# **11A.8** EVALUATION OF CIRRUS CLOUD PREDICTIONS FROM THE MM5 AND WRF/NAM WEATHER MODELS

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## 1. INTRODUCTION

Cirrus clouds have been shown to have an impact on certain Air Force missions and systems. Some examples are high altitude reconnaissance and laser propagation for communications and missile defense. Norquist et al. (2007) executed laser propagation models in slant paths using cirrus cloud properties as retrieved from observations. Their results showed that the laser beam can experience significant attenuation in long paths through the cirrus when the source and receiver are close in altitude but separated by distances of 30 km or more horizontally. Therefore, accurate predictions of cirrus locations, altitudes and coverages are a must for mission planning 24-36 hours in advance.

Having characterized the effects of cirrus on laser propagation in the earlier study, it is of interest to document the ability of current weather prediction systems to produce realistic simulations of cirrus clouds a day ahead of time. Results from Norquist et al. (2007) suggest that since any visible cirrus clouds are likely to have an appreciable impact on laser propagation, their macrophysical properties (location, altitude, coverage) are probably more important for mission planning than their microphysical properties. Thus, the current study focuses on the ability of mesoscale numerical weather prediction (MNWP) models to predict the spatial and temporal characteristics of cirrus over a region of interest. In particular, emphasis is placed on determining area of coverage by cirrus and the reliability of MNWP models to correctly predict which portions of the region will be covered.

Some recent studies have been conducted to evaluate the ability of MNWP models to predict ice clouds. Chiriaco et al. (2006) compared the predictions by several microphysical schemes in the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5; Dudhia 1993) with active and passive remote sensors at a single location over long time periods. Their focus was on the microphysical and optical properties of the clouds, and they found that the best scheme simulated cirrus at the site in about 2/3 of the selected cirrus events. Lewis (2006) looked at two cirrus episodes in the southwestern United States as simulated by the MM5 as executed operationally at the Air Force Weather Agency (AFWA). A subjective assessment of the mass, motion and moisture fields of the model predictions showed that the dynamical and hydrological processes necessary for cirrus formation were present, but that for the two cases studied produced less cirrus in area covered than was detected from satellite imagery.

The goal of the current project is to comprehensively assess the cirrus prediction performance of the AFWA MM5 and the National Center for Environmental Prediction (NCEP) North American Mesoscale (NAM) model. Diagnoses of cirrus clouds from the AFWA Diagnostic Cloud Forecast algorithm (AFWA, 2007) applied as a post processor to AFWA MM5 forecasts will also be evaluated. The plan is to conduct evaluations of the three forecast methods over approximately 30-day periods in each season over two different climatic regions. Satellite imagery will be used as a reference for these evaluations to allow assessments of the models' ability to predict cirrus on horizontal scales of 100s of km. It is hoped that this assessment will provide information on the use of these forecasts to support Air Force system tests in the near future.

In this paper, the MM5 and NAM model predictions of ice cloud have been evaluated for periods in Fall 2006 and Winter 2007 over two regions in North America: the northeast United States (NEUS) region (40-47 N latitude, 70-81 W longitude) and the southwest United States (SWUS) region (30-40 N latitude, 105-122 W longitude). Twice-daily forecasts were compared with ice cloud masks, ice water path and cirrus top height as retrieved from the Geostationary Operational Environmental Satellite – 12 (GOES-12) imagery for the NEUS region and GOES-11 imagery for the SWUS region. Statistics based on objective comparisons of the gridded representations of model forecasts and GOES analyses are reported for the two seasonal periods in both regions. Some preliminary conclusions are

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reached about the characteristics of the cirrus predictions of the two models based on the limited study to date.

## 2. DATA

AFWA executes the MM5 over North America on a grid of 45 km grid spacing with a nested window over the continental United States (CONUS) of 15 km grid spacing. Both nests are discretized vertically into 41 model layers with a model top at 50 hPa. Physical parameterizations relevant to cirrus formation utilized in the AFWA MM5 are the moist convective scheme of Kain and Fritsch (1990) and the explicit microphysics formulation of Reisner et al. (1998). The model is executed at 06 and 18 UTC each day out to 72 hours (45 km grid) and 48 hours (15 km grid).

AFWA MM5 06 and 18 UTC 15 km grid forecasts of 21, 24, 33 and 36 hours were obtained each day for the periods 1 November – 2 December 2006 and 13 February – 14 March 2007. The gridded pressure, temperature, height, humidity and ice water mixing ratio (≥ 0.001 g/kg) on the model layers were extracted for the NEUS and SWUS regions. These data represented the MM5 forecasts in the comparisons conducted in this project.

NCEP executes the Weather Research and Forecasting (WRF) system with the Nonhydrostatic Mesoscale Model (NMM) core, which is referred to as the WRF-NMM (NCEP, 2007). NCEP currently utilizes this forecasting system as their North American Mesoscale (NAM) weather prediction model. Forecasts of 12 km grid spacing are executed from 00, 06 12 and 18 UTC daily. NCEP interpolates the forecast fields to a Lambert Conformal grid of 32.46 km grid spacing covering North America and surrounding ocean areas, on constant pressure levels of 25 hPa intervals to 50 hPa, then 30, 20 and 10 hPa levels. The current operational NAM uses the Janjic (1994) moist convective scheme and the Ferrier et al. (2002) explicit cloud microphysics algorithm.

