SENSITIVITY OF PLANETARY BOUNDARY LAYER PARAMETERIZATION SCHEMES ON FORECASTING BLIZZARD CONDITIONS FOR THE 11-12 DECEMBER 2010 SNOWSTORM

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ABSTRACT

Producing blowing snow and visibility forecasts for severe winter storms poses a significant challenge to numerical models. Changing the planetary boundary layer (PBL) parameterization schemes in numerical weather models may improve the forecast for blizzard conditions, but it is uncertain how much the forecast is dependent on different PBL parameterization schemes. The study examines five experiments, each with a different PBL scheme, using the Weather Research and Forecasting (WRF) model for a winter storm that occurred 11-12 Dec 2010 in the upper Midwest. Of the five experiments, the MYJ does not produce any blizzard conditions, while the MYNN and ACM2 provide the most accurate forecast of blizzard conditions with a significant area of surface winds 15-17 m s^{-1} in western Iowa. Liquid precipitation and model visibility are also considered. Although very similar over areas with widespread blizzard conditions, MYJ and QNSE produce accurate maximum precipitation forecasts with 55 mm. The model visibility does not show any significant changes from scheme to scheme.

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1. INTRODUCTION

Winter snowstorms and blizzards that are associated with large amounts of blowing snow are very hazardous for public safety. Forecasting surface wind speeds and the subsequent decline in visibility is a significant challenge. Changing the planetary boundary layer (PBL) parameterization schemes in numerical weather models may improve the forecast for blizzard conditions, but it is uncertain how much the forecast is dependent on different PBL parameterization schemes. On 11-12 Dec 2010 a notable severe winter storm moved though the upper Midwest and provided long lasting blizzard conditions that caused a great deal of damage. This study will assess the sensitivity to PBL parameterization for the winter storm on 11-12 Dec 2010.

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Blowing snow is defined as snow particles that are raised by the wind to sufficient levels above the ground to reduce the horizontal visibility to 9.7 km (6 mi) or less (Atmospheric Environment Service 1977). The combination of strong winds and falling or blowing snow result in localized "white out" conditions that cause extremely low visibilities (Schwartz and Schmidlin 2002). As a result, blowing snow can be very dangerous for transportation and can potentially strand travellers. Each year 26 million Americans and $551 million worth of property damage result from blizzards in the United States (Ransford 2001). Additional loses result due to closures of schools, highways, and airports along with the halting of many societal activities for a prolonged period of time (Schartz and Schmidlin 2002). Improving short-term forecasts for blizzard conditions can help to alleviate these hazards.

However, attempting to predict the occurrence of blowing snow and the reduction of visibility can be difficult because of the numerous complexities of the snowpack and its interaction with the lowest part of the atmosphere (Baggaley and Hanesiak 2005). Since the wind speed, air temperature, and the snowpack conditions often vary from case to case, the true visibility cannot be determined by one parameter alone. Nonetheless, previous studies (Huang et al. 2007, Baggaley and Hanesiak 2005) have determined that the visibility has a strong correlation to the wind speed for blowing snow events and forecasting the wind speed can be used as a predictor for visibility in the operational setting.

Currently, operational forecasting techniques for forecasting blizzard conditions involve using numerical weather models to predict the magnitude of the wind speed. To accurately predict the blizzard conditions the model must precisely parameterize the planetary boundary layer (PBL) due to created turbulence (Stensrud 2007). As a result, the surface wind speed will be affected by changing the PBL parameterization scheme as demonstrated with Zhang and Zheng (2004). Currently, it is unclear how different PBL parameterization schemes will influence the forecast for the surface wind speed in regards to a classic severe winter storm set-up, such as the case being evaluated.

The goal of the present study is to evaluate the impact of changing the planetary

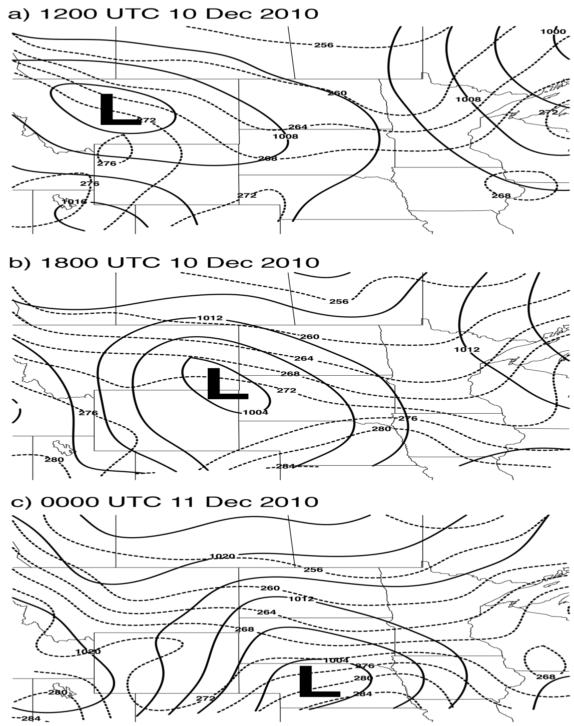

Fig 1. Sea-level pressure (hPa; contoured) and 2-m temperature (K; dashed). The L indicates the position of the surface low-pressure area.

