8A.1 WSI REALTIME WINTER PRECIPITATION FORECASTING USING WRF

Peter J. Sousounis* and Todd A. Hutchinson
Weather Services International Corporation
Andover, MA

1. INTRODUCTION

Despite increases in NWP model resolution and improvements in model physics parameterizations, the accuracy of forecasts for some parameters directly output by NWP models continues to benefit from post-processing. Two good examples are precipitation type and snowfall accumulation.

At WSI Corporation, version 2.0.3 of the Weather Research and Forecast (WRF) model is used to generate 51 hr real-time forecasts every three hours for the continental US (CONUS). The model is run at 12 km horizontal grid separation distance (GSD) and 35 vertical levels. More information on the WRF model can be found in Michalakes et al. (2001) and Skamarock et al. (2001). More information on the real-time modeling activities at WSI can be found in a companion preprint by Hutchinson et al. (2005).

Winter precipitation type and snowfall accumulation are part of the WRF realtime output at WSI. The winter weather forecasts come from a suite of algorithms. The suite consists of two existing precipitation type algorithms plus two snow density algorithms - providing a total of four snowfall algorithms. Very recently, forecasts of (winter) precipitation type and snowfall amounts from this past winter (2004-2005) were evaluated internally – both subjectively and objectively. Performance of the algorithms was evaluated by comparison with observations, direct model output from the WRF, and with 40km model output from the Eta and one-degree model output from the Global Forecast System (GFS) available from the National Centers for Environmental Prediction (NCEP).

*Corresponding Author Address: Dr. Peter J. Sousounis, WSI Corporation, 400 Minuteman Road, Andover, MA 01810. Email: psousounis@wsi.com.

2. WINTER PRECIPITATION ALGORITHMS

The precipitation type and snow density algorithms are described in some detail below. The summaries for the precipitation type algorithms are from Cortinas and Baldwin (1999).

2.1. BTC Algorithm

The algorithm developed by Baldwin et al. (1994), hereafter referred to as the BTC algorithm, diagnoses a single precipitation type (e.g., rain, snow, freezing rain, ice pellets) from an observed thermodynamic vertical profile. It is also the algorithm used in the ETA and GFS models. The basic procedure used by the algorithm is to examine the vertical thermal structure that a falling hydrometeor encounters as it descends to the ground to determine the potential for freezing or melting. It identifies warm (> 0°C) and cold (< or = 0°C) layers above a particular location by computing the area between 0°C and the wet-bulb temperature, *Tw*. The area is computed separately for warm and cold layers and is used, along with the surface temperature, *To*, to determine precipitation type.

The algorithm begins by determining whether precipitation initially begins as supercooled water or ice. The precipitation generation level is assumed to exist at the highest saturated layer ($T — Td < 6°C$). Next, it computes the area between -4°C and *Tw* up to 500 hPa, and the area between 0°C and *Tw* of the surface-based warm or cold layer.

Snow occurs if the lowest temperature at any level below 500 hPa is < or = -4°C, and the area of the sounding between -4°C and *Tw* is not large (< 3000 deg. m.).

Freezing rain occurs if the lowest temperature in a saturated layer is > -4°C and *To* is < 0°C. Freezing rain also occurs if the net area, with respect to 0°C, of the surface-based layer is > -3000 deg. m, and the area between -4°C and *Tw* is > 3000 deg. m, and *To* is < or = 0°C.

Ice pellets occur if the lowest *Tw* in a saturated layer is < or = -4°C, and the area between -4°C and *Tw* is > 3000 deg. m, and the surface-based cold layer is < or = -3000 deg. m. Ice pellets also occur if the net area between 0°C and *Tw* within the lowest 150 hPa is < or = -3000 deg. m and the surface-based warm layer is < 50 deg. m.

Rain occurs if the lowest *Tw* in a saturated layer is > -4°C and *To* is > 0°C. Rain also occurs if *To* > 0°C and the area between -4°C and *Tw* is > 3000 deg. m, and the net area between 0°C and *Tw* within the lowest 150 hPa is > -3000 deg. m, or the surface-based warm layer is > 50 deg. m.

