A simulation of a lake effect snowstorm with a cloud resolving numerical model

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[1] Lake-effect snowstorms (LES), linearly organized bands of convective clouds, are a major source of snowfall and severe weather in the North American Great Lakes region. LES develop as cold and dry air flows over the warm lake surfaces triggering convection that is often organized into quasi-linear structures known as band clouds. The small horizontal width of these bands, often less than 5 km, combined with their regional-scale evolution that is impacted by the distribution of open water, lake-ice and land makes the forecasting of LES particularly challenging. Here, we describe the simulation of an observed LES event using a cloud resolving numerical model in a domain that includes much of the Great Lakes region. The model was able to successfully capture many of the characteristics associated with the event. This simulation suggests that it soon may be possible to forecast the development of this class of convective weather systems. **Citation:** Maesaka, T., G. W. K. Moore, Q. Liu, and K. Tsuboki (2006), A simulation of a lake effect snowstorm with a cloud resolving numerical model, *Geophys. Res. Lett.*, *33*, L20813, doi:10.1029/2006GL026638.

1. Introduction

[2] Lake-effect snowstorms (LES) are recognized as being an important class of weather systems that produce heavy snowfall and severe weather downstream of the North American Great Lakes [*Peace and Sykes*, 1966; *Jiusto and Kaplan*, 1972; *Niziol et al.*, 1995]. LES contribute to the 100–300% increase in the annual mean precipitation that occurs downstream of the lakes as compared to upstream [*Eichenlaub*, 1979; *Scott and Huff*, 1996]. Individual LES can produce highly localized snowfalls in excess of 100 cm and winds in excess of 20 m/s [*Niziol et al.*, 1995; *Sousounis et al.*, 1999; *Kristovich et al.*, 2000]. These snowstorms typically occur after the passage of a synoptic-scale low-pressure system when northwesterly flow is established over the region [*Liu and Moore*, 2004]. As the cold and dry air flows over the lakes, it is warmed and moistened as a result of the transfer of sensible and latent heat. This energy transfer can trigger atmospheric convection that is typically organized into long quasi-two-dimensional features known as cloud streets or band clouds that are aligned with the mean wind and which are responsible for the severe weather associated with the LES [*Kristovich et al.*, 2000; *Young et al.*, 2002]. The distribution of lake, lake-ice and land surfaces in the region impacts their development and evolution [*Niziol et al.*, 1995].

[3] Figure 1 represents a MODIS true-color satellite image of a LES over the Great Lakes region at 1645 UTC 13 January 2003. The large-scale comma-shaped cloud feature along the southeastern corner of the image is associated with the synoptic-scale cyclone that established the northwesterly flow conducive to the initiation of the LES. At this time, cloud bands occur over and downstream of Lake Superior, Michigan and Huron as well as Georgian Bay. In addition to these bands that are oriented approximately perpendicular to the upwind shore of the lakes, there also exist cloud bands oriented parallel to the upwind shore of western Lake Superior. These bands are associated with gravity waves excited by the flow over topographic features along this shore [*Winstead et al.*, 2002].

[4] From this image, the convective nature of the band clouds as well as their significant extent in the direction of the mean wind is apparent as is the impact that the varying land surface characteristics has on their development. These characteristics suggest that cloud resolving large domain simulations are required to forecast the severe weather associated with LES. Such simulations have until recently been prohibitively expensive in terms of computer time. Recent advances in computer technology including the development of massively parallel distributed memory computer systems such as Japan's Earth Simulator [*Normile*, 2002; *Sato*, 2004] as well as the development of cloud resolving numerical models [*Tsuboki and Sakakibara*, 2002; *Randall et al.*, 2003] allows for the possibility of simulating convective weather systems such as LES. In this paper, we describe a simulation of a LES that occurred on January 13th 2003 that was performed with one such model on the Earth Simulator.