NAM 06 and 18 UTC forecasts of 21, 24, 33 and 36 hours duration on the 32.46 km grid were obtained each day for the same time periods as mentioned above in the AFWA MM5 data description. Gridded temperature, height, humidity and ice water mixing ratio (≥ 0.001 g/kg) on constant pressure levels were extracted for the NEUS and SWUS regions. These data constituted the NAM forecasts utilized in the comparisons for this report.

GOES-11 imagery channels of 0.65, 3.7, 6.7 10.8 and 12 µm on picture elements (pixels) of approximately 5 km on a side were obtained from the Naval Research Laboratory in Monterey, CA. Image files containing data for western North America and the eastern Pacific Ocean were obtained for image times of 06 and 18 UTC (or if missing, the nearest available image times within three hours of these times). Imagery data were extracted for the SWUS region. GOES-12 imagery files created by the Air Force Research Laboratory GOES-12 groundstation at image times nearest but before 06 and 18 UTC contained data for eastern North America and the western Atlantic. GOES-12 imagery channels of 0.65, 3.7, 6.7 10.8 and 13 µm on approximately 5 km pixels were extracted for the NEUS region. The GOES-11 and GOES-12 imagery data served as the basis for comparison with MM5 and NAM ice cloud predictions in the NEUS and SWUS regions.

## 3. METHOD

Each regional GOES image file was processed to conduct cloud detection, cloud phase discrimination and cloud property retrieval. The cloud detection and property retrieval algorithm of Gustafson and d'Entremont (2000) was utilized to distinguish between clear, liquid cloud and ice cloud pixels, and for the ice pixels it retrieved estimates of (among other properties) ice water path (IWP), cloud top height (CTH) and visible optical depth. Norquist et al. (2007) compared GOES-12 ice cloud retrievals from this algorithm with radar and lidar measurements of CTH and radar/lidar retrievals of IWP for a series of cirrus events at Hanscom Air Force Base, MA in 2005. They found that the GOES-12 CTH estimates were on average about 1.8 km lower in altitude than the radar/lidar measurements. They also found that GOES-12 IWP retrievals were on average smaller than the radar/lidar retrievals by a factor of 3 to 4. Cloud detection is considered the strongest feature of the algorithm, and cloud phase discrimination is also thought to be reliable. It should be emphasized, however, Norquist et al. (2007) found that the GOES ice cloud detection failed to detect cirrus with visible optical depths of approximately 0.5 or less as determined from the radar/lidar retrievals. Therefore, the comparisons presented in this paper are limited to cirrus of an optical depth of about 0.5 and higher and do not account for optically thinner cirrus.

The first step in the forecast model – GOES comparison processing was to identify the GOES pixels associated with (lying closest to) each MM5 or NAM model grid point. We can think of these pixels as lying within the corresponding grid cell.

For the 15 km MM5 grid, on average 9 pixels were within each cell, while for the 32.5 km NAM grid, about 40 pixels on average were within each cell. This needed to be done just once for each combination of region and forecast model.

The pixels in each grid cell were considered when each model grid cell was processed in turn in subsequent computations. In each grid cell, the tropopause is computed from the pressure, temperature and height profile using the algorithm of Roe and Jasperson (1980). Next, the vertical profiles of predicted pressure (for MM5 only), temperature, height, humidity and ice water content (converted from ice water mixing ratio by multiplying by air density), and the computed tropopause, were interpolated in time (if necessary) between the 21 and 24 or 33 and 36 hour forecast times, to the time of the comparative GOES image. For the time-interpolated MM5 profiles, the height at the top of each model layer was computed. The average height between constant pressure levels was used as the height at the top of each "pressure layer" for NAM. Next, the model layers (or pressure layers for NAM) with non-zero ice water content were identified, and were numerically integrated (each multiplied by layer depth and summed) to compute the IWP, and the height of the top of the topmost ice layer was set as the CTH. Only model grid cells with CTH ≥ 6 km were considered in the comparison with GOES. Such a grid cell was counted as a model ice grid point and it's computed IWP and CTH were stored. Then the GOES ice pixels within the grid cell with a CTH ≥ 6 km (if any) were counted, and for a non-zero count the retrieved IWP and CTH were averaged. If the within-cell ice pixel count was at least one, then the collective within-cell ice pixels were considered as a GOES ice grid point and the averaged IWP and CTH were stored. If both model and GOES were ice grid points, then the fcst Y / GOES Y counter was incremented for that grid cell and the respective IWP and CTH values were paired for comparison. If either or both model or GOES were not ice grid points, then the corresponding category (fcst Y / GOES N, fcst N / GOES Y, fcst N / GOES N) was incremented.