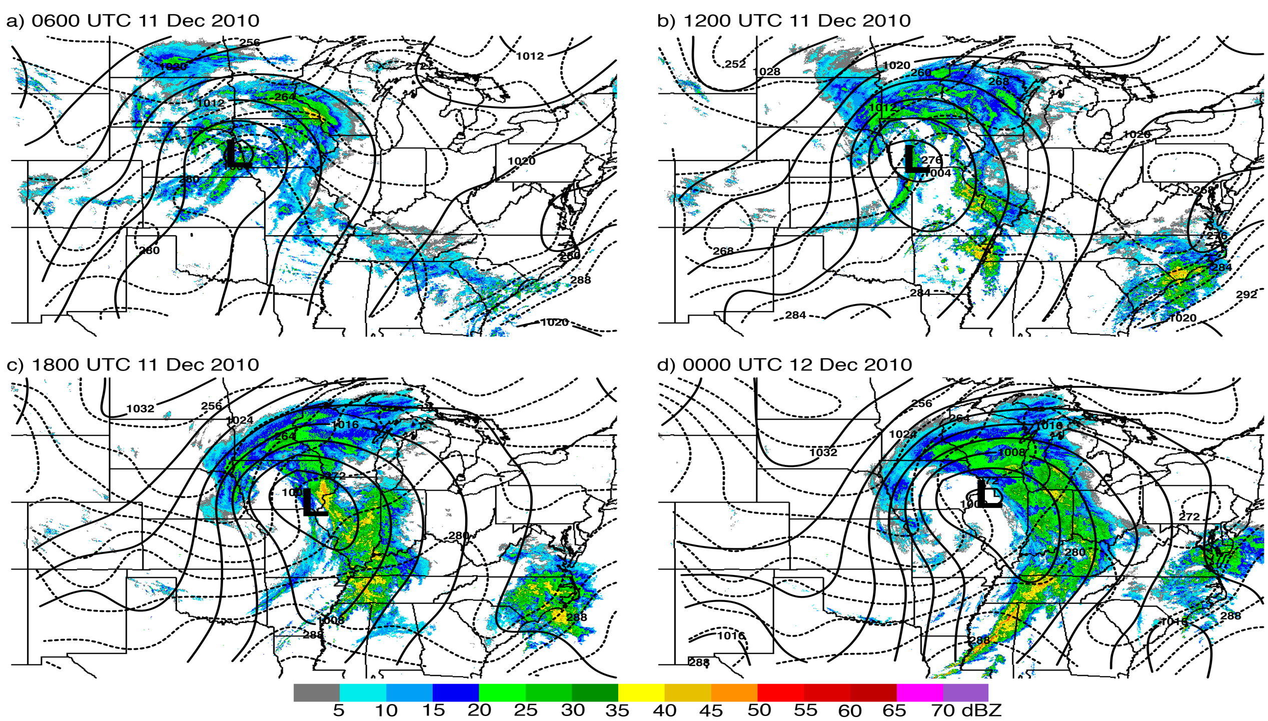

Fig 2. Sea-level pressure (hPa; contoured), 2-m temperature (K; dashed), and radar reflectivity. The L indicates the position of the surface low-pressure area.

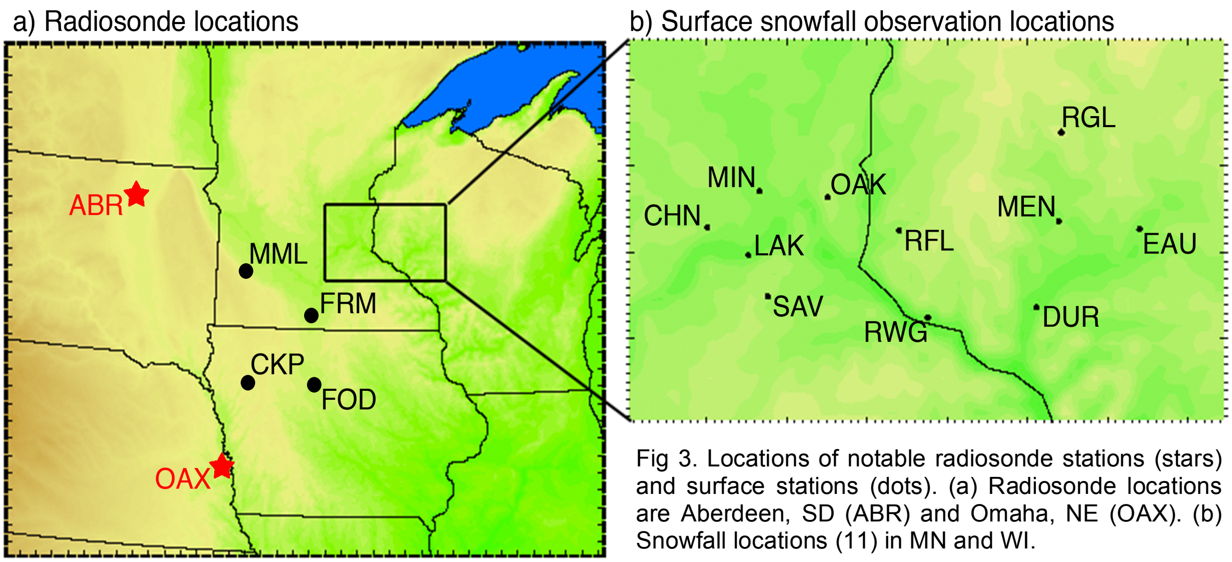

Fig 3. Locations of notable radiosonde stations (stars) and surface stations (dots). (a) Radiosonde locations are Aberdeen, SD (ABR) and Omaha, NE (OAX). (b) Snowfall locations (11) in MN and WI.

boundary layer parameterization scheme for a blizzard moving through the upper Midwest on 11-12 Dec 2010. We will assess many different aspects of the storm, particularly the wind speed and visibility. In essence, this study will evaluate if there needs to be further investigation into the PBL parameterization scheme with other winter storm cases.

