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Analysis and Model Simulation of Wind Convergence over the Sea of Japan

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***Abstract*:** In the winter, the wind system over the Sea of Japan strongly affects the weather of the Japan islands. In this paper, wind distributions over the Sea of Japan during cold-air outbreaks observed by the NASA scatterometer were analyzed. Strong northwesterly to westerly winds of 15 to 20 m/s were observed off Vladivostok and off the Korea Peninsula, respectively. A weak wind region, in which the wind speed is less than 9 m/s, is seen downwind of the mountains and extends more than 200 km. A strong wind convergence zone was formed in the further lee of the weak wind region.

Numerical experiments using a three-dimensional mesoscale model are performed to compare the wind distribution observed by NSCAT. The results show that the simulated winds agree well with those observed by NSCAT except for the intensity of the convergence.

***Keywords* :** NASA scatterometer, ocean wind, numerical experiment.

1. Introduction

The wind system often determines the regional weather and climate. In the winter season, moisture flux from the surface of the Sea of Japan is quite large, since the low level temperature in the atmosphere is much lower than the sea surface temperature when cold air breakout from Siberia. The moisture evaporated from the ocean into the atmosphere causes heavy snowfall on the Sea of Japan sides of the Japan main island. The amount of snowfall depends on the distributions of moisture and cloud over the Sea of Japan. From satellite cloud images, it is obvious that the cloud distribution is affected by the mesoscale wind system generated by the topography located near the windward coast.

By investigating satellite cloud images, Okabayashi and Satomi (1971), Yagi et al. (1986) found that a convergent cloud band is often formed over the Sea of Japan in winter, extending from off Wonsan, Korea to the Hokuriku district of Japan. The convergent cloud band often causes heavy snowfall on Japan islands under winter monsoon conditions. Nagata et al. (1986) conducted numerical experiments using a model assuming different lower boundary conditions at the Korea Peninsula. They stated that the land-sea contrasts of thermal properties between the Peninsula and the Sea of Japan play leading roles in forming the convergent cloud band. Their later experiment (Nagata, 1991) showed that the three lower boundary forces (the land-sea thermal contrast, the dynamic effect of the mountain and the characteristic sea surface temperature distribution) are similarly important in forming the convergent cloud band.

Understanding the orographic effect on the wind system and moisture distribution over the Sea of Japan is important for predicting snowfall in these areas. However, wind data in winter season over the Sea of Japan were only acquired from infrequent reports from ships and buoys because of the severe winter weather conditions. Studies on the flow over the Sea of Japan were mainly based on theory, numerical models and cloud images observed by satellites in the past.

The NASA Scatterometer, NSCAT, aboard Japan's ADEOS Satellite measured near-surface vector winds over the global oceans from mid September 1996 through June 1997. The purpose of this study is to investigate the wind distribution and the effect of upwind topography on the wind distribution over the Sea of Japan by using the wind data obtained by NSCAT. Numerical experiments are also performed to investigate the formation mechanisms of the wind convergence over the Sea of Japan. Wind observed by NSCAT and winds obtained by the numerical experiments are compared for this purpose.

2. Wind Data Observed by NASA Scatterometer

The NASA scatterometer (NSCAT) is one of the eight Earth-observing instruments that were carried aboard Japan's Advanced Earth Observing Satellite (ADEOS). NSCAT is an active microwave radar which measures winds over the oceans by transmitting Ku band microwave pulses (13.995 GHz) and receiving backscatter signals from the ocean surface. The backscatter signals are subject to changes in direction due to surface waves. Multidirectional measurements were used to determine wind speed and direction.

A new model function algorithm named NSCAT-2 relates the backscatter signal strength to wind speed and determines the wind direction by modeling the azimuthal dependence as a truncated Fourier cosine series. Multiple solutions (ambiguities) for wind speed and directions are derived due to the azimuthal variation of the model function. The final wind fields are selected from the derived solutions by using ambiguity removal algorithm with the initialization using wind data from the Numerical Weather Prediction (NWP). This initialization is called "NWP nudging."