Once all model grid cells were processed for an individual forecast time (24-h or 36-h), the total number of all model ice grid points, the total number of all GOES ice pixels, and the count of the four ice grid point Y/N categories were recorded, along with the IWC and CTH pairs and tropopause height for the Y/Y ice grid points. Then after processing of all forecasts for both 24-h and 36-h durations was completed for the time period, a totaling of the individual forecast totals and their percentages of the total number of grid points (for total model ice grid points and Y/N category counts) and total number of pixels (for total GOES ice pixels) was done. Individual forecast averages and overall period averages of the model and GOES IWP and CTH was computed for all Y/Y ice grid points. In addition, all such CTH values were compared to the tropopause heights for each grid point, and if it exceeded the trop height it was adjusted to the trop height. Then a subsequent CTH average was computed over all Y/Y ice grid points for both models and GOES, which is referred to as the trop adjusted CTH averages. Finally a count and percentage of the Y/Y grid points whose CTH was so adjusted were computed.

## 4. RESULTS

In Figure 1, CTH is depicted for an individual MM5 forecast (a 21- to 24-h forecast interpolated to 21.65-h) and the corresponding valid time GOES image (0339 UTC 2 November 2006) in the NEUS region. The main reasons for showing the diagrams are to depict the comparison regions and to give an example of cirrus coverage, predicted and analyzed, for a single forecast. In this case the MM5 predicted more coverage than detected by the GOES algorithm, with only the northwestern corner of the region free of predicted cirrus. In Figure 2, CTH determined from a 24-h NAM forecast is compared with the valid time (06 UTC 14 February 2007) GOES CTH retrievals in the SWUS region. Here, the NAM under-predicts the cirrus coverage of the region in comparison with GOES-detected ice cloud. In both figures, the coarse, blocky depiction of the model CTH is due to assigning all pixels within each model grid cell the model's CTH value in order to contrast the spatial resolution of the models with that of the GOES imagery.

Table 1 shows the summary statistics for the model – GOES comparisons for different regions, forecast durations and time periods. The lower number of NEUS region comparisons in the Fall 2006 period is due to problems with the GOES-12 imagery data archive, which were corrected for the Winter 2007 period. The much larger SWUS has many more model grid points and GOES pixels than does the smaller NEUS region. Relative sizes of the MM5 (15 km) and NAM (32.5 km) grid cells results in more than four times as many MM5 grid points in each region.

The last four columns of Table 1 compare the percentages of all model grid points (GOES pixels) for which ice cloud with top height ≥ 6 km was predicted (detected). This is the same as the percentage of the region covered by cirrus averaged over all comparison times. These results show that, in the NEUS region, both models predict greater cirrus coverage on average than is detected by GOES. The excess seems to be slightly greater for MM5. In the SWUS region, the NAM predicts less cirrus coverage than GOES detects, while MM5 forecasts a comparable coverage to that of GOES. In both regions the Fall 2006 cirrus coverage was somewhat greater than the Winter 2007 coverage as detected by GOES. This is true of both models except for MM5 in the SWUS region where the two time periods had nearly the same coverage.

Table 1 indicates that the models tend to over-predict cirrus coverage in the NEUS for the study periods as a whole, but how well do they predict the day-to-day changes in cirrus coverage? Figure 3 shows the percent coverage of the region by both models (24-h forecasts) and the GOES analysis for the Winter 2007 period. The figure shows eight events of GOES ice cloud regional coverage of more than 50%. Both models also depict greater than half coverage for these events, although the percent coverage is excessive. The figure also shows about 20 events with GOES ice coverage of the region less than 10%. In just three of these cases do either model predict more than 25% coverage. So there seems to be a fairly good ability by the models to replicate the extremes of regional cirrus coverage as detected by the satellite algorithm. Figure 4 shows a remarkable agreement between the temporal trend of the ice cloud forecast coverage and the coverage by detected ice cloud for the Fall 2006 period in the SWUS region.

Table 2 shows the contingency tables for the four ice cloud grid point Y/N category percentages. The last three columns show parameters commonly derived from contingency tables (Wilks, 1995). The hit rate is the total percent of grid points where model forecast outcome agreed with the GOES analysis outcome. The results suggest that at any given grid point in a 24-h or 36-h forecast, the cirrus Y/N forecast has a better than 66% chance of being correct. The odds are somewhat better for the Winter 2007 period, and seem to decline slightly with forecast duration. Hit rate is comparable between MM5 and NAM in the NEUS region, but favors MM5 in the SWUS.

False alarm rate (FAR) is the percentage of grid points that were forecasted to have ice clouds but where GOES did not detect ice to the total of all predicted ice grid points. High FAR values indicate the tendency to over-predict cirrus occurrence or predictions in areas where cirrus was not detected. MM5 has consistently higher FARs than the NAM in ice cloud prediction as shown in Table 2. The values of FAR for both models are higher in the NEUS region than in the SWUS region. That these results are largely due to over-predicted cirrus occurrence in the NEUS region and mislocation of cirrus predictions in the SWUS region is reflected in the bias scores. Bias is the ratio of the total percentage of ice grid points predicted to ice grid points detected. Table 2 shows more predicted than detected ice grid points for the NEUS for both models (greater for MM5) and more detected than predicted for the SWUS (more under-predicted by NAM). Recall that just a single GOES pixel in a grid cell constitutes a GOES ice cloud grid point for the purposes of these statistics. This suggests that in the SWUS the models, especially NAM, misses the frequent scattered, isolated GOES-detected ice cloud (see for example Figure 2). And even though the SWUS FARs are not negligible for either model, the occurrence of fcst Y / GOES N in both models is much smaller in SWUS than in NEUS.