2.2. Bourgouin Algorithm

The algorithm developed by Bourgouin (1994) is similar to the BTC algorithm and determines whether enough energy is available in the environment to melt or freeze hydrometeors. It computes the areas bounded by 0°C and the observed temperature > 0°C (melting energy) and the observed temperature < 0°C (freezing energy) on a standard tephigram. The Bourgouin algorithm determines precipitation type by examining the magnitude of the melting and freezing energies: Snow occurs when the melting energy of a surface-based layer is < 5.6 J kg^{-1} or the melting energy available in a mid-level warm layer (a warm layer above a surface-based cold layer) is < 2 J kg^{-1} when no surface-based warm layer is present. If the surface-based melting energy is between 5.6 and 13.2 J kg^{-1}, then frozen and melted precipitation are equally likely, and either snow or rain is chosen at random. Rain will also occur if the elevated layer of melting energy is < 2 J kg^{-1} and the surface-based melting energy is > 13.2 J kg^{-1}.

If snow is not diagnosed, then the algorithm diagnoses freezing rain if the freezing energy < 46 + 0.66 X melting energy. Although not suggested by Bourgouin (1994), it is also required that *To* < 0°C. Otherwise, if *To* > or = 0, then rain is diagnosed. Ice pellets occur when the freezing energy > 66 + 0.66 X melting energy and the surface-based melting energy is < or = 5.6 J kg^{-1}. As in the snow diagnosis, if the surface-based melting energy is between 5.6 and 13.2 J kg^{-1}, both types are equally likely, so once again either ice pellets or rain are chosen at random. Additionally, for any freezing energy between 46 + 0.66 X melting energy and 66 + .66 X melting energy, there is an equally probable chance of freezing rain or ice pellets. In these cases, once again, one of the two types is chosen at random, subject to the proper *To* or surface-based melting energy test described previously. The various constants used in the Bourgouin algorithm were empirically chosen by Bourgouin (1994) after examining cases during the 1989-1990 and 1990-1991 cold seasons.

2.3. NWS Algorithm

The NWS snow density algorithm is so-called because it is a modified version of a simple relationship used by the National Weather Service. This relationship is more or less widely known and is probably the next most frequent order of correction to the 10:1 rule. Thus, on one hand it may not even be recognized as an algorithm. But on the other hand because it is not part of direct model output and is based on empirical observational evidence it is used here as an algorithm. Also, because it is a highly popular way to recover snowfall amounts from liquid water equivalent values, it is used to compute snowfall amounts from the GFS and ETA models as bases for comparison. It is also applied within the WRF model in this study (Algorithm 6).

The version used at WSI is a 3rd-order polynomial:

$$\rho_s = aT^3 + bT^2 + cT + d;$$

where ρ_s is snow density and T is the two-meter temperature in degrees Fahrenheit and a, b, c, and d are specified coefficients.

2.4. Dube Algorithm

The formulation and implementation of this snow density algorithm was based on a study by Dube (2003). The algorithm generates 25 main diagnoses which correspond to a "mean" or "suggested" value for the snow/water ratio, associated with 6 snow categories: very heavy snow (R= 4:1), heavy snow (R= 7:1), ordinary snow (R= 10:1), light snow (R= 15:1), very light snow (R= 20:1), and ultra light snow (R= 25:1). A 26th main diagnosis is added to cover cases of snow completely melting in the atmosphere, therefore not generating any snow accumulation (R=0).

The heart of this algorithm is determining the crystallization temperature, which involves locating the level where maximum ascent is occurring in high relative humidity air. Depending on the temperature at which crystallization is occurring, mixed crystals, needles, spatial dendrites, mixed crystals with stellar nucleus, stars (or stellar crystals) are determined to be the predominant crystal type. Each crystal type has a characteristic density associated with it. Lowest snow density occurs when primary and secondary crystallization temperatures are between –12 and –18 °C, which corresponds to the formation of stellar crystals. These intricately shaped structures yield snow:water ratios on the order of 25:1.

High ambient relative humidities can decrease high ratios in this algorithm via ice accretion. Additionally, in windy conditions, high fragmentation rates can further decrease high ratios by breaking up the very fragile crystal structures.