2. Case study description

At 1200 UTC 10 Dec, a low-pressure system is over central Montana resembling that of a typical Alberta clipper (Fig. 1a). The cyclone strengthens as it moves quickly to the southeast and by 0000 UTC 11 Dec the cyclone is centered in northern Nebraska (Fig. 1b). Afterward, warm air surges northward ahead of the storm, keeping temperatures at or above freezing over much of Iowa and parts of southern Minnesota (Fig. 1c). At 0600 UTC a wintry mix of freezing rain and sleet is observed over much of Iowa, while heavy snow blankets Minnesota and parts of western Wisconsin (Fig. 2a). By 1200 UTC there is strong cold air advection to the northwest of the surface cyclone (Fig. 2b). As the cold air begins to wrap around the cyclone, the precipitation falls entirely as snow in Iowa and Minnesota. Additionally, the lowest 100 mb of the atmosphere cool by nearly 10 C°. Upper air soundings from KABR and KOAX

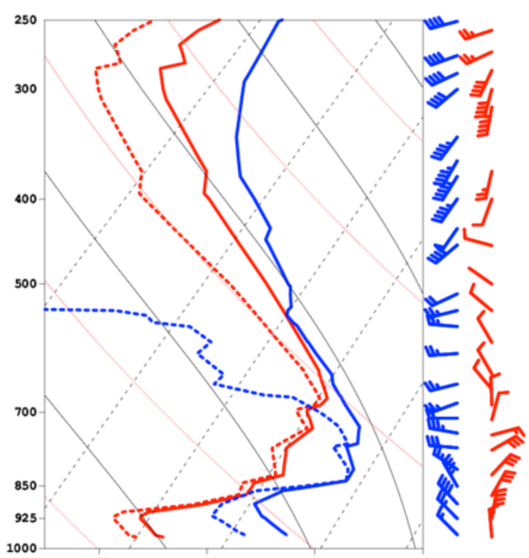

Fig 4. Radiosonde data for Aberdeen, SD (red) and Omaha, NE (blue) at 1200 UTC December 2010.

Table 1: The snowfall totals from the winter storm event 11-12 Dec 2010. The time indicates the final observed snowfall report.

Inches	Location	ID	Time
22.00	Eau Claire, WI	EAU	0500 AM
21.00	Oakdale, MN	OAK	0330 AM
20.00	River Falls, WI	RFL	0700 PM
20.00	Red Wing, MN	RWG	0800 AM
18.00	Menomonie, WI	MEN	0800 AM
17.40	Lakeville, MN	LAK	0900 PM
16.00	Durand, WI	DUR	1030 AM
17.10	Minneapolis, MN	MIN	0130 AM
16.50	Savage, MN	SAV	1130 PM
16.00	Ridgeland, WI	RGL	1100 AM
15.50	Chanhassen, MN	CHN	0130 AM

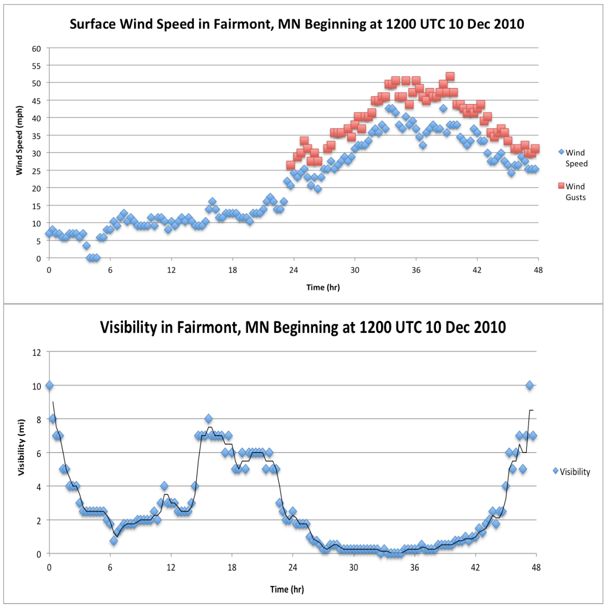

Fig 5. Plots of surface wind speed and visibility for Fairmont, MN at 1200 UTC 10 December 2010.

(see Fig. 3a for locations) at 1200 UTC illustrate the differences in temperature profile for the 1000-850 hPa layer in and ahead of the cold air, respectively (Fig. 4).

The reflectivity begins to develop a comma-head structure that extends south of Nebraska over the next 12 hours (Fig. 2c,d). Maximum reflectivities near 35 dBZ are seen in eastern Minnesota and western Wisconsin where the heaviest snowfall accumulations occur (Fig. 3b, Table 1). Shortly after 0600 UTC 12 Dec this snowfall led to the collapse of the Hubert H. Humphrey Metrodome in Minneapolis, Minnesota. From 0600 UTC to 0800 UTC wind speeds reach blizzard criteria in eastern Minnesota and western Wisconsin. Meanwhile, the surface observations report extreme falling and blowing snow with widespread blizzard conditions to the west of the cyclone where a strong pressure gradient exists. Wind speeds gust above 50 mph throughout a very large area that reduces the visibility to zero. Automated Surface Observing Station data show these conditions lasted in excess of 8 hours in some locations such as Fairmont, Minnesota (Fig. 5) and other locations in southern Minnesota and western Iowa throughout 11 Dec. The cyclone continues tracking eastward and the snow ends by the early morning of 12 Dec (not shown).