2. Model Description

[5] The model used in this study is the Cloud Resolving Storm Simulator (CReSS) version 2.1 developed at Nagoya University [*Tsuboki and Sakakibara*, 2002]. CReSS employs the non-hydrostatic and fully compressible equations of motion with a terrain-following vertical coordinate. CReSS employs a 1.5 order turbulent closure scheme and a bulk parameterization of cold rain cloud physics with predicted ice concentration. Prognostic variables are three components of velocity, perturbations of pressure and potential temperature, and turbulent kinetic energy, mixing ratios of water vapor and five species of hydrometeors, and number concentration of ice particles. To reduce the computer time required to explicitly represent sound waves in the model, a mode-

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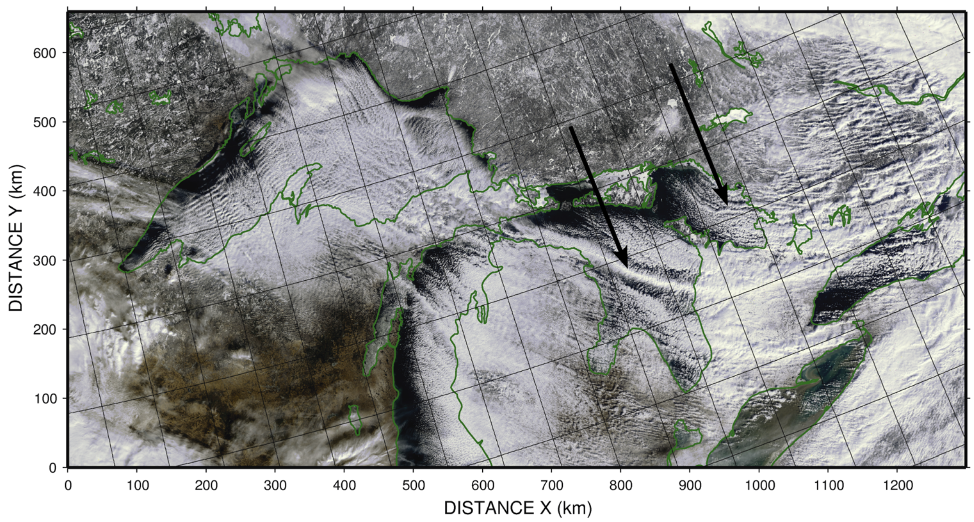

Figure 1. MODIS true-color satellite image of the Great Lakes region of North America at 1645 UTC 13 January 2003. The banded cloud features associated with the lake effect snowstorm that was occurring at this time can be seen in the image. The Type I band clouds that develop over and downstream of Lake Huron and Georgian Bay are indicated by the arrows.

splitting time integration technique was used [*Klemp and Wilhelmson*, 1978].

[6] The computational domain used in the study was 1300 km long by 660 km wide and extended from the surface to 10 km. Please refer to Figure 1 for the horizontal extent of the domain. A horizontal grid resolution of 500m was used in the simulation. Variable grid resolution was employed in the vertical with 40 m resolution near the surface and 453 m at the top of the domain. As a result, the number of grid points per field used in this simulation was 2600 by 1320 by 40. Time steps of 2 and 0.25 seconds were used in the integration.

[7] Initial and boundary conditions were given by the output of the Weather Research and Forecasting (WRF) model version 2.0 with the horizontal resolution of 5 km [*Michalakes et al.*, 2004]. The WRF model was initialized by the ETA/AWIP regional analysis at 00 UTC 13 January 2003 and used the analysis fields as boundary conditions. The CReSS simulation was initialized by the WRF model output of the horizontal wind, specific humidity, temperature and geopotential height fields interpolated to the model domain at 06 UTC 13 January and run for 12 hours on the Earth Simulator using 120 computational nodes (960 processors). For this simulation, CReSS achieved a sustained processing rate of 1.6 Teraflops. The simulation took 8 hours of computer time to complete.

3. Results

[8] Figure 2 represents the vertically integrated hydrometeor field from the model at 1700 UTC 13 January, the approximate time of the satellite image shown in Figure 1. This field was calculated by the vertical integration of all 5 hydrometeors contained in the model (cloud water, cloud ice, rain, snow and graupel). This field provides a succinct diagnostic of the characteristics of the clouds in the model. Given the shallow nature of the cloud bands, most of the hydrometeors reside in the lower 1 km of the atmosphere. This is not the case for the deep clouds along the eastern and southern boundaries of the domain that are associated with the parent low-pressure system. As can be seen from Figure 2, these clouds contain the highest values of the integrated hydrometeor field.