2.5. Implementation

Hourly WRF-forecasted snowfall amounts are calculated at each horizontal grid point for each hour by first determining which precipitation type is possible using one of the precipitation type algorithms. Then the snowfall algorithm determines whether precipitation actually fell at all in the preceding hour. If it did fall, and if it fell in the form of snow (precipitation type category 4), then the density of that snow is determined by using the forecast information valid at each horizontal grid point for the hour of interest as input to one of the snow density algorithms. The calculated snow density is then multiplied by the WRF-forecasted liquid equivalent amount of precipitation to complete the hourly snowfall forecast calculation.

The two precipitation type algorithms and two snow density algorithms combined to form a total of four snowfall algorithms that were evaluated. Two additional snowfall algorithms were also evaluated with respect to the WRF model. One came simply from taking the average of the four snowfall algorithms (Algorithm 5). The other came from applying the NWS algorithm directly to the hourly liquid equivalent *winter* precipitation amount that is output by the WRF model (Algorithm 6).

3. SNOWFALL VERIFICATION

Standard verification techniques of equitable threat score (ETS) and BIAS were used to evaluate model performance for snowfall forecasts. The ETS and BIAS scores are defined respectively as:

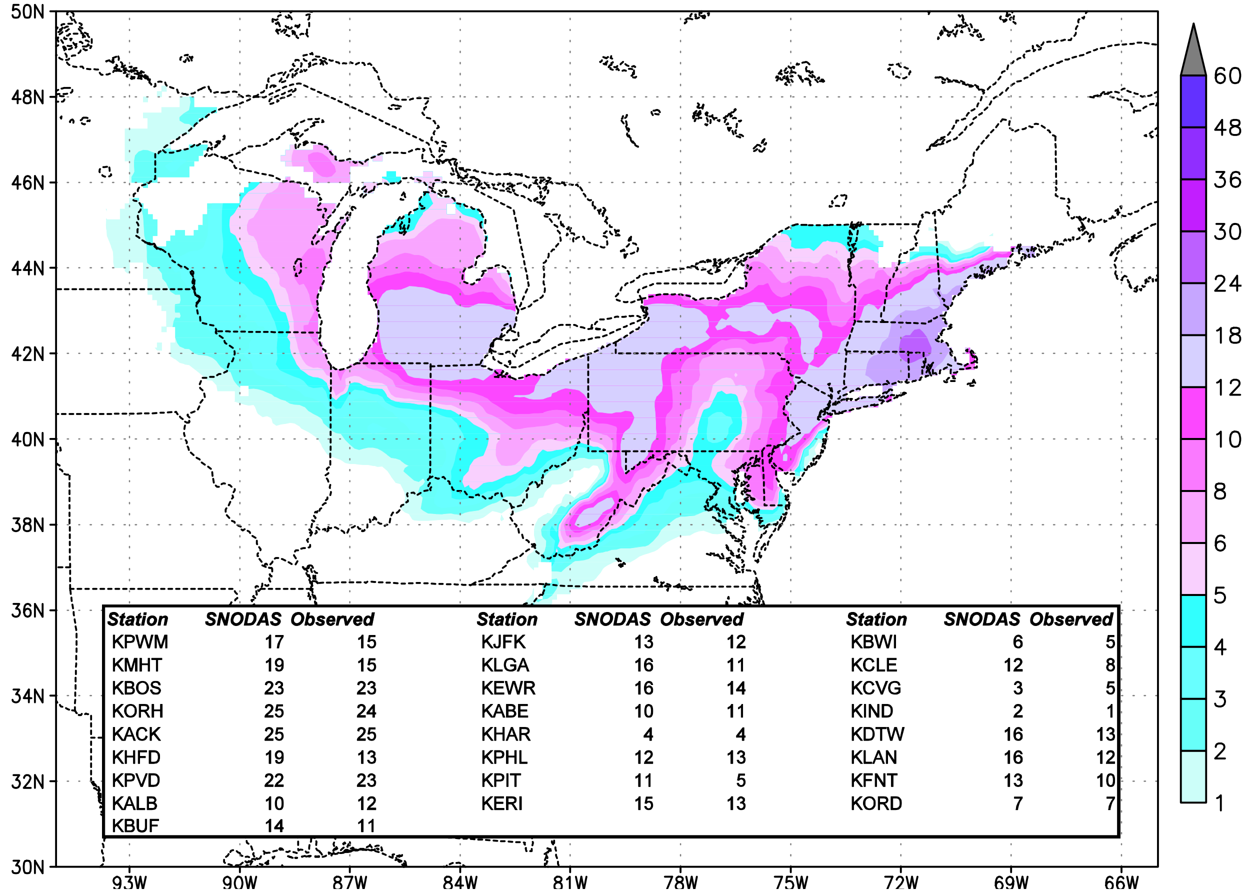
$$ETS = (a-e)/(a+b+c-e) ,$$

$$BIAS = (a + b)/(a + c) ,$$

where,

a = the number of grid points where the phenomenon was forecasted and observed,
b = the number of grid points where the phenomenon was forecast but not observed,
c = the number of grid points where the phenomenon was observed but not forecast,
d = the number of grid points where the phenomenon was not observed and not forecast,
e = the number of grid points with a correct forecast that would be expected from random chance.

Additional standard metrics of Threat Score, Probability of Detection, and False Alarm Ratio, were used to evaluate the precipitation type forecasts.



Station	SNODAS	Observed	Station	SNODAS	Observed	Station	SNODAS	Observed
KPWM	17	15	KJFK	13	12	KBWI	6	5
KMHT	19	15	KLGA	16	11	KCLE	12	8
KBOS	23	23	KEWR	16	14	KCVG	3	5
