100 LST, January 15.

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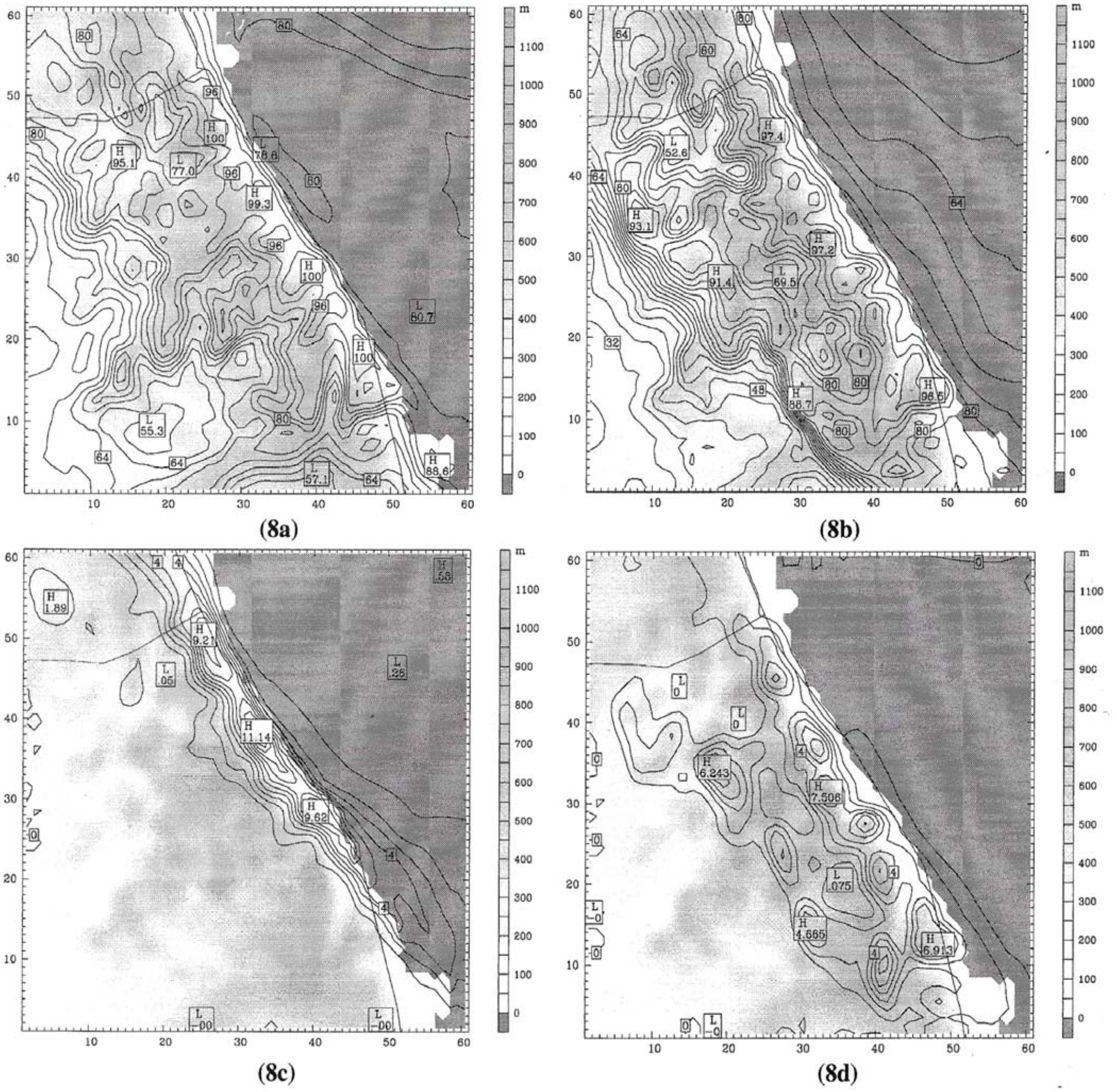

(8a) (8b) (8c) (8d)

Fig. 8: (a) Relative humidity (RH; %) at (a) 0900LST, January 14 and (b) 1500LST, January 14, 2003 and (c) precipitation amount in the past 3 hours at 0900 LST and 1500 LST. RH band (inclined thick black line) over 95 % in the coastal inland parallel to the coast coincides with precipitation area (snowfall area). Maximum snowfall (rainfall) amount reaches 19.8 cm (14.9mm) at 1200 LST.

