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Numerical study of a thick snow band along the Okhotsk Sea coast of Hokkaido Island, Japan.

*A dissertation submitted to Faculty of
Environmental Earth Science
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Doctor of Philosophy

by

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Abstract

In winter, the cold Siberian air mass often breaks out from the east coast of the Eurasian Continent, and many cloud bands develop over sea areas around Japan. In particular, frequent formations of a thick cloud band are known to occur at specific locations. One of such locations is the Okhotsk Sea coast of Hokkaido Island, northern part of Japan. Thick cloud bands along this coast have been categorized into a strong wind type and a weak wind type, based on the ambient wind speed estimated from the gradient of sea level pressure around the Hokkaido coast.

Numerical simulations were made to investigate the formation and maintenance mechanisms of a strong-wind type snow band using Weather Research and Forecasting Model (WRF). A strong-wind type snow band appeared on 26 Dec 2008 was simulated along the coast of Hokkaido Island, moved offshore toward the Sea of Okhotsk, where it intensified, and was sustained for one and a half days. The results show that Sakhalin Island plays an important role in the maintenance of a convergence line and thus the snow band.

Cold air advection from Sakhalin Island produces a strip of warm air between the advected cold air and Hokkaido Island and thus controls the location of the snow band, while topographic blocking by Sakhalin creates the lower level convergence at the Soya Strait and hence enhances the snow band. Temperature and surface-roughness contrast between Hokkaido Island and the Sea of Okhotsk are also important for the initial formation of the snow band.

The results of different sensitivity experiments of strong wind type case indicated that 1) the land-sea contrast along the Hokkaido coast largely contributed to the initial formation, 2) the cold advection from Sakhalin Island was important in the maintenance of the snow band, although cold land surface over Hokkaido Island was also important for the enhancement of the snow band, and 3) topography over Sakhalin strengthened the snow band by blocking the low level winds to form the convergence at the Soya Strait.

In addition, ambient wind direction played important role in the advection of snow band.

Chapter 1

Introduction

1.1 Background

In winter, the cold Siberian air mass often breaks out from the east coast of the Eurasian Continent, and many cloud bands develop over sea areas around Japan. Figure 1.1 shows the monthly mean wind velocity at the surface level (10 *m* level) for December 2008. The mean wind comes from Eurasian Continent mostly north-westerlies and pass over to the Sea of Japan as westerlies. As the cold wind blows on to the warm Sea of Japan, streets of convective cloud bands form with moisture and heat flux provided from the sea surface. Low pressure systems often form and pass over the Sea of Okhotsk. They create a strong westerly to north westerly wind near the northeastern coast of Hokkaido Island.

Figure 1.2, which is an MTSAT¹ image for 26 Jan 2010, shows an example for such a phenomenon. A series of band clouds developed across the whole northern Sea of Japan directed east to west along the blowing winds. In such situations, frequent formations of a thick cloud band are known to occur at specific locations. For example a thick band visible at the west of Hokkaido Island (marked as 1, colored red in the Figure) stretches across the Sea of Japan on to Hokkaido Island and is known to form at the same location and was studied by Ohtake et al. (2009) (discussed in the next section).

These prevailing cloud bands sometimes extend over to the Sea of Okhotsk. Another thick

¹Multifunctional Transport satellites (MTSAT) are series of weather (and other purposes) satellites, belongs to Japanese Meteorological Agency (JMA)

snow band often forms along the northeastern coastline of Hokkaido Island (marked as 2, colored red in the Figure 1.2). This cloud band is also interesting as it frequently appears at this location. Figure 1.3 depicts another instance of this band formation.

Fujiyoshi et al. (2010) are the first to report that a thick cloud bands appear frequently along the northeastern coast of Hokkaido Island during cold air outbreaks from the Eurasian Continent. The cloud bands, such as those in Figure 1.2 are usually associated with large snow fall and affect the local climate. Fujiyoshi et al. (2010) named these bands ‘Thick Cloud Bands along the Okhotsk Sea Coast of Hokkaido’ and showed three-dimensional structures of these bands, using two X-band Doppler radars. They categorized the cloud bands into a strong wind type and a weak wind type, based on the ambient wind speed estimated from the gradient of sea level pressure around the Hokkaido coast.

Fujiyoshi et al. (2010) also found that cloud bands of the weak wind type tend to appear in the night times and disappear in the mornings. They attributed the formation of weak-wind type bands to the development of land breeze blowing from Hokkaido Island to the Sea of Okhotsk. On the other hand, cloud bands of the strong wind type appear regardless of the local time. Strong-wind type bands form or last even after temperature difference between land and sea reduces (Fujiyoshi et al., 2010). Accordingly, the mechanism behind the formation and maintenance of strong-wind type cloud bands is still not clear. Figure 1.4 shows the occurrence of such cloud bands for 2006, 2007 and 2008 winters both for strong and weak wind cases. It is evident that the frequency of strong wind type bands were higher. It also shows that the ice cover over the Sea of Okhotsk acts to prevent the development of cloud bands as it prevents the supply of water vapor from the sea surface. Figure 1.5 compares the temporal evolutions of strong and weak wind cases. It is clear that in the strong wind case the cloud band sustained even after the land breeze disappeared. Thus, this particular snow band did maintain to stay

even after the land breeze disappeared which was the cause of its generation.

In the next section, we proceed literature review to seek similar studies conducted in the past and look into possible reasons for such formation and maintenance to occur.

1.2 Literature Review

Here we review several mechanisms of forming cloud bands around/along the coastline. Atlas et al. (1983) pointed out that land breeze, coastal shape, and sea surface temperature (SST) patterns have profound effects on the development of such cloud bands. Due to differential heating between land and sea in the wind path, a convergence (or divergence) line forms along a downwind of the major bend in the coastline (Figure 1.6). A vertical wind shear caused by the induced pressure field to the west of convergence line forces cloud street to form along the convergence line (S-W direction).

Roeloffzen et al. (1986) demonstrated that the difference in surface roughness between land and sea can also produce a convergence line along a coastline at lower levels, which could lead to the formation of a cloud band. The secondary flow pattern forced by a roughness discontinuity under homogeneous conditions along the coastline may cause a frictional convergence.

Andersson and Nilsson (1990) discussed the topographically induced convective snow bands over the Baltic Sea. Andersson and Gustafsson (1994) also pointed out the importance of the shape of coasts (similar to Atlas et al., 1983) and the orography and surface roughness on the formation and evolution of the snow bands.

Yoshihara et al. (2004) examined successive developments of snow bands at a convergence line near the coastal region of Hokuriku district of Japan through Doppler radar data. A meso scale convergence line was formed due to land breeze blowing opposite to the prevailing westerly wind and a series of convective cells developed the snow band formation.

Kawase et al. (2005) analyzed satellite images and made numerical experiments on cloud bands that appeared over south of Japan, particularly in the lee of Mt. Tsurugi and the Kii Channel. Figure 1.7 (after Kawase et al., 2005) shows the domain and results. They suggested that the thermal contrast is the main trigger of cloud streets in the lee of channels and bays, while mechanical force is the main trigger of cloud streets in the lee of mountains. The contrast in surface roughness between land and sea does have a significant effect on the formation of cloud streets, at least in the chosen case. It is worth noting that in Kawase et al. (2005) study the surface roughness has minor effects even though surface roughness can play a role in the formation of convergences at coastlines as studied by Roeloffzen et al. (1986).

Ohtake et al. (2009) numerically studied a thick cloud band that frequently appears over the northern Sea of Japan and produces localized heavy snowfall in the western coastal region of Hokkaido Island. Their sensitivity experiments showed the importance of upstream topography (especially a specific mountain in the Sikhote-Alin mountain range). They suggested that upstream topography, where the cloud band is initiated, creates a mesoscale frontal zone over the sea, which in turn causes a further development of the cloud band downstream.

1.3 Objective of thesis

As discussed in the previous studies, the band cloud formation occurs due to different reasons, namely upstream topographical structures, shape of coastline, land breeze and surface roughness. The cloud band along the coastline of Hokkaido may be generated due to land breeze from the Hokkaido Island but it continues to maintain in a longer duration for unknown reasons in the case of a strong wind type as described by Kamisho (2010). This study discusses the mechanisms of the formation and maintenance of a strong wind type cloud band with the help of numerical simulations.

First we simulate the cloud band observed on 26 and 27 Dec 2008 shown in Figure 1.8. This cloud band was identified as the strong wind type by Kamisho (2010). Then we conduct series of sensitivity experiments to access each factor that contributes to the formation and its maintenance.

1.4 Thesis Outline

Chapter 2 discusses methodology employed in the numerical study, model description, domain setup and input data. Chapter 3, describes the results of a strong wind case study. In Chapter 4 we discuss more details about the strong wind case with several sensitivity experiments. Chapter 5 describes the summary and ends with final conclusions.

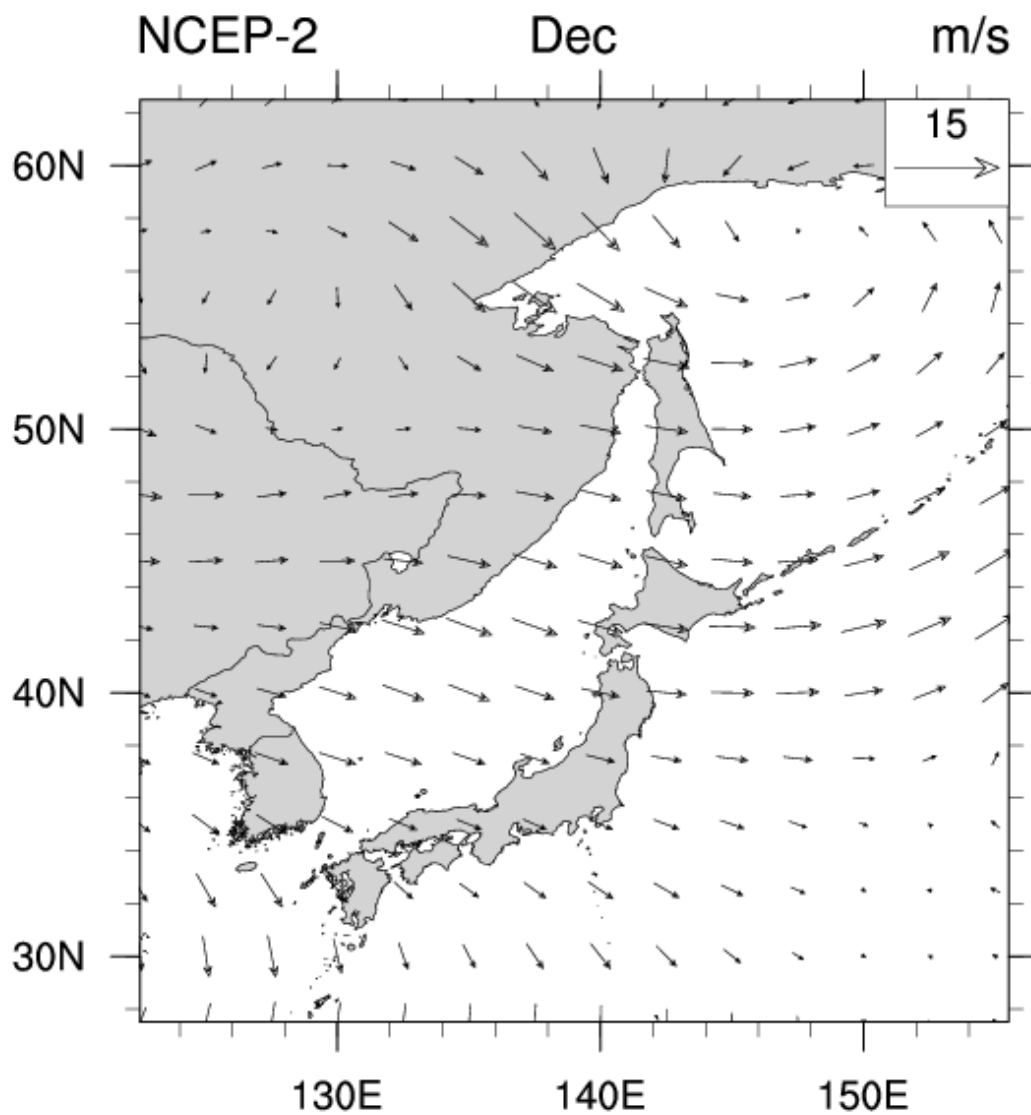


Figure 1.1: NCEP reanalysis monthly mean wind at 10 *m* from the ground for Dec 2008.

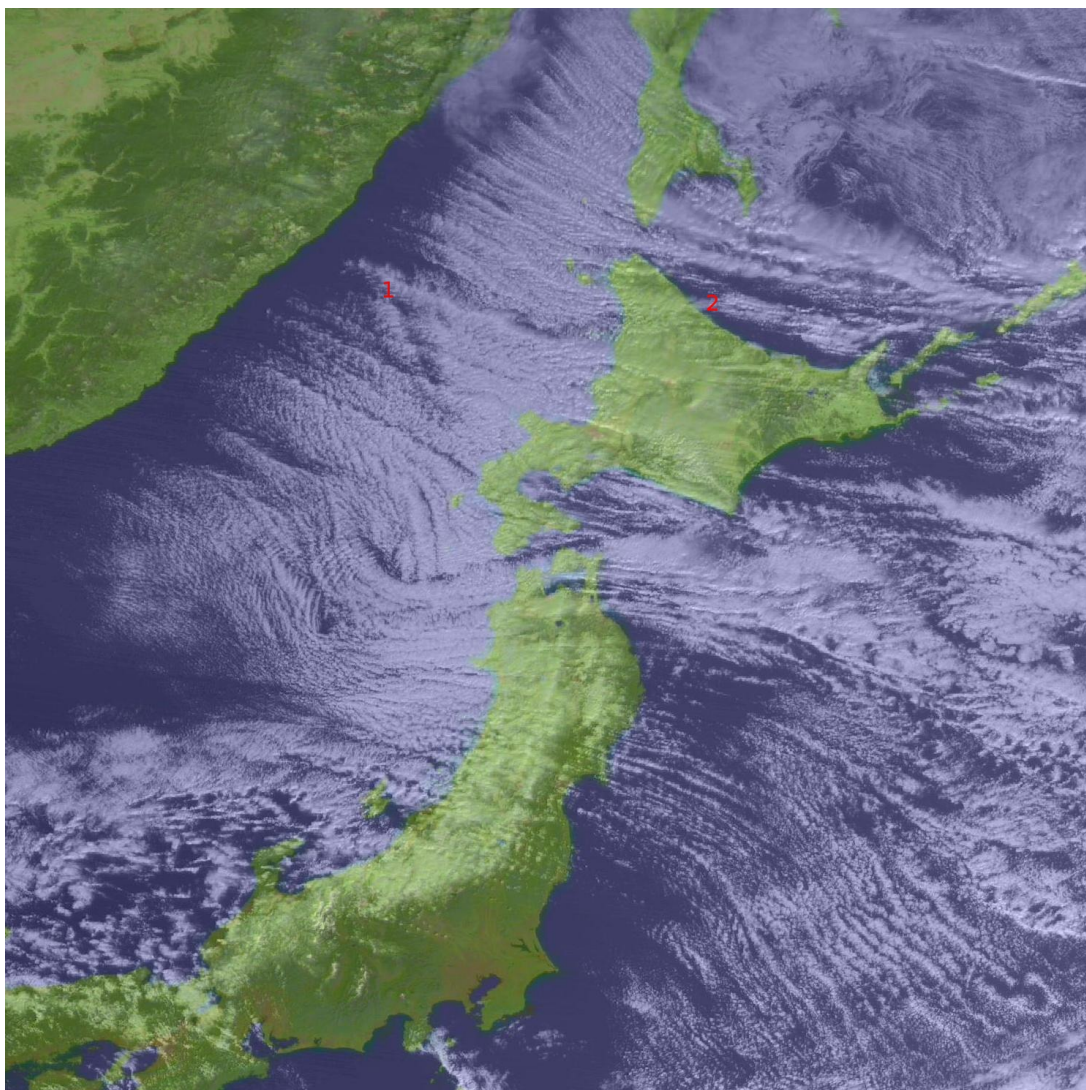


Figure 1.2: Cloud streets during a winter over the Sea of Japan (MTSAT image on 26 Jan 2008).

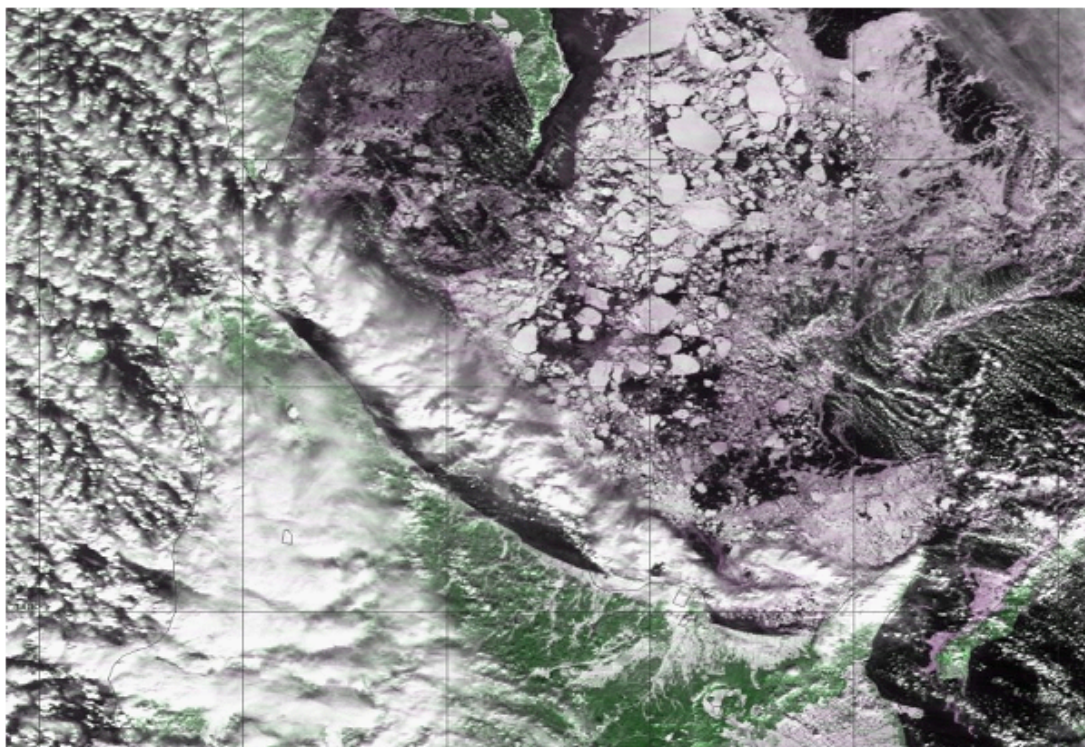
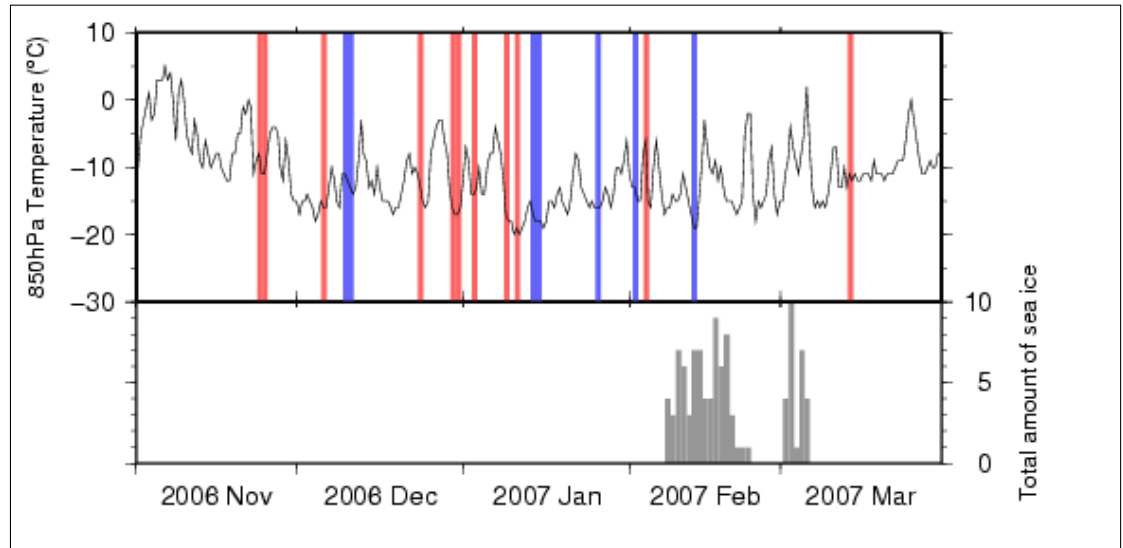


Figure 1.3: Snow band along the northeastern coast of Hokkaido Island in Feb 2008 (MODIS)
(After Kamisho, 2010)

a



b

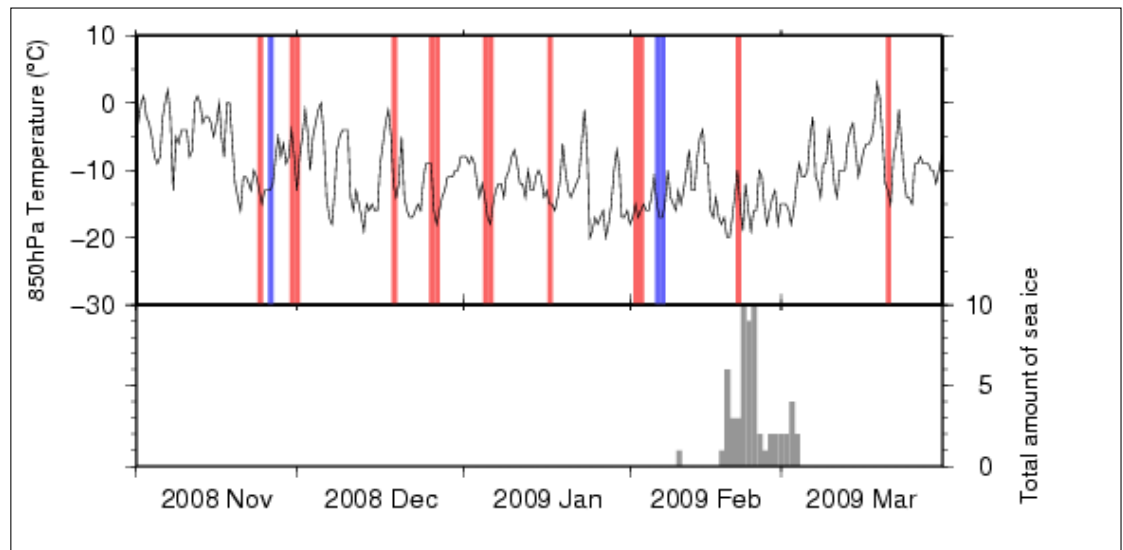


Figure 1.4: Seasonal formation of cloud bands for 2006, 2007 and 2008 winters both for strong wind case (red bars) and weak wind (blue bars) cases of cloud band. The bar charts beneath show the amount of sea ice (After Kamisho, 2010).