3. Experiment design and results

a. Experiment design

Five experiments are conducted using the Weather Research and Forecasting (WRF) model version 3.4. The horizontal grid spacing is 3 km, there are 51 vertical levels and 600 grid points in the *x* and *y* directions. All of the experiments use the Noah land-surface model, Thompson microphysical parameterization, long wave rapid radiative transfer model and the Dudhia shortwave

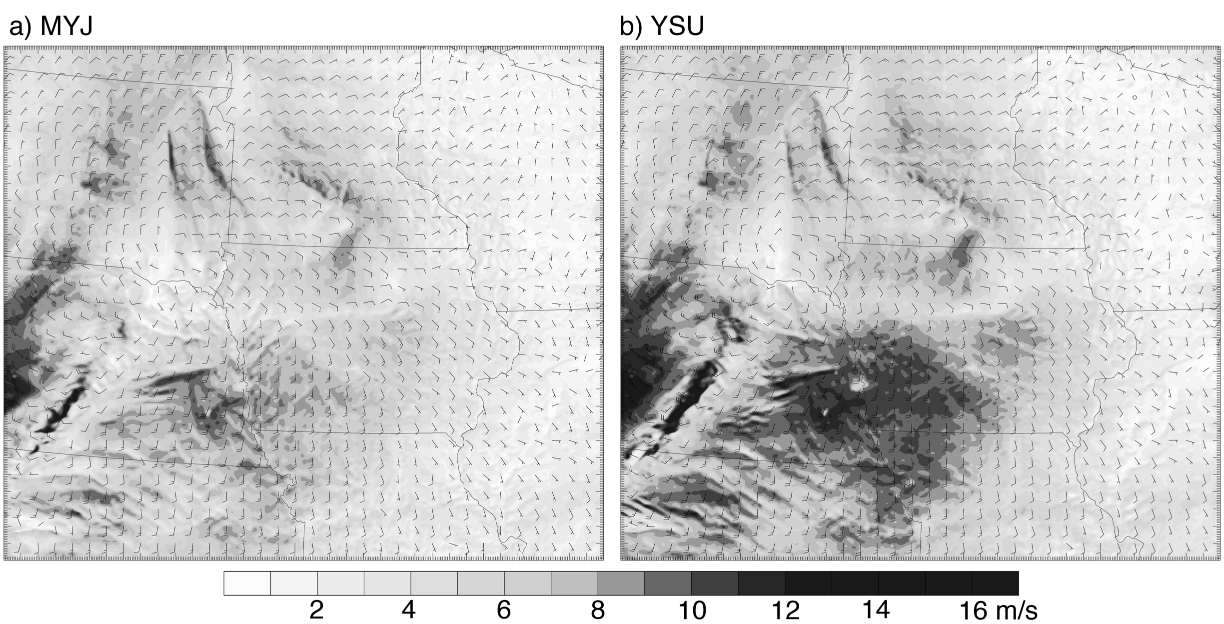

Fig 6. Comparison of 3-hour surface wind forecasts for MYJ and YSU at 0300 UTC 11 December 2010.

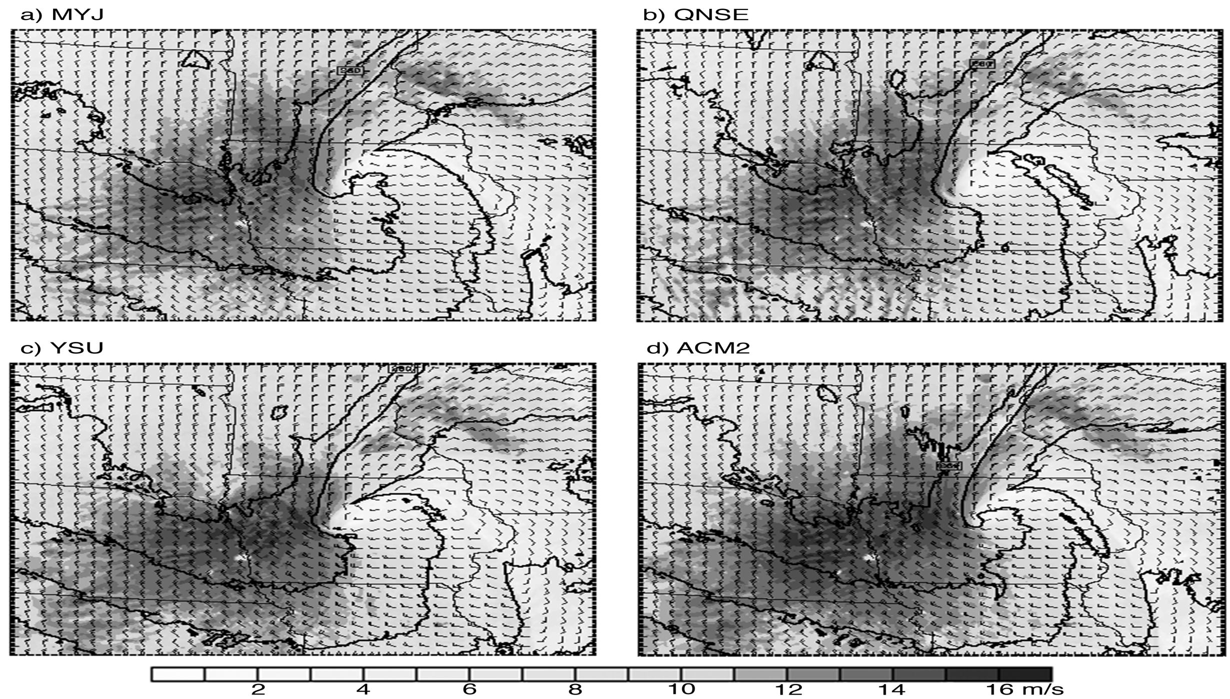

Fig 7. Comparison of 24-hour forecasts of surface wind speed at 0000 UTC 12 December 2010. ACM2 and MYNN are very similar. (MYNN not shown).

radiation parameterization. No convective parameterization scheme is used in this study. The 12-km North American Mesoscale (NAM) model analysis provides the initial and the boundary conditions, which are updated every three hours from the NAM model forecast. All experiments are initialized at 0000 UTC 11 Dec 2010 and integrated for 24 h.

