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THE DEVELOPMENT AND INTENSIFICATION OF MULTIPLE MISOCYCLONES IN SHALLOW CUMULUS CONVECTION OVER THE WARM OCEAN DURING WINTER COLD OUTBREAK

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1. INTRODUCTION

A recent observational study of cold outbreaks and convective storms in a coastal region of the Sea of Japan in northern Japan in winter have revealed that there are unexpectedly frequent occurrences of tornado-like, microscale vortices (i.e., misocyclones (Fujita 1980)) embedded in banded convective storms (Kusunoki et al. 2008). The observation in the Shonai Plains, Yamagata Prefecture during October 2007 and January 2008 suggests that there were 10 gusty wind events that were associated with vortice (Kusunoki et al. 2008). On the other hand, there are only 5 events that are considered as tornadoes and/or downbursts during 1991 and 2007 in Yamagata Prefecture, according to the official reports of Japan Meteorological Agency (JMA) summarized on its web site. The type of these vortices in the area can be classified as a non-supercell tornado (Wakimoto and Wilson 1989) (or microscale vortex) which is generated in regions where horizontal wind shear is strong. These vortices in some instances evolve into well-defined tornadoes which lead to wind disasters. Since the population and the social infrastructure of Japan are concentrated in coastal regions, diagnosing and forecasting the development and evolution of such microscale vortices are critically important for the prevention and mitigation of wind disasters. In accordance with these requirements, the recent development of mesoscale meteorological models enables one to simulate more accurately the local wind variability under realistically represented meteorological conditions, which lead to evaluating quantitatively the simulated wind fields against observational data in complex terrain (Jimenez et al. 2008; Rife and Davis 2005). Therefore, realistically and accurately representing steep/complex terrains in meteorological models is critical for quantitative wind forecasts.

One of the unique features of winter-season convection over the Japan Sea is that the environmental condition for convection is very unstable owing to high sea surface temperature (SST) relative to cold-air outbreak from Siberia (i.e., winter monsoon). Because of this unstable state in addition to cold outbreaks, cumulus convection actively develops over the warm sea, which leads to heavy snowfall and severe lightening over the coastal regions to the Japan Sea. Another unique feature is that the cloud-top height is generally lower than that of a common cumulonimbus cloud whose top reaches the tropopause; therefore, the measure of stability indices appears to indicate less unstable: e.g., convective available potential energy (CAPE) amounts at most to some hundreds. The observations indicate that multiple misocyclones are generated within the convective systems that are organized by shallow cumulus convection over the Japan Sea.

The present study investigates the development and intensification of multiple misocyclones in a banded convective system during the winter cold outbreak by conducting very-high-resolution simulations with the Weather Research and Forecasting (WRF)-Advanced Research WRF (ARW) model. The high-resolution simulation incorporates a high-resolution topography dataset in order to better represent the terrain features and hence to realistically represent surface wind variability that is affected by complex topography (Takemi 2009). A case on 1-2 December 2007 over the Shonai Plains, Yamagata Prefecture, Japan is chosen for the present analysis. The Doppler Radar observation indicated that a banded convective system had four misocyclones, one of which evolved into a 0-Fujita-scale tornado.

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2. CASE DESCRIPTION AND MESOSCALE METEOROLOGICAL MODELING

2.1 *CASE DESCRIPTION*

The case studied here is a high-wind event in Yamagata Prefecture around 0000 to 0200 Japan Standard Time (JST) on 2 December 2007. During the event, gusty winds, thunders, and hail falls were observed over the Shonai Plains, and a F0-scale wind disaster occurred in Sakata City. A precipitating convective band developed off the coast of the Shonai Plains with the passage of the synoptic-scale trough. The precipitating convective band is a mesoscale disturbance which is not under the influence of any synoptic-scale disturbances such as a midlatitude cyclone and a front (Fig. 1). A characteristic feature in the synoptic-scale environment is that a weak trough existed at the 500-hPa level. This trough had a cold-temperature anomaly that created an unstable condition for convection.

The maximum wind speed at the Sakata weather station was 20.6 m s^{-1} at 0005 JST 2 December. The surface pressure reached at its minimum value (1015.8 hPa) at 0136 JST, followed by an intense precipitation of 6 mm/10 min and a temperature drop of 2 K. The observation by the Doppler Radar implemented at a railway station of East Japan Railway Company indicated that four misocyclones were embedded within the precipitation convective band, one of which was identified as a F0-scale tornado[7]. The vorticity estimated from the Doppler velocity fields was 0.1 - 0.3 s^{-1}.