[9] A comparison of Figures 1 and 2 highlights the fidelity with which the model is able to reproduce the spatial characteristics of the cloud field associated with this LES. In particular, the model is able to simulate the development of the cloud field over and downstream of the Great Lakes. In addition to the gross characteristics of the cloud field, the model is able to simulate many of its fine scale features. For example, the transition from 2D roll to 3D cellular convection is often observed to occur in LES [*Brummer*, 1999; *Kristovich et al.*, 1999]. Such a transition occurred over eastern Lake Superior during this event and was captured in the model. Such transitions are believed to occur as a result of momentum mixing associated with the convection that eliminates the vertical shear in the background wind [*Atkinson and Zhang*, 1996; *Liu et al.*, 2004]. The representation of this transition suggests that the model is accurately representing the development of the planetary boundary layer associated with this LES. This view is supported by a comparison between the observed and model sounding at Gaylord Michigan during this event, which both showed a deep and well-mixed boundary extending to a height of approximately 2 km.

[10] Embedded within the cloud field shown in Figure 1 are distinct band clouds that extend downstream from Lake Huron and Georgian Bay. Such band clouds, known as Type I or mid-lake snow bands, are often associated with particularly heavy but highly localized snowfall [*Niziol et al.*, 1995; *Laird et al.*, 2003]. These bands develop when the orientation of the background wind is parallel to the long axis of the lake resulting in enhanced horizontal convergence and an extended fetch over open water leading to organized convection that results in the formation of the bands [*Niziol et al.*, 1995]. These snow bands are captured in the simulation as the band-shaped aggregates of convective cells with large values of the integrated hydrometeor field over and downstream of Lake Huron and Georgian Bay. Given the sensitivity of their existence to the characteristics of the large-scale flow and

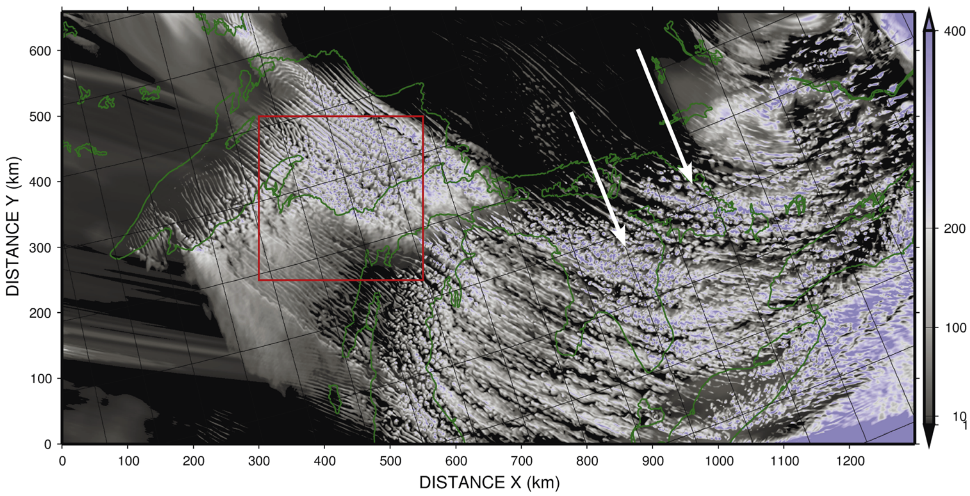

Figure 2. Vertically integrated hydrometeors (cloud water, cloud ice, rain, snow, and graupel) (g m^{-2}) simulated by the numerical model (CReSS). The domain is the same as that shown in Figure 1. The Type I band clouds that develop over and downstream of Lake Huron and Georgian Bay are indicated by the arrows. The red rectangle indicates the domain of Figure 3.

its orientation with respect to the lakes, their presence is an example of the importance of using a large domain in the simulation of LES.

[11] To examine the ability of the model to forecast the precipitation associated with this LES, simulated radar reflectivity fields were calculated from the model hydrometeor fields [*Rogers and Yau*, 1989]. Figure 3 shows the comparison of this simulated field with observations at 1309 UTC 13 January 2003 made with the WSR-88D radar at Marquette, Michigan. The maximum observation range of WSR-88D radar is 450 km; however the observation range for the LES are typically only 100–150 km as a result of the shallow nature of clouds and the earth's curvature. At these ranges, the horizontal resolution of the radar is approximately 2 km. For reference, the region displayed in Figure 3 is also shown in Figure 2. As was the case with Figures 1 and 2, the similarity between the observed and simulated reflectivity fields is striking. In both instances, the bands are aligned with the mean wind, which was from the northwest. Both the observed and simulated reflectivity fields indicate that the bands were well developed over Lake Superior and at this time, tended to become less organized upon landfall. There is also good agreement in the magnitude of the observed and simulated reflectivity field. The observed bands tend to narrower and more linear in character as compared to the model bands. Nevertheless, the aspect ratio, the ratio of the wavelength of the roll clouds to their depth, of the bands in the vicinity of Marquette during this event was on the order of 8. This is consistent with previous observations of band clouds associated with LES [*Young et al.*, 2002].