Five different PBL parameterization schemes are analyzed and tested. These are the Yonsei University (YSU; Hong et al. 2006), Mellor-Yamada-Janjic (MYJ; Janjic 2002), Eddy Diffusivity Mass Flux, Quasi-Normal Scale Elimination (QNSE; Sukoriansky et al. 2006), Mellor-Yamada-Nakanishi-Niino (MYNN; Nakanishi and Niino 2004), and the asymmetric convective model scheme, version 2 (ACM2; Pleim 2007) schemes.

b. Surface wind speeds

The forecast surface wind speeds for 0300 UTC show considerable differences in the YSU compared to the other PBL schemes (Fig. 6). The YSU forecast shows a large area of 8-10 m s^{-1} wind speeds in eastern Nebraska and western Iowa, while the MYJ and the other three PBL schemes forecast a much smaller area of weaker (5-6 m s^{-1}) wind speeds. This trend in the YSU is observed for the first 6 hours of the model forecast and then converges back toward the results of the other four PBL schemes.

The 24-hour forecast of the surface wind speeds at 0000 UTC 12 Dec exhibits significant variance in the different PBL schemes (Fig. 7). In this study the threshold used to indicate blizzard conditions is 15 m s^{-1} because this value is commonly used by the National Weather Service (North 1996, p. 855). The MYJ shows the weakest observed wind speeds around 13-14 m s^{-1} over a small region (Fig. 7a). Consequently, the MYJ does not forecast any blizzard conditions in western Iowa. The QNSE and YSU exhibit very limited areas that fulfill the threshold for a blizzard (Fig. 7b,c). The YSU also fails to accurately forecast the blizzard conditions in southern Minnesota and northern Iowa by showing weaker wind speeds in this region. The YSU is the only PBL scheme to show this characteristic. The MYNN and ACM2 produce the strongest forecast wind speeds with a very large area of 15-17 m s^{-1} wind speeds in western Iowa and eastern Nebraska (Fig. 7d). Compared to the actual surface wind speeds at 0000 UTC 12 Dec the MYNN and ACM2 most accurately forecast the magnitude of the wind speeds and the large area

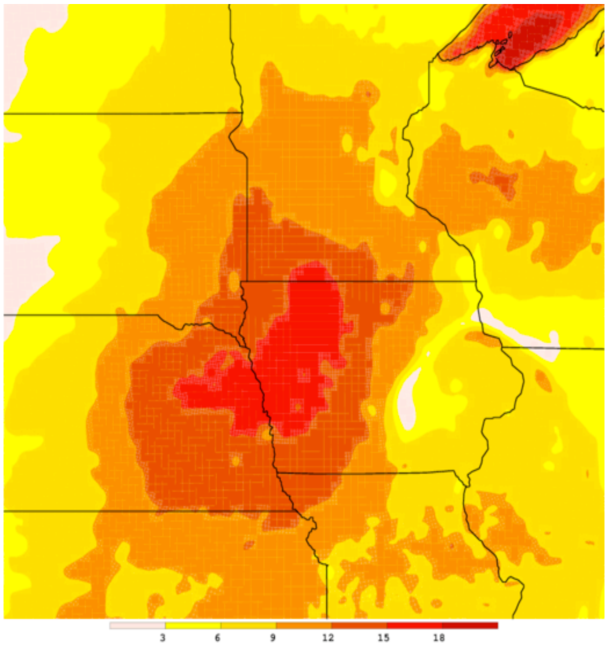

Fig 8. Observed surface wind speed (m/s) at 0000 UTC 12 December 2010.

in western Iowa where these conditions are observed (Fig. 8).

Comparisons of the model surface wind speeds to the observed surface wind speed at stations in southern Minnesota, western Iowa, and eastern Nebraska (Fig. 3a) show the models underestimated the wind speed in Marshall, MN (KMML) throughout the entire 24-hour period from 0000 UTC 11 Dec to 0000 UTC 12 Dec (Fig. 9). Significant model errors of approximately 15-20 mph are found between hours 6 and 12. The YSU also exhibits the lowest overall model wind speeds from hour 12 to hour 24. This demonstrates how the YSU further under-predicted the blizzard conditions in southern Minnesota as previously noted.

The models are far more skillful at forecasting surface wind speeds for Cherokee, IA (KCKP) as the strongest blizzard conditions are being observed (Fig. 10). After the low-pressure center moves over the area at hour 6, the model under-predict the wind speed. However, as the wind speed increases the model forecast wind speed also increases. At hour 18 the models begin to overestimate the wind speed for the next 6 hours as the observed wind speeds decrease.

The model runs underestimate the surface wind speed considerably at Omaha, NE (KOAX) throughout the entire day (Fig. 11). The YSU

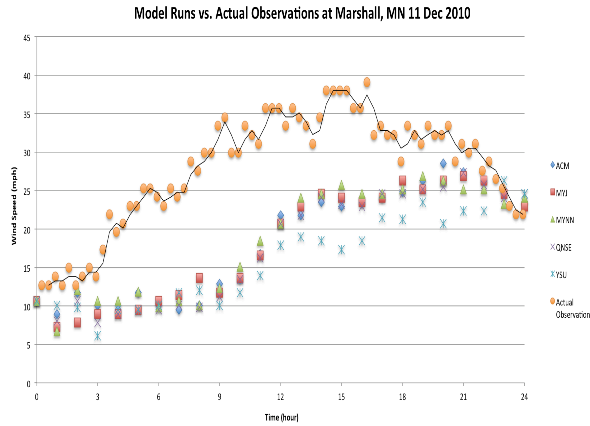

Fig 9. Comparison of model runs and observations at Marshall, MN 11-12 December 2010.