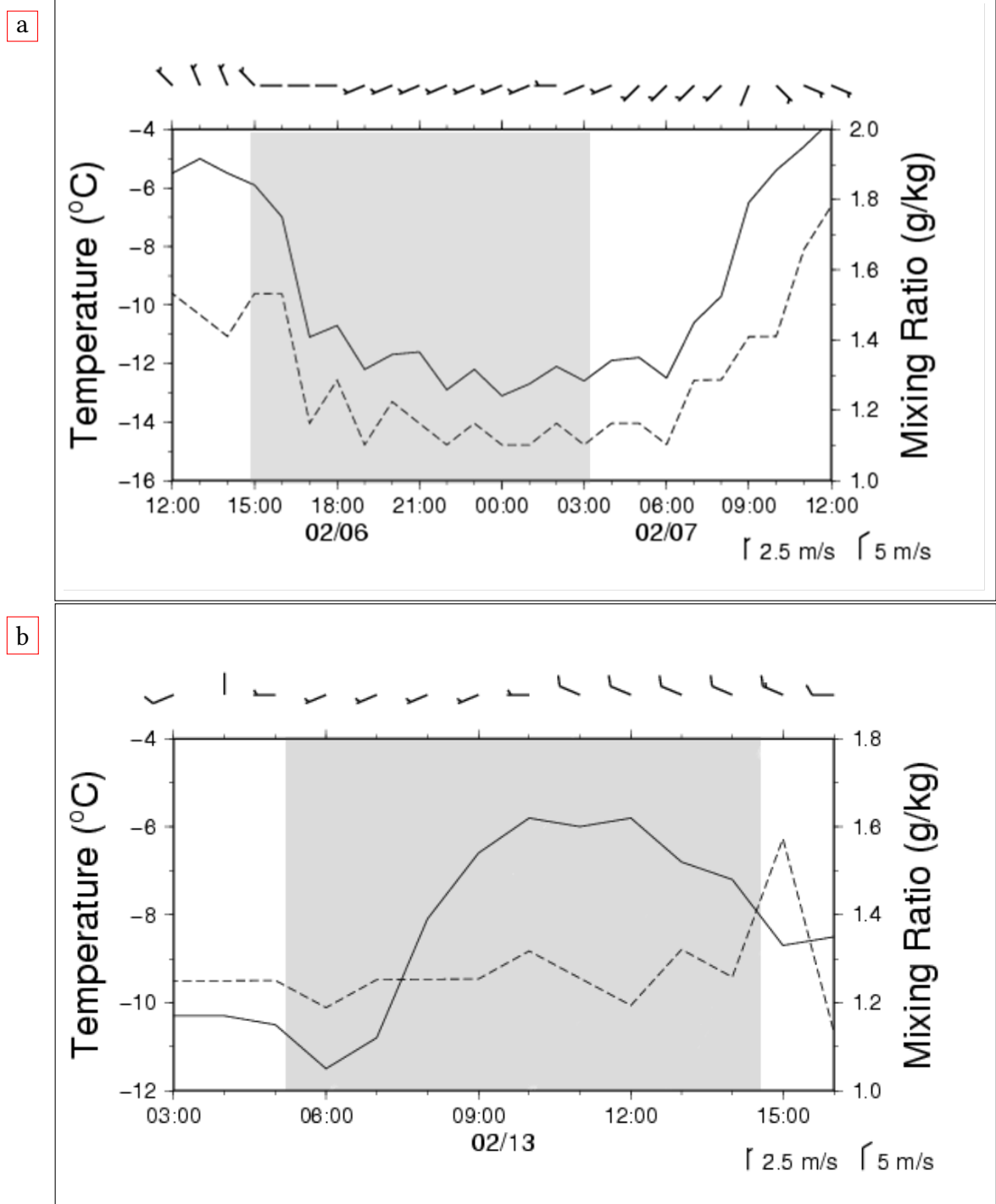


Figure 1.5: Temperature (solid lines) and water vapor mixing ratio (dashed lines) variations during band formation for a) weak wind case on 6 Feb 2008 and b) strong wind case on 13 Feb 2008. Overhead arrows show wind direction at a station in the northeast coastline of Hokkaido (After Kamisho, 2010). Shades indicate time durations of the snow band presence.

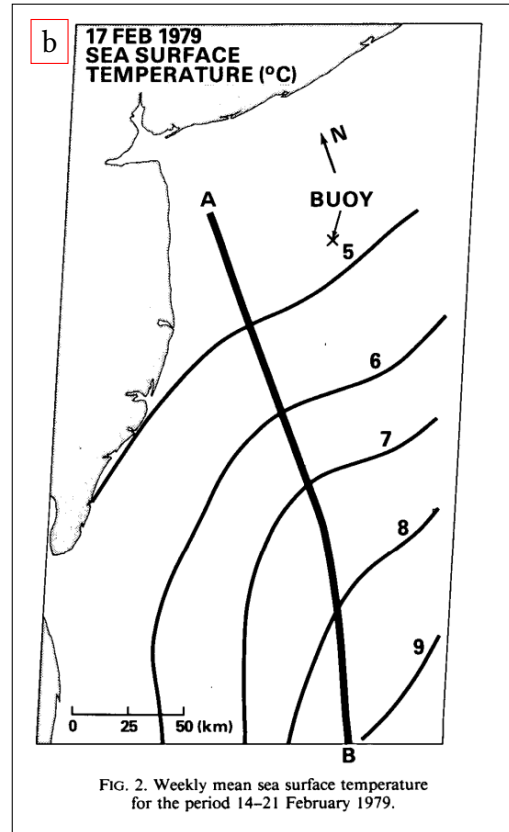
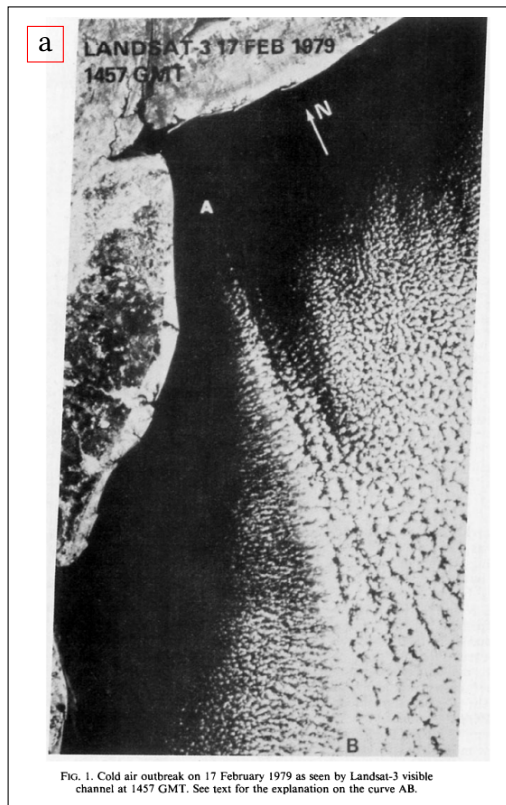


Figure 1.6: a) Cold air outbreak on 17 Feb 1979 as seen by landsat-3 visible channel. b) Weekly mean SST for the period 14-21 Feb 1979. (After Atlas et al., 1983).

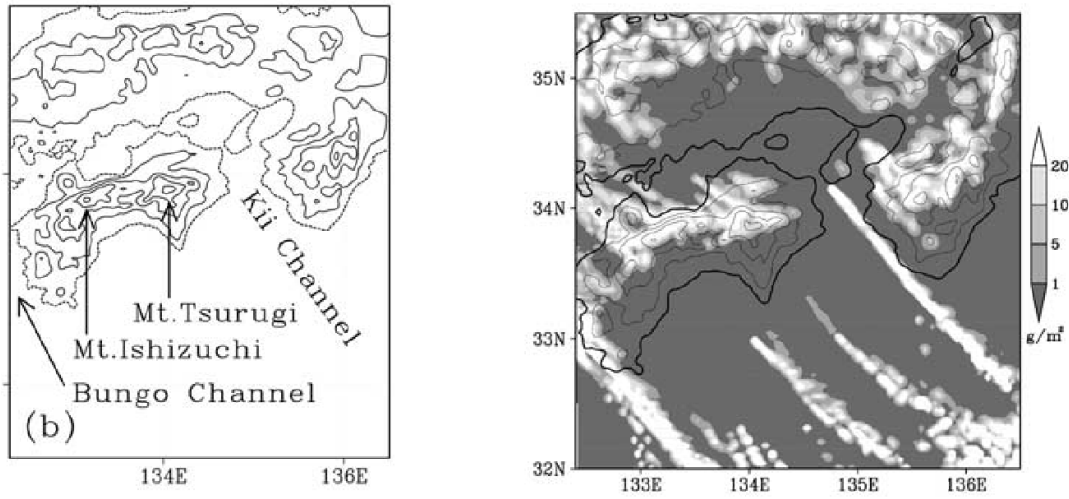


Figure 1.7: (Left) Model domain and (right) simulated cloud bands after Kawase et al. (2005). Contour shows topography with an interval of 300 m.

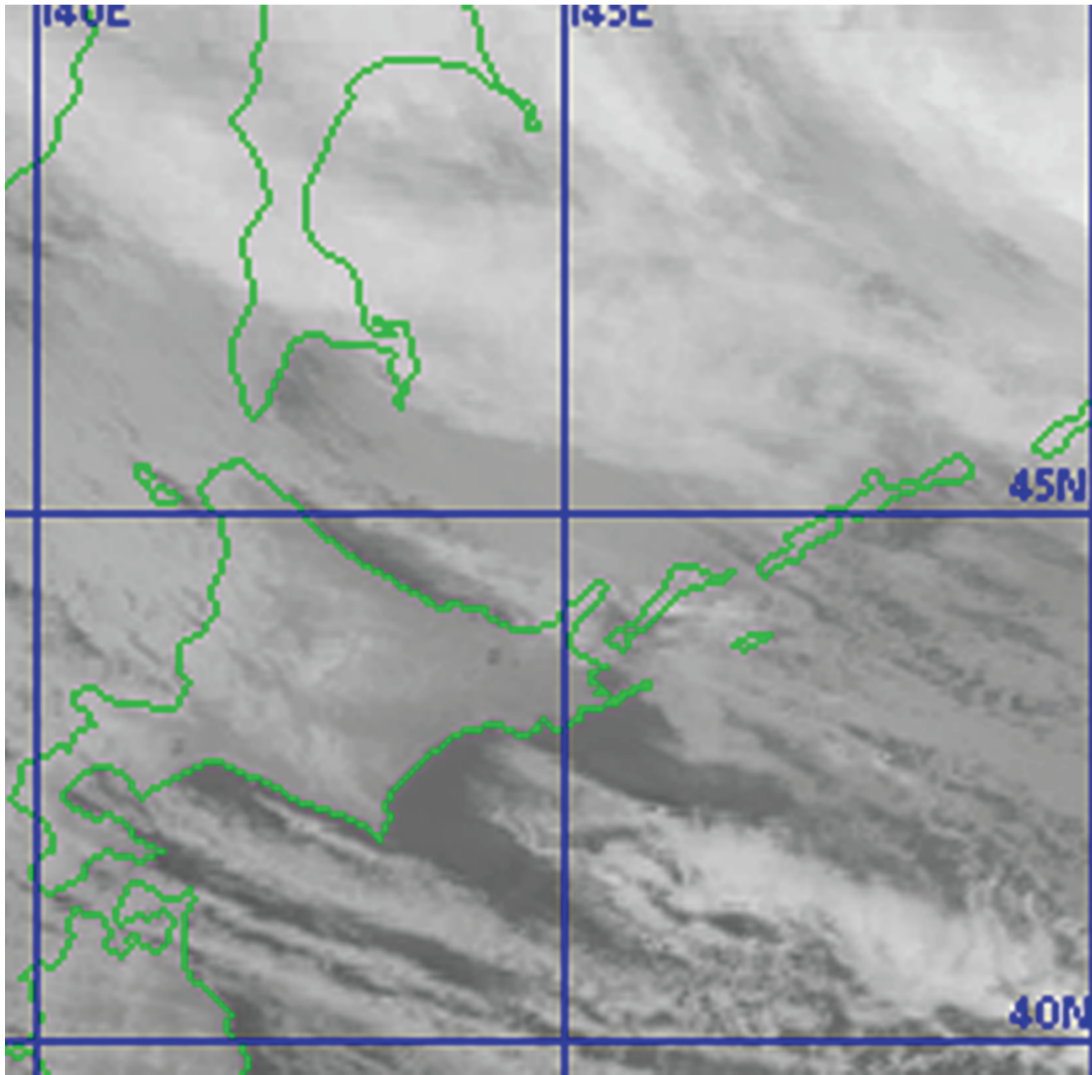


Figure 1.8: a) Satellite infrared image of the snow band at 1600UTC 26 Dec 2008 by MTSAT-1R (IR1) of the Japan Meteorological Agency (JMA). White colored shades represent clouds.

Methodology

2.1 WRF Model

2.1.1 Model Description

The Weather Research and Forecasting (WRF) Model is a numerical weather prediction and atmospheric simulation system designed for both research and operational applications. The WRF model mainly developed at National Center for Atmospheric Research (NCAR) and with collaboration of many research institutions and universities. Skamarock et al. (2008) described technical details of the WRF model setup and its equations. In this study, the numerical simulations were performed using the version 3.3.1.

The principal components and high level architecture of the WRF system are depicted in Figure 2.1. The WRF Software Framework (WSF) provides the infrastructure that accommodates the dynamics solvers, physics packages that interface with the solvers, programs for initialization. In this study, Advanced Research WRF (ARW) dynamics solver was used.

The ARW solver equations are fully compressible and nonhydrostatic with a run-time hydrostatic option available. The vertical coordinate is terrain-following hydrostatic-pressure. Arakawa C-grid staggering horizontal grid used with the capability of nesting of one-way, two-way and moving nests at run-time, though we only used one-way nesting in this study.

The architecture of WRF model facilitates many components embedded seamlessly within the system. The important modules from the flow chart (Figure 2.1, important since they are

used in the run) are WRF Terrestrial Data, Gridded data, WPS, REAL, ARW Model and NCL.

WPS is a pre-processing system which processes terrestrial data that comes with the WRF model. The terrestrial data contains static data such as topography, land use, soil type. WPS also processes gridded data (meteorological data typically in GRIB format) that is generated from a global reanalysis. WPS transforms these datasets to be fed to REAL program as input data. The REAL program defines physical grid (projection type and location on the globe, number of grids and nests) and interpolates fields to the prescribed domain. It also interpolates meteorological data and prepares horizontal and vertical coordinates and creates actual input to WRF model run. Once this pre-processing is completed, the actual WRF model is run. As described, the WRF model designed on the predictive equations with a time independent reference state. Time integration is conducted by a third order Runge-Kutta scheme with a smaller time split for short waves (acoustic and gravity waves). As the time integration progresses, state variables are output in the netcdf format. For this study we recorded the output variables for every 30 minutes after considering disk space. The recorded output is processed and visualized using NCL (later subsection has more details). Skamarock et al. (2008) technical note from NCAR discusses in-depth about the data flow in the model and the fundamentals of WRF.

2.1.2 Initial and Boundary Conditions

The WRF model can be run with initial conditions of an idealized scenarios or may be using a real interpolated data from a large scale analysis. For this study, the model only needed to run for a real case with meteorological data.

The initial and boundary conditions, including the initial snow cover, were derived from National Centers for Environmental Prediction Final Analysis data (NCEP FNL¹). This NCEP

¹As of this writing, the data can be retrieved from <http://rda.ucar.edu/datasets/ds083.2/>

FNL Operational Global Data are on $1.0^{\circ} \times 1.0^{\circ}$ grids prepared operationally every six hours. NCEP FNL data is produced from the Global Data Assimilation System (GDAS). The Analysis data is available on the surface, at 26 mandatory levels from 1000 *hPa* to 10 *hPa*, in the surface boundary layer and at some sigma layers, the tropopause and a few others. Parameters include surface pressure, sea level pressure, geopotential height, temperature and sea surface temperature.

A daily, high-resolution, Real-Time Global, Sea Surface Temperature (RTG-SST) analysis has been developed at the National Centers for Environmental Prediction/Marine Modelling and Analysis Branch (NCEP/MMAB). The daily sea surface temperature product is produced on a half-degree (latitude, longitude) grid, with a two-dimensional variational interpolation analysis of the most recent 24-hours buoy and ship data, satellite-retrieved SST data, and SST is derived from satellite-observed sea-ice coverage.

As described in the previous subsection, the FNL, RTG-SST data sets along with the static data were interpolated on the prescribed physical domain as initial and boundary conditions for every six hours throughout the run duration.

2.1.3 Physics Options

WRF has multiple options to choose the parameterization of different physical processes. WRF system framework is designed to pick up any given choice of parameterization schemes at the run time. A cumulus parameterization scheme (CPS) calculates the sub-grid scale convective clouds. Use of cumulus parameterization is not required when the grid size is smaller than $4 \sim 5$ *km*. For this study the CPS was used in the outer and coarser domains in which the grid spacing was larger than a such threshold (domain setup is discussed in the next subsection). For the outer domains the Kain-Fritsch cumulus parameterization (Kain, 2004) was employed.

Kain-Fritsch scheme is a deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale. It uses Lagrangian parcel method, including vertical momentum dynamics to estimate whether instability exists or any instability will become available for the cloud growth. This scheme is an “update” from the earlier KF scheme with refinements described in Kain (2004). A run time option in WRF model allows to choose the frequency with which CPS can be called. For this study, CPS was called for every five minutes.

A Bulk Microphysics Parameterization (BMP) is required when there is grid-scale saturation, and when there is a net evaporation or sublimation of hydrometeors. Thompson et al. (2008)’s “new scheme” (as it is called in the WRF) with cloud ice, snow and graupel in addition to water vapor, cloud water and rain water processes suitable for high-resolution simulations was used for the model run. Unlike any other BMP, the assumed snow size distribution depends on both ice water content and temperature and is represented as a sum of exponential and gamma distributions. Furthermore, snow assumes a non-spherical shape with a bulk density that varies inversely with diameter as found in observations, in contrast to nearly all other BMPs that assume spherical snow with constant density. This scheme is newly added in the version 3.1 of WRF model.