Though the emphasis of this study is to evaluate the predicted location of the cirrus and its coverage, it is also of interest to consider briefly the comparison between predicted and retrieved CTH and IWP. Given the limitations of the GOES retrievals as mentioned in the first paragraph of Section 3 (low CTH bias, low IWP bias), the pixel average for GOES ice cloud grid points can be directly compared with the model ice cloud grid point values for all fcst Y / GOES grid points. Table 3 shows the results of this comparison when the respective ice grid points are averaged over all forecasts in each period. The MM5 IWP averages are 2-3 times larger than the GOES retrieval averages, which is consistent with the suspected low bias of the latter values. But the striking result is the extremely low IWP averages of the NAM forecasts – they are consistently an order of magnitude smaller than the MM5 IWP averages, and much smaller than the suspected small GOES values. The average CTH are similar for the two models except in the SWUS region for Fall 2006. Average CTH for both models are greater than the GOES averages by at least 1 km in virtually every case. Given the known low bias of the GOES CTH retrievals, this result is favorable for the model predictions. Some of this difference is lost when some of the model CTH values are adjusted to the tropopause height. The last column of Table 3 indicates that, except for SWUS for Fall 2006, the percentage of ice grid points with CTH that exceed the tropopause height are somewhat greater in the MM5 forecasts than in the NAM predictions.

## 5. SUMMARY AND FUTURE STUDY

The following summarizes the basic results of the comparison of MM5 and NAM ice cloud forecasts with GOES ice cloud detection and property retrievals:

- Regional cirrus coverage (wrt GOES detection)
  - -- Both models over-predict in the NEUS
  - -- NAM under-predicts in the SWUS
  - -- MM5 SWUS coverage agrees with GOES
  - -- Both models capture temporal trends well
- Comparison of cirrus location
  - -- Probability Y/N forecast correct (HR) 66-79%
  - -- HR is better for Winter 2007 than Fall 2006
  - -- HR about same for both models in NEUS
  - -- HR is better for MM5 than NAM in SWUS
  - -- False alarm rate (FAR) of MM5 > FAR of NAM
  - -- FAR in NEUS > SWUS FAR for both models
  - -- NEUS: # predicted > # detected ice grid pts.
  - -- SWUS: # detected > # predicted ice grid pts.
- Average IWP comparisons
  - -- MM5 IWP ~ 2-3 times suspected low GOES
  - -- NAM IWP ~ 1/10$^{th}$ MM5 IWP consistently
- Average CTH comparisons
  - -- MM5, NAM comparable except SWUS Fall 06
  - -- MM5, NAM both 1 km > known low GOES
  - -- More MM5 than NAM CTH > tropopause ht.

As the project continues, ice cloud forecasts from the AFWA Diagnostic Cloud Forecast (DCF) algorithm will be included in the evaluation. The study will be extended to add a 30-day spring and summer period for both regions. A comprehensive report will be written that includes a summary guide for use of MM5, NAM and DCF ice cloud forecasts to support tests of relevant Air Force systems.

In addition, a study of the evolution of cirrus events will be conducted. A series of lidar and radiosonde measurements will be made in a location that begins with no visible cirrus and experiences a growth of cirrus in time overhead. Mesoscale weather model forecasts for such cases will be executed and the terms in the moisture budget equations diagnosed to determine the dominant terms related to ice cloud growth. In this way, it is hoped that some knowledge of the strengths and weaknesses of the ice cloud microphysical formulations can be ascertained. The eventual goal is to seek improvements to ice cloud predictions in mesoscale numerical weather forecast models.