The NSACT High-Resolution Wind Vectors Data Product (25 km selected wind) was used in this paper. The NSCAT winds are defined as equivalent neutral stratification wind at 10 m altitude. This data set provides vector measurements collocated in 25×25 km wind vector cell. Wind vectors are only retrieved in ocean cells.

NSCAT covers a 600 km swath on either side of the spacecraft. The two swaths are separated by a gap of about 330 km directly below the satellite where no wind data is available. The data used in this study were provided by the Jet Propulsion Laboratory, NASA. The difference between NSCAT wind speeds and wind observed by buoys is less than 2 m/s for winds under 20 m/s. Wind speeds over 20 m/s have a standard deviation of less than 10% of the buoy wind. Wind direction has a standard deviation of less than 20 degrees.

3. Description of the Numerical Model

To compare the wind distribution observed by NSCAT, numerical experiments are conducted with a three-dimensional local circulation model, which is the same as the model developed by Kikuchi et al. (1981), and modified by Kimura and Arakawa (1983).

The model was described in detail by Kimura and Takahashi (1991) and Kimura and Kuwagata (1993). The governing equations are the Boussinesq hydrostatic equations, which are written in a terrain-following coordinate system. The numerical experiments are performed on a domain covered by 100×100 grid points with an interval of 10 km. The model atmosphere is divided into 22 layers with higher resolution in the lower layer.

The numerical integrations are carried out for 26 hours in each experiment starting at 1200 UTC of the day before, which is about 26 hours before the NSCAT observation. Initial data and boundary data for winds, potential temperature and specific humidity are interpolated from global analysis data (GANAL) obtained by the Japan Meteorological Agency.

4. Wind Convergence over the Sea of Japan Observed by NASA Scatterometer

The topography surrounding the Sea of Japan is shown in Fig. 1. The Changbai mountains with a peak of 2744 meters (Baitou or Paektu mountain) are located in the north of the Korean Peninsula. The Sikhote Alin mountain range is located along the coast northeast of Vladivostok. Between these two mountainous areas, there is a low elevation area around Vladivostok making a topography gap from the inland plain to the Sea of Japan.

Figure 2a is the surface weather map showing pressure (hPa) and fronts for 0000 UTC 02 January 1997. A strong cyclone with a cold front passed over the Japan Main Island to the Pacific Ocean. A large anticyclone having double centers around 52N/115E and 32N/120E expanded to western parts of the Japan Main Island. The pressure gradient is very large around the Sea of Japan. This pattern shows a typical cold air outbreak situation. Figure 2b is the same as Fig. 2a, but for 0000 UTC 29 January 1997. The main feature of the surface weather map is similar to that on 2 January 1997.

Figure 3 shows the surface wind velocity over the Sea of Japan observed by NSCAT at 1352 UTC 2 January 1997. The background color in the image represents wind speed in meters per second. The cooler colors show lower speeds; The warmer colors show higher speeds. The stream lines indicate the direction of the wind.

The detailed distribution of the surface wind indicates the effect of the topography located near the windward coast of this wind system. Although the sea of Japan is almost covered by a strong northwesterly wind, the wind velocity is not uniform. There is a strong wind system with a maximum velocity of about 20 m/s around the sea off Vladivostok. Strong westerly winds (about 16 m/s) are also observed off the Korean Peninsula. A region of weak wind, where wind speed is less than 9 m/s, is seen in the lee of the Changbai mountains and extends leeward more than 200 km.