KORH	25	24	KABE	10	11	KIND	2	1
KACK	25	25	KHAR	4	4	KDTW	16	13
KHFD	19	13	KPHL	12	13	KLAN	16	12
KPVD	22	23	KPIT	11	5	KFNT	13	10
KALB	10	12	KERI	15	13	KORD	7	7
KBUF	14	11						

***FIG. 1**. Snowfall totals for 2005 Blizzard (Jan 22-24). Contours show SNODAS derived totals (inches) for the period 06 UTC 22 Jan 22 to 06 UTC Jan 24. Inset box lists observed (OBS) versus SNODAS (SND) totals in inches for selected sites.*

More information on the metrics used may be found in Wilks (1995) and in Colle et al. (2000).

For snowfall verification, the ETS calculation was based on 24 hour amounts of actual gridded snowfall that were generated using National Operational Hydrologic Remote Sensing Center Snow Data Assimilation System (SNODAS) 24 hr accumulated liquid equivalent snowfall (LES) output available from the National Snow and Ice Data Center (NSIDC) (Barrett 2003). The 24 hr SNODAS values were converted to snowfall amounts using 6 hourly accumulated Stage 4 precipitation amounts and RUC-analyzed mean surface temperatures to determine the fraction of 24 hour LES that fell in any 6 hour period. The fraction was then multiplied by the snow density relationship (e.g., NWS algorithm).

Although the SNODAS and Stage 4 data are both available at very high spatial resolution, the resulting snowfall amounts were regridded to a 0.125 degree resolution. The forecasted snowfall amounts from the WRF, ETA, and GFS models were also regridded to the same resolution.

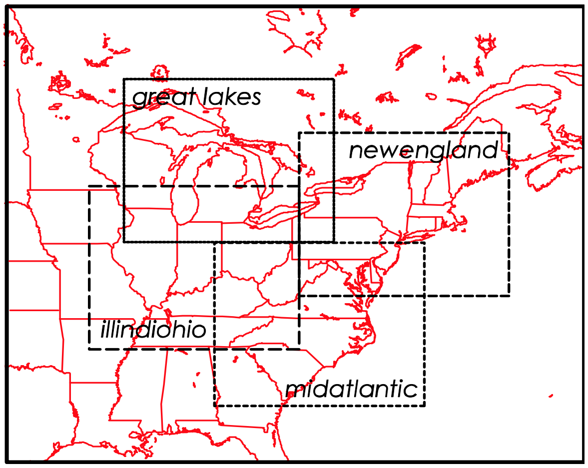


FIG. 2. Regions where snowfall verification scores were computed for the current study.

While this strategy for deriving 24 hr snowfall may seem unsatisfying from a pure observational perspective, it did yield reconstructed values that were within about 10-15% of snowfall amounts as measured by human observers and snowspotters. Figure 1 shows an example of reconstructed snowfall values over a grid as well as reconstructed versus observed ones for the Blizzard of January 2005 at select locations. The real utility of the reconstruction technique is that it provides a gridded 24 hr snowfall dataset that is more appropriate for verifying model forecasts over entire domains rather than just at select stations. Additionally, there is the potential to generate snowfall accumulation grids at shorter intervals (e.g., 6 hours).