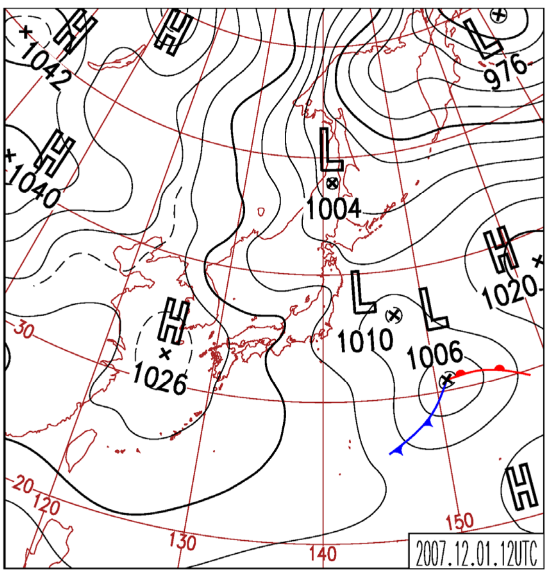

Figure 1: Surface weather map at 2100 JST 1 December 2007, obtained from Japan Meteorological Agency.

2.2 *MODELING SETUP*

The mesoscale meteorological model used here is the Advanced Research Weather Research and Forecasting model (WRF/ARW, version 3.0.1.1) (Skamarock et al. 2008) which is developed mainly by the U.S. National Center for Atmospheric Research. The WRF model has a nesting capability that can resolve the area of interest with a fine grid spacing. In this study, four nested computational domains (with the top being at 50 hPa) are set. Two simulations are conducted here: one of which is a baseline simulation to examine the development and evolution of microscale vortices and the representation of surface winds, while the other is a sensitivity simulation in order to examine the effects of low-level static instability. In both the simulations, we set the outermost domain (1800 km by 1440 km) covering the main island of Japan with a horizontal grid spacing of 9 km, focus domain region with decreasing the grid spacing with each inner domain as 3 km and 600 m, and thereby define the innermost domain (48 km by 40 km) covering the Shonai area and its surroundings with a 120-m grid. The vertical coordinate system is a terrain-following system based on the hydrostatic pressure which is normalized by the pressures at the surface and the upper boundary. The number of vertical grids is 40, with 10 grids in the lowest 500 m.

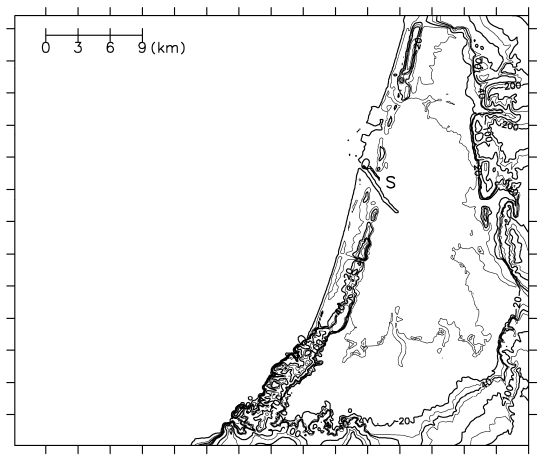

Figure 2: Surface topography of the innermost computational domain with the 120-m grid spacing. "S" indicates the location of the Sakata weather station.

The terrain data used to create the modeled topography are the global 30-second topography data (GTOPO30) from the U.S. Geological Survey (USGS) for the outer 3 domains and the 50-m mesh digital elevation dataset by the Geographical Survey Institute of Japan (GSI50) for the innermost domain. The procedure for the data processing is found in Takemi (2009). For creating the land-use/land-cover (LU/LC) data, the USGS Global Land Cover Characterization dataset is used. Figure 2 shows the surface topography represented in the innermost domain with the 120-m grid spacing.

In determining the initial and boundary conditions, we use the 6-hourly Mesoscale Analysis data (MANAL) of Japan Meteorological Agency (JMA), the 6-hourly Final Analysis data of the U.S. National Centers for Environmental Prediction (NCEP), and the daily Merged Sea Surface Temperature (MGDSST) analysis of JMA. The horizontal resolutions of MANAL and MGDSST are 10 km and 0.25 degree, respectively, which are useful for high-resolution regional simulations. Six-hourly SST data are made by interpolating in time the daily MGDSST analyses. These 6-hourly data are provided as the boundary conditions at the lower and the lateral boundaries of the outermost domain as well as the initial condition for the outermost domain.