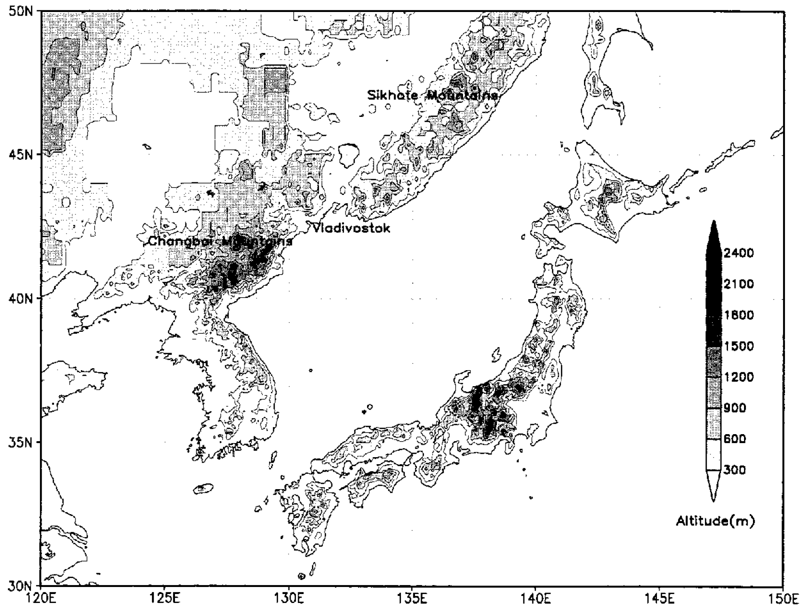

Fig. 1. Topography surrounding the Sea of Japan.

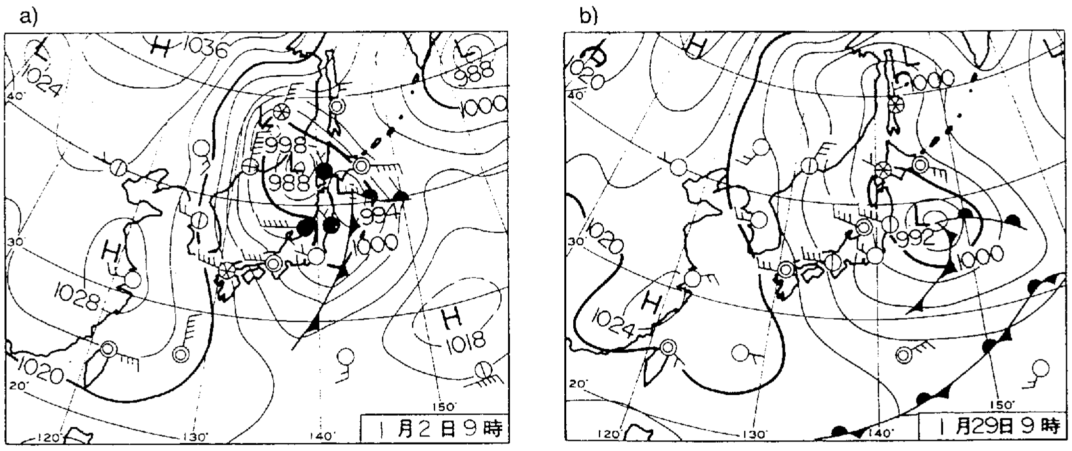

Fig. 2. Surface weather map (hPa) for a) 00 UTC 02 January 1997 and b) 00 UTC 29 January 1997 (Japan Meteorological Agency).

A strong horizontal wind convergence zone is formed in the lee of the weak wind region. The two strong wind systems mentioned above, the northwesterly from Vladivostok and the westerly from the northern end of the Korean Peninsula, seem to converge in this zone. The convergence zone extends toward Japan Main Island with some meandering. The convergence zone seems to correspond to the cloud band, which is frequently observed around this area in visible and infrared satellite images.

A similar convergence zone was observed at 1354 UTC 28 January (Fig. 4), although wind speed is lower than that on 2 January. In this case, the region of weak wind in the lee of the Changbai mountains extends more than 300 km. The wind speed in this region is less than 6 m/s. The convergence zone is clearer than that on 2 January. A weak wind region followed by a long convergence zone was also observed on 9, 18, 20, 24 and 29 January 1997 (the figures are not shown here).

