7.3 **An Historical Overview of NOAA's National Blend of Models (NBM)**

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1. INTRODUCTION

The blending of Numerical Weather Model Predictions (NWP) (Woodcock and Engel 2005) and various Model Output Statistics (MOS) guidance (Baars and Mass 2005) has been shown to generate more skillful guidance than any singular input. Over the past decade, various NWS Weather Forecast Offices (WFOs) along with National Centers for Environmental Prediction (NCEP) have been successfully experimenting with a host of advanced post-processing blending techniques. In many instances, these innovations have been adopted locally by NWS forecasters and are routinely used in their daily forecast preparation process allowing them to focus on Impact-based Decision Support Services (IDSS). An added benefit of this methodology is that it provides WFOs with a spatially and temporally consistent and skillful set of guidance with neighboring WFOs minimizing cross boundary inconsistencies. On the heels of the success of this NWS Field project, the Disaster Relief Appropriations Act of 2013 (Sandy Supplemental) provided funds to be used to transfer this science and technology and to be applied at a national scale. This new NWS national product would henceforth be referred to as the National Blend of Models (NBM).

With Sandy Supplemental funds in place by 2014, the Meteorological Development Laboratory began leveraging the blending techniques developed at NWS field offices and integrating them into MDL's statistical post-processing software architecture. At the same time, MDL and the Office of Oceanic and Atmospheric Research (OAR) began working on additional blending techniques. The first version of the NBM was implemented on NOAA's Weather and Climate Operational Supercomputing System (WCOSS) in January 2016, and has been upgraded on a roughly annual basis ever since.

Section 2 of this paper provides a general historical overview of the evolutionary steps taken by WFOs to improve their guidance via model blends. Section 3 discusses the various NWS cross-cutting teams (at various NWS levels) that have been established to both govern and shepherd the NBM project as it evolves. Section 4 follows with a general description of the NBM methodology. Section 5 highlights the various models and weather elements that have been populated in the NBM to date. Section 6 discusses MDL's NBM web page and its contents. Section 7 briefly discusses what probabilistic guidance lies ahead for NBM v4.0.

2. BRIEF HISTORY OF WFO POST-PROCESSING

In the early 2000s, WFOs began generating gridded forecasts for the National Digital Forecast Database (NDFD) at a higher spatial resolution (e.g., 5 km, later 2.5 km) than most gridded NWP model output. Since the effects of localized terrain features (e.g., for temperature and quantitative precipitation) were not sufficiently resolved by these lower resolution models, it was evident that innovative gridded downscaling techniques were needed. Many WFOs began developing "Smart Inits" to intelligently ingest and downscale model data into the Graphical Forecast Editor (GFE), while others were spending their time on improving NDFD forecasts as a whole by intelligently blending NWP and gridded MOS guidance (Glahn et al. 2009). At this time, localized "Smart Tools and Procedures" were developed in AWIPS as a means to populate and quality control the NDFD grids. However, without a governance process in place many of the innovations were not being pollenated across WFOs even within the same region. To this end, the Central Region Gridded Methodology Advisory Team (CRGMAT) was established in 2008, whose charter was expressed in the confidential *Final Team (CRGMAT) Report of 2009*, to "Promote the use of methods and tools that provide the best forecast utilizing an efficient process" and "Promote the development and implementation of science-based techniques and tools in the Graphical Forecast Editor (GFE)". Much of the blending experimentation and innovation originated in the Milwaukee/Sullivan (KMKX) WFO and soon after was adopted by other WFOs in the Central Region via the

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CRGMAT. By 2012, with these CRGMAT procedures in place, a noticeable improvement in verification scores for many of the NDFD weather elements was apparent at both the local WFOs and Regional levels (Craven et al. 2013).

3. TRANSITIONING NWS CENTRAL REGION'S BLENDING SCIENTIFIC INNOVATIONS NATIONALLY

One of the findings in the 2013 National Academy of Public Administration (NAPA) report (NAPA Report 2013) indicated that scientific innovations at both the NWS local and regional levels were (such as regional blends) being poorly managed and leading to the duplication of efforts. The Operations and Workforce Analysis (OWA) Report, a response to the NAPA Report, detailed how the NWS planned to improve its business model and improve customer service through IDSS. One of the targets of opportunity became an important NWS Evolve initiative (NWS Evolve 2016) (the action plan for OWA findings) that being the necessity for a common suite of guidance to be used as the starting point in the forecast process at WFOs and National Centers. With Central Region's mature model blending approach in place, Sandy Supplemental funds afforded the NWS the opportunity to transition many of these scientific innovations nationally. This national product would be called the NBM and would require several simultaneous coordination efforts with WFOs, Regional Headquarters, NWS Headquarters and within MDL itself spearheaded by Dr. Stephen Lord and Kathryn Gilbert. What follows in the next subsections is a brief discussion of some of those coordinated efforts.

3.1 *NBM and URMA Partnership*

An integral component of the NBM process and success involves bias correcting each model's input prior to blending. As such, the NBM required a national gridded operational analysis. At this time, NCEP's Environmental Modeling Center's Real-Time Mesoscale Analysis (RTMA) (De Pondeca et al. 2011) product was gaining traction as a suitable surface analysis for basic weather elements for the conterminous United States (CONUS). To account for late arriving observations, EMC later added a delayed version of the RTMA called the Unrestricted Real-time Mesoscale Analysis (URMA). With URMA in place, the NBM would then use the analysis for both bias correction and the verifying observation.

Given the importance of the URMA analysis to the success of the NBM, the NBM and URMA development teams began meeting regularly in 2014 to coordinate analysis issues. This partnership opened up the channels of communication to (1) provide constructive feedback to the URMA team, (2) keep the URMA Team informed about upcoming requirements, and (3) provide a forum for the URMA team to demonstrate scientific innovations and project timelines. Since then, the URMA and NBM teams have been working synergistically to provide constructive product feedback.