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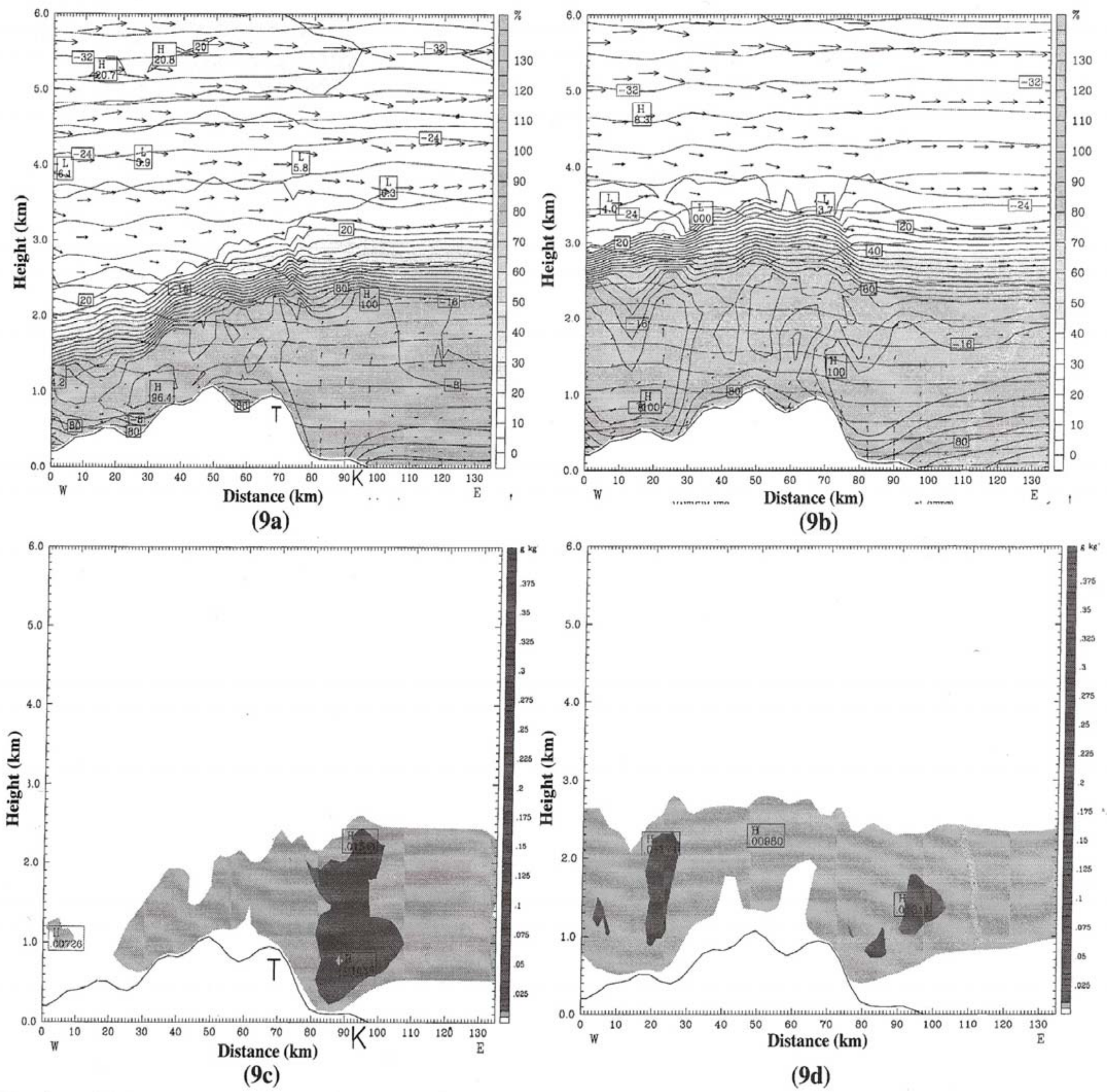

(9a) (9b)

(9c) (9d)

Fig. 9: (a) Vertical profiles of wind (m/s), temperature (°C) and relative humidity (%) on a straight line from T (Mt. Taegulyang) to K (Gangneung city) in fig. 8a at 0900 LST (start of snowfall) and (b) 1500 LST, January 14, and (c) total cloud mixing ratio (g/kg) at 0900 LST and 1500 LST. Atmospheric boundary layer over the inland (coast) confined to about 2 to 2.5 km (3.2 km) in (a) and 3.5 km in (b). Thick black (upper) and blue (lower) lines denote – 8^0C and 0 °C in (a) and – 6 °C in (b). Cloud tops reach 2.6 km in (a) and 2.8 km in (b)