These features indicate that the strong northwesterly winds from Siberia are blocked by the Changbai mountains. They go around both sides of the mountains and form the strong northwesterly winds off Vladivostok and the westerly winds on off the Korean Peninsula. The weak wind region is seen on the downwind of the Changbai mountains. The strong northwesterly off Vladivostok seems to be a gap wind, which was discussed by Jackson and Steyn (1994a, b). The strong stratified flow is accelerated when it goes through a narrow topography gap between mountains.

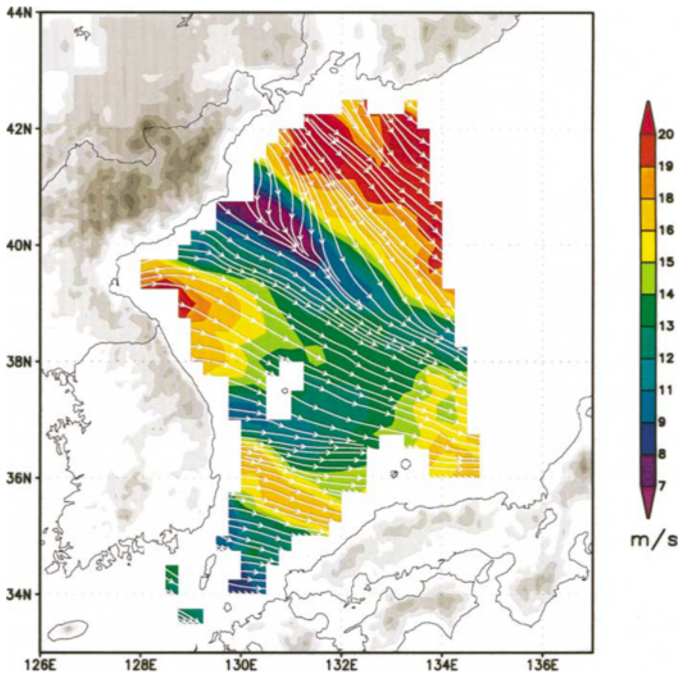

Fig. 3. Winds over the Sea of Japan observed by NSCAT during 13:52-13:54 UTC on 2 January 1997.

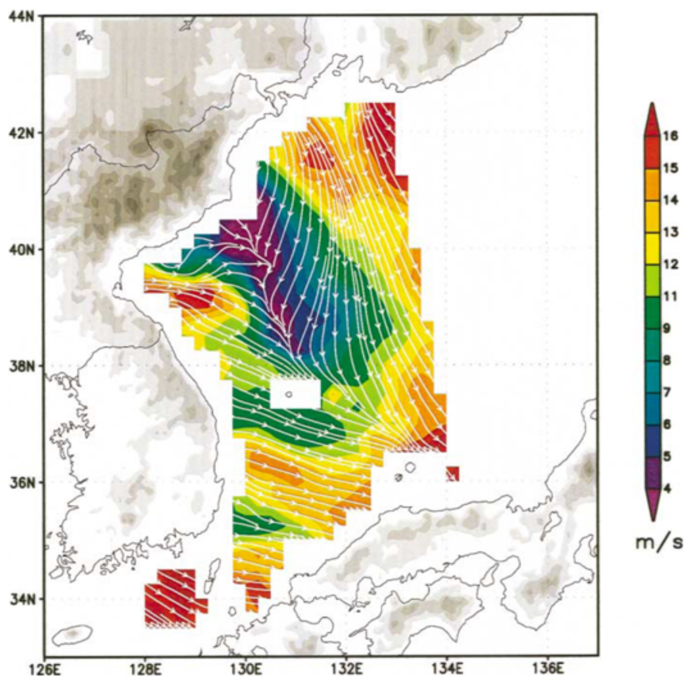

Fig. 4. As in Fig. 3, except for 13:54-13:56 UTC on 28 January 1997.