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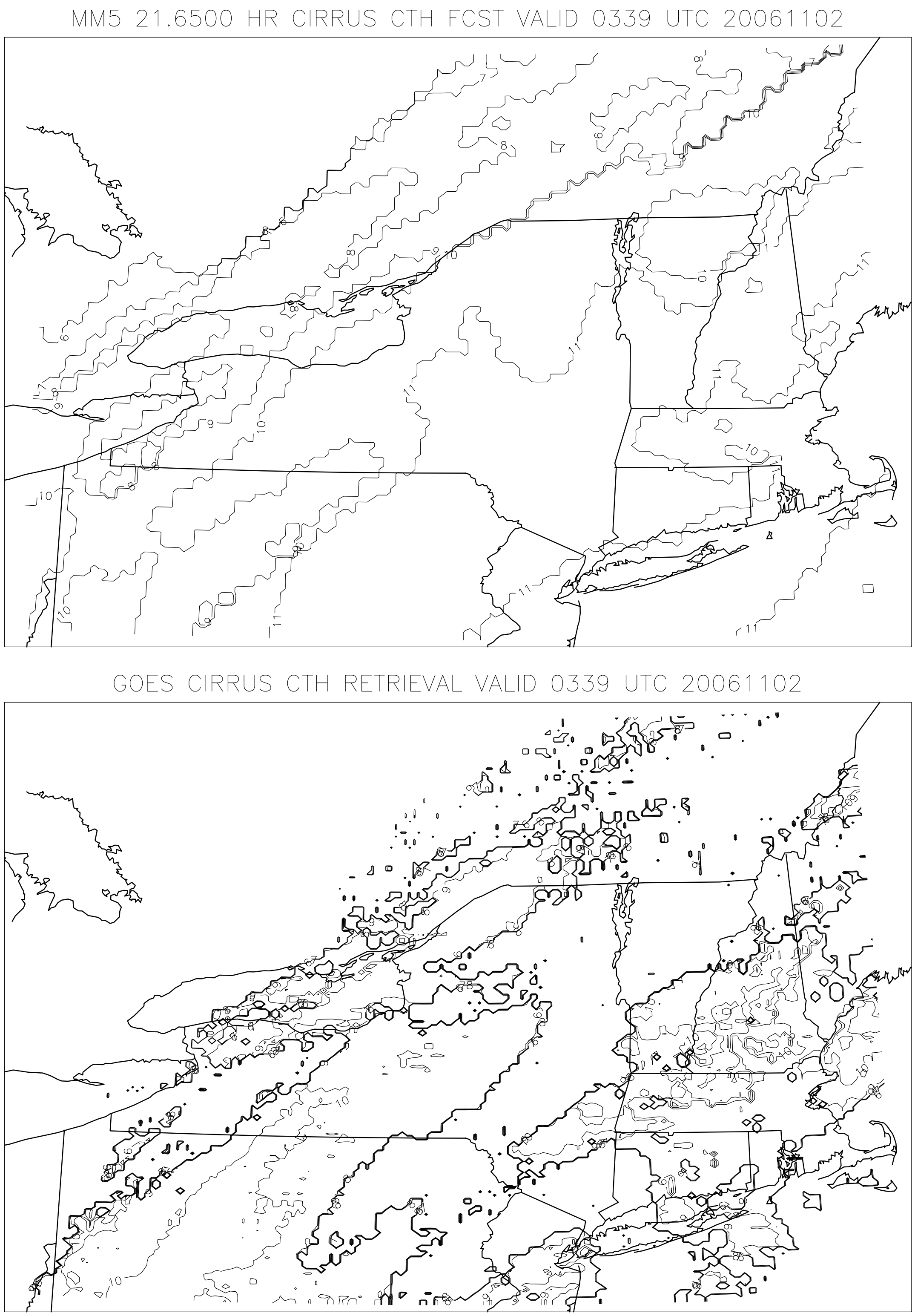


Figure 1. Cloud top height (CTH, km) as determined from 21-h and 24-h MM5 forecast of ice water mixing ratio (converted to ice water content, interpolated in time to 21.65-h, uses the height of the highest ice cloud model layer as the CTH) valid at 0339 UTC 2 November 2006 (upper panel), and as retrieved from GOES-12 imagery of the same time and date (lower panel). Contour interval is 2 km from 6 to 10 km, then 1 km to 15 km. The NEUS region is depicted.