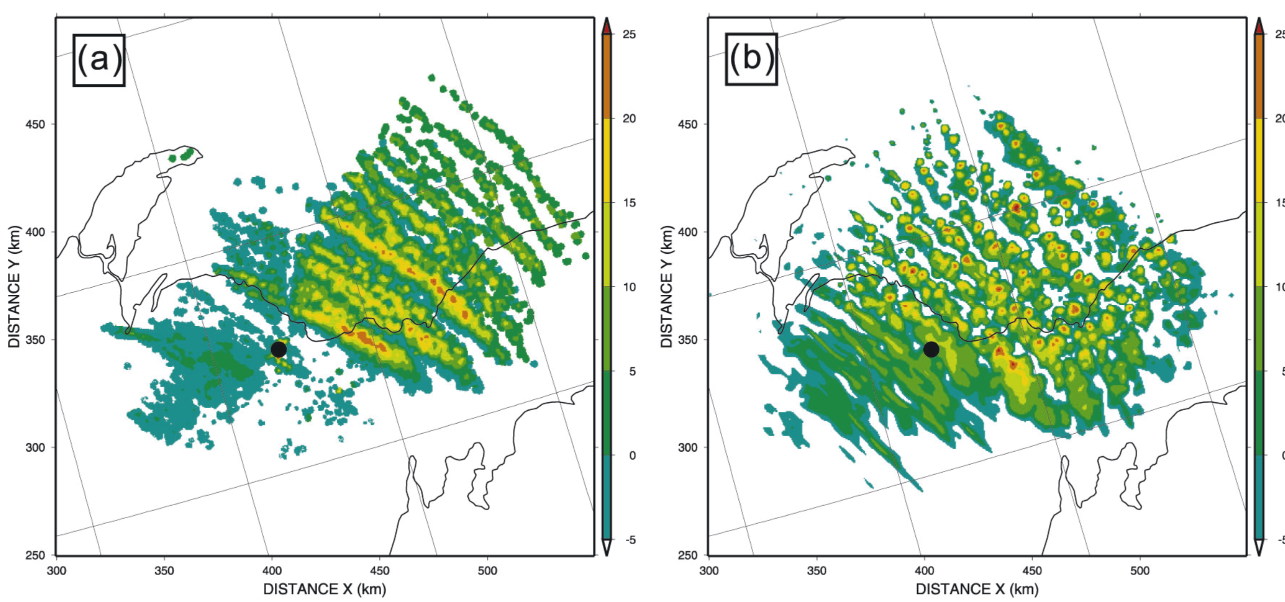

Figure 3. Radar reflectivity PPI (Plan Position Indicator) image with an elevation of 0.5°. The domain is indicated by the rectangle in Figure 2. (a) Observed by WSR-88D at Marquette, Michigan at 1309 UTC 13 January 2003. (b) Simulated by the model at 7 hours after initialization (corresponding to 1300 UTC 13 January 2003).