Reverse winds and lee vortices appear in the lee of the isolated mountain when the flow has a strong stratification (Smith and Grubisc, 1993). Some numerical studies on the lee vortices have been reported by Schär and Smith (1993a, b). The most recent work has been done by Schär and Durran (1997) mainly on non-stationary lee vortices. The formation mechanism of gap winds and lee eddies depends on the Froude number, which is defined by:

$$Fr = U/NH,$$

where U is the mean velocity, N, the Brunt-Väisälä frequency; and H, the height of the mountain. When Fr number is larger than one, flow tends to go over mountains and makes no lee vortex and no gap wind.

Although the observation of the surface winds in both cases does not reveal lee vortices or reverse flow in the lee of the Changbai mountains, the weak wind region may be associated with the stationary lee vortex. As mentioned later, *Fr* numbers are roughly estimated to be 0.44 and 0.23 on 2 and 28 January 1997. These values are small enough to form lee vortices.

Numerical experiments have been performed to compare the winds observed by NSCAT. The numerical integrations are carried out for 26 hours in each experiment starting from 12 UTC of the day before, which is about 26 hour before the NSCAT observation. Initial and boundary data are interpolated from global analysis data (GANAL) obtained by the Japan Meteorological Agency (JMA). Sea surface temperature is also provided by JMA.

Wind velocities at 10 m above sea level at 1300 UTC 2 January 1997 calculated by this model are shown in Fig. 5. The simulated distribution of the surface wind velocity shows a structure similar to the observation by the NASA Scatterometer (NSCAT). The two strong wind systems, the northwesterly from Vladivostok and the westerly from the

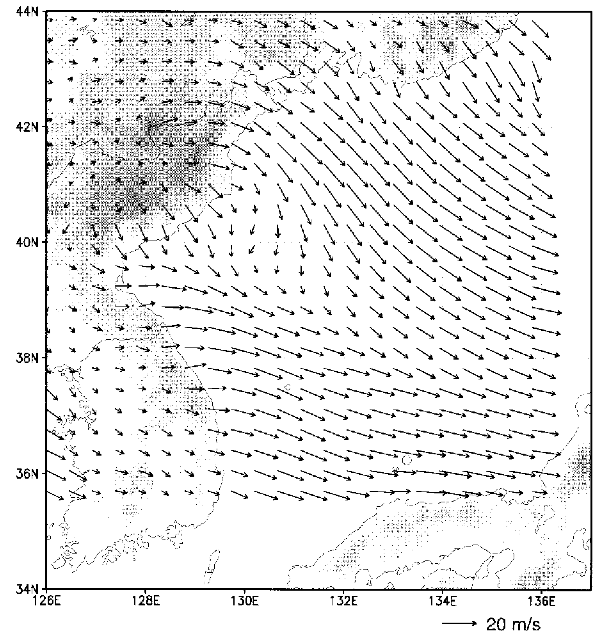

Fig. 5. Winds calculated by numerical simulation for 1400 UTC 2 January 1997.

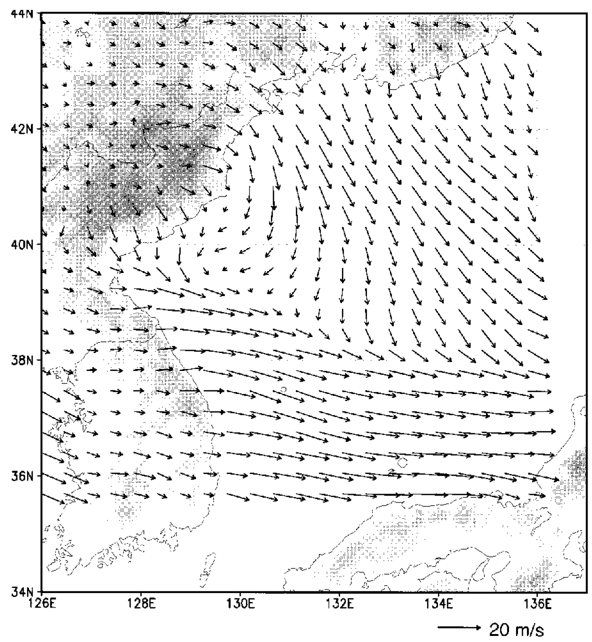

Fig. 6. As in Fig. 5, except for 1400 UTC 28 January 1997.