Full physics processes are included in the present simulation in order to realistically reproduce the meteorological phenomena. A physics parameterization that is closely relevant to the simulation of wind fields is a PBL mixing parameterization. We chose a Mellor-Yamada Level 2.5 (MYJ) scheme (Janjic 1990). This scheme, formulated based on a Reynolds-averaging approach, solves a prognostic equation for turbulent kinetic energy (TKE) that determines the eddy viscosity coefficients with a diagnostic equation of length scale. The mixing is done locally between the adjacent grid levels.

The model is initialized at 0900 JST 1 December 2007 and integrated for 24 hours. The time integration for the third and fourth domains is started at 2100 JST 1 December 2007.

3. RESULTS

In the simulation, a precipitation convective band that has similar appearance with the observed structure was reproduced, although the time of the development and evolution was more than one hour earlier than in the observed case. Figure 3 indicates that there are several vortices with a significant intensity of relative vorticity (on the order of 10^{-2} s^{-1}), aligned in a northeast-southwest direction at the leading edge of the convective band over the Japan Sea. The horizontal size of the vortices is about 500m, and the maximum intensity of the vortices reaches 0.06 s^{-1}. These strong vortices were seen to be located in or near the area of strong updraft. The surface winds due to these vortices were locally enhanced and in some instances exceed 20 m s^{-1}. For example, at the central area of the southernmost vortex in the convective band the wind speeds were greater than 20 m s^{-1}. The intensities of the simulated vortices are a little smaller than those estimated from the Doppler-Radar observation but are considered as a fair result considering that the grid spacing is 120 m. The maximum wind speed in the simulation is comparable to the observed wind gust in Sakata.

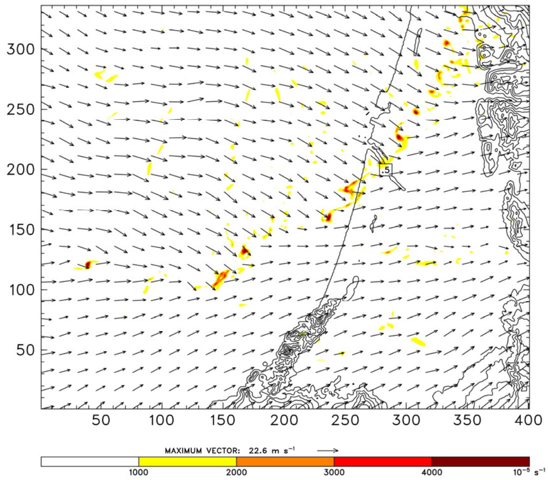

Figure 3: Horizontal distribution of vertical-component relative vorticity (shaded) at the 500-m height as well as surface winds (vectors) at 2354 JST 1 December 2007 from the baseline simulation. The digits in the axes indicate the grid number.

The vertical structure of one of the intense vortices is exhibited in Fig. 4. The strong vortex is concentrated in the lowest 500-m depth and is seen to be stretched in the vertical by convective clouds that had strong updrafts (the maximum exceeding 10 m s^{-1}).

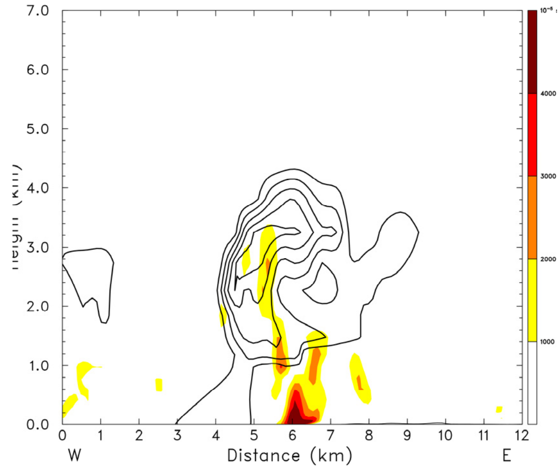

Figure 4: Vertical cross section across a significant intensity of vortex at y=184 in Fig. 3. Vertical component of relative vorticity (shaded) and condensation mixing ratio (contoured at 0.5 g kg^{-1}) are indicated.

We examined the mesoscale environment for the development of vortices and found that there was a weak temperature gradient (by a decrease of 2 K) that corresponded to the leading edge of the cold-air pool. Horizontal convergence was enhanced at this boundary, and thus the updrafts developed at the leading edge of the advancing cold-air pool. This suggests that the intensification of vortices is due to the vertical stretching.