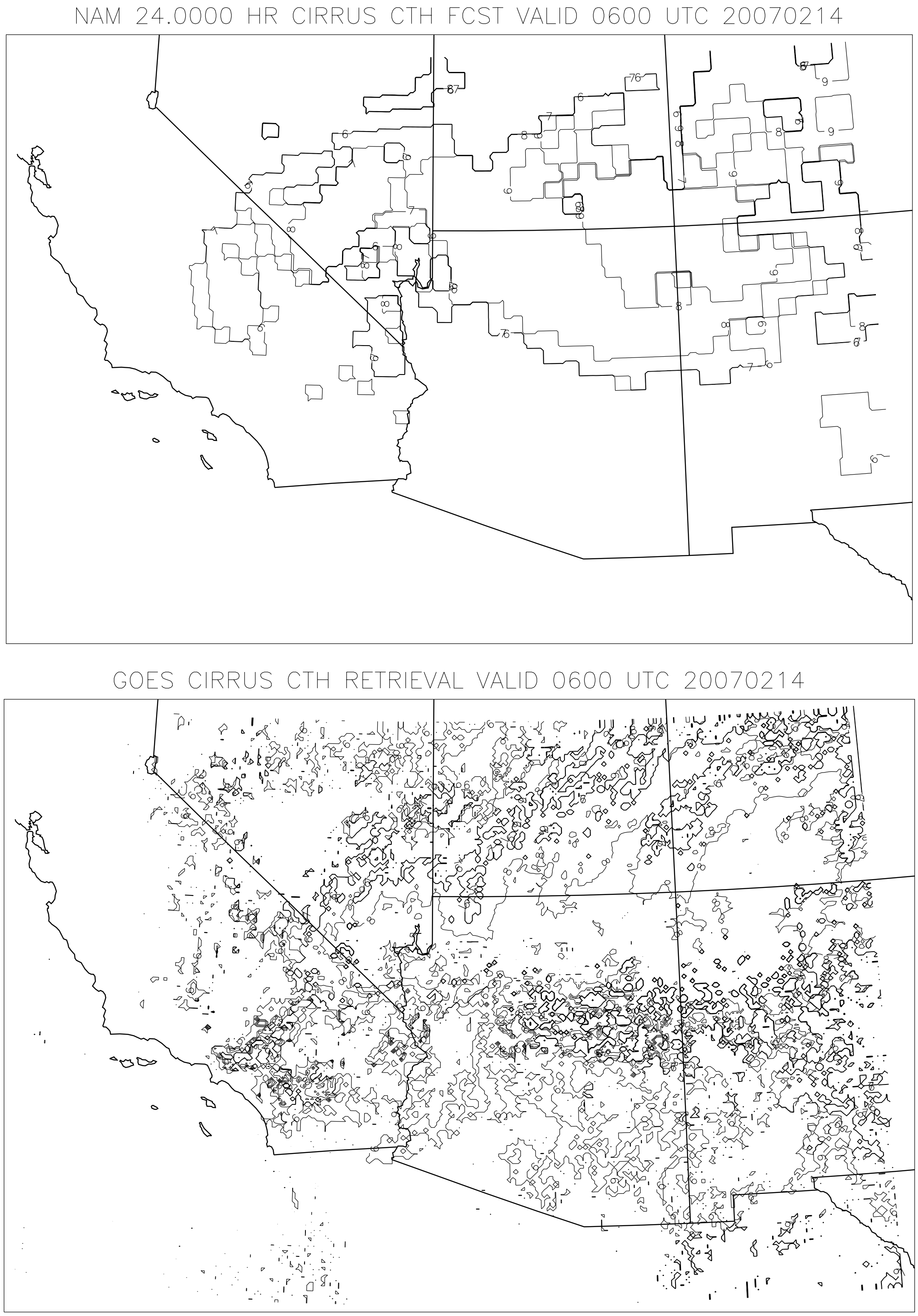


Figure 2. Same as in Figure 1 except upper panel depicts CTH determined from 24-h NAM ice water mixing ratio forecast valid 06 UTC 14 February 2007 while lower panel is CTH retrieved from a GOES-11 image of the same date and time. Contour interval is 1 km from 6 to 10 km. Depicted is the SWUS region.

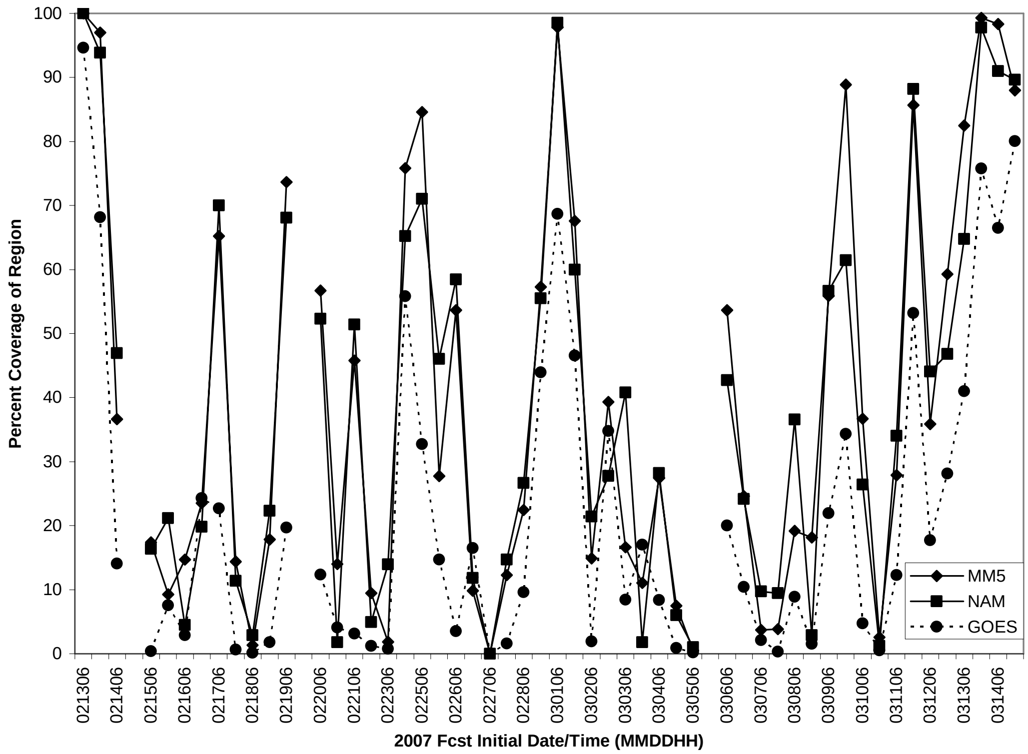


Figure 3. Percent coverage of the NEUS region by MM5 and NAM 24-hour forecast ice cloud grid points compared with percent regional coverage by ice cloud pixels of the GOES analysis for the 13 February – 14 March 2007 period. For each forecast the GOES image at the valid time of the forecast is used.