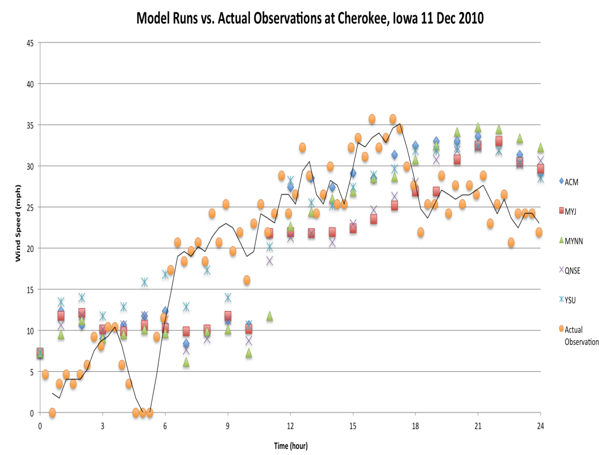

Fig 10. Comparison of model runs and observations at Cherokee, IA 11-12 December 2010.

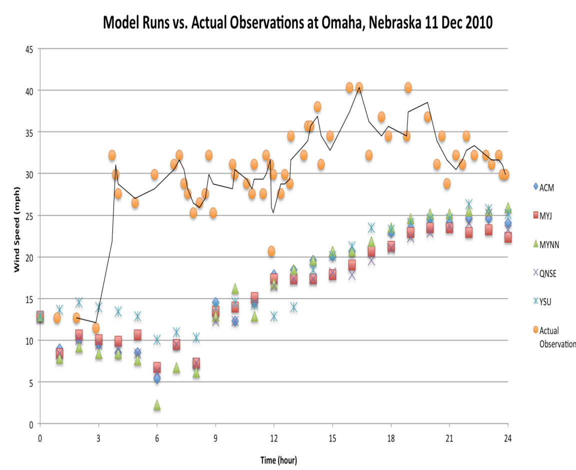

Fig 11. Comparison of model runs and observations at Omaha, NE 11-12 December 2010.

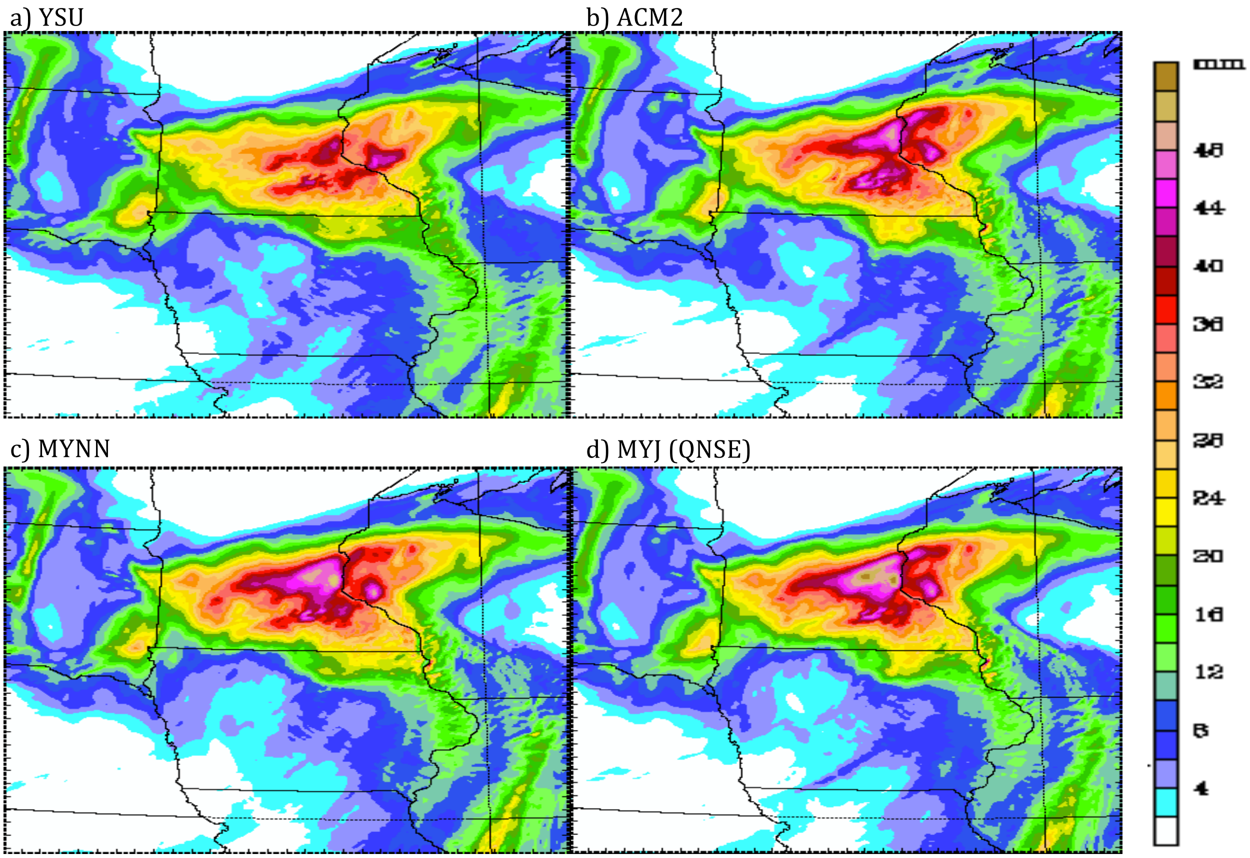

Fig 12. Comparison of 24-hour forecasts of liquid precipitation at 0000 UTC 12 December 2010.