For precipitation type verification, the ETS calculation was applied for each one of four different precipitation types: snow, ice pellets (sleet), freezing rain, and rain at selected METARS stations at selected hours. The regions where ETS values were computed and from which METARS stations were selected are shown in Fig. 2.

Equitable Threat Scores for 06-30 hr accumulated snowfall forecasts from the six different WRF snowfall algorithms were computed for the regions shown in Fig. 2. Results from two of the regions are shown in Fig. 3 for different thresholds. The WRF1 algorithm uses the BTC and Dube algorithms. The WRF2 algorithm uses the BTC and NWS algorithms. The WRF3 algorithm uses the Bourgouin and Dube algorithms. The WRF4 algorithm uses the Bourgouin and NWS algorithms. The threshold categories correspond to 01 inch (Cat 1), 04 inch (Cat 2), 09 inch (Cat 3), and 15 inch (Cat 4). The

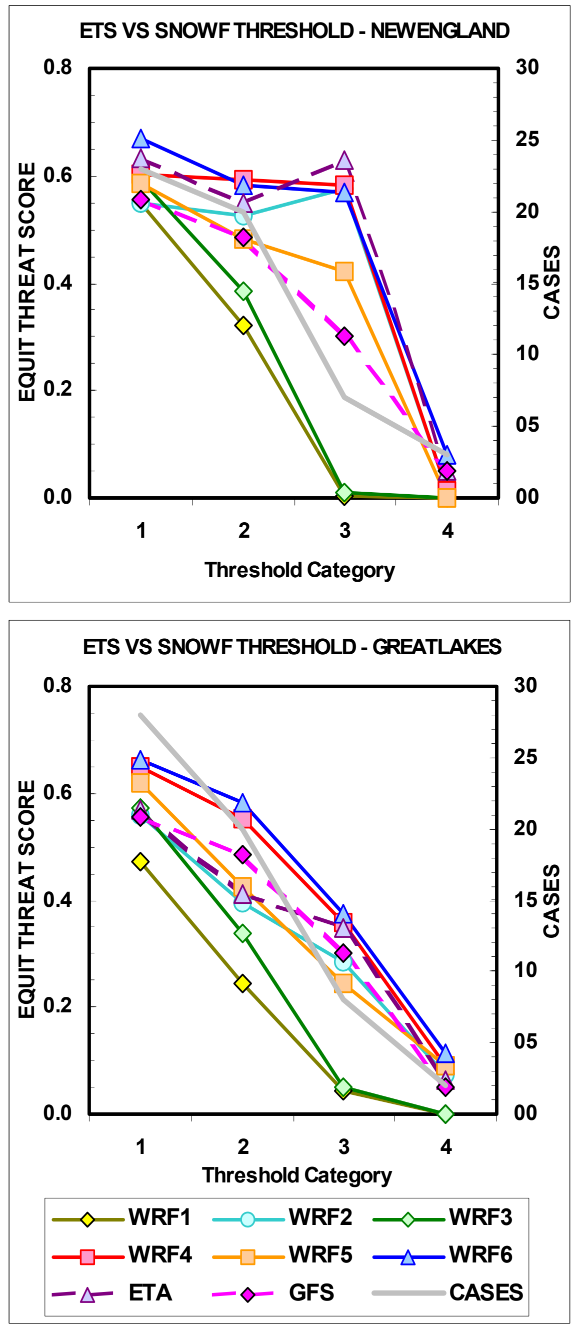


FIG. 3. Equitable Threat Scores for 06-30 hr accum snowfall forecasts at selected thresholds for the New England and Great Lakes regions shown in Fig. 2.