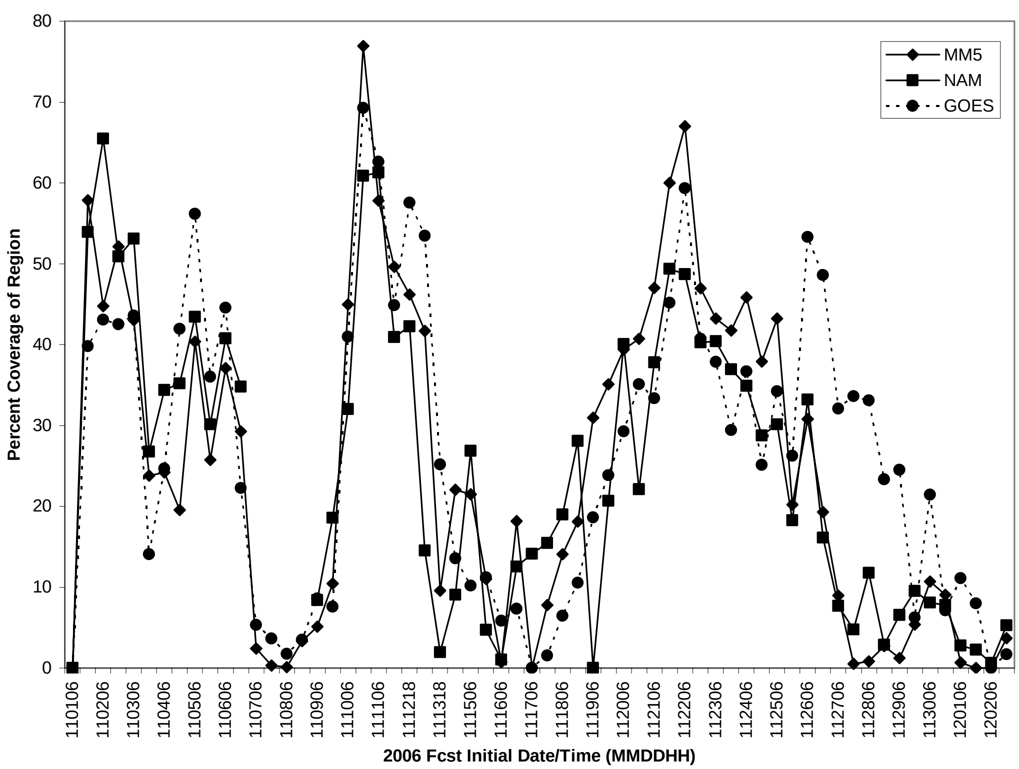


Figure 4. Same as in Figure 3 except for SWUS region, 1 November – 2 December 2007.

| Region / Fcst Dur. | Ave. Fcst Dur. (H) | # MM5 Fcsts | # NAM Fcsts | # MM5 Grid Pts. | #GOES Pixels - MM5 | # NAM Grid Pts. | #GOES Pixels - NAM | % MM5 Ice Pts. | % Ice Pixels - MM5 | % NAM Ice Pts. | % Ice Pixels - NAM |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 November – 2 December 2006 | | | | | | | | | | | |
| NEUS/24 | 22.65 | 29 | 25 | 83259 | 802459 | 16675 | 694000 | 54 | 29 | 48 | 27 |
| NEUS/36 | 34.65 | 29 | 26 | 83259 | 802459 | 17342 | 721760 | 48 | 29 | 46 | 28 |
| SWUS/24 | 23.98 | 62 | 58 | 458738 | 4306892 | 101094 | 4018936 | 26 | 28 | 26 | 29 |
| SWUS/36 | 35.98 | 62 | 58 | 458738 | 4306892 | 101094 | 4018936 | 27 | 27 | 24 | 29 |
| 13 February – 14 March 2007 | | | | | | | | | | | |
| NEUS/24 | 22.59 | 53 | 53 | 152163 | 1466563 | 35351 | 1471280 | 40 | 21 | 39 | 21 |
| NEUS/36 | 34.61 | 52 | 52 | 149292 | 1438892 | 34684 | 1443520 | 40 | 20 | 37 | 20 |
| SWUS/24 | 23.97 | 59 | 59 | 436541 | 4098494 | 102837 | 4088228 | 26 | 25 | 20 | 25 |
| SWUS/36 | 35.97 | 58 | 58 | 429142 | 4029028 | 101094 | 4018936 | 25 | 25 | 19 | 25 |

Table 1. Summary statistics for comparison of MM5 and NAM ice cloud predictions with ice cloud retrievals from GOES imagery. Numbers of grid points and pixels shown are the total number involved in the comparison over all forecasts. Percent of ice points and pixels shown are the percentages of the total number of grid points or pixels in which ice cloud was predicted (MM5, NAM) or detected (GOES). The headings "% Ice Pixels – MM5" and "% Ice Pixels – NAM" are the GOES pixels associated with the MM5 and NAM grid cells in a region respectively.