exhibits stronger wind speeds in the first 6 hours, as previously discussed. The model spread begins to decrease as the model wind speeds increase from hour 12 to hour 21. Despite this increase in model wind speed, the model errors still range from 15-20 mph at the peak of the observed wind speeds.

c. Forecast precipitation

The 24-hour forecast of the accumulated liquid equivalent precipitation shows very few differences in the regions of observed blizzard conditions (Fig. 12). Throughout western Iowa and southern Minnesota light to moderate liquid precipitation is forecast with little variation amongst the PBL schemes. The only noticeable differences are the location and amount of the maximum. The YSU has the least with 40-44 mm (Fig. 12a), while the ACM2 and MYNN have 48 mm (Fig. 12b,c). The MYJ and QNSE exhibit the largest maxima in eastern Minnesota at 55 mm (Fig. 12d, Fig. 13a). A comparison of the Stage IV analyses (Lin and Mitchell 2005) to the QNSE indicate that the maximum liquid precipitation center is offset to the southeast of the model forecast (Fig. 13b). However, the MYJ and QNSE schemes accurately forecast the amount of the maximum liquid precipitation at 55 mm.

d. Forecast visibility

The 24-hour forecast of the model visibility for 0000 UTC 12 Dec shows very minor differences across all five PBL schemes (Fig. 14). The visibility across southeastern Minnesota is less than a mile throughout all the model runs and the visibility remains consistent across Iowa from scheme to scheme. This is a consequence of the model visibility algorithm relying solely on the hydrometeor mixing ratio. Consequently, the surface wind speed has no effect on the model visibility calculation. Because the PBL had little effect on the forecast liquid precipitation, there were insignificant changes in the model visibility from scheme to scheme. The YSU exhibits subtle

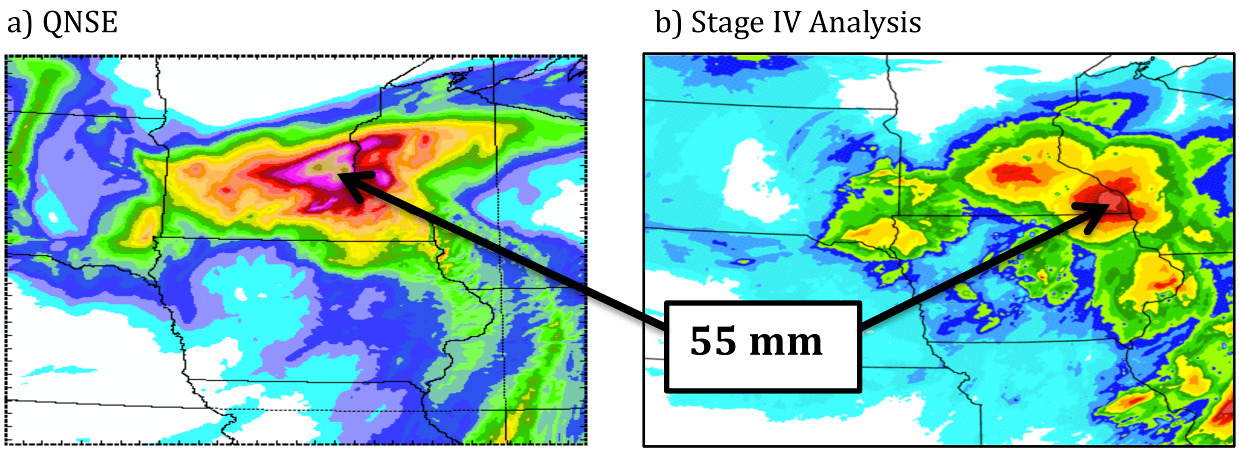

Fig 13. Comparison of model and observed liquid precipitation for 11-12 December 2010.

increases in visibility in southern Minnesota compared to other model runs (Fig. 14a). This is possibly due to the YSU predicting less liquid precipitation in this region than the other schemes. The ACM2, MYJ, MYNN, and QNSE all demonstrate similar visibility forecasts (Fig. 14b,c,d).

Graphical analysis of the model visibility at Fort Dodge, Iowa (KFOD) was done to compare the observed visibility with the model visibility while there were existing blizzard conditions (Fig. 15). The observed visibility begins to decrease shortly after hour 6 and blizzard conditions are observed at hour 16. However, the models show mainly clear conditions and 10 mi visibilities for the first 18 hours. The model visibilities only decrease for the last 6 hours and do not accurately indicate the observed visibility conditions.