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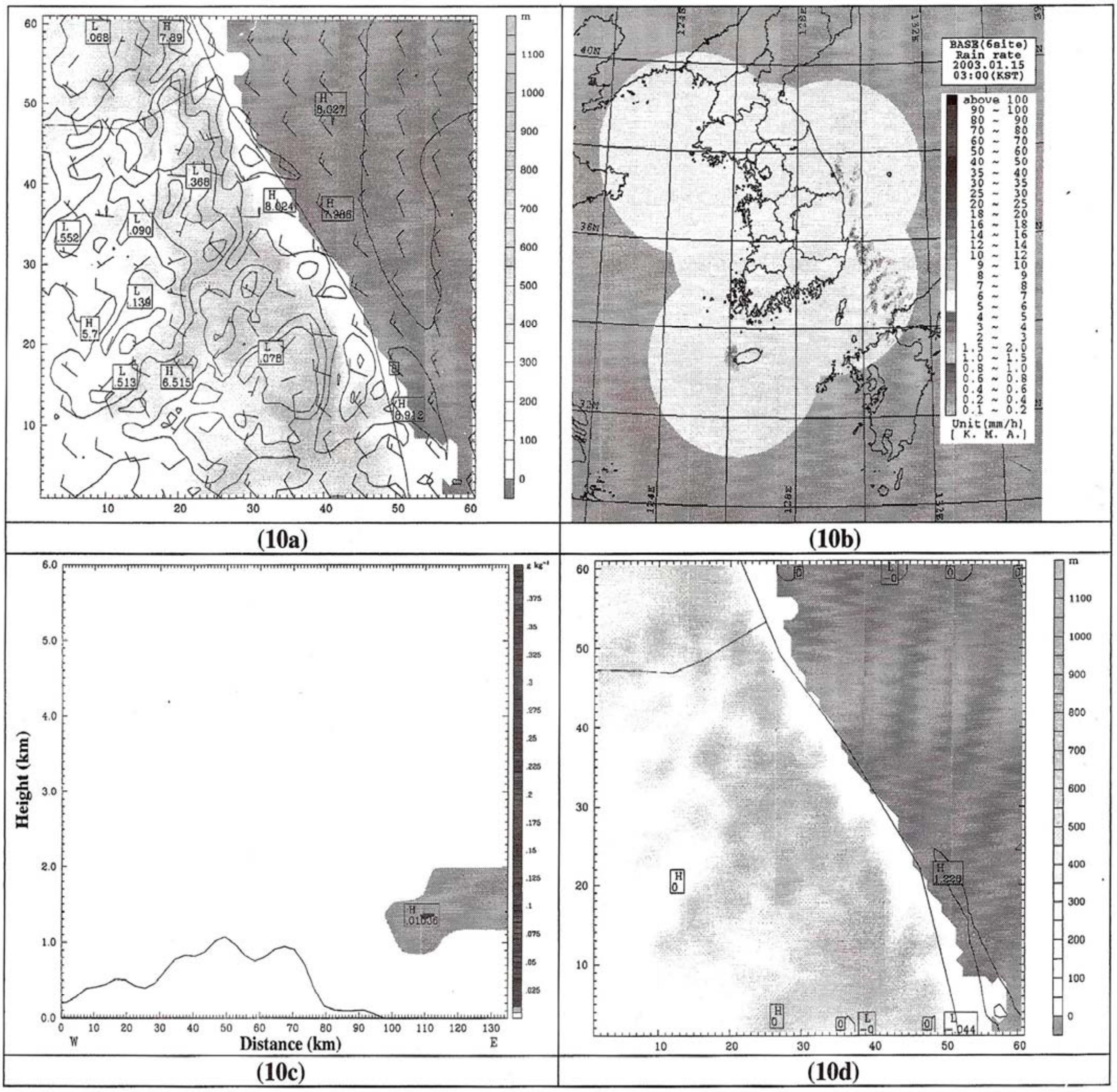

(10a)

(10b)

(10c)

(10d)

Fig. 10: (a) Surface wind (m/s), (b) radar image, (c) vertical profiles of total cloud mixing ratio (g/kg) and (d) precipitation amount in the past 3 hours at (a) 0900LST (0000 UTC), January 15, 2003. Cycle denotes Gangneung city. A limited amonnt of moisture transported from the sea by the northwesterly wind (340^0) causes a limited amount of cloud to form over the Gangneung coastal area. Snowfall stopped after 0100 LST, January 15 and no cloud and hence no snowfall at 0300 LST.

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