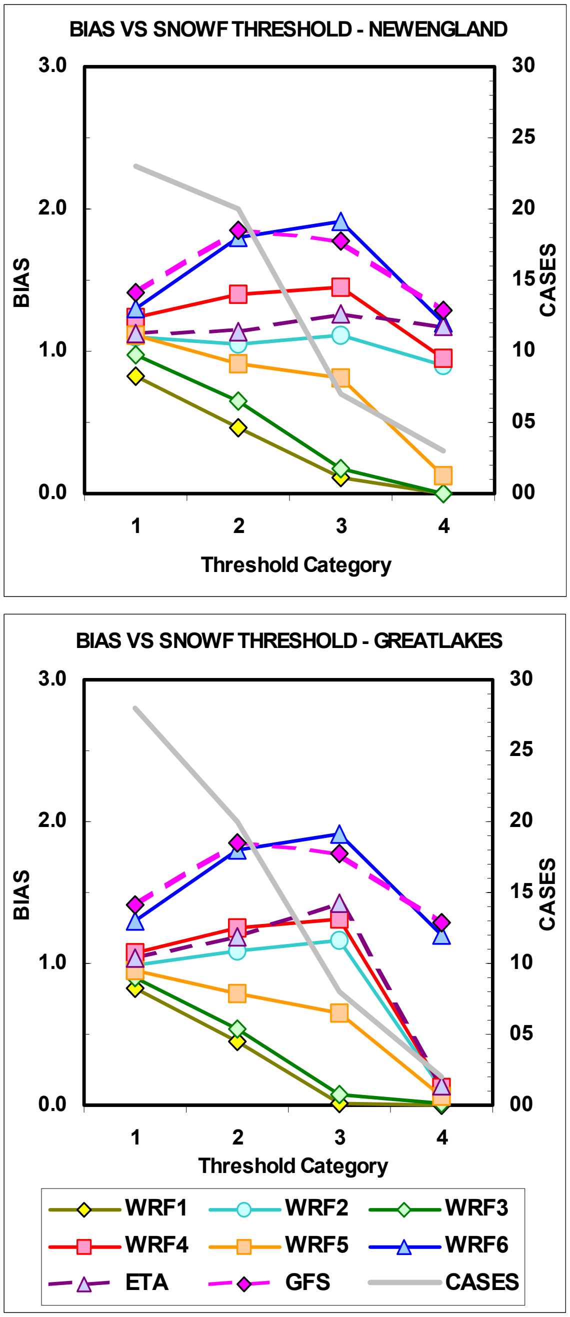


***FIG. 4**. Bias Scores for 06-30 hr accum snowfall forecasts at selected thresholds for the New England and Great Lakes regions shown in Fig. 2. Biases at Category 4 are actually 10X the values shown.*

ETS results show a rapid drop in skill by all the algorithms with increasing threshold for both the New England and the Great Lakes regions. The number of cases analyzed for each threshold also decreases rapidly and it is likely that the results may not even be statistically significant at category 4 (15 inches). Other noteworthy aspects of the results include good skill from the WRF4 and WRF6 algorithms. In contrast, the WRF1 and WRF3 algorithms did not do very well. Recall these use the Dube snow density algorithm. One hypothesis regarding the poor performance of these algorithms is that the wind fragmentation term as currently specified may be too intense. The BIAS scores shown in Fig. 4 support this hypothesis. Specifically, the scores for all the WRF algorithms are comparable at category 1. But, the scores for the WRF1 and WRF3 algorithms are significantly less than unity for categories 2-4. Further analyses, additional verification, and subsequent adjustments to the Dube algorithm will likely improve performance of the WRF1 and WRF3 algorithms.

Winter precipitation forecasts were verified using METARS from selected sites from the same set of forecasts available during the period Dec 2004-Jan 2005. Forecast hours from 03 to 24 hr at 3 hour intervals were verified. A total of 27 different sites were used, which resulted in over 6000 hourly observations being used for verification. Some form of precipitation was indicated in roughly 25% of the reports. Snow accounted for nearly 52% (868 reports) of the reported precipitation, rain accounted for nearly 42% (702 reports), freezing rain accounted for less than 6% (71 reports), and sleet (ice pellets) accounted for less than 2% (24 reports). For verification purposes, the observed weather type was always taken to be the first one reported in the METAR. More than 97% of the time when precipitation was reported, there was only one type reported anyway so there was no ambiguity in using the single-precipitation type method.