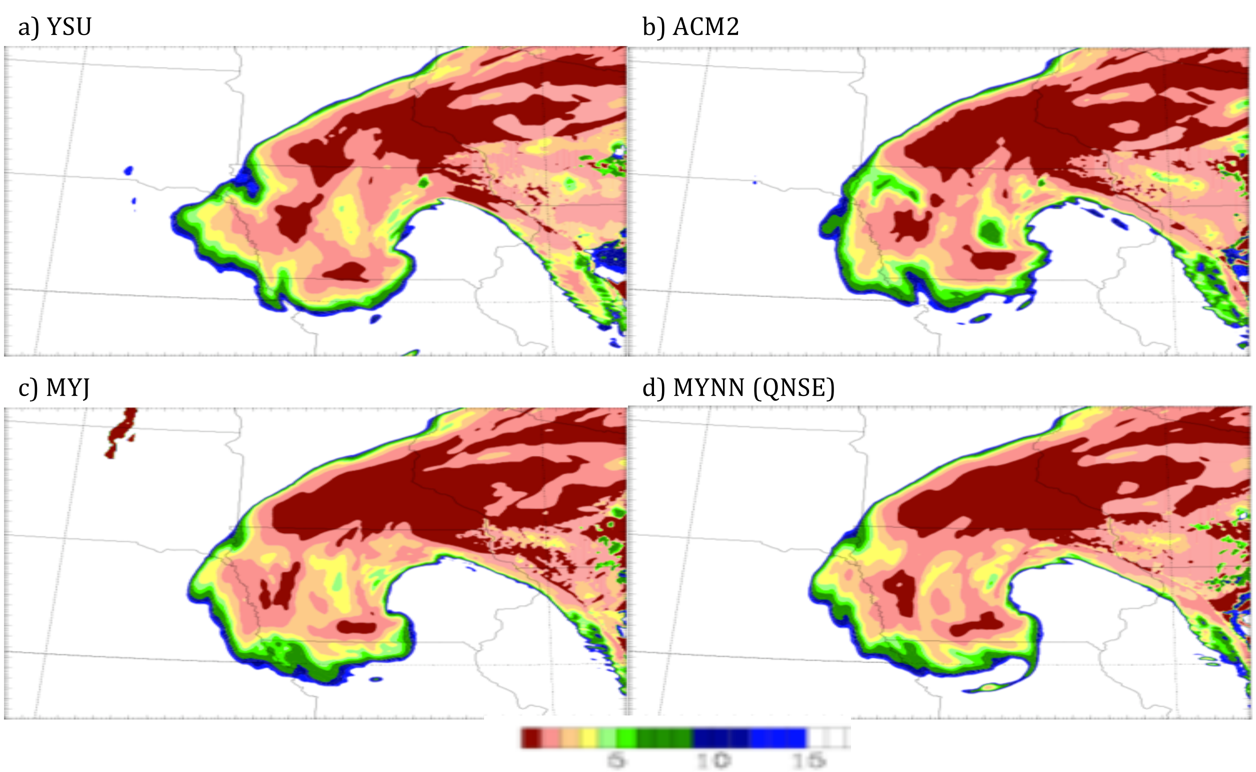

Fig 14. Comparison of 24-hour forecasts of visibility at 0000 UTC 12 December 2010. (QNSE not shown).

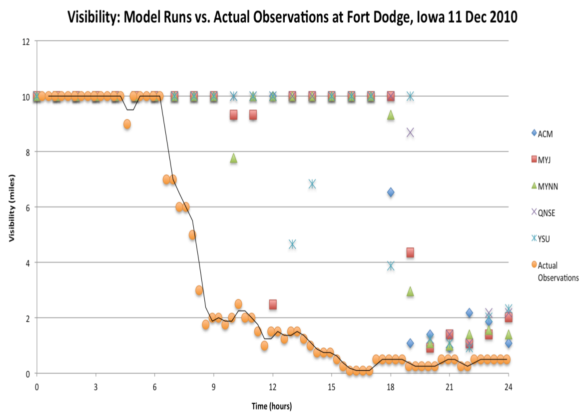

Fig 15. Comparison of the model visibility and observed visibility at Fort Dodge, IA 11-12 December 2010.

4. Conclusion

Five experiments were conducted using the WRF for a winter storm that occurred on 11-12 December 2010 in the upper Midwest to investigate how changing the PBL parameterization schemes will affect the forecast for blizzard conditions. The YSU scheme exhibited stronger wind speeds in eastern Nebraska and western Iowa in the first 3-6 hours of the forecast period while the other four schemes did not demonstrate this characteristic. The 24-hour surface wind speeds forecast for 0000 UTC 12 Dec was used to compare the five PBL schemes during a period of heavily observed blizzard conditions in western Iowa and southern Minnesota. The forecast shows the MYJ had the weakest wind speeds and the smallest area of maximum winds. The QNSE and YSU show very limited areas that exceeded the blizzard threshold of 15 m s^{-1} in western Iowa. The MYNN and ACM2 produce the strongest wind speeds of approximately 15-17 m s^{-1} over a very large area in western Iowa and extreme southern Minnesota. Comparing these forecasts to the actual surface wind speeds for 0000 UTC 12 Dec show that the MYNN and ACM2 were accurate in establishing a large area of forecast blizzard conditions.

The precipitation and visibility were compared using 24-hour forecasts of the liquid precipitation accumulation and the 24-hour model visibility. There were very little differences between the liquid precipitation forecasts throughout the areas with observed blizzard conditions. The YSU exhibited the least amount of maximum liquid precipitation between 40-44 mm, the ACM2 and MYNN exhibited around 48 mm, while the MYJ and QNSE exhibited the most liquid precipitation with around 55 mm. Other differences in the liquid precipitation forecasts were minimal. Likewise, the model visibility forecasts demonstrate insignificant differences between all five PBL schemes. This is likely due to the algorithm for the model visibility being completely dependent on the hydrometeor mixing ratio and independent of the surface wind speed.

To create more reliable results, future work must be done experimenting with multiple winter storm cases. Additionally, varying the initialization period of the model before the blizzard occurs can also help to produce more decisive results with respect to the PBL parameterization schemes.

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