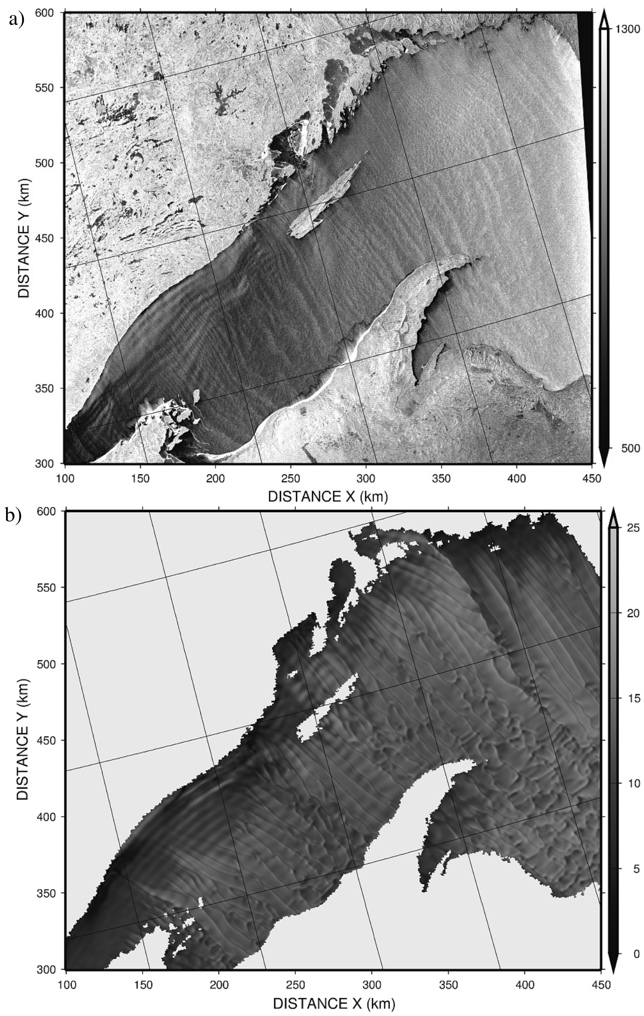

Figure 4. (a) RADARSAT-1 SAR image at 1213 UTC 21 January 2000). (b) Simulated wind speed (m s^{-1}) at z = 10 m over Lake Superior 6 hours after initialization (corresponding to 12 UTC 13 January 2003). The data over land are masked in Figure 4b.

[12] Recently synthetic aperture radar (SAR) images from space-based platforms such as RADARSAT have been shown to provide very high resolution (~100 m) information of the surface wind field of marine weather systems such as LES [*Katsaros et al.*, 2000]. SAR is sensitive to the backscatter of capillary waves on the surface of the lake or other body of water. In general, the higher the wind speed, the greater the backscatter. Unfortunately, SAR imagery of the LES in question is not available, although an image exists of a very similar event from 2000 [*Winstead et al.*, 2002]. In Figure 4 we compare the surface wind field from the model with this SAR image. Although the events are different, there is again a striking similarity between the model and observations. In particular both clearly show the surface expression of the band clouds over eastern Lake Superior. This expression leads to variations in surface wind speed that result from the secondary circulation associated with the band clouds [*Liu et al.*, 2004]. Over western Lake Superior, the surface expression of the clouds associated with topographic gravity waves excited along the northern shoreline and that are oriented perpendicular to the background wind can be seen in both the model and observations. In agreement with observations, these waves in the model were stationary with respect to the topography and had an amplitude of approximately 6 m/s [*Winstead et al.*, 2002]. The complex interference pattern that develops when both the band clouds and gravity wave clouds interact can also be seen near the southern shoreline in this region. It should however be noted that there is a mismatch between the scale of the simulated band clouds, about 5 km, and those observed by RADARSAT, about 2 km.

4. Conclusions

[13] In this study, we used a cloud resolving numerical weather prediction model in a large domain to simulate the evolution of a LES that developed over the North American Great Lakes region on January 13th 2003. The significant computational resources required for this study did not unfortunately allow us perform simulations of other LES. Nevertheless, the results of this study suggest that it is possible to such models to produce realistic simulations of mesoscale weather systems such as LES that develop as the result of the interaction of synoptic-scale and cloud-scale circulations in the presence of varying surface conditions.

[14] As we have shown, such simulations can produce highly realistic cloud, precipitation and wind fields associated with the LES' band clouds in the absence of such features being present in the initial conditions. There are however still some inconsistencies in the structure of the band clouds that may be the result of inadequate resolution, errors in the boundary and initial conditions or in the parameterization of the microphysics or sub-gridscale turbulence. In addition to the applicability of such simulations to forecasting the severe weather associated with these systems, the fidelity of the simulated cloud field suggests that these simulations may also shed light on the important role that clouds play in the climate system [*Randall et al.*, 2003] as well as in the interpretation of new space-based cloud observing systems such as CloudSat and the A-Train [*Stephens et al.*, 2002].

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References

Atkinson, B. W., and J. W. Zhang (1996), Mesoscale shallow convection in the atmosphere, *Rev. Geophys.*, *34*, 403–431.

Brummer, B. (1999), Roll and cell convection in wintertime arctic cold-air outbreaks, *J. Atmos. Sci.*, *56*, 2613–2636.

Eichenlaub, V. L. (1979), *Weather and Climate of the Great Lakes Region*, 335 pp., Univ. of Notre Dame Press, Notre Dame, Ind.

Jiusto, J. E., and M.L. Kaplan (1972), Snowfall from lake-effect storms, *Mon. Weather Rev.*, *100*, 62–66.