Figure 5 shows the equitable threat scores from the two WRF algorithms and from the GFS and ETA models. The BTC algorithm corresponds to WRFA and the Bourgouin algorithm corresponds to WRFB. Scores for snow, freezing rain, and rain are shown. Sleet was not included in the scores shown in Fig. 5 because there were so few. The results in Fig. 5 indicate that for snow, the WRFA algorithm performed better than the WRFB algorithm and statistically as well as the ETA algorithm. For rain, the WRFA algorithm still performed better than the WRFB algorithm, but not as well as the ETA

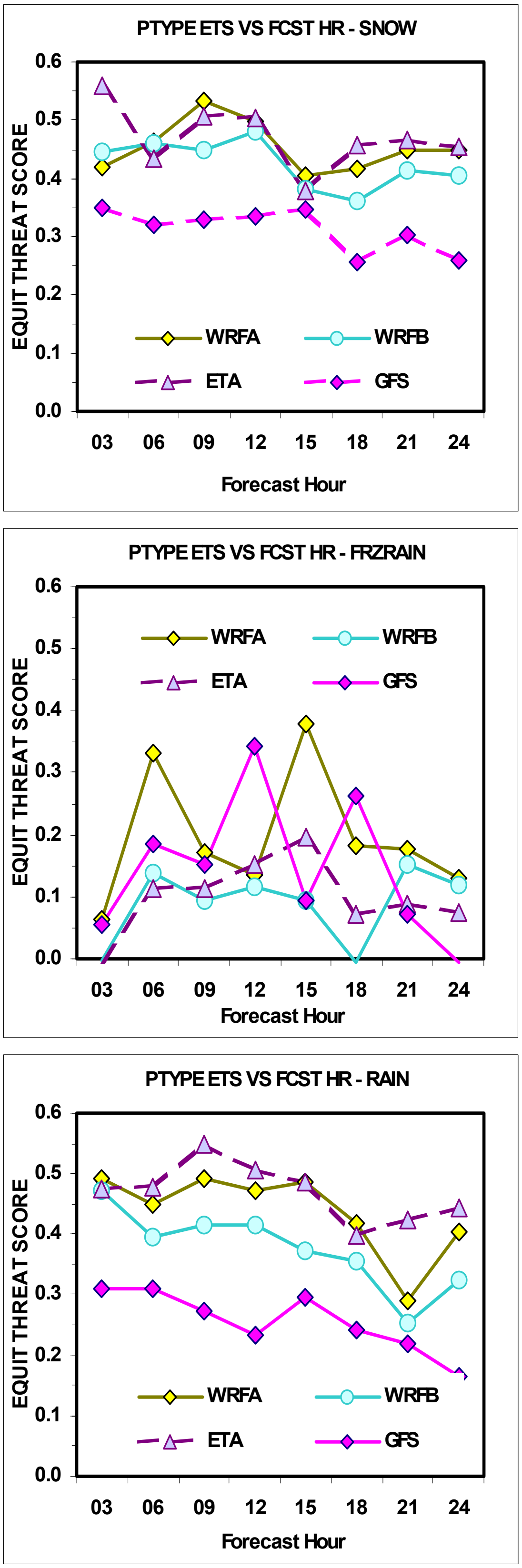


***FIG. 5**. Equitable Threat Scores from model algorithms for several different winter precipitation types as a function of forecast hour*

algorithm. The GFS algorithm performed most poorly. For freezing rain, the WRFA algorithm likely performed the best, although the paucity of freezing rain reports makes it difficult to draw a hard conclusion. An interesting difference between the GFS precipitation type forecasts and all the others (but not shown) is that most of the erroneous snow forecasts from the GFS came in the form of false alarms, while in the ETA and WRF they came in the form of no forecasted precipitation.

Table 1 shows a summary of additional metrics for the precipitation type forecasts. The summary includes all forecasts from all hours (at 3 hour intervals). The ETA and WRFA algorithms perform with comparable skill for snow and rain forecasts – although the ETA shows a slight but statistically significant edge in rain forecasts. For freezing rain, the WRFA algorithm shows a slight edge over the ETA. For ice pellets, the results suggest that the WRFB algorithm may have a slight edge over the WRFA algorithm. The GFS in general seems to forecast too much of all types of precipitation.