Radiation schemes estimate the amount of incoming shortwave radiation as well as outgoing longwave radiation from clouds should be calculated. The Rapid Radiative Transfer Model (RRTM) scheme for longwave radiation was used for this study. RRTM scheme is an accurate scheme using look-up tables for efficiency (Mlawer et al., 1997). Goddard shortwave scheme was used for shortwave radiation. This is a two-stream multi-band scheme with ozone from climatology and cloud effects (Chou and Max J. Suarez, 1994). The parameterization scheme includes the absorption due to major gaseous absorption and of the minor trace gases as well

as clouds and aerosols. This parameterization accurately computes fluxes to within 1% of the high spectral-resolution line-by-line calculations.

Planetary boundary layer (PBL) scheme is responsible in the calculation of vertical sub-grid-scale fluxes due to eddy transports in the whole atmospheric column, not just the boundary layer itself. The Mellor-Yamada-Janjic PBL scheme (Janjić, 2002) was employed here. This parameterization uses the Mellor-Yamada 2.5 turbulence closure model (Mellor and Yamada, 1982). The upper limit of diffusibility is calculated using turbulent kinetic energy (TKE) and a function of buoyancy and shear of the driving flow. In stable conditions, the upper limit is derived from the requirement that the ratio of the variance of the vertical velocity deviation and TKE cannot be smaller than that corresponding to the regime of vanishing turbulence.

The surface layer schemes calculate friction velocities and exchange coefficients that enable the calculation of surface heat and moisture fluxes in the land-surface models and surface stress in the PBL scheme. The Noah land surface model (LSM) for the land surface processes was used for this study. LSM is a unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics. New modifications are added in Version 3.1 to better represent processes over ice sheets and snow covered area (Tewari et al., 2004).

2.2 Domain Setup

WRF model can be run with nested domains. In a nested domain setup, simulated state data of outer (or larger) domain supplied as boundary conditions for its first inner domain (generally with a finer grid). For this study, model was set up with three one-way nested domains.

Figure 2.2 shows the three domain rectangular boxes. The outer-most domain has a grid spacing of 13.5 *km* and covers a wider horizontal area where generally cold out breaks occur.

The second domain (denoted as d02) has a horizontal grid space of 4.5 *km*. The grid space ratio with parent domain is restricted to an integer (in this case 3 adopted) in WRF model and the last and smallest domain (denoted as d03) has the finest grid spacing of 1.5 *km*. This finest domain covers the area of the cloud band of our interest.

The vertical grid consists of 35 η coordinate levels in each domain with 7 levels located below 0.9 η (about 890 *hPa* over the sea) with the model top at 50 *hPa*. The outer-most domain was constructed wider enough to insulate boundary effects upon inner domains.

2.3 Post Processing

Model generated output files are in the format of netcdf. Model stores the results of each domain separately. The results were processed and visualized using NCAR Command Language (NCL). NCL² is an interpreted language (implemented in C and Fortran) specifically designed for scientific data analysis and visualization. NCL has a number of routines to support easy IO operations of WRF output.

²NCL Website: <http://www.ncl.ucar.edu/>

WRF Modeling System Flow Chart

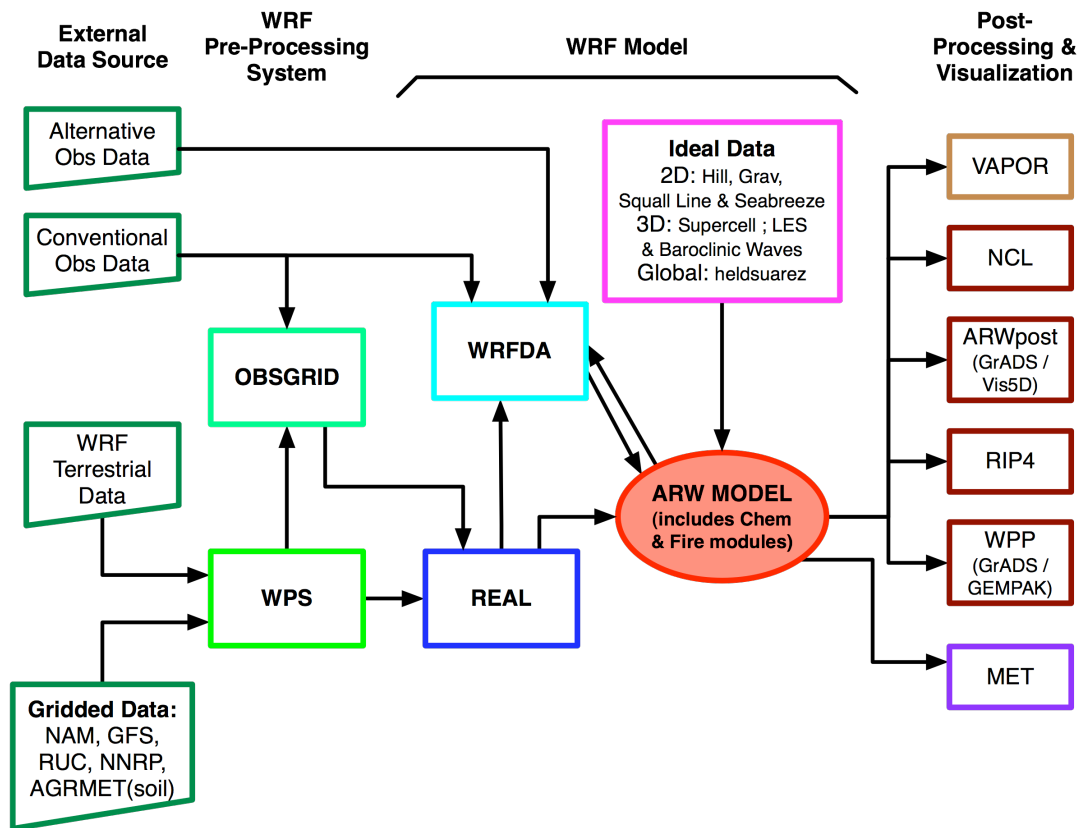


Figure 2.1: WRF flowchart: components of WRF Software Framework (After Skamarock et al., 2008)

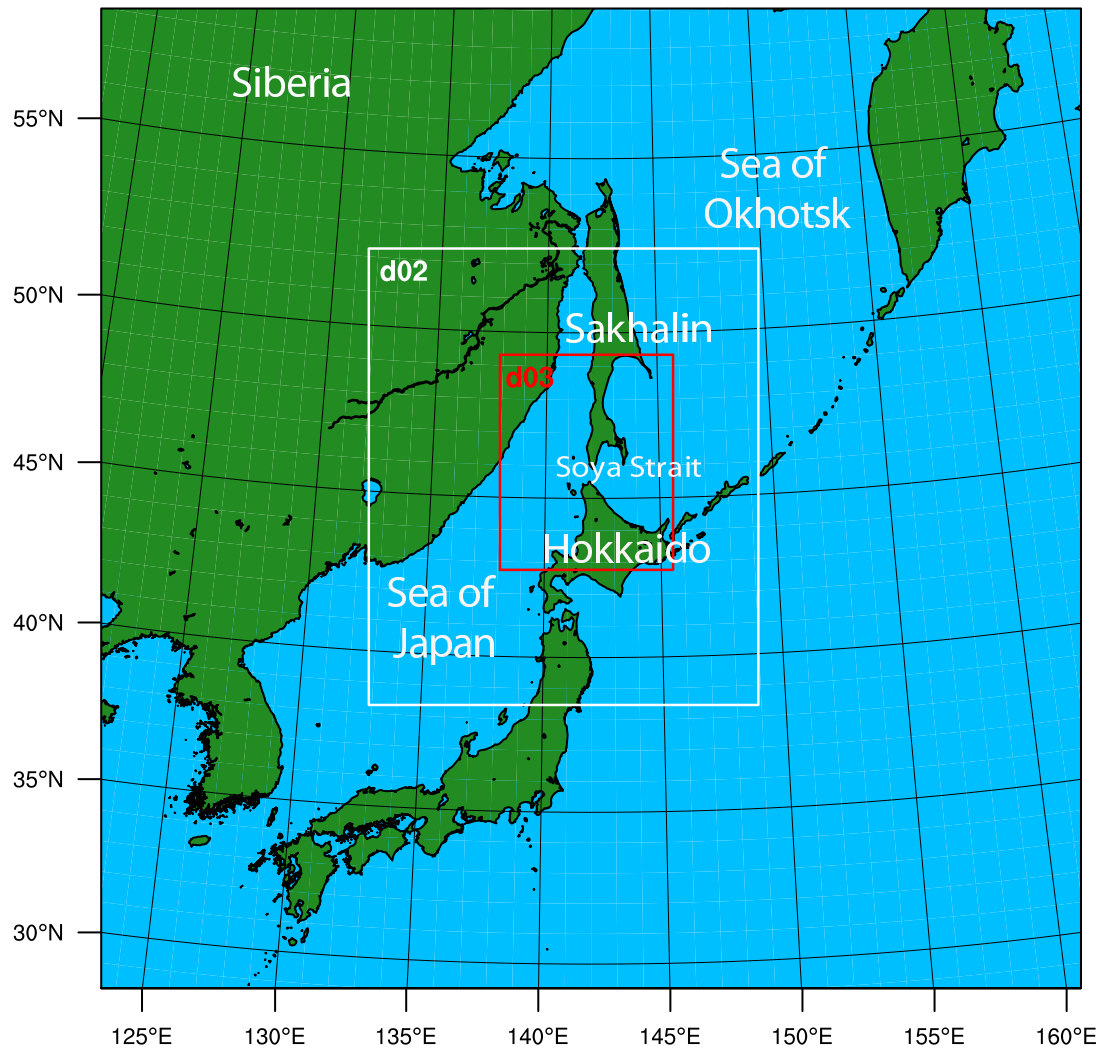


Figure 2.2: The study area used in the numerical model. Boxes labeled d02 and d03 denote the inner nests of the model setup.

Strong Wind Case.

3.1 Case Study

As introduced earlier the cloud band investigated here was identified as the strong wind type by Kamisho (2010). It was formed when a synoptic scale low-pressure system was located over the southern part of the Sea of Okhotsk and induced strong surface winds (~ 15 m/s). Doppler radar observations showed that the cloud band first appeared along the northeastern coastline of Hokkaido and then moved offshore to the Sea of Okhotsk and that it had a width of 10–20 *km* and a height of 3–4 *km* (Kamisho, 2010). Numerical simulation with the WRF model was run from 0000UTC 25 Dec 2008 to 0000UTC 28 Dec 2008. Figure 3.1 shows the model topography and sea surface temperature (SST) used in the model run for the inner most and highest grid resolution domain (d3). The sea surface temperature kept unchanged throughout the model run.

3.2 Formation and maintenance of snow band

The simulation reproduced a cold air outbreak from the Eurasian Continent caused by a synoptic scale low pressure system, which moved eastward in the southern part of the Sea of Okhotsk. Figure 3.2, the surface weather map at 0000UTC 27 Dec 2008, shows the synoptic scale system over northeastern part of the Sea of Okhotsk. From the satellite figures (not shown), it is evident that this strong system moved northeast-ward as it intensified. The model was able

to capture this synoptic scale system within the simulation. Figure 3.3 shows the evolution of sea level pressure with time which elucidates the system movement and its development on 26 and 27 Dec 2008. The pressure drops significantly at the core of the system (over the north eastern part of Sea of Okhotsk) by 1600UTC 26 Dec the pressure contours align parallel to the north eastern coast line of Hokkaido Island. The synoptic scale low pressure system continuous to become stronger over time (Figure 3.3c-d).

Figure 3.4 shows the divergence at lowest eta level. From the Figure, the evolution of convergence line along the north eastern Coastline of Hokkaido Island. The direction of ambient low-level winds turned from north (At 0600UTC 26 Dec) to north westerlies. The convergence line advected from the coast line of Hokkaido over to Sea of Okhotsk (at 1600UTC 26 Dec). As the time progresses (to the next day 0200UTC 27 Dec and to 1200UTC 27 Dec) the advection of convergence line relatively slow and remain almost stationary over the Sea of Okhotsk. Note that timings of Figure 3.3 and Figure 3.4 are chosen to give overall horizontal wind profile of simulation period, whereas the timings of figures to come are focused to elucidate the band initial development and thereafter development of snow band.

Figure 3.5 shows vertically integrated snow mixing ratio and air temperature at 940 *hPa*. Simulated mixing ratios of cloud ice and graupel produced by the Thompson et al. (2008) scheme are much smaller than the snow mixing ratio and are not shown for brevity. It should be mentioned here that test simulations indicated that simulated amount of each hydrometeor showed considerable variability depending on the choice of microphysics schemes. However, the choice of the ice-phase microphysics scheme does not affect the main conclusion of this study. As the direction of ambient low-level winds turned from north to northwest, a snow cloud band formed along the Okhotsk Sea coast of Hokkaido (Figure 3.5a) and moved offshore (Figures 3.5b-d). The simulated snow band (Figure 3.5b) is similar to the satellite image (Fig-

ure 1a) and the one observed by Doppler radars (Kamisho, 2010) at the corresponding time in terms of the shape (length and width) and the location.

As the air temperature decreased over the land and the temperature difference between land and sea increased across the northeastern coast of Hokkaido, a convergence line and a snow band formed along the coast (Figure 3.5a). In fact, the difference in surface air temperature exceeded 6 K across the northern coastline of Hokkaido at the time of 1130 UTC 26 December 2008 (not shown). The data from the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency (JMA) have also shown a similar drop in the temperature over the land along the coast (Kamisho, 2010).

Roeloffzen et al. (1986) numerically showed that difference in surface roughness between land and sea can also produce a frictionally-induced convergence along a coastline when the geostrophic wind blows along the coast with a land on the right-hand side in the Northern Hemisphere. In the present case, the near-surface geostrophic wind is north-northwesterly as suggested by Figure 1.8b, thus the wind blows along the coast with the land on the right-hand side. It is difficult to assess the relative importance of the land-ocean temperature contrast that lead to the formation of a land breeze and surface roughness difference in forming the snow band, because a change in the roughness parameter in the model entails a change in the surface heat flux and therefore the near-surface air temperature contrast between the land and ocean. We suppose, however, that the effect of surface roughness difference will be also important in the initial formation of the convergence line, because the direction of the geostrophic wind, along with the large wind speed, is favorable for the formation of frictionally-induced convergence line. The effects of topography over Hokkaido were minor, as discussed later in the next section.

After the formation, the snow band moved over to the warm Sea of Okhotsk and became

stronger both in terms of width and integrated snow mixing ratio (Figure 3.5b). The snow band continued to grow owing to the convergent wind field even though the surface air temperature over the land increased (Figures 3.5c, d).

Meanwhile, cold winds from Sakhalin Island created a colder region in the downstream (Figure 3.5). This cold air advection, together with the cold air over near Hokkaido Island, formed a strip of relatively warm air over the Sea of Okhotsk. The snow band and convergence zone were located on this strip. Figure 3.6b-d shows this cross coastal wind with time visualizes this.

Figure 3.7a shows a vertical cross section of the snow band along the line drawn in Figure 3.5c at the time of the figure when the snow band was most developed. The snow band was associated with the lower level convergence and upper level divergence, and the top of snow band reached as high as 650 *hPa*. The convergent wind field was constituted by a relatively strong wind from the cold coast on the left in the figure and a relatively weak wind from the cold region downstream of Sakhalin Island on the right. These relatively cold air masses extended to ~ 850 *hPa* on both sides of the convergence (Figure 3.7b), and the near-surface air temperature increased toward the convergence line where the snow band was situated. The heights of cloud top (3–4 *km*) and the low-level winds from Hokkaido (1–2 *km*) are comparable to those measured by Doppler radars (Kamisho, 2010).

The above results suggest that land breeze from Hokkaido Island and the cold air advection from Sakhalin Island contribute to the development and maintenance of the convergence line and snow band.

Figure 3.8 shows a Hovmöller diagram representing the snow band development in the mode run along the same cross section as shown in Figure 3.7. It illustrates that the snow band formed along the coastline, moved offshore to the Sea of Okhotsk as the time progressed,

and lasted for nearly a day and a half. The snow band intensified as it moved offshore and the intensity of the snow band became maximum at about 0000UTC 27 Dec. The snow band stayed around there for ~ 2 hours. It then started moving offshore again and weakened.

The next chapter we will discuss about different sensitivity experiments conducted to access the importance of Hokkaido Island and Sakhalin Island for the formation and maintenance of the snow band

SST and Terrain

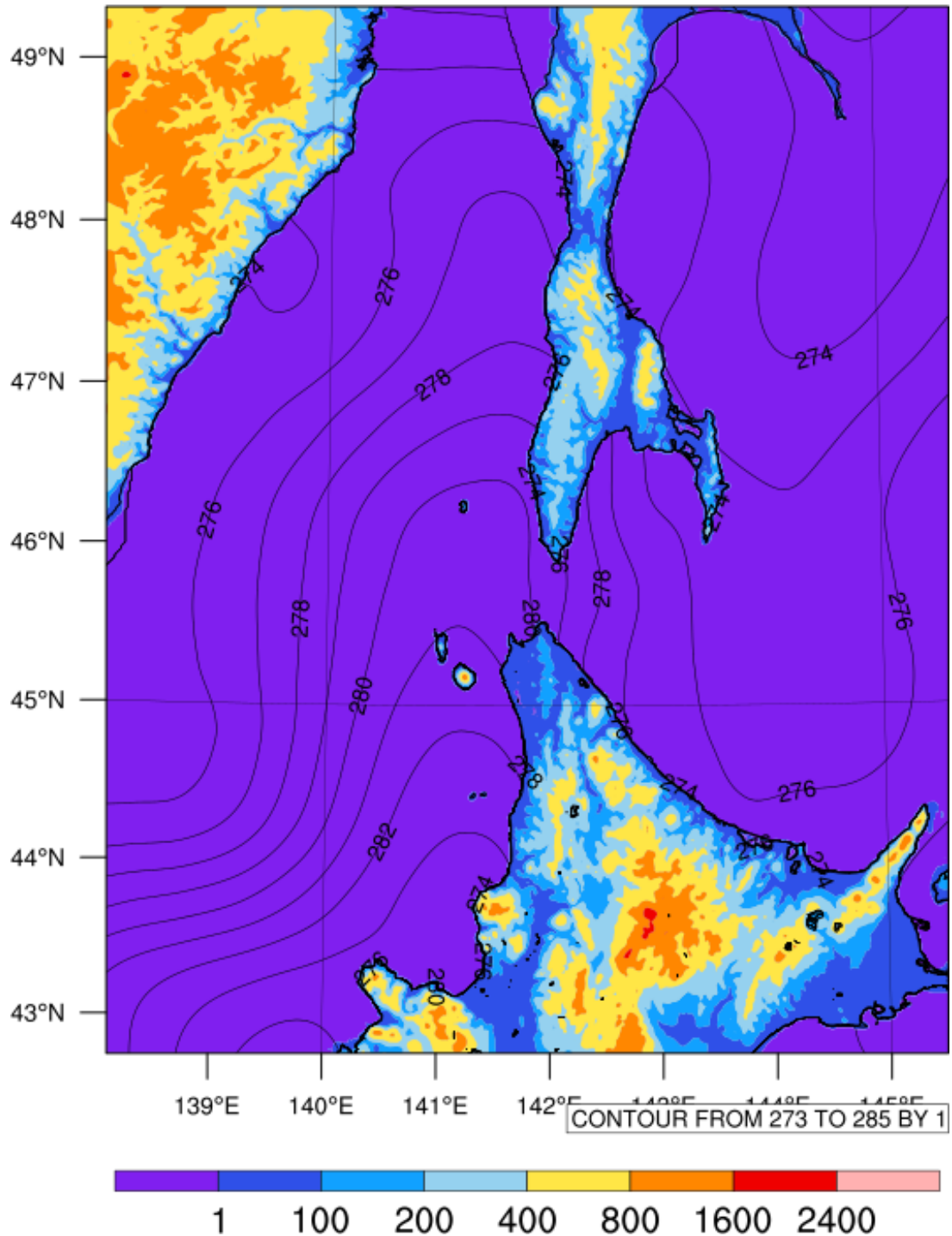


Figure 3.1: Sea surface temperature and topography used in the model. The contour lines are sea surface temperature in K and shade represents the topographic height (m) in the simulation.