northern end of the Korean Peninsula, are simulated well. The weak wind region similar to the observation mentioned above are also formed in the lee of the Changbai mountains. The long convergence zone can be seen in the lee of the weak wind region. The simulated westerly winds over the sea off the Korean Peninsula are a little stronger than that observed by NSCAT.

The discontinuity of the simulated wind velocity at the convergence zone seems to be less clear than that in the observation, especially downwind far from the Changbai mountains. This means that the intensity of the simulated convergence is weaker than that of the observed wind field.

The results of the numerical experiment at 1300 UTC 28 January 1997 are shown in Fig. 6. Similar to the results on 2 January, the weak wind region downwind of the Changbai mountains is well reproduced by the numerical simulation, but the convergence is somewhat weaker than that observed by NSCAT.

5. Remarks

In this paper, wind distributions over the Sea of Japan during cold-air outbreaks observed by the NASA scatterometer were analyzed. Strong northwesterly to westerly winds of 15 to 20 m/s were observed off Vladivostok (the Korean Peninsula). A weak wind region, in which the wind speed is less than 9 m/s, is seen downwind of the mountains and extends more than 200 km. A strong wind convergence zone was formed in the further lee of the weak wind region.

The strong wind convergence downwind of the mountains observed by NSCAT is well simulated. The Strong northwesterly winds are blocked by the Changbai mountains. They go around both sides of the mountains and are accelerated by the mechanical effects of the topography to form the strong winds off Vladivostok and the westerly winds off the Korean Peninsula. The acceleration in the lee of the mountain range depends on the Froude number and the topography (Saito,1993). The Froude number is estimated to be about 0.44 and 0.23 on 2 and 28 January 1997, if the mountain height is assumed to be 2000 m. The mean wind velocity in the lower layer up to the mountain height at the center of the Sea of Japan is estimated to be about 15.5 m/s and 7.5 m/s. Since the Froude numbers are quite small, the blocking effects of the Changbai mountains and the Sikhote Alin mountains range seem to have been large on these days.

In spite of the small Froude numbers, no reverse flows or vortices were observed in the lee of the Changbai mountains. The numerical results do not show any reverse flow either. The numerical experiments made by Kang and Kimura (1997) show that the quasi-steady eddies appear in the lee of the mountain when the Froude number is about 0.25 at the inflow boundary. However, the lee vortices are clear only when the sea surface temperature is not higher than that of the lower atmosphere. In this case, the convergence zone becomes unclear. If the sea surface temperature is about 10K higher than the lower atmosphere, a long and prominent convergence zone is formed, but the quasi-steady eddies in the lee of the mountain become unclear. The temperature difference between the lower atmosphere and the sea surface was about 10 to 12K on these two cases, so the vortices would have difficulty forming in the lee of the mountain.

The discontinuity at the convergence zone of the simulated wind field is less clear than that of the observation in the two cases. The observed convergence zone is narrower and sharper. The reasons of these discrepancies may be as follows:

1) Since a slight difference in wind direction would not be observed accurately by NSCAT, the discontinuity of the wind direction may be overestimated.
2) The model's horizontal resolution (10 km) is not fine enough to simulate the convergence zone.
3) The sea surface temperature assumed in the model may be lower, or the temperature of the low-level atmosphere may be higher than the actual situation.

As a result, the convergence becomes weak for the reason discussed by Kang and Kimura (1997). To confirm the probability of 2 and 3, we must perform numerical experiments with higher resolution, which will require a much more powerful computer.

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