1 November – 2 December 2006

| | | GOES (≥ 1 pixel w/ice) Y | GOES (≥ 1 pixel w/ice) N | Model | Hit Rate (%) | False Alarm Rate (%) | Bias |
|---|---|---|---|---|---|---|---|
| NEUS/24 MM5, *NAM* | Y | 32, *33* | 22, *15* | MM5 | 72 | 41 | 1.42 |
| | N | 6, *12* | 40, *40* | NAM | 73 | 31 | 1.07 |
| NEUS/36 MM5, *NAM* | Y | 28, *31* | 20, *15* | MM5 | 71 | 42 | 1.30 |
| | N | 9, *14* | 43, *40* | NAM | 71 | 33 | 1.02 |
| SWUS/24 MM5, *NAM* | Y | 18, *19* | 8, *7* | MM5 | 73 | 31 | 0.70 |
| | N | 19, *27* | 55, *47* | NAM | 66 | 27 | 0.57 |
| SWUS/36 MM5, *NAM* | Y | 17, *18* | 10, *6* | MM5 | 71 | 37 | 0.75 |
| | N | 19, *28* | 54, *48* | NAM | 66 | 25 | 0.52 |

13 February – 14 March 2007

| | | GOES (≥ 1 pixel w/ice) Y | GOES (≥ 1 pixel w/ice) N | Model | Hit Rate (%) | False Alarm Rate (%) | Bias |
|---|---|---|---|---|---|---|---|
| NEUS/24 MM5, *NAM* | Y | 23, *26* | 17, *13* | MM5 | 78 | 43 | 1.43 |
| | N | 5, *8* | 55, *53* | NAM | 79 | 33 | 1.15 |
| NEUS/36 MM5, *NAM* | Y | 21, *24* | 20, *14* | MM5 | 75 | 49 | 1.52 |
| | N | 6, *9* | 54, *53* | NAM | 77 | 37 | 1.15 |
| SWUS/24 MM5, *NAM* | Y | 17, *16* | 9, *3* | MM5 | 74 | 35 | 0.76 |
| | N | 17, *27* | 57, *54* | NAM | 70 | 16 | 0.44 |
| SWUS/36 MM5, *NAM* | Y | 16, *14* | 9, *4* | MM5 | 73 | 36 | 0.74 |
| | N | 18, *28* | 57, *54* | NAM | 68 | 22 | 0.43 |

Table 2. Contingency tables (%) for MM5 (regular font) and NAM (italics font) grid point comparisons with the GOES pixels lying within each model grid cell. A "Y GOES" means ice cloud was detected in at least one within-cell pixel. Hit rate = %Y/Y + %N/N, false alarm rate = (% fcst Y/GOES N ÷ % fcst Y) X 100, and bias = % fcst Y ÷ % GOES Y.

| Region/Fcst Dur. | Fcst/Analysis | Ave. IWP (g $m^{-2}$) | Ave. CTH (km) | Ave. Trop Adj CTH | % Trop Adj Pts. |
|---|---|---|---|---|---|
| 1 November – 2 December 2006 | | | | | |
| NEUS/24 | MM5 | 48 | 10.9 | 10.5 | 58 |
| | NAM | 4 | 10.5 | 10.2 | 43 |
| | GOES | 22 | 9.4 | 9.4 | 4 |
| NEUS/36 | MM5 | 39 | 10.7 | 10.3 | 51 |
| | NAM | 4 | 10.6 | 10.2 | 46 |
| | GOES | 21 | 9.4 | 9.4 | 3 |
| SWUS/24 | MM5 | 42 | 10.8 | 10.6 | 31 |
| | NAM | 3 | 11.6 | 11.0 | 45 |
| | GOES | 16 | 9.8 | 9.8 | 3 |
| SWUS/36 | MM5 | 44 | 10.8 | 10.6 | 31 |
| | NAM | 3 | 11.6 | 11.0 | 42 |
| | GOES | 17 | 9.8 | 9.8 | 3 |
| 13 February – 14 March 2007 | | | | | |
| NEUS/24 | MM5 | 60 | 10.3 | 9.7 | 68 |
| | NAM | 6 | 10.0 | 9.6 | 53 |
| | GOES | 23 | 9.0 | 9.0 | 6 |
| NEUS/36 | MM5 | 54 | 10.0 | 9.6 | 59 |
| | NAM | 6 | 9.9 | 9.6 | 52 |
| | GOES | 23 | 8.9 | 8.9 | 7 |
| SWUS/24 | MM5 | 41 | 10.1 | 9.8 | 39 |
| | NAM | 3 | 10.1 | 9.8 | 34 |
| | GOES | 19 | 9.4 | 9.3 | 7 |
| SWUS/36 | MM5 | 38 | 10.2 | 9.9 | 39 |
| | NAM | 3 | 10.2 | 9.9 | 35 |
| | GOES | 18 | 9.4 | 9.4 | 5 |

Table 3. Ice water path (IWP) and cloud top height (CTH) averaged over all fcst Y/GOES Y grid cells (all GOES ice pixels averaged in cell) over all forecasts in the respective time periods. The column "Ave. Trop Adj CTH" refers to the overall average of CTH when those exceeding the tropopause height are adjusted to the trop height, and "% Trop Adj Pts." refers to the percentage of fcst Y/GOES Y grid cells whose CTH was adjusted to the trop height.