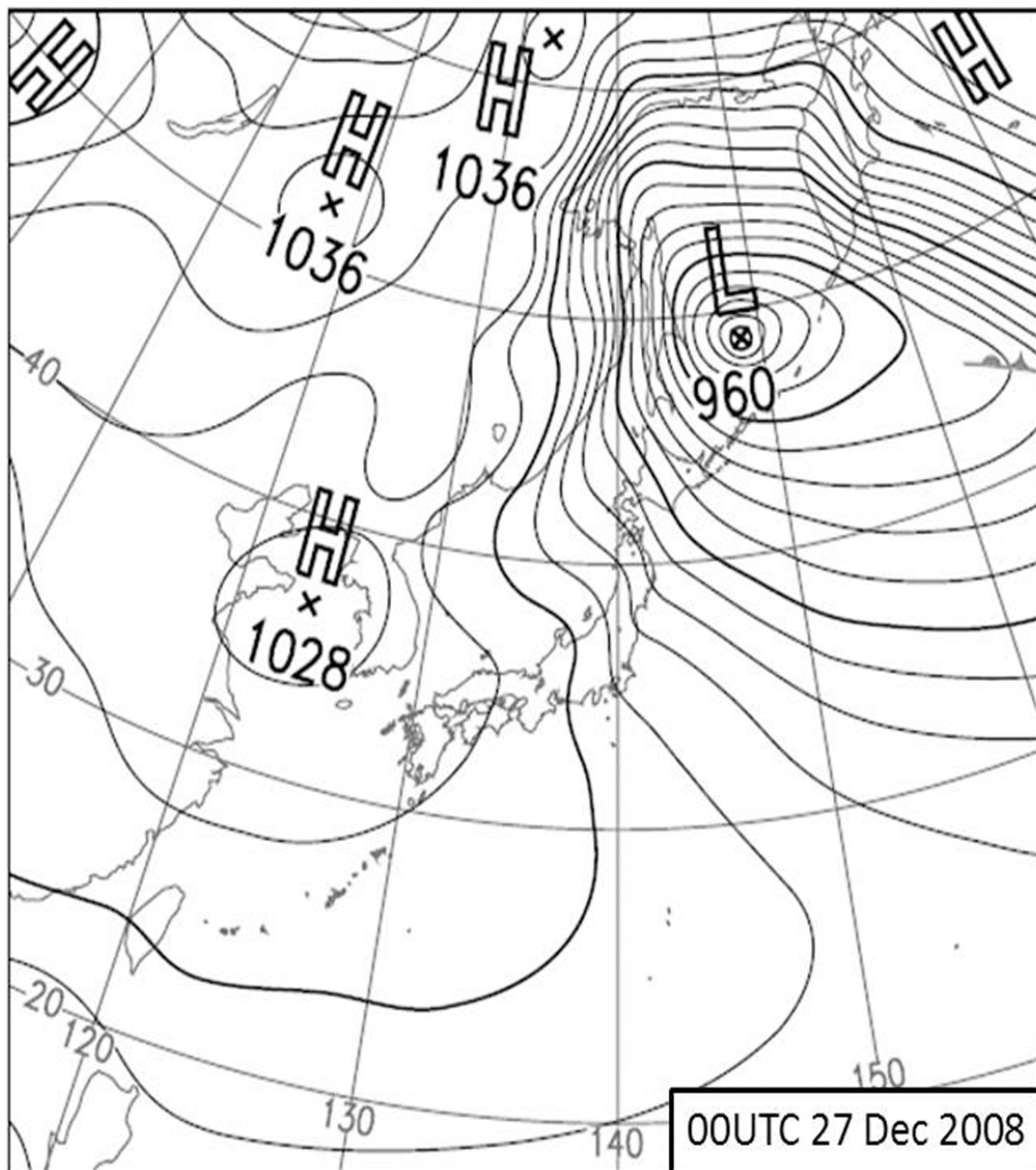


Figure 3.2: Synoptic chart at 0000UTC 27 Dec 2008 provided by JMA.

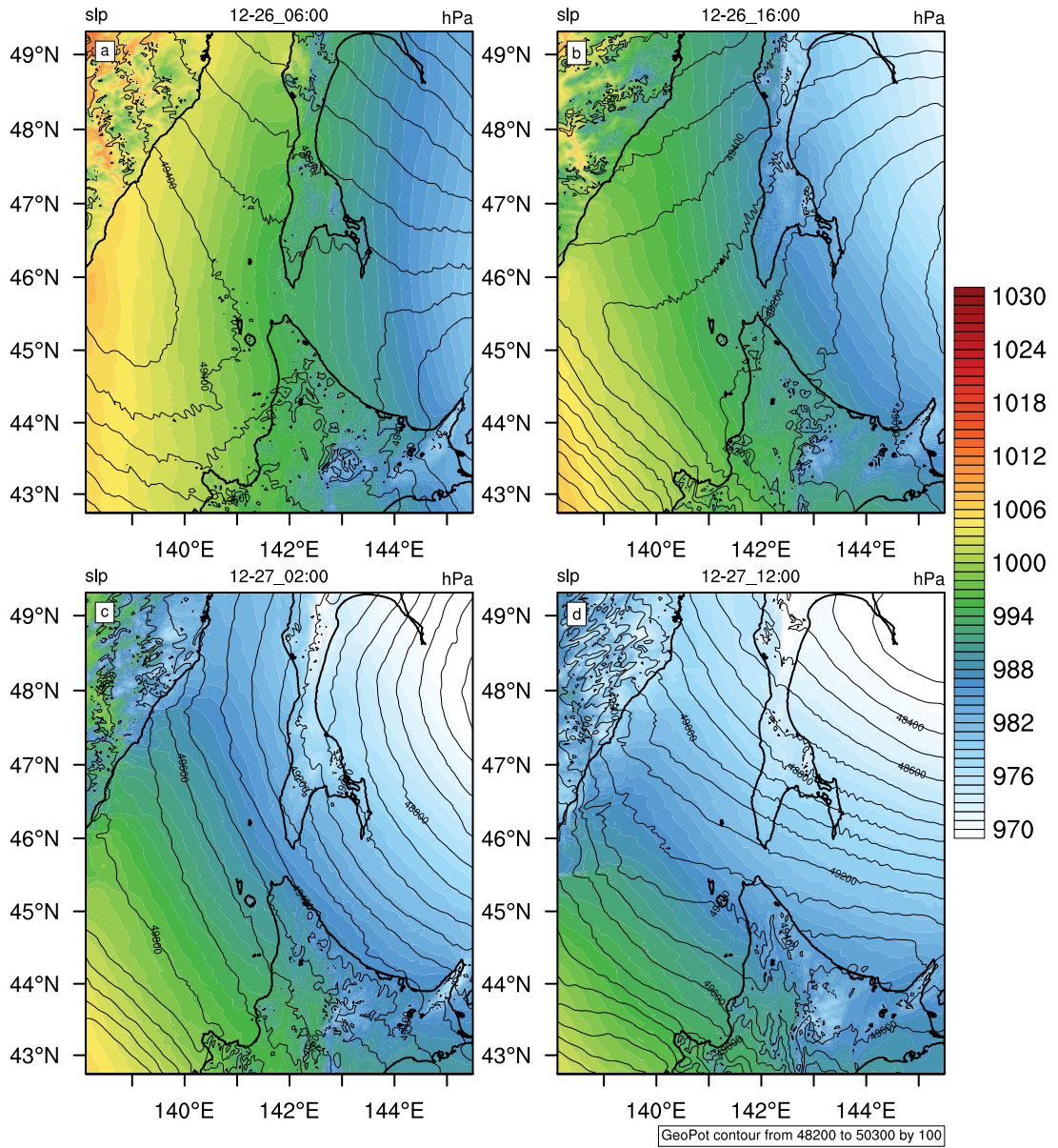


Figure 3.3: Evolution of sea level pressure (shaded) with 500 hPa geopotential (contours) with time. The contours of geopotential are drawn from 48000 to 50300 with an interval of 100 m^2s^{-2} . The plots are drawn at a) 0600UTC 26 Dec b) 1600UTC 26 Dec c) 0200UTC 27 Dec and d) 1200UTC 27 Dec 2008.

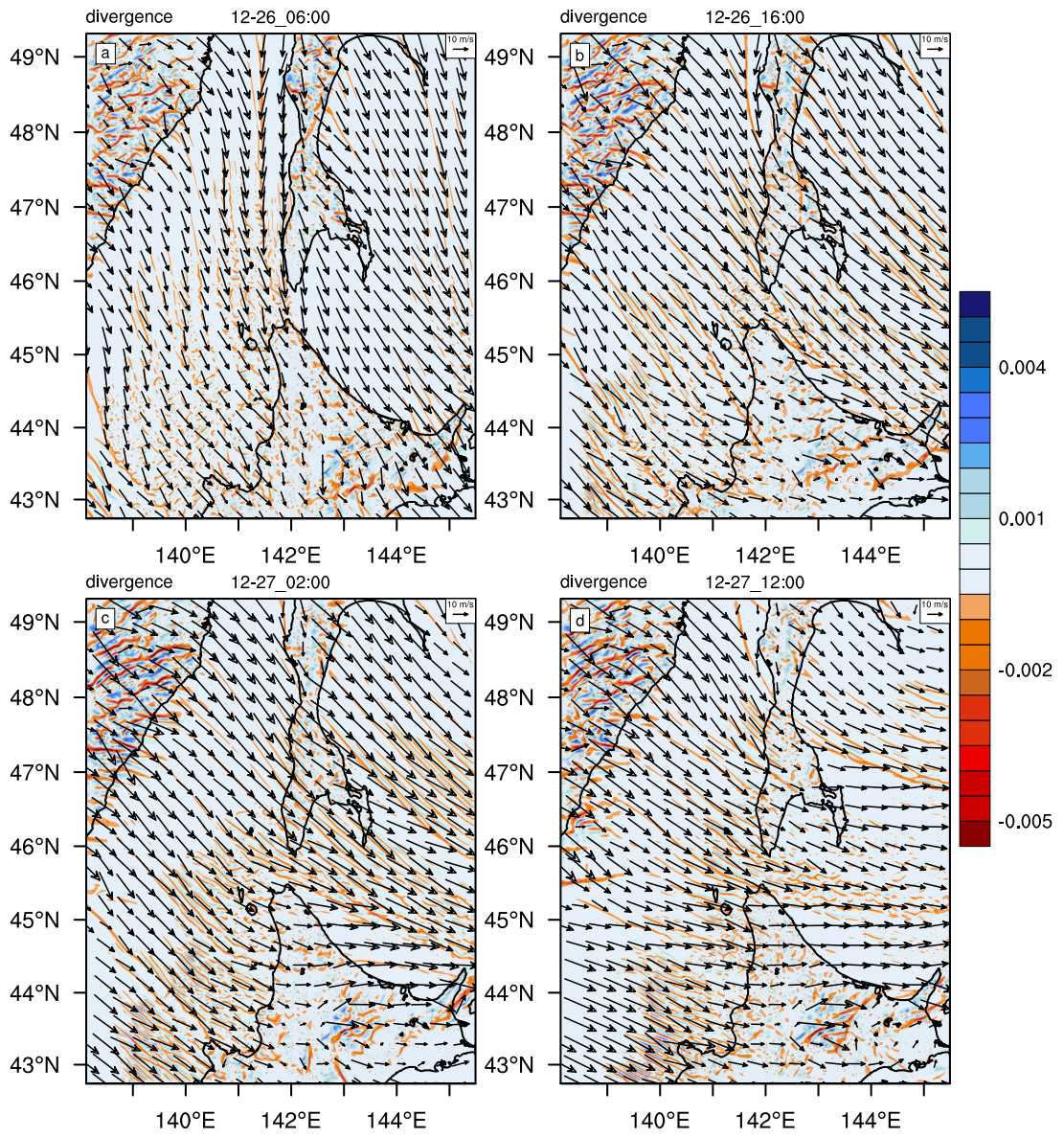


Figure 3.4: Horizontal divergence (shaded) and wind vectors at the lowest eta level (drawn at the same times with the previous figure).

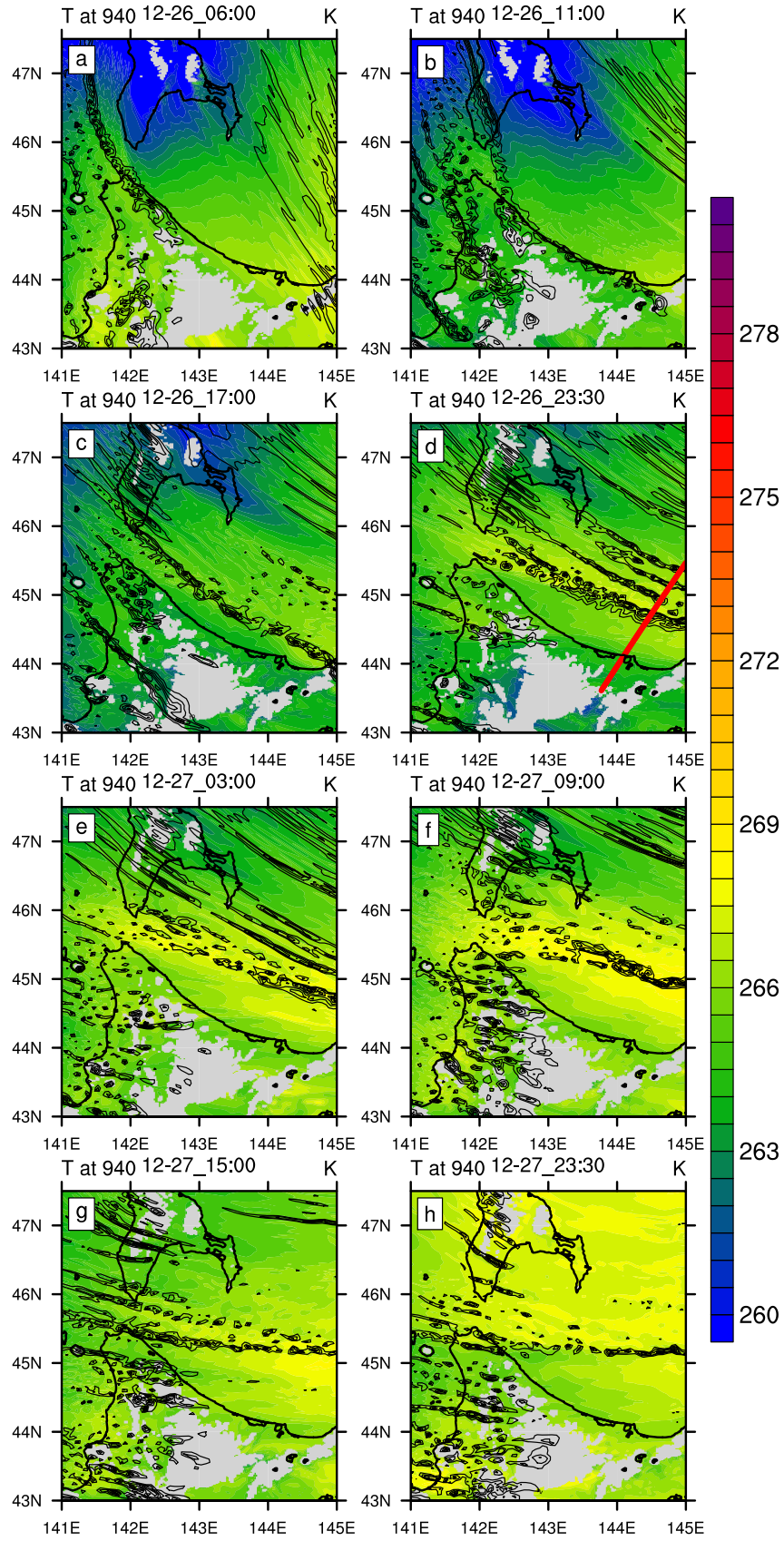


Figure 3.5: Time series of snow band generation and development (snow mixing ratio q_s) with air temperature at 940 hPa (shaded). The plots drawn at a) 0600UTC 26 Dec b) 1100UTC 26 Dec c) 1700UTC 26 Dec d) 2330UTC 26 Dec e) 0300UTC 27 Dec f) 0900UTC 27 Dec g) 1500UTC 27 Dec and h) 2330UTC 27 Dec 2008.

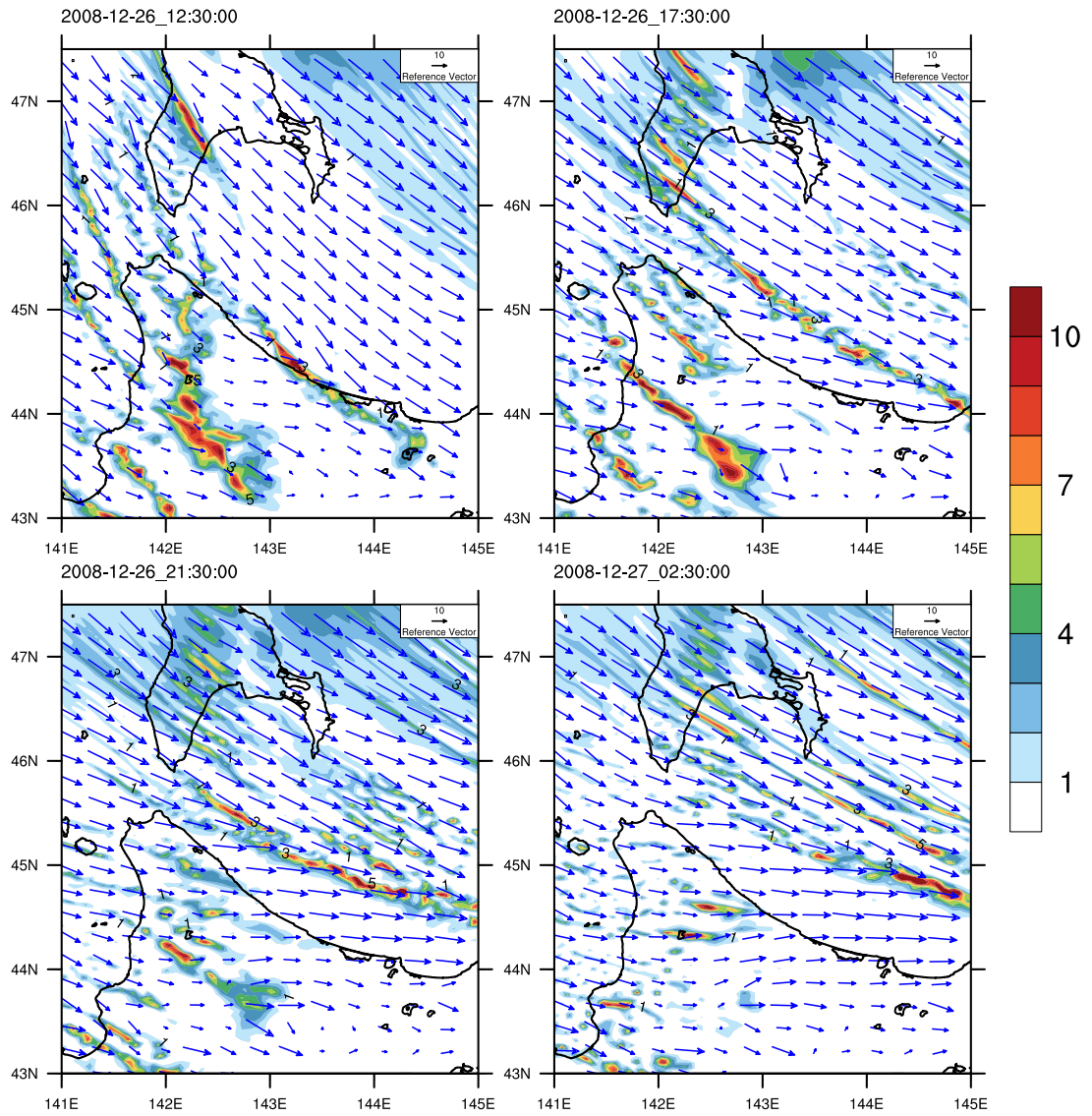


Figure 3.6: Time series of snowband similar to Figure 3.5 but with lowest level wind vectors. The plots are drawn at a) 1200UTC 26 Dec b) 1730UTC 26 Dec c) 2130UTC 26 Dec and d) 0230UTC 27 Dec 2008.