An interesting point is that despite the relatively shallow updraft and convective cloud (cloud top is around 5 km) as compared with those of cumulonimbus clouds and supercell storms, a well-organized vortex with a significant intensity is generated and enhanced. This is because the lower atmosphere is very unstable with colder-air in the middle and upper levels overriding the warm ocean and therefore this strong instability is favorable for the rapid development of strong updrafts in shallow convective clouds. Such shallow convective clouds are a common feature found within winter storms in the coastal region of the Japan Sea (Ohigashi and Tsuboki 2005; Eito et al. 2005), and the shallowness of vortex-producing convective clouds seems to be a unique feature for the convective systems over the Japan Sea in winter.

A sensitivity simulation with SST uniformly decreased by 5 K was also performed in order to examine the effects of warm SST. Although the overall features of the synoptic-scale and mesoscale meteorological disturbances were less affected by the SST change, the strength of convective updrafts within the mesoscale precipitating convective band was significantly reduced. The reduced convective updrafts led to the reduction in the number and strength of microscale vortices. Therefore, it was said that high SST provided an environment favorable for the development and enhancement of convective clouds and hence the associated microscale vortices. However, even decreasing SST, the lowest atmosphere indicated an unstable state, and therefore strong convection occurred, in spite of less degree of organization, to produce occasionally intense vortex in the horizontal shear zone. In other words, high SST is favorable for the organization of convection and the generation of multiple vortices within the convective system. The warm sea surface is regarded as a unique feature for the generation of microscale vortices such as misocyclones and waterspouts in the coastal regions of Japan during the winter-monsoon season.

From the comparison of surface winds simulated by the WRF model and observed by dense surface observation network, the present simulation captures observed high wind speeds due to the strong vortices, which indicates that resolving microscale disturbances is important for the representation of strong wind events in numerical weather prediction models.

4. SUMMARY

The present high-resolution simulation showed that microscale vortices (i.e., misocyclones) are produced and enhanced by strong convective updrafts due to strong low-level instability as well as a weak forcing by cold pool. Although the cloud height in winter storms in the coastal regions of the Sea of Japan is significantly lower than that of thunderstorms and supercellular storms in general, the strength of updrafts is sufficient to enhance the misocyclones. Since the model well reproduced the misocyclones, high wind speeds, like observed ones, resulted from these vortices were also represented. The results further suggest that the representation of misocyclone-producing convective clouds as well as their unstable environment is important in simulating misocyclones and the associating wind speeds.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Eito, H., T. Kato, M. Yoshizaki, and A. Adachi, 2005: Numerical simulation of the quasi-stationary snowband observed over the southern coastal area of the Sea of Japan on 16 January 2001, *J. Meteor. Soc. Japan*, **83**, 551-576.

Fujita, T. T., 1980: Tornadoes and downbursts in the context of generalized planetary scales, *J. Atmos. Sci.*, **38**, 1511-1534.

Inoue, H. Y. et al., 2008: High resolution X-band Doppler radar observation of low-level misocyclones –First result from the Shonai area railroad weather project-, *Proc. ERAD2008*, Helsinki, Finland, 30 June-4 July 2008, P4.4.

Janjic, Z. I., 1990: The step-mountain coordinate: physical package, *Mon. Wea. Rev.*, **118**, 1429-1443.

Jimenez, P.A., J.F. Gonzalez-Rouco, J.P. Montavez, J. Navarro, E. Garcia-Bustamante, and F. Valero, 2008: Surface wind regionalization in complex terrain, *J. Appl. Meteor. Clim.*, **47**, 308-325.

Kusunoki, K. et al., 2008: The Shonai Area Railroad Weather Project: Scientific objectives and experimental design, *Proc. 13th Conf. on Aviation, Range and Aerospace Meteorology*, New Orleans, LA, 20-24 January 2008, Amer. Meteor. Soc., P2.16.

Ohigashi, T., and K. Tsuboki, 2005: Structure and maintenance process of stationary double snowbands along the coastal region, *J. Meteor. Soc. Japan*, **83**, 331-349.

Rife, D.L., and C.A. Davis, 2005: Verification of temporal variations in mesoscale numerical wind forecasts, *Mon. Wea. Rev.*, **133**, 3368-3381.

Takemi, T., 2009: High-resolution numerical simulations of surface wind variability by resolving small-scale terrain features, *Theoretical and Applied Mechanics Japan*, **57**, 421-428.

Wakimoto, R.M., and J.W. Wilson, 1989: Non-supercell tornadoes, *Mon. Wea. Rev.*, **117**, 1113-1140.