Katsaros, K. B., P. W. Vachon, P. G. Black, P. P. Dodge, and E. W. Uhlhorn (2000), Wind fields from SAR: Could they improve our understanding of storm dynamics?, *Johns Hopkins APL Tech. Dig.*, *21*, 86–93.

Klemp, J. B., and R. B. Wilhelmson (1978), Simulation of 3-dimensional convective storm dynamics, *J. Atmos. Sci.*, *35*, 1070–1096.

Kristovich, D. A. R., N. F. Laird, M. R. Hjelmfelt, R. G. Derickson, and K. A. Cooper (1999), Transitions in boundary layer meso-gamma convective structures: An observational case study, *Mon. Weather Rev.*, *127*, 2895–2909.

Kristovich, D. A. R., et al. (2000), The Lake-Induced Convection Experiment and the Snowband Dynamics Project, *Bull. Am. Meteorol. Soc.*, *81*, 519–542.

Laird, N. F., J. E. Walsh, and D. A. R. Kristovich (2003), Model simulations examining the relationship of lake-effect morphology to lake shape, wind direction, and wind speed, *Mon. Weather Rev.*, *131*, 2102–2111.

Liu, A. Q., and G. W. K. Moore (2004), Lake-effect snowstorms over southern Ontario, Canada, and their associated synoptic-scale environment, *Mon. Weather Rev.*, *132*, 2595–2609.

Liu, A. Q., G. W. K. Moore, K. Tsuboki, and I. A. Renfrew (2004), A high-resolution simulation of convective roll clouds during a cold-air outbreak, *Geophys. Res. Lett.*, *31*, L03101, doi:10.1029/2003GL018530.

Michalakes, J., J. Dudhia, D. Gill, T. Henderson, J. Klemp, W. Skamarock, and W. Wang (2004), The weather research and forecasting model: Software architecture and performance, in *11th ECMWF Workshop on the Use of High Performance Computing in Meteorology*, edited by G. Mozdzynski, *Eur. Cent. for Medium-Range Forecasts*, Reading, U. K.

Niziol, T. A., W. R. Snyder, and J. S. Waldstreicher (1995), Winter weather forecasting throughout the eastern United States. 4. Lake effect snow, *Weather Forecasting*, *10*, 61–77.

Normile, D. (2002), Geosciences 'Earth simulator' puts Japan on the cutting edge, *Science*, *295*, 1631–1663.

Peace, R. L., and R. B. Sykes (1966), Mesoscale study of a lake effect snow storm, *Mon. Weather Rev.*, *94*, 495–507.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski (2003), Breaking the cloud parameterization deadlock, *Bull. Am. Meteorol. Soc.*, *84*, 1547–1564.

Rogers, R. R., and M. K. Yau (1989), *A Short Course in Cloud Physics*, 3rd ed., 293 pp., Elsevier, New York.

Sato, T. (2004), The Earth Simulator: Roles and impacts, *Parallel Comput.*, *30*, 1279–1286.

Scott, R. W., and F. A. Huff (1996), Impacts of the Great Lakes on regional climate conditions, *J. Great Lakes Res.*, *22*, 845–863.

Sousounis, P. J., G. E. Mann, G. S. Young, R. B. Wagenmaker, B. D. Hoggatt, and W. J. Badini (1999), Forecasting during the Lake-ICE/SNOWBANDS field experiments, *Weather Forecasting*, *14*, 955–975.

Stephens, G.L., et al. (2002), The Cloudsat mission and the A-train—A new dimension of space-based observations of clouds and precipitation, *Bull. Am. Meteorol. Soc.*, *83*, 1771–1790.

Tsuboki, K., and A. Sakakibara (2002), Large-scale parallel computing of cloud resolving storm simulator, in *High Performance Computing*, edited by P. Z. Hans, et al., pp. 243–259, Springer, New York.

Winstead, N. S., T. D. Sikora, D. R. Thompson, and P. D. Mourad (2002), Direct influence of gravity waves on surface-layer stress during a cold air outbreak, as shown by synthetic aperture radar, *Mon. Weather Rev.*, *130*, 2764–2776.

Young, G. S., D. A. R. Kristovich, M. R. Hjelmfelt, and R. C. Foster (2002), Rolls, streets, waves, and more—A review of quasi-two-dimensional structures in the atmospheric boundary layer, *Bull. Am. Meteorol. Soc.*, *83*, 997–1001.

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