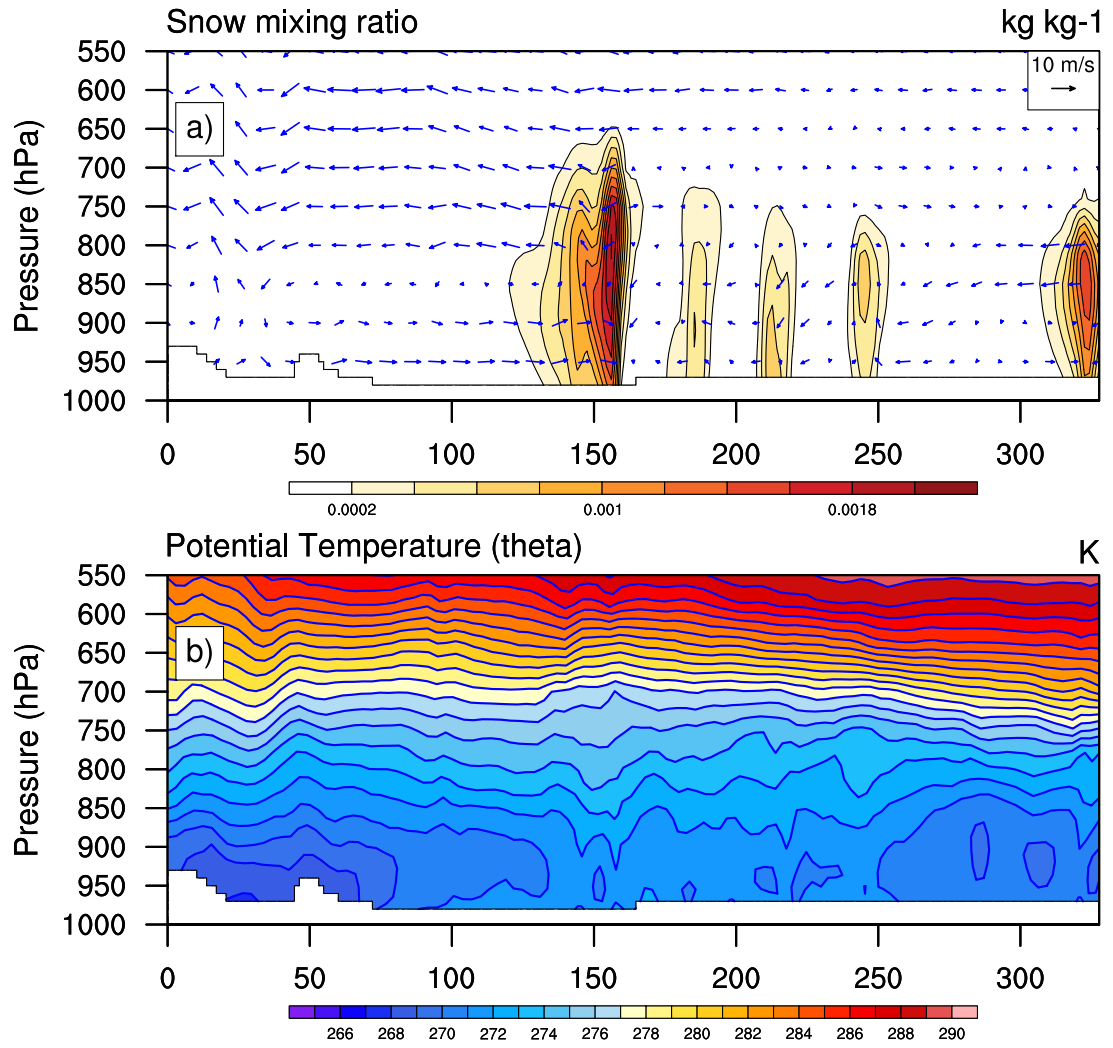


Figure 3.7: a) Vertical cross section of snow mixing ratio (kg/kg) and wind component parallel to the section. The time is same as that of Figure 3.5d (at 2330UTC 26 Dec), in which the location of the section is indicated by the red line. Horizontal axis is the distance (km) starting from the left of the line. Coastline is located at approx. 70 km . b) Vertical cross section of potential temperature (K) along the same line.

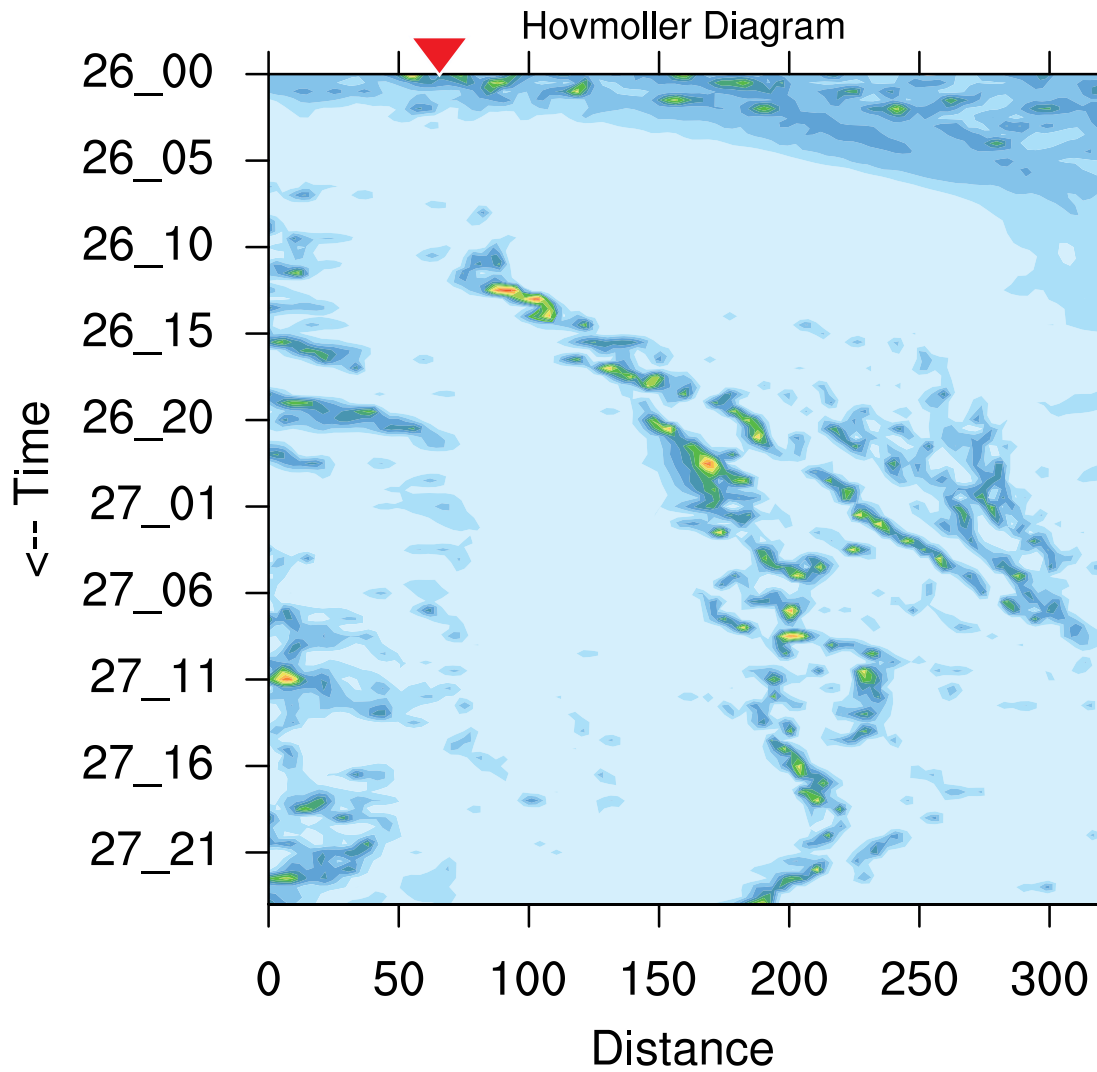


Figure 3.8: Hovmöller plot of column integrated snow mixing ratio (kg) along the cross section of Figure 3.7. Horizontal axis is the distance (km) starting from the left edge of the referenced red line. Inverted red triangle on top horizontal axis indicates the position of coastline.

Sensitivity experiments.

4.1 Experimental settings

In order to examine the importance of Hokkaido and Sakhalin Islands for the formation and maintenance of the snow band, five sensitivity experiments were conducted to be compared with the control experiment (CTRL) described in the previous section. The effects of Sakhalin and Hokkaido Islands were investigated by removing lands, i.e., land grids in the model domains were replaced by sea grids using spatially interpolated SST (provided by RTG-SST). Sakhalin Island, Hokkaido Island, and both Islands were replaced by sea grid in experiments named NSAK, NHOK, and NHOKSAK respectively. To distinguish the dynamical effects of topography from the effects of land-sea contrast, two more experiments were conducted: NTOPSAK with flattened Sakhalin Island and NTOPHOK with flattened Hokkaido Island.

Figure 4.1 and Figure 4.2 give the details of the experimental setup used in the study. Figure 4.1 shows the model setup used to run the model for NTOPHOK and NHOK cases. A comparison with Figure 3.1 explains the difference with CTRL case to each sensitivity experiment. In the experiment NTOPHOK (4.1a), the topography over Hokkaido Island was flattened and in NHOK experiment (4.1b) the land grids over Hokkaido Island were totally replaced by sea grids with sea surface temperature filled by a Cressman interpolation to produce a complete data.

Similarly, Figure 4.2 explains the NTOPSAK, NSAK and NHOKSAK cases. The experiment

names are self explanatory and again with comparison to Figure 3.1 the differences from CTRL case can be understood.

In the next couple of sections we discuss the results of these sensitivity experiments in comparison with CTRL case. Note that the order of the discussion of the experiments follow their significance rather than the prior introduction of their setup.

4.2 Effects of Sakhalin

In order to understand effects of Sakhalin Island, the results of NSAK case are firstly described and then the effect of topography is discussed using NTOPSAK case.

Figure 4.3 shows the temporal evolution of snow bands for NSAK case. In this case (see also Figure 4.4a) a snow band was generated along the coast line of Hokkaido Island as in CTRL case, but disappeared in ~ 9 hours around 1800 UTC 26 (Figure 4.3b-d). This demonstrates the necessity of Sakhalin Island in the maintenance of the snow band. Instead of the disappeared band, another snow band appeared far offshore of the coast at about 2000UTC 26 Dec (Figure 4.3d, ~ 250 km in Figure 4.4a). Without Sakhalin Island (i.e., NSAK case), the strip of warm air and the convergence shifted northeast compared to CTRL, where large mixing ratio of snow was simulated. This indicates that the effects of Sakhalin Island are substantial in determining the location of the snow band.

A vertical cross section (Figure 4.5) facilitates the comparison with CTRL case (Figure 3.7). In NSAK case, land breeze below 850 hPa penetrated farther offshore from Hokkaido (Figure 4.5b) compared to Figure 3.7b. As the upper level wind was almost the same as in CTRL case, this change of the lower-level wind was caused by the absence of cold advection from Sakhalin, which blocked the northeastward propagation of the snow band over the Sea of Okhotsk and enhanced the snow band in CTRL case (Figure 3.7, 230 $\sim$ 300 km).

Figure 4.6 shows the temporal evolution for NTOPSAK case. The topography of Sakhalin Island also affected the strength of the snow band. In NTOPSAK case (Figure 4.7a), the snow band was initially located at a similar position as that of CTRL case. In fact, the horizontal distributions of snow mixing ratio and temperature were similar to those in CTRL case (Figures 3.6a and 4.6b). However, the snow band was weaker compared to that in CTRL case and was initiated downstream of the Soya Strait. The comparison of the wind field indicates that the topography over Sakhalin Island turned the wind to enhance the convergence at the Soya Strait and thus the snow band along the Hokkaido coast. Therefore, we can say that the thermal contrast due to Sakhalin Island maintains the snow band, while the topography of Sakhalin Island enhances its strength. Figure 4.8 shows the vertical section of the snow band at 2330UTC 26 Dec. As seen from the horizontal plots a thinner snow band was present at the same location as the CTRL case. Also, a similar vertical potential temperature profile to CTRL case can be seen in Figure 4.8b as expected.

4.3 Effects of Hokkaido

In this section, the effects of Hokkaido Island is discussed by comparing CTRL, NHOK, NTOPHOK and NHOKSAK cases.

In NTOPHOK case, features of the generated snow band (location of generation and its motion) were almost similar to CTRL case, although the snow band was slightly stronger. Figure 4.9 again shows the temporal evolution of the snow band. The snow band generation and movement were almost similar to those of CTRL case though the band was slightly stronger. The Hovmöller diagram (Figure 4.10) also indicates the same fact regarding the generation and propagation of the snow band. The cross section diagram (Figure 4.11) exhibits the similar distribution of potential temperature and the snow band structure. Thus, it can be safely

concluded that topography of Hokkaido Island has a relatively minor influence on the snow band.

In NHOK case (Figure 4.12) the appearance of the snow band was delayed due to the absence of the coastline. Thus confirms the importance of land breeze from Hokkaido or difference in surface roughness in the initial generation of the snow band. After this stage, a snow band similar to that found in CTRL developed, as also seen in Figure 4.13 though the snow band was less organized compared to the CTRL case. Figure 4.14b shows the cold advection from the Sakhalin Island as expected and the formation of several smaller short lived convective bands can be observed over the Hokkaido Island (Figure 4.14a).

Finally, in NHOKSAK (Figure 4.15 and Figure 4.16), where both Hokkaido and Sakhalin Islands were replaced by sea, the corresponding snow band disappeared and an offshore snow band similar to that in NSAK case appeared ($\sim 250 \text{ km}$). Weaker snow bands appeared instead of a single strong band and occasionally passed the line. Figure 4.17b shows no sign of the warm strip seen in the CTRL case.

In summary, the results of sensitivity experiments indicate that 1) the land-sea contrast along the Hokkaido coast largely contributed to the initial formation, 2) the cold advection from Sakhalin Island was important in the maintenance of the snow band, although cold land surface over Hokkaido Island was also important for the enhancement of the snow band, and 3) topography over Sakhalin strengthened the snow band by blocking the low level winds to form the convergence at the Soya Strait.

In the next chapter we summarize the results and give the final conclusion of the study and glimpse of future scope of the current study.

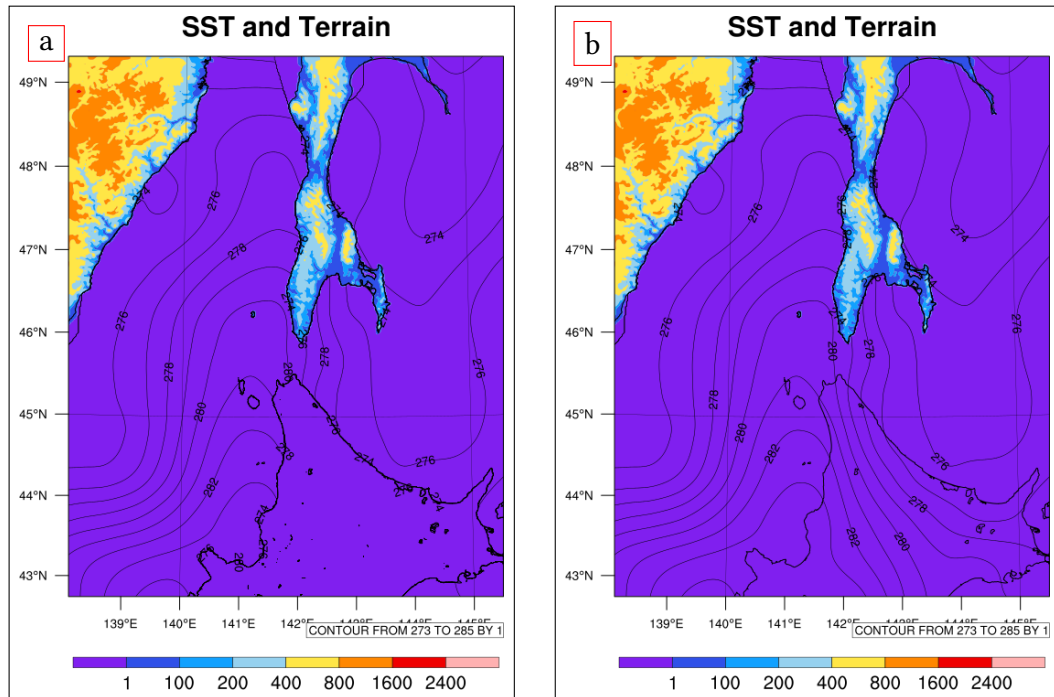


Figure 4.1: Sea surface temperature and topography used in the model for a) NTOPHOK case and b) NHOK case.

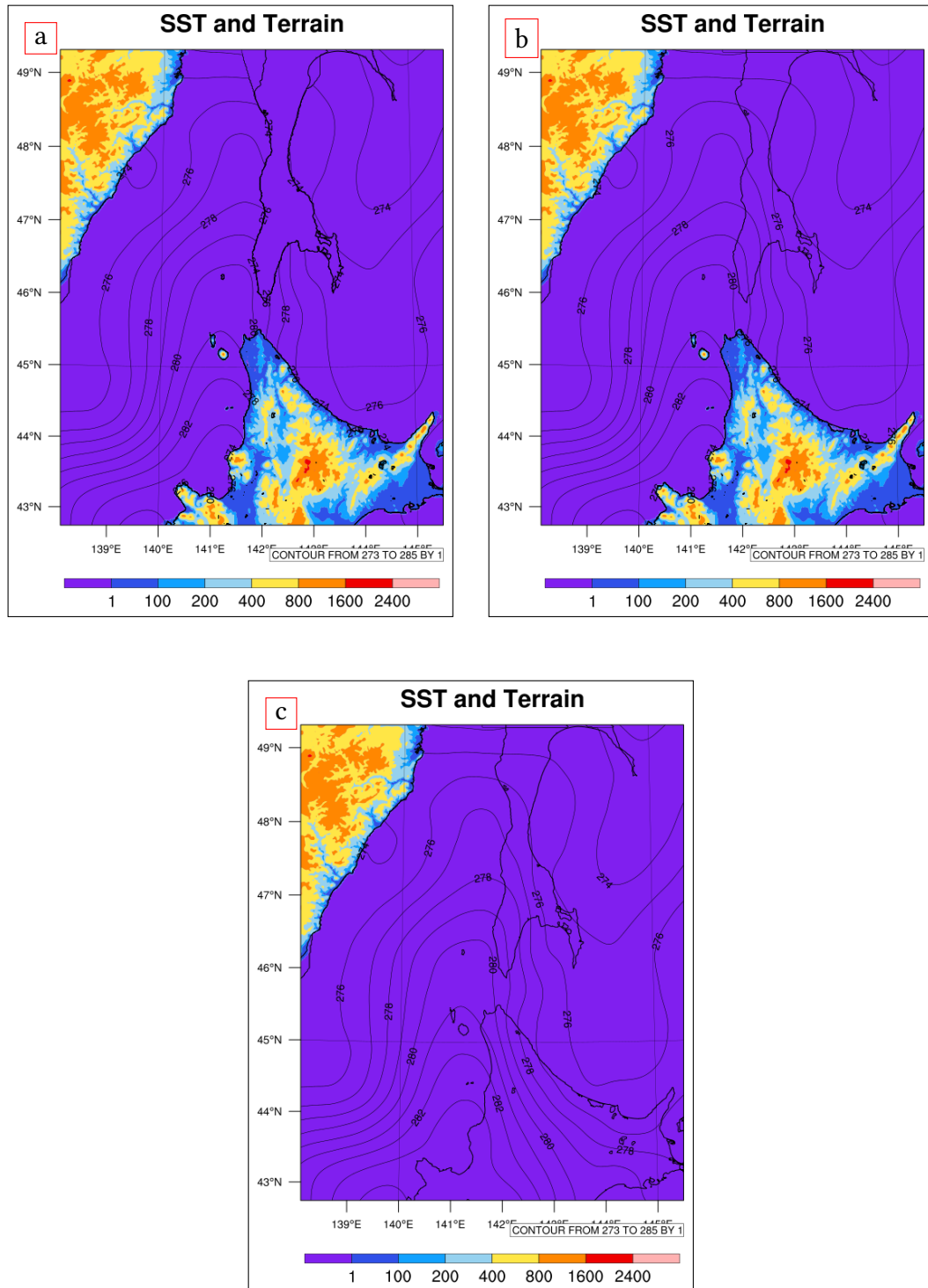


Figure 4.2: Same as Figure 4.1 but for a) NTOPSAK case b) NSAK case and c) NHOKSAK case.