4. CLOSING REMARKS

WSI Corporation has made an initial attempt to improve the winter weather forecasting capabilities of the WRF model. Results were evaluated over a portion of the 2004-2005 winter. Specifically, existing algorithms were implemented to forecast precipitation type and snow density. Performance of these algorithms was evaluated with respect to comparable forecasts from the ETA and GFS models. Some of the algorithms or combinations of algorithms show skill equal to or greater than that provided by the ETA model. The GFS model exhibited significantly less skill, despite the fact that the precipitation type algorithm was the same as in the ETA model.

The WRF-based results are encouraging. Specifically, there exists now a foundation at WSI from which the skill of the winter weather algorithms, as they are currently defined, may be improved. Further evaluation and modifications will likely occur after the 2005-2006 winter season.

snow	***GFS***	***ETA***	***WRFA***	***WRFB***
THS	0.3921	0.5161	0.5040	0.4802
POD	0.8888	0.6636	0.6498	0.7001
FAR	0.5876	0.3010	0.3080	0.3954
BIAS	2.1553	0.9493	0.9389	1.1580

icepel	***GFS***	***ETA***	***WRFA***	***WRFB***
THS	0.0111	0.0388	0.0146	0.0222
POD	0.0417	0.1667	0.0833	0.0417
FAR	0.9851	0.9518	0.9826	0.9545
BIAS	2.7917	3.4583	4.7917	0.9167

frzrain	***GFS***	***ETA***	***WRFA***	***WRFB***
THS	0.1517	0.1157	0.1880	0.0938
POD	0.3099	0.1972	0.3099	0.2113
FAR	0.7708	0.7813	0.6765	0.8558
BIAS	1.3521	0.9014	0.9577	1.4648

rain	***GFS***	***ETA***	***WRFA***	***WRFB***
THS	0.3262	0.5167	0.4850	0.4213
POD	0.8675	0.7507	0.6923	0.5641
FAR	0.6567	0.3763	0.3817	0.3754
BIAS	2.5271	1.2037	1.1197	0.9031

Table 1. Verification metrics for various precipitation types. See text for additional explanation.

REFERENCES

Baldwin, M., R. Treadon, and S. Contorno, 1994: Precipitation type prediction using a decision tree approach with NMCs mesoscale eta model. Preprints, *10th Conf. On Numerical Weather Prediction*, Portland, OR, AMS 30—31.

Barrett, A. P., 2003: National Operational Hydrologic Remote Sensing Center SNOw Data Assimilation System (SNODAS) Products at NSIDC. *Special Report #11, National Snow and Ice Data Center, Boulder, CO.* 17 pp.

Bourgouin, P., 2000: A method to determine precipitation types. *Wea. Forecasting.* **15**, 583-592.

Colle, Brian A., Mass, Clifford F., Westrick, Kenneth J. 2000: MM5 Precipitation Verification over the Pacific Northwest during the 1997–99 Cool Season. *Wea. Forecast.* **15**, 730–744.

Cortinas, J. V. Jr., and M. E. Baldwin, 1999: A Preliminary Evaluation Of Six Precipitation-Type Algorithms For Use In Operational Forecasting. Proceedings, *6th Workshop on Operational Meteorology*, Halifax, Nova Scotia, Environment Canada, December 1999, 207-211.

Dube, I., 2003: From mm to cm…Study of snow/liquid water ratios in Quebec. *Unpublished Manuscript*, 127 pp. Available from P. Sousounis.

Hutchinson, T. A., S. Marshall, P. Sousounis, and C. Liu, 2005: WSI's operational implementation of the WRF model. *Preprints, Seventeenth Conference on Numerical Weather Prediction. Washington D.C. Amer. Meteor. Soc.*

Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff, and W. Skamarock, 2001: Development of a Next Generation Regional Weather Research and Forecast Model. *Developments in Teracomputing*: Proceedings of the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology. Eds. Walter Zwieflhofer and Norbert Kreitz. World Scientific, Singapore. 269-276.

Skamarock, W. C., J. B. Klemp, and J. Dudhia, 2001: Prototypes for the WRF (Weather Research and Forecasting) Model. *Preprints, Ninth Conf. on Mesoscale Processes, Fort Lauderdale, FL, Amer. Meteor. Soc.,* J11-J15.

Wilks, D., 1995: *Statistical Methods in the Atmospheric Sciences: An Introduction.* Academic Press, 467 pp.