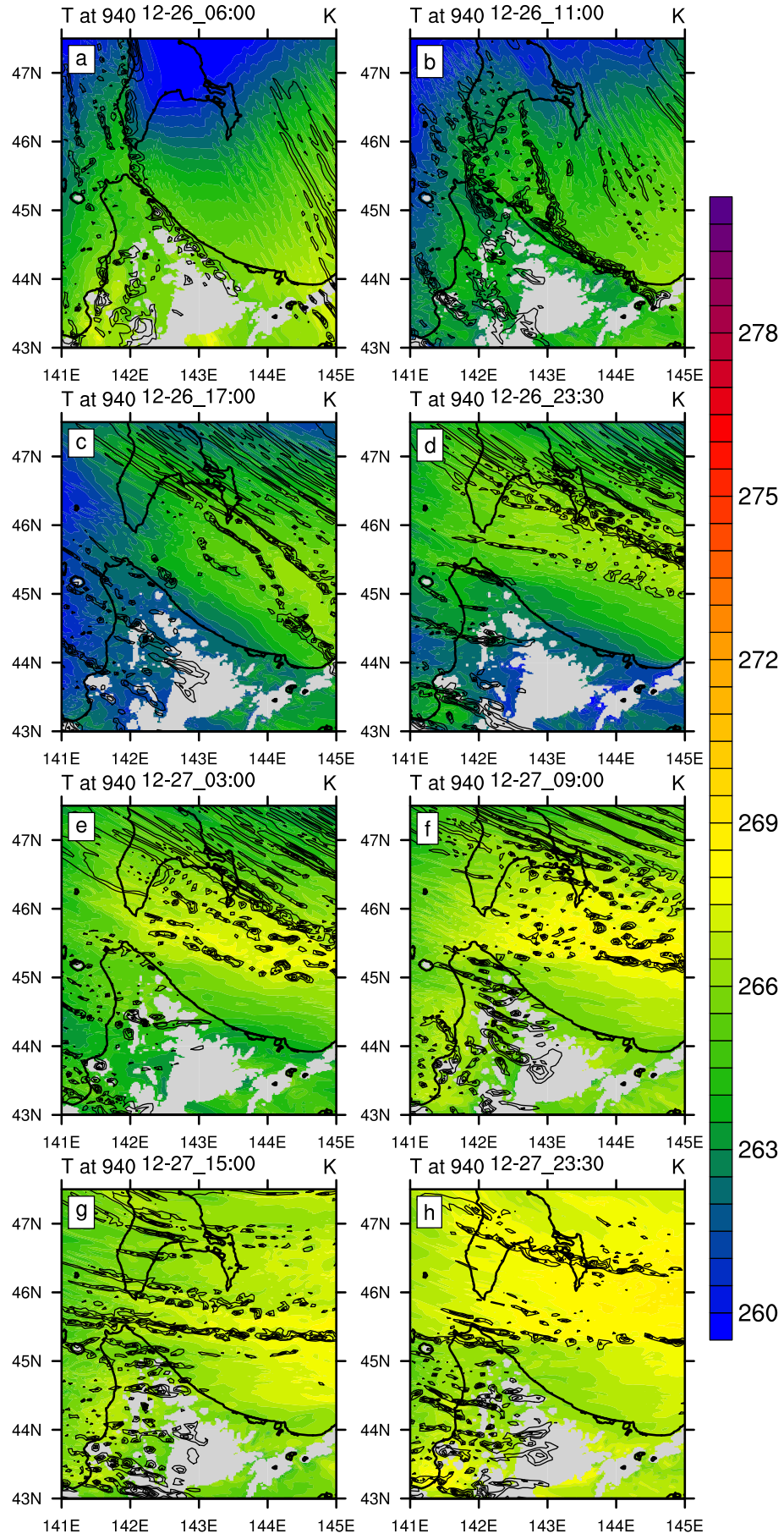
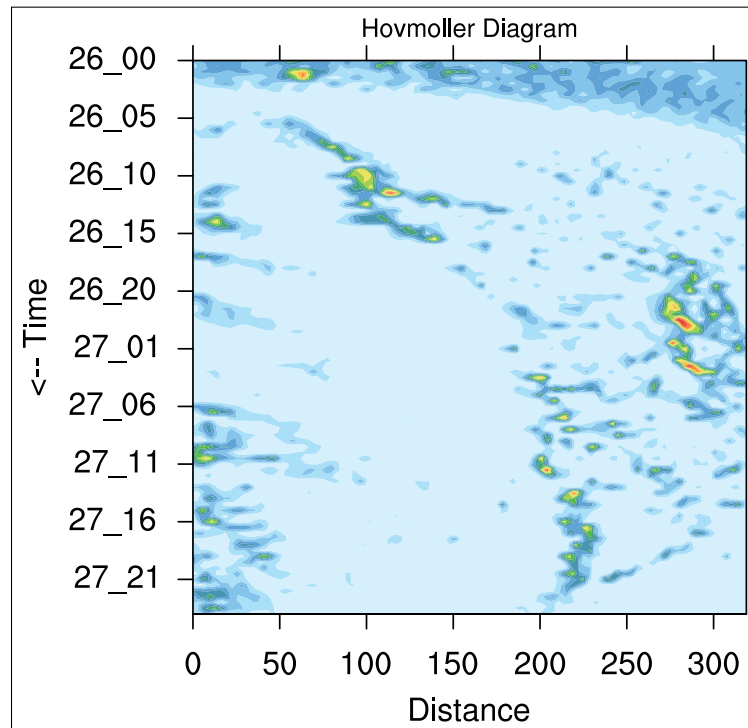


Figure 4.3: Temporal evolution of snow band for the case of NSAK case (contours of snow mixing ratio q_s). Shade represents horizontal temperature distribution at 940 hPa level.

NSAK case



CTRL Case

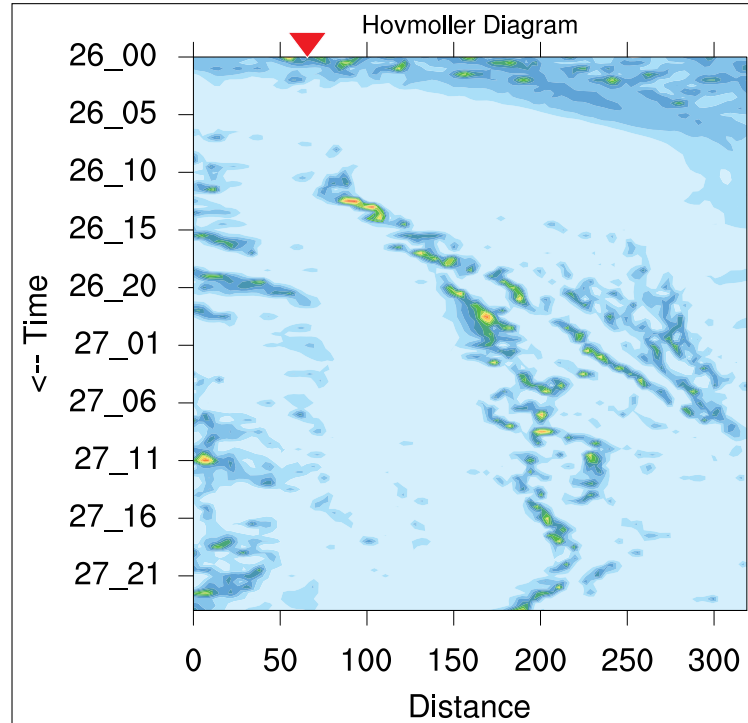


Figure 4.4: Comparison of NSAK case with CTRL case. Note that CTRL case plot is a repetition from the previous chapter and reinserted for the convenience. The similar duplication follows to all the cases henceforth.

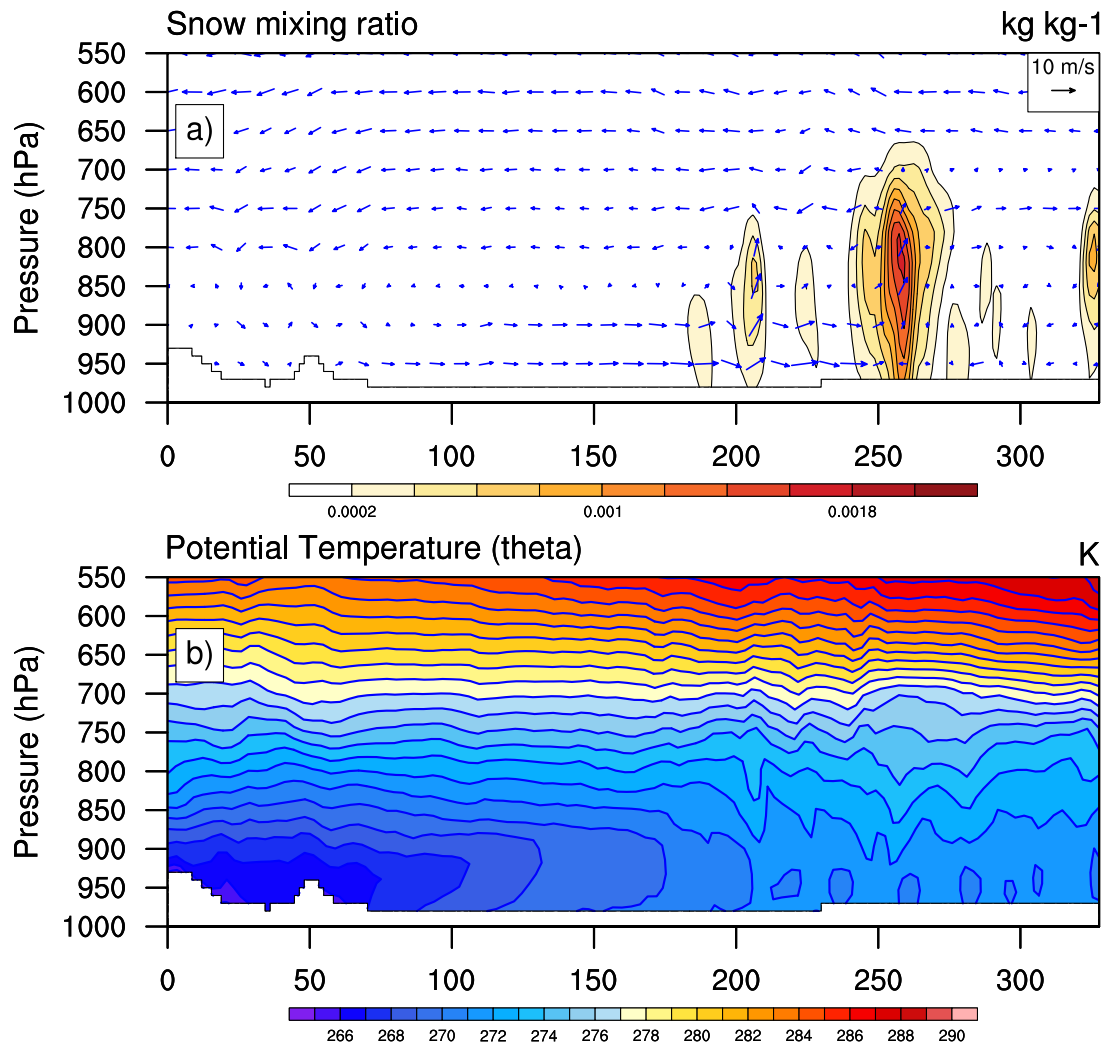


Figure 4.5: Same as Figure 3.7 but for NSAK case.

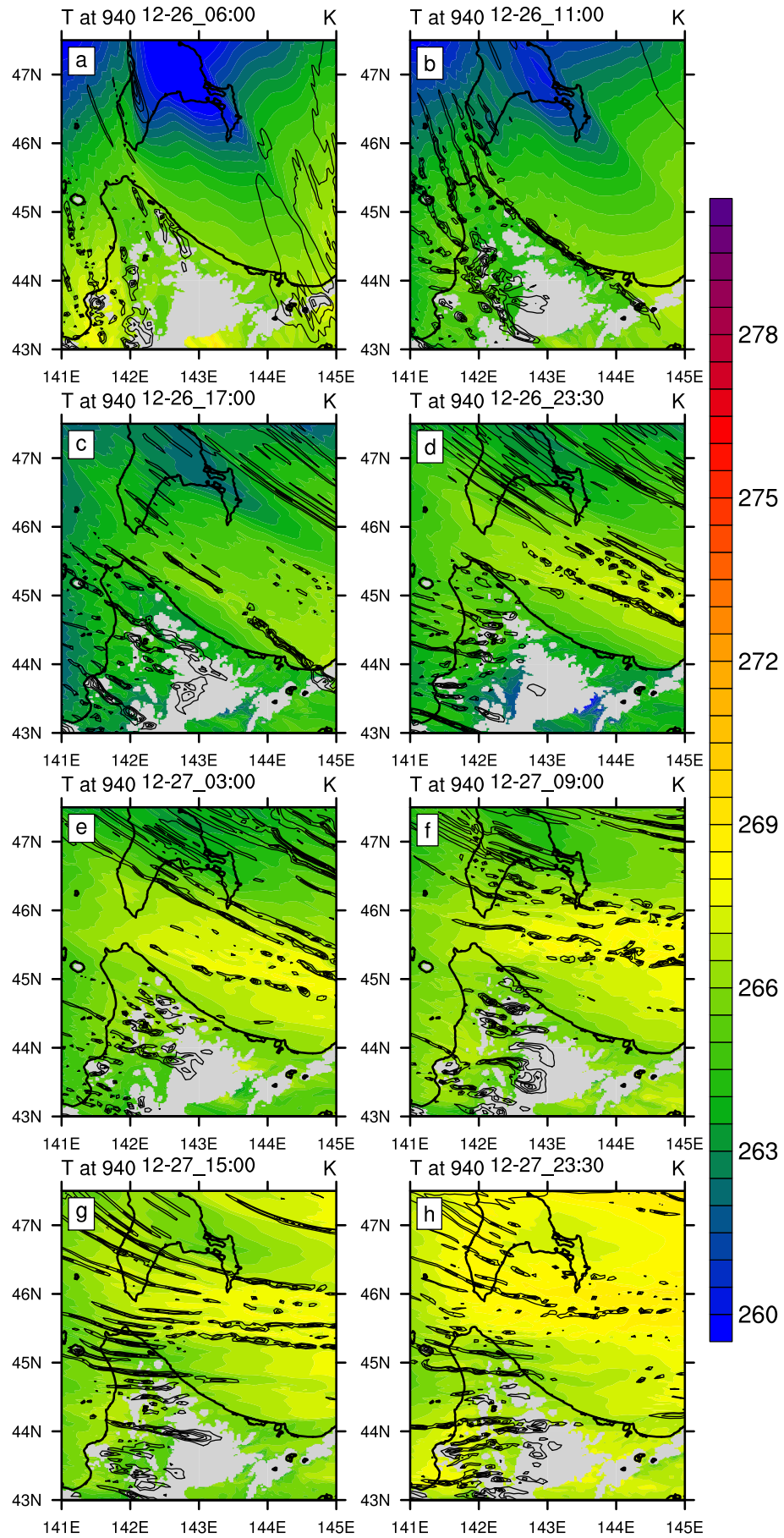
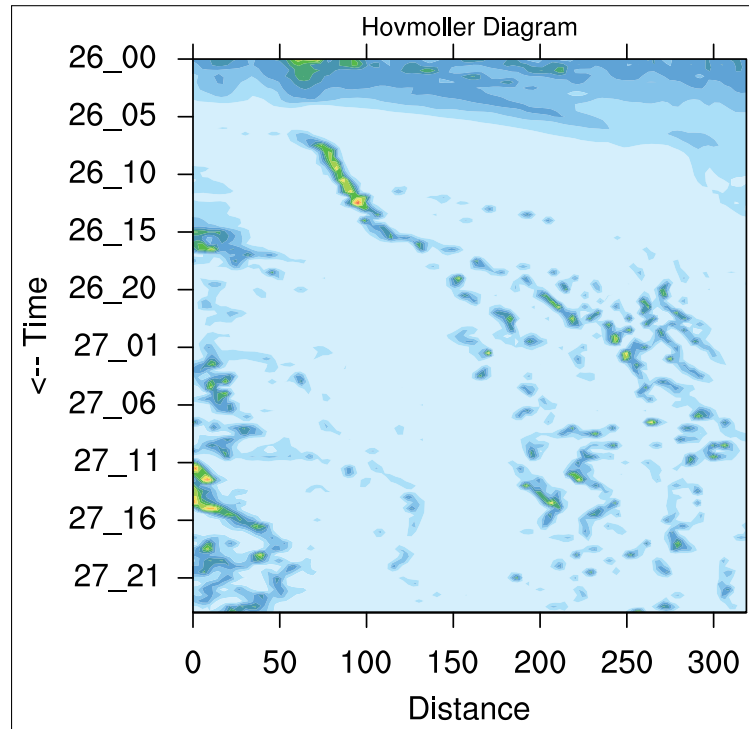


Figure 4.6: Same as Figure 4.3 but for NTOPSAK case.

NTOPSAK case



CTRL Case

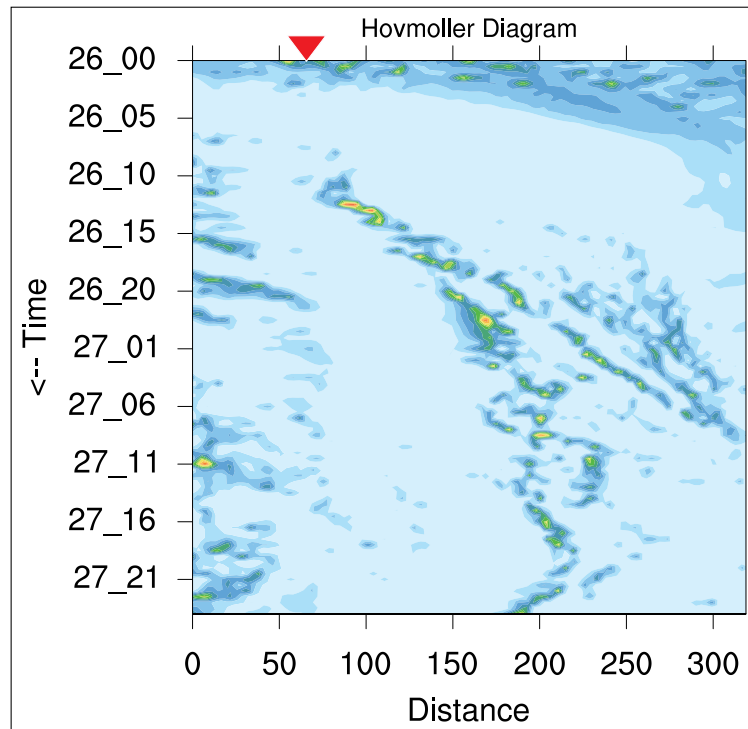


Figure 4.7: Comparison of NTOPSAK case with CTRL case.

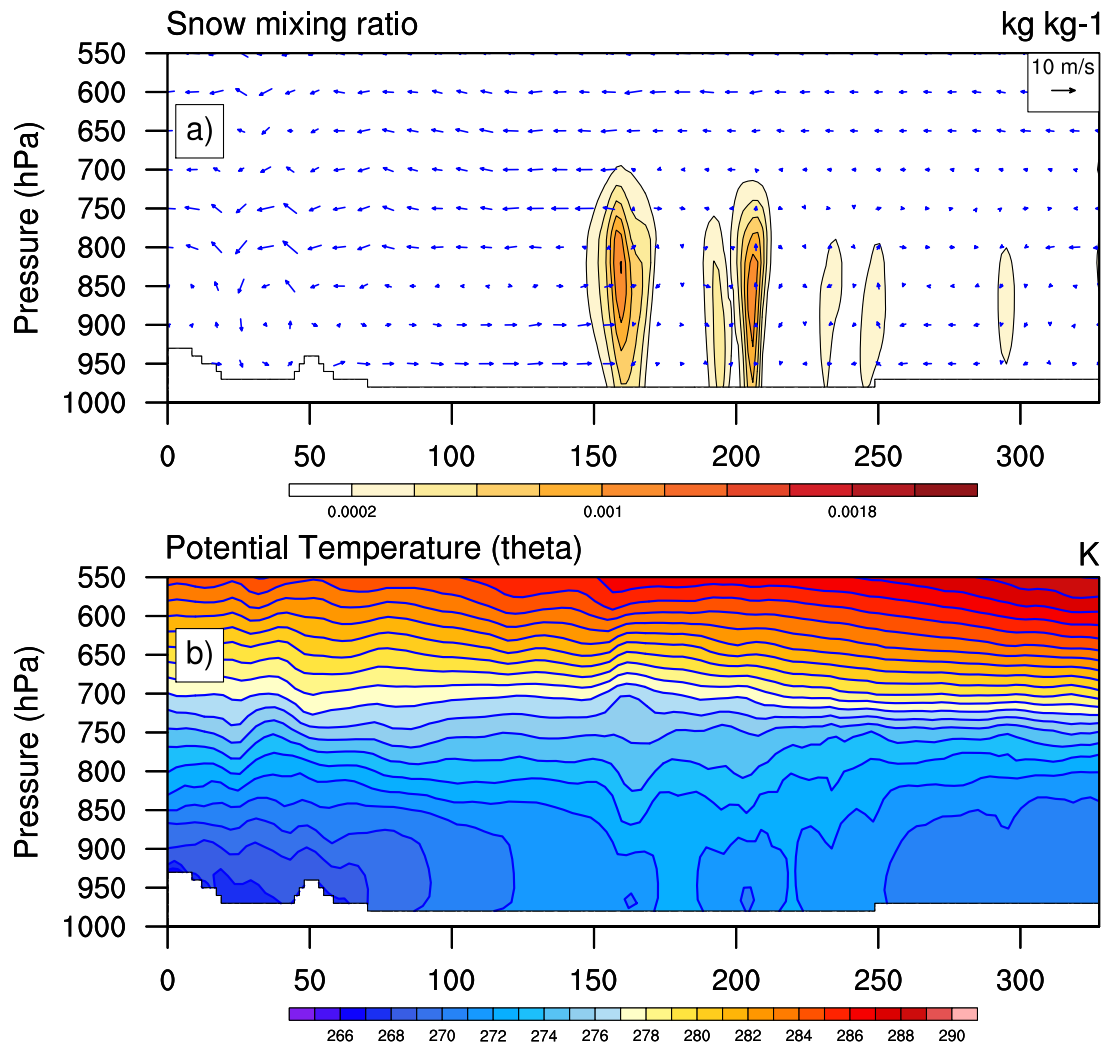


Figure 4.8: Same as Figure 3.7 but for NTOPSAK case.

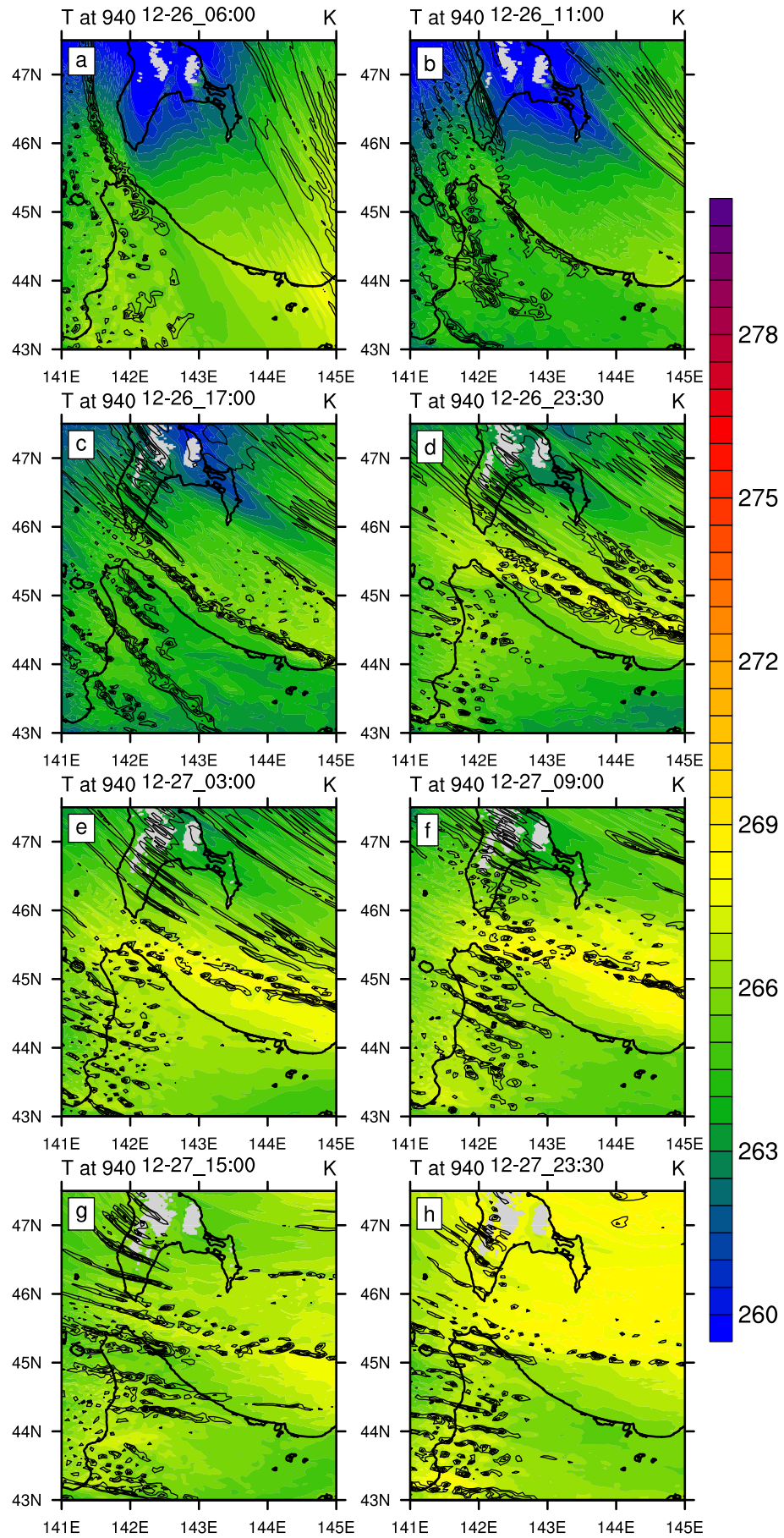
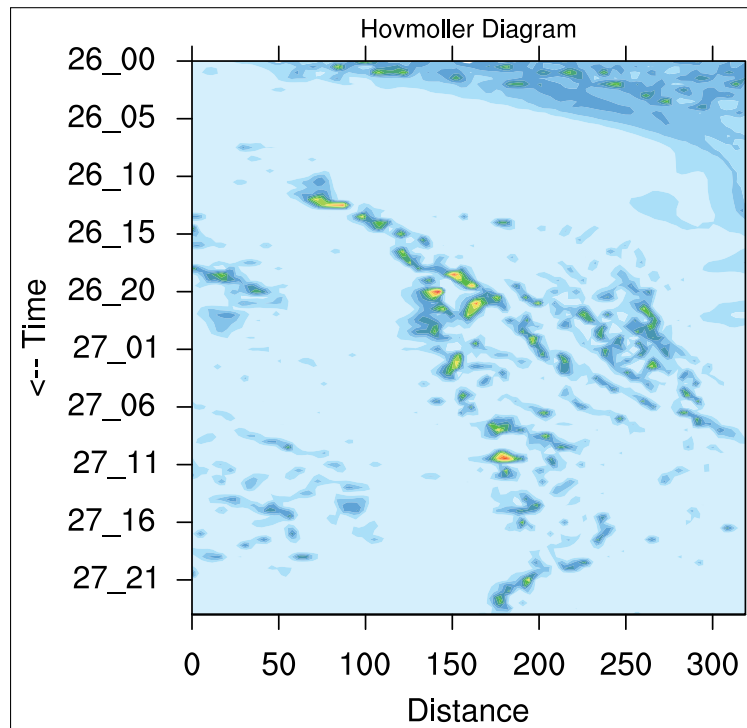


Figure 4.9: Same as Figure 4.3 but for NTOPHOK case.

NTOPHOK case



CTRL Case

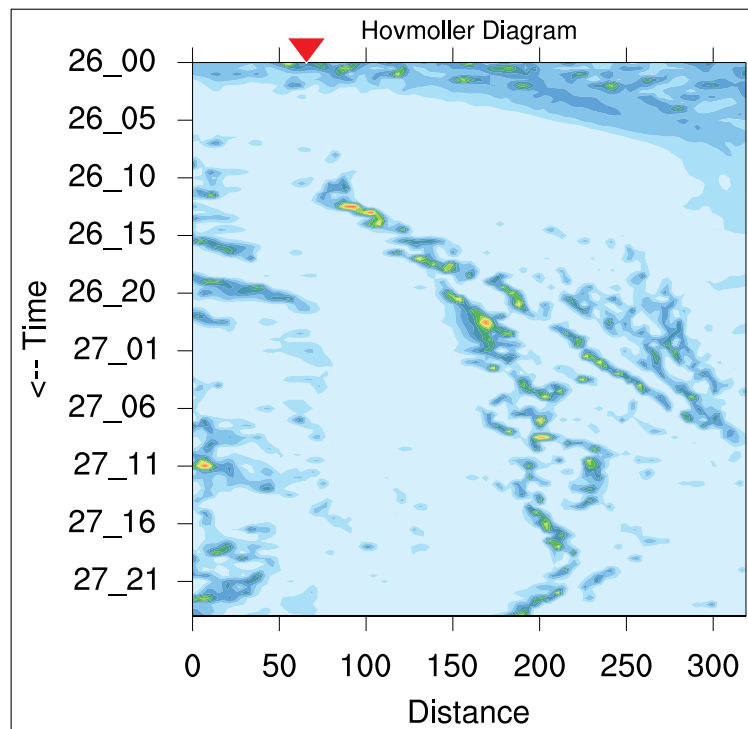


Figure 4.10: Comparison of NTOPHOK case with CTRL case.

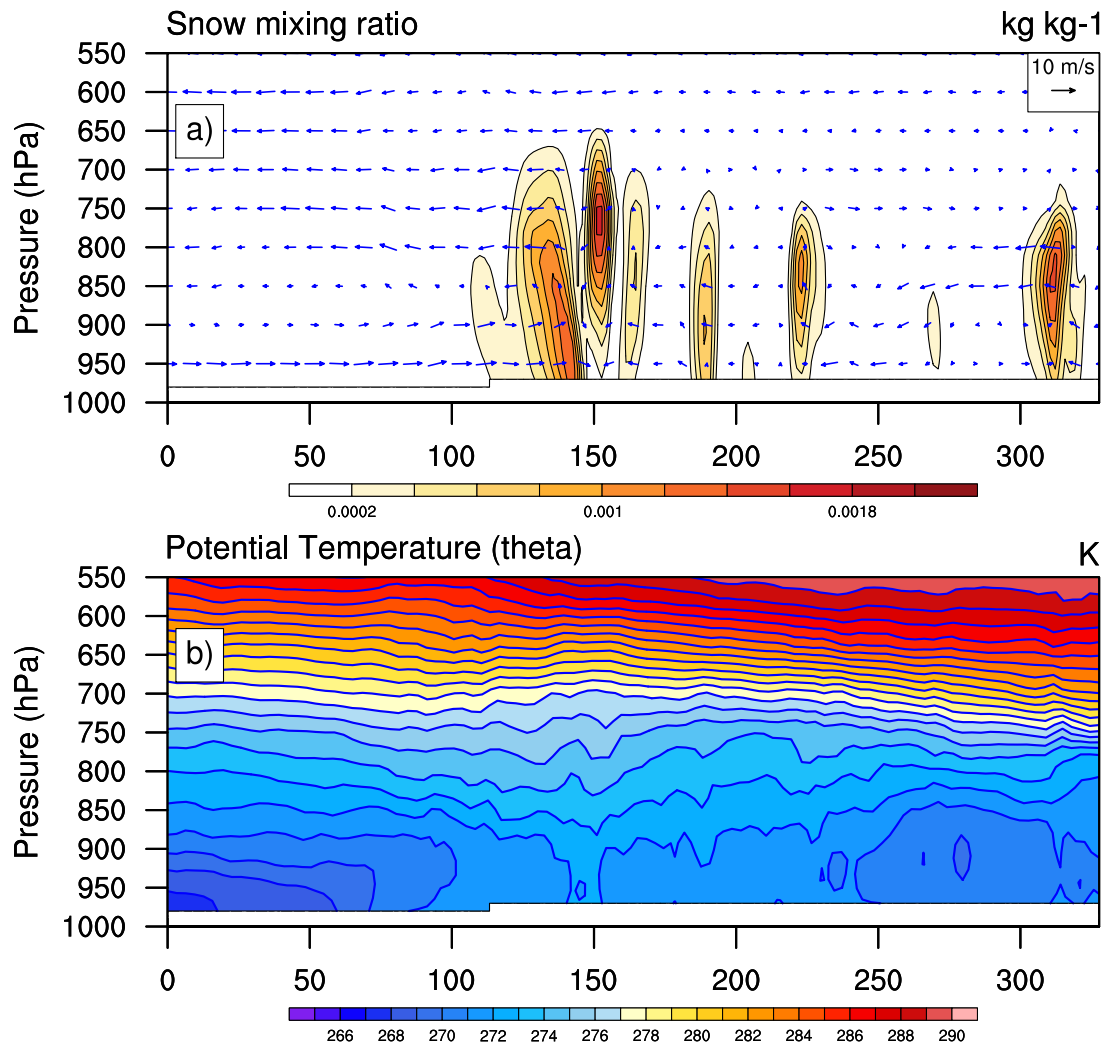


Figure 4.11: Same as Figure 3.7 but for NTOPHOK case.

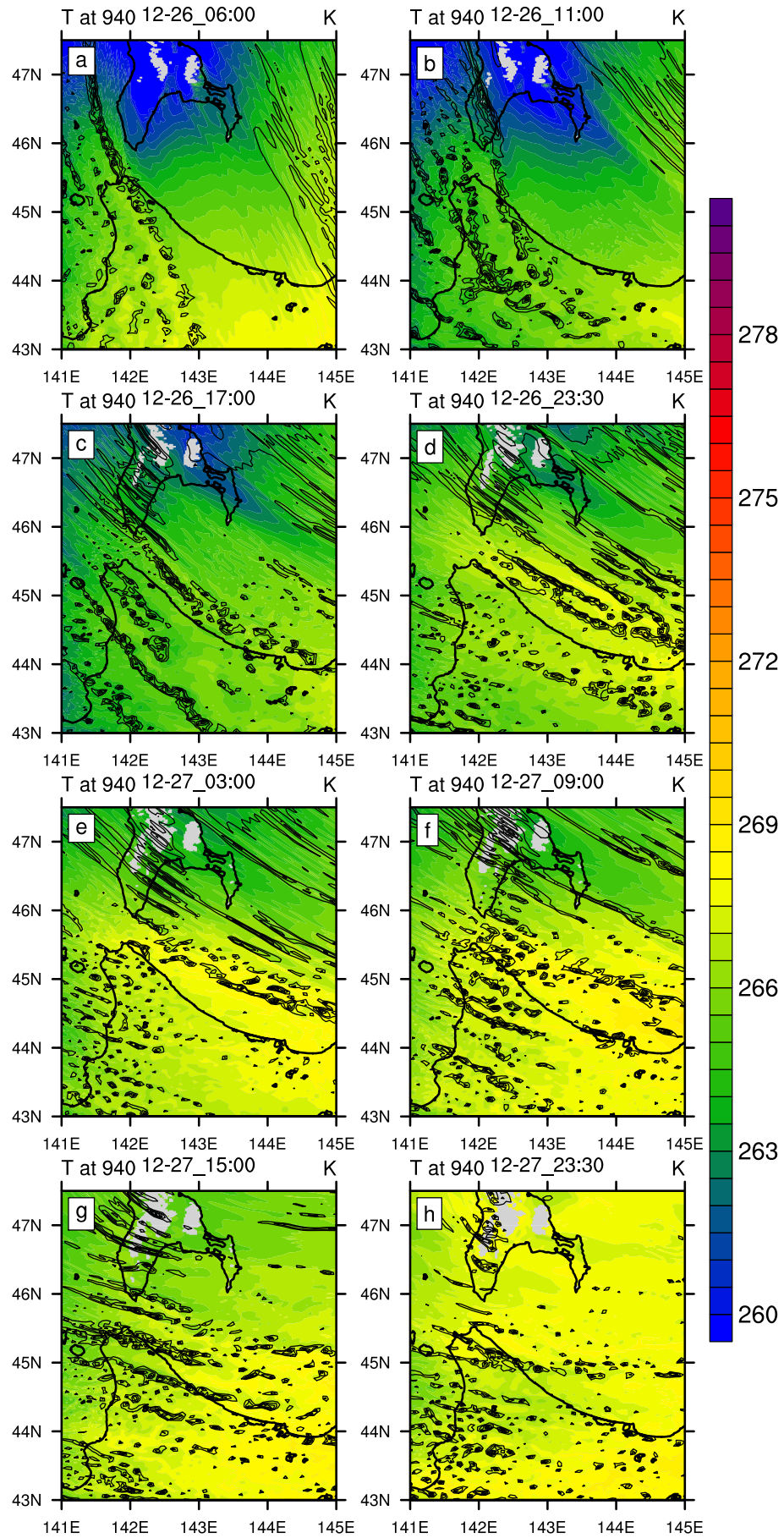
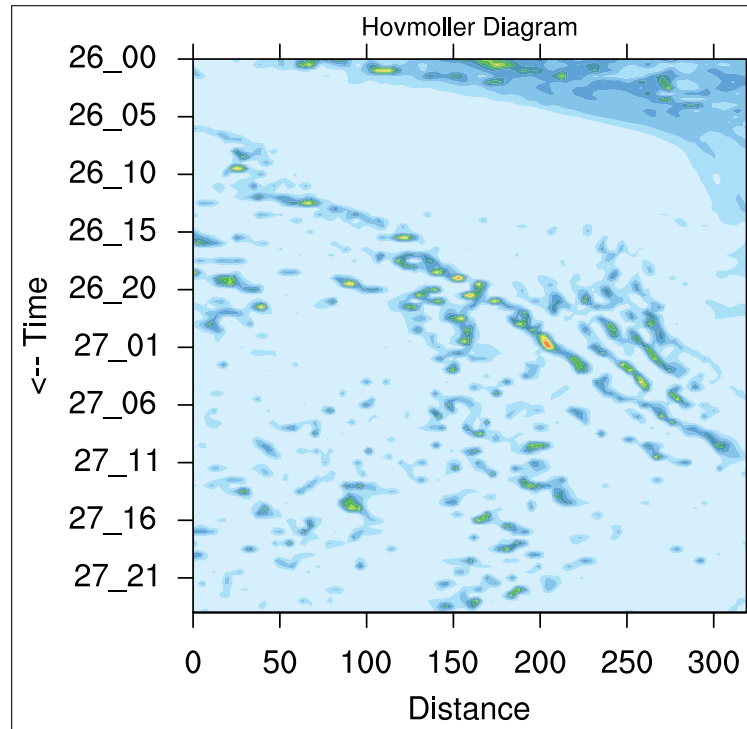


Figure 4.12: Same as Figure 4.3 but for NHOK case.

NHOK case



CTRL Case

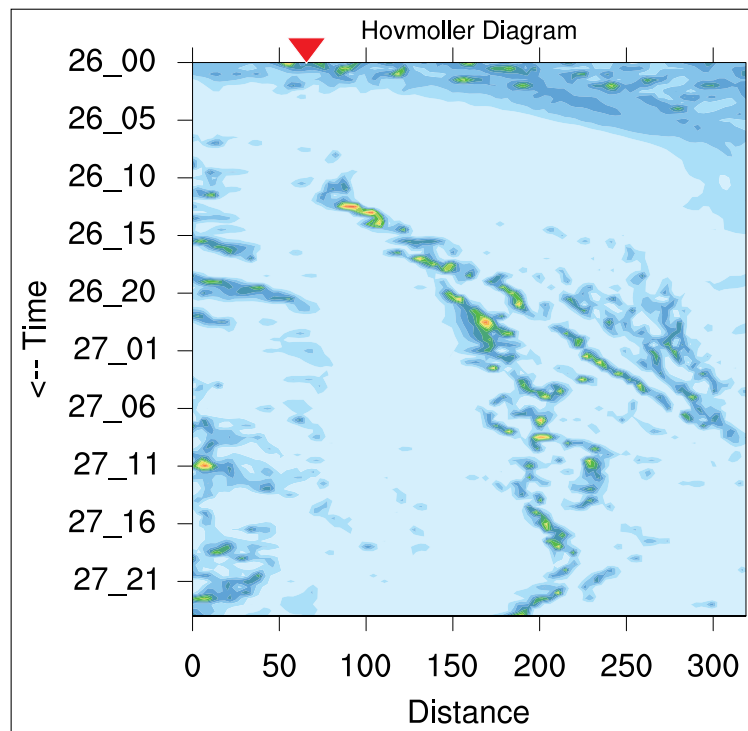


Figure 4.13: Comparison of NHOK case with CTRL case.

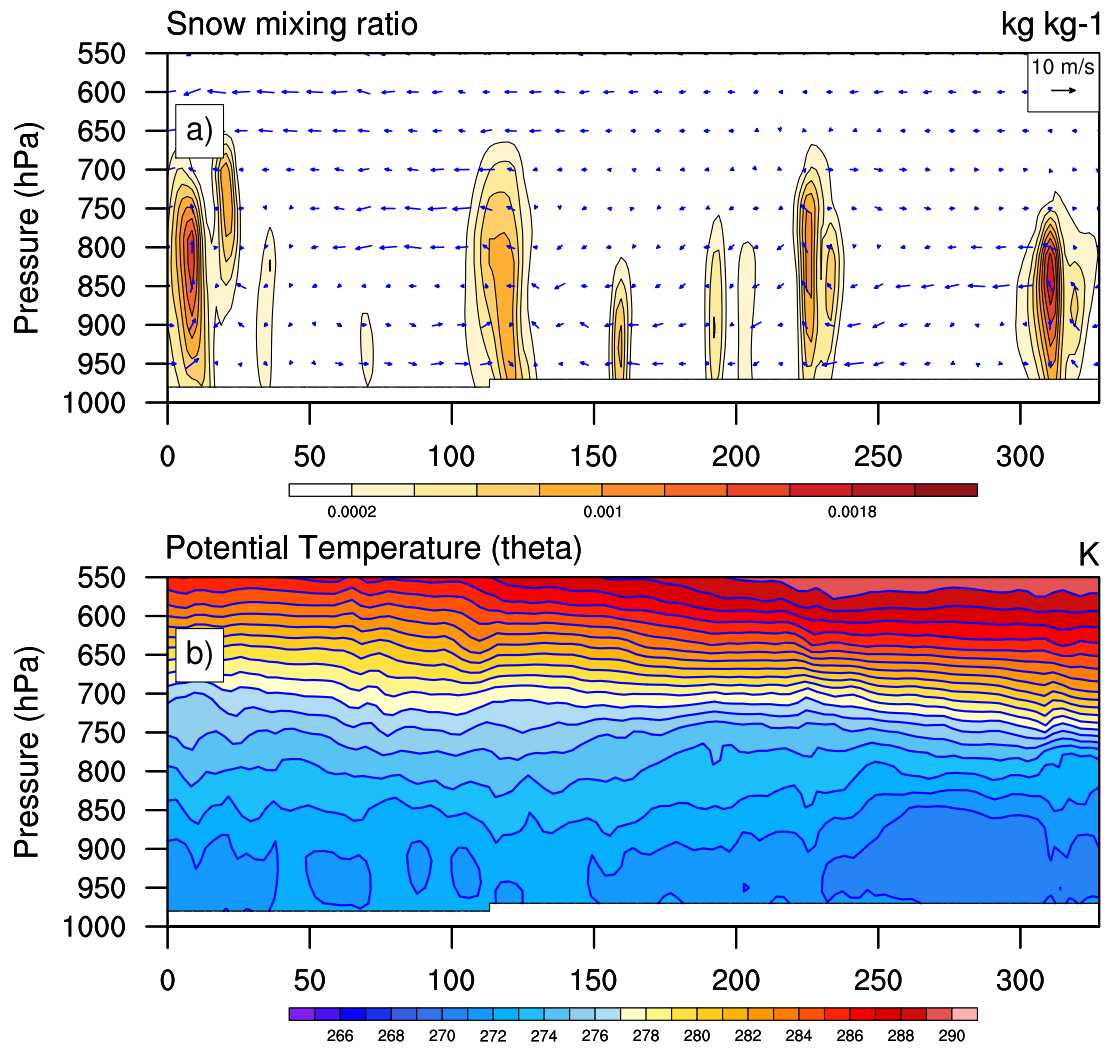


Figure 4.14: Same as Figure 3.7 but for NHOK case.

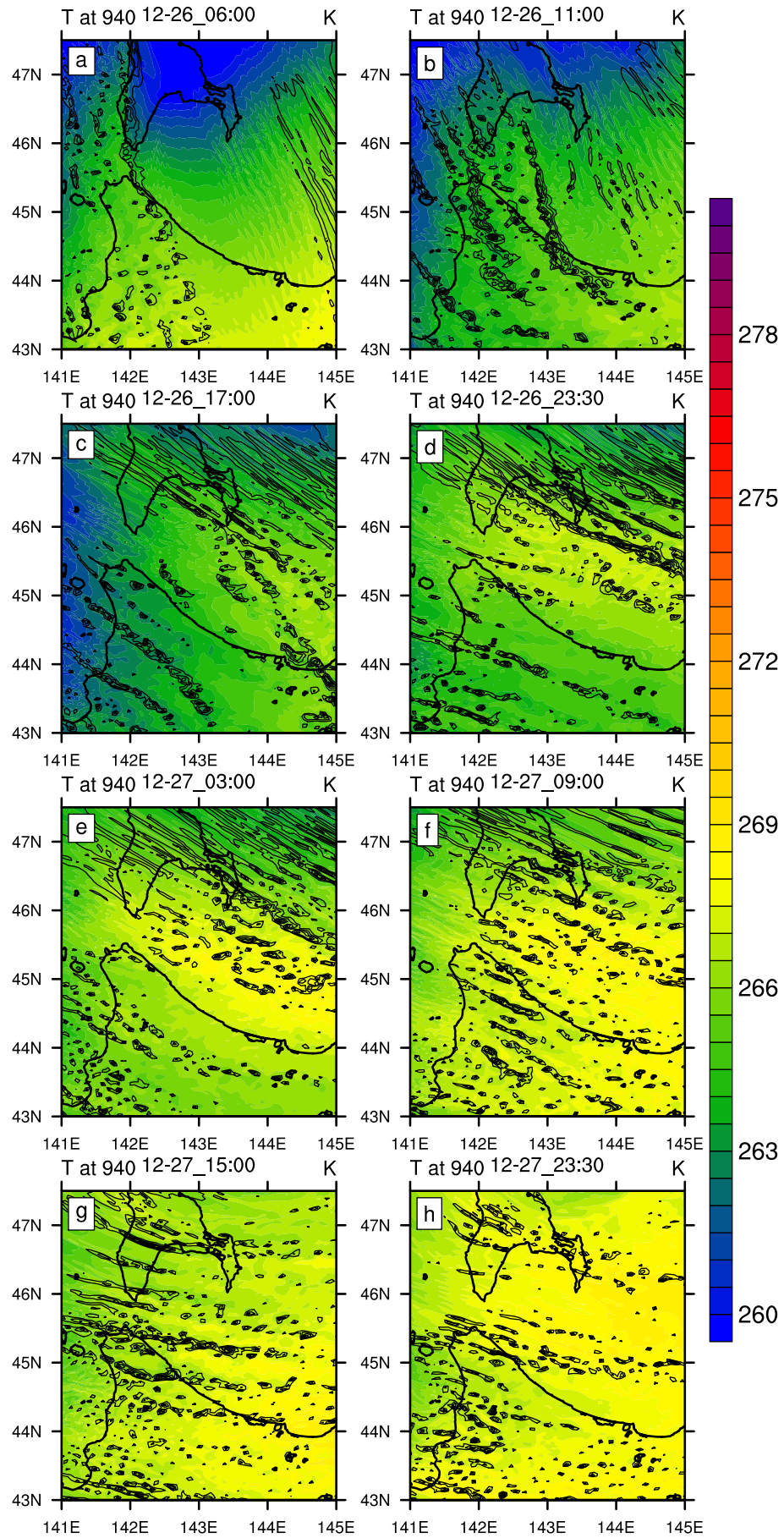
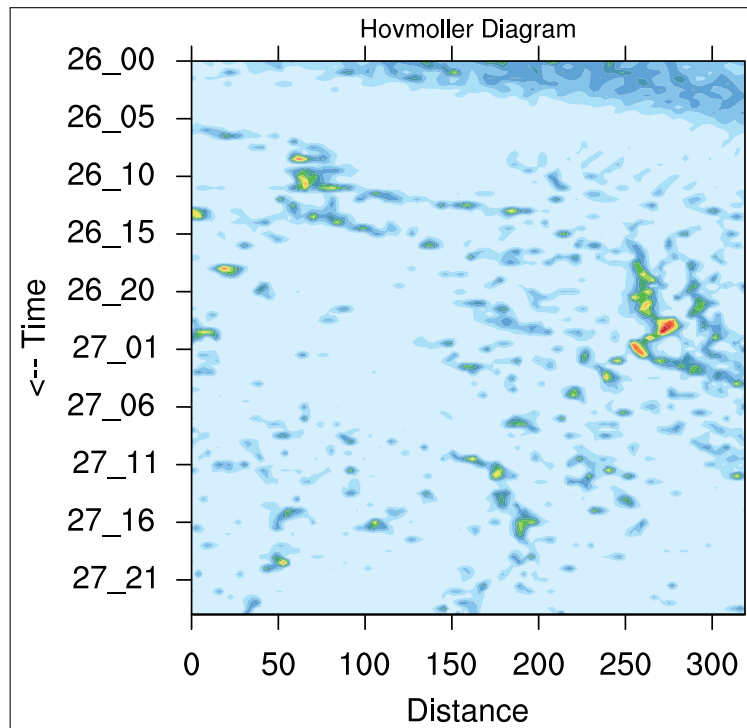


Figure 4.15: Same as Figure 4.3 but for NHOKSAK case.

NHOKSAK case



CTRL Case

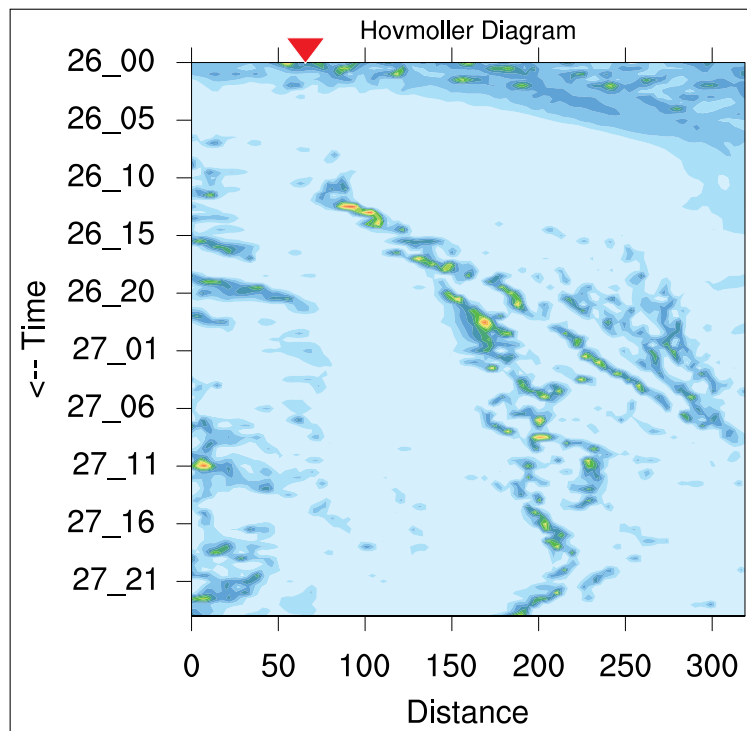


Figure 4.16: Comparison of NHOKSAK case with CTRL case.

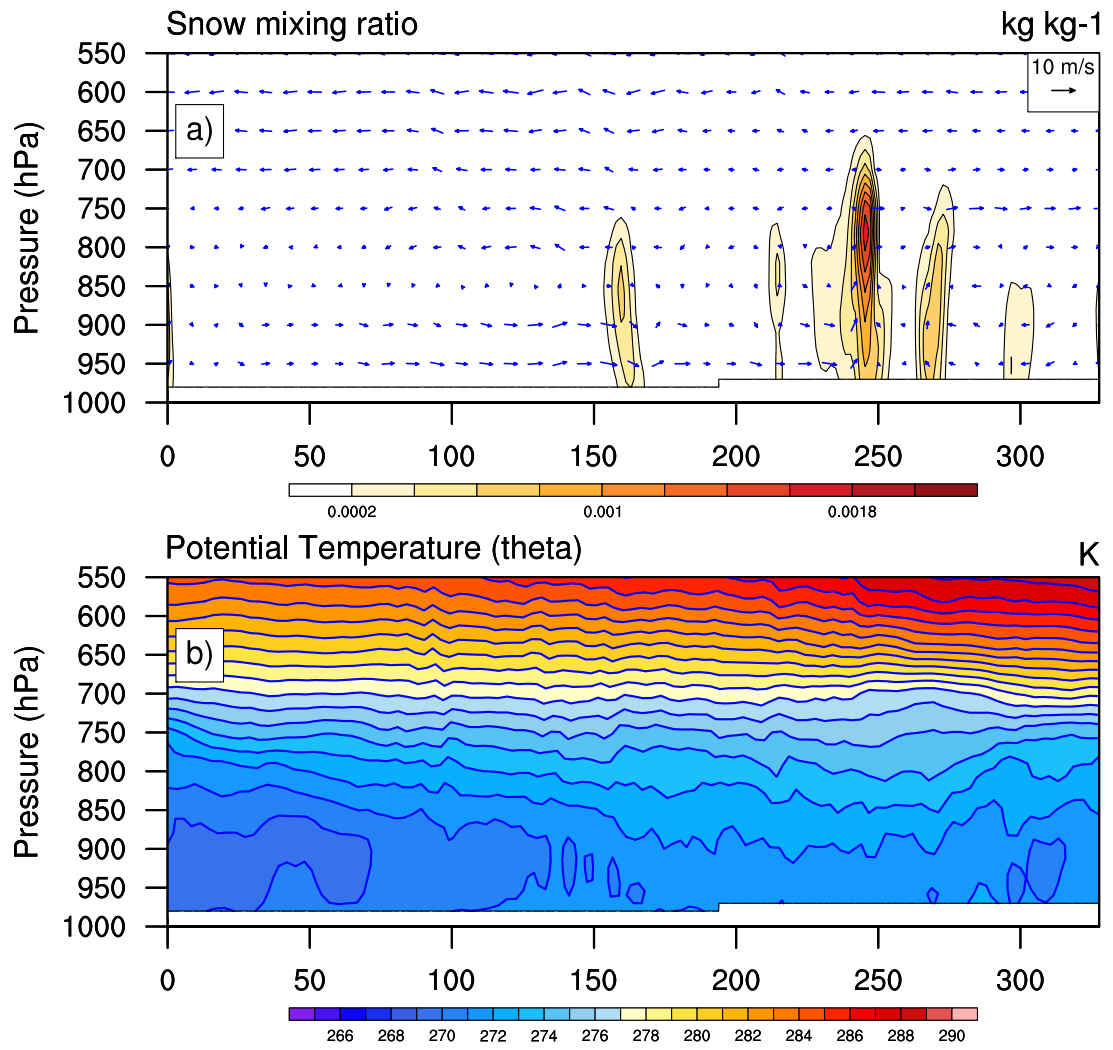


Figure 4.17: Same as Figure 3.7 but for NHOKSAK case.

Conclusion and Discussion

5.1 Conclusions

‘Thick Cloud Band along the Okhotsk Sea Coast of Hokkaido’ often forms in winter seasons. Numerical simulations were made to investigate its formation and maintenance mechanisms. Weather Research and Forecasting Model (WRF) was used for the numerical simulations for the period of 72 hours from 0000UTC 25 Dec 2008 to 2400UTC 27 Dec 2008.

The results revealed that the snow band formed on 26 Dec 2008 along the coast of Hokkaido Island, moved offshore toward the Sea of Okhotsk where it intensified, and was sustained for one and a half days. Experimental results also revealed that the land breeze was important for the initial formation and a series of sensitivity experiments showed the importance of cold air advection from Sakhalin Island in the maintenance of the snow band and the importance of topography over Sakhalin, which intensified the convergence at the Soya Strait and thus the snow band.

5.2 Discussion

The cold advection created horizontal temperature gradient offshore of the Hokkaido coast and blocked the propagation of the snow band further offshore. On the other hand, the land breeze from Hokkaido Island, which was thought to be the dominant cause of the cloud bands of the weak wind type, or land-sea difference in surface roughness was important in the initial

formation of the cloud band, whereas topography over Hokkaido had a minor influence.

The cold advection from Sakhalin Island would be significant as long as the northwesterly wind is sufficiently strong, whereas it would be insignificant with weak winds since the cold air from Sakhalin would be warmed by air-sea heat exchange before reaching the offshore of Hokkaido. Because the strong northwesterly is often sustained more than a day during cold air outbreaks from Siberia, this is a possible reason for the difference in duration between the weak and strong wind types.

In addition to the above effects of islands, Fujiyoshi et al. (2010) suggested the importance of sea ice extent, which would work against cloud band formation. The effect of sea ice extent, as well as the roles of Hokkaido and Sakhalin Islands, should be investigated by simulating various cases to further improve our understanding of the thick snow bands.

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Bibliography

- Tage Andersson and Nils Gustafsson. Coast of Departure and Coast of Arrival: Two Important Concepts for the Formation and Structure of Convective Snowbands over Seas and Lakes. *Monthly Weather Review*, 122(6):1036–1049, June 1994. ISSN 0027-0644, 1520-0493. doi: 10.1175/1520-0493(1994)122<1036:CODACO>2.0.CO;2.
- Tage Andersson and Stefan Nilsson. Topographically Induced Convective Snowbands over the Baltic Sea and Their Precipitation Distribution. *Weather and Forecasting*, 5(2):299–312, June 1990. ISSN 0882-8156, 1520-0434. doi: 10.1175/1520-0434(1990)005<0299:TICSOT>2.0.CO;2.
- David Atlas, Shu-Hsien Chou, and William P. Byerly. The Influence of Coastal Shape on Winter Mesoscale Air-Sea Interaction. *Monthly Weather Review*, 111(2):245–252, February 1983. ISSN 0027-0644, 1520-0493. doi: 10.1175/1520-0493(1983)111<0245:TIOCSO>2.0.CO;2.
- Ming-Da Chou and Max J. Suarez. *An efficient thermal infrared radiation parameterization for use in general circulation models*, volume 3 of *Technical report series on global modeling and data assimilation*. NASA, November 1994.
- Yasushi Fujiyoshi, Takuya Kamisho, and Masayuki Kawashima. Dual doppler radar observation of thick cloud bands developed along the Hokkaido coast in the Sea of Okhotsk. In *Proceedings of the 25th International Symposium on Okhotsk Sea & sea ice*, pages 12–15, Mom-betsu, Hokkaido, Japan, February 2010.

Zaviša I. Janjić. Nonsingular implementation of the Mellor–Yamada level 2.5 scheme in the NCEP Meso model. *NCEP Office Note*, 437:61, 2002.

John S. Kain. The Kain–Fritsch Convective Parameterization: An Update. *Journal of Applied Meteorology*, 43(1):170–181, January 2004. ISSN 0894-8763. doi: 10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2.

Takuya Kamisho. *Structure and formation mechanism of thick cloud bands along the Okhotsk Sea coast of Hokkaido. (In Japanese)*. Master Thesis, Hokkaido University, Sapporo, 2010.

Hiroaki Kawase, Tomonori Sato, and Fujio Kimura. Numerical experiments on cloud streets in the lee of island arcs during cold-air outbreaks. *Geophysical Research Letters*, 32:4 PP., July 2005. doi: 200510.1029/2005GL023256.

George L. Mellor and Tetsuji Yamada. Development of a turbulence closure model for geophysical fluid problems. *Reviews of Geophysics*, 20(4):851–875, 1982. ISSN 1944-9208. doi: 10.1029/RG020i004p00851.

Eli J. Mlawer, Steven J. Taubman, Patrick D. Brown, Michael J. Iacono, and Shepard A. Clough. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *Journal of Geophysical Research: Atmospheres*, 102(D14):16663–16682, 1997. ISSN 2156-2202. doi: 10.1029/97JD00237.

Hideaki Ohtake, Masayuki Kawashima, and Yasushi Fujiyoshi. The Formation Mechanism of a Thick Cloud Band over the Northern Part of the Sea of Japan during Cold Air Outbreaks. *Journal of the Meteorological Society of Japan*, 87(2):289–306, 2009. doi: 10.2151/jmsj.87.289.

Johannes C. Roeloffzen, W. D. Van Den Berg, and J. Oerlemans. Frictional convergence at coastlines. *Tellus A*, 38A(5):397–411, 1986. ISSN 1600-0870. doi: 10.1111/j.1600-0870.1986.

tb00473.x.

C Skamarock, J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and G. Powers. A description of the Advanced Research WRF Version 3. Technical report, 2008.

Mukul Tewari, F. Chen, W. Wang, J. Dudhia, and M. A. LeMone. Implementation and Verification of the unified Noah Land Surface Model In The Wrf Model. pages 11–15, 2004.

Gregory Thompson, Paul R. Field, Roy M. Rasmussen, and William D. Hall. Explicit Forecasts of Winter Precipitation Using an Improved Bulk Microphysics Scheme. Part II: Implementation of a New Snow Parameterization. *Monthly Weather Review*, 136(12):5095–5115, December 2008. ISSN 0027-0644, 1520-0493. doi: 10.1175/2008MWR2387.1.

Hanako Yoshihara, Masayuki Kawashima, Ken-ichiro Arai, Jun Inoue, and Yasushi Fujiyoshi. Doppler radar study on the successive development of snowbands at a convergence line near the coastal region of Hokuriku district. *Journal of the Meteorological Society of Japan*, 82(4): 1057–1079, 2004.