One significant and noteworthy task not given the attention it deserved was the creation of a Unified Terrain Data set. Although the downscaling of gridded data using elevation information in AWIPS was common practice, a nationally recognized elevation data set was still non-existent. The absence of such a data set was critical from a collaborative standpoint. With an agreed upon elevation data set derived from GMTED2010 high-resolution terrain (USGS 2019; NOAA 2019), WFOs, National Centers, and the URMA and NBM development teams could now be assured that all downscaling techniques would be performed on a consistent grid. While this directly addressed the downscaling of phenomenon at or above the spatial scale of the elevation grid, it did not eliminate the necessity for grid editing after downscaling.

3.2. Partnership with OAR

In addition to EMC partnering with MDL on the NBM project, Sandy Supplemental funds were also set aside for the purpose of transitioning NOAA OAR's latest quantitative precipitation forecast (QPF) research (using quantile mapping) into operations. Shepherding scientific research through the "R2O valley of death" into operations has always been challenging and this partnership would prove to be no different. A small MDL NBM tiger-team was tasked to port OAR's existing software designed to work in a research computing environment onto WCOSS. This posed two primary challenges which included the availability and compatibility of software modules between OAR, MDL, and NCEP Central Operations (NCO), and Operational run-time code efficiency (Christina Maurin, personal communication, September 27, 2019). These hurdles were eventually overcome with the science and software being implemented into NCO operations in 2017. Since that time, further improvements have been made to OAR QPF's basic algorithm and have been transitioned to NCO operations. To allow these updates to still run in a reasonable amount of time on WCOSS, MDL has since re-engineered the underlying software.

3.3 NWS NBM Support Teams

Although the NBM had gained traction in the Central Region, the NBM had not yet gained popularity in other NWS Regions. For this purpose, an NBM Demonstration Team was established in 2016, after NBM v1.0 became operational. The Demonstration Team is co-chaired by the NWS's Analysis and Forecast Division Chief and one Regional Meteorological Services Division (MSD) Chief. According to the confidential document, *NBM Demonstration Team Charter of 2017* (personal communication, November 18, 2019), members are primarily comprised of NWS subject matter experts, who would act as technical advisors to "Successfully message, support the successful field demonstration, test, evaluate, and validate the National Blend of Models (NBM) using an inclusive communications strategy… Additionally, demonstrate and message the NBM to internal users and external partners, as needed… [To] serve as the nexus of AFS requirements between the development team and the National Service Programs (NSP).**"**

A variety of messaging platforms were/are used to keep both NWS forecasters and management informed on the status of NBM development. One such platform is the quarterly NBM update seminar hosted by the NBM manager. This is an opportunity to brief and engage NWS WFOs and NCEP Centers on the NBM work taking place at MDL. Specifically, discussions centered around (1) what NBM weather elements were being integrated into the NBM, (2) the blending science used in producing those weather elements, and (3) the deliverables and deliverable timelines. A second messaging initiative involved producing several training modules developed by the Cooperative Program for Operational Meteorology, Education, and Training (COMET) hosted on UCAR's Teaching and Training MetEd Website (Appendix A). A third platform includes the community side of NOAA's Virtual Laboratory (VLab) where much of the communication occurs between NBM developers and NWS forecasters. Under the VLab NBM Forum, one can engage in topical discussions addressing NBM performance, follow recent NBM blogs by the NBM Manager, and locate NBM project status information. It should be noted that while NOAA VLab is only accessible to NOAA employees, special access can be granted upon request.

Since many of the scientific ideas originating at NWS Field offices were now being integrated into the NBM, a Science Advisory Group (SAG) was established to (1) formally vet the fidelity and merit of these scientific ideas, (2) review the methods used to derive end user grids in AWIPS, and (3) provide recommendations on how to improve the NBM, including how the NBM could provide more probabilistic information to support IDSS. The SAG is comprised of one representative from each NWS Region and NCEP Centers who have extensive experience in the area of NWP post-processing and NWS forecasting. To date, the SAG has been very helpful in providing constructive feedback leading to the improvement of NBM precipitation type, quantitative precipitation, and wind-speed guidance to name a few.

As stated above in (2), AWIPS has the capability of generating derived fields from foundational input grids. These foundational grids can either originate from an edited grid by a forecaster or from pure model guidance. In either case, the foundational grids are run through a series of AWIPS tools (e.g., ForecastBuilder, used in Central Region) to produce a series of derived weather element grids such as precipitation type, snow and ice amount, blowing snow, and freezing spray. While Hazard grids are very critical to customers, they are also very time consuming to produce and do not leave the forecaster with much time for IDSS. Since 2018, the ForecastBuilder Team has been working to continually improve this process by ensuring its scientific integrity, operationally efficiency, inter-weather element grid consistency, and utility to be a common starting point for the Collaborative Forecast Process (NWS Evolve 2016). Steady progress is being made, especially by leveraging some of the ideas and GridSimp methodologies (ForcastBuilder-like program) developed by Western Region WFOs.

As these collaborative efforts were occurring outside of MDL, MDL's Verification Team was busy developing visualization and verification tools (referred to as the "NBM Viewer") to display and evaluate NBM guidance, NDFD forecasts, and URMA analyses (Huntemann et al. 2017)**.** As an example, Fig. 1 shows a four panel display of 120-h maximum daytime temperature forecasts valid for 0000 UTC, Monday, September 23, 2019 for NDFD, NBM v3.1, NBM v3.2, and the Weather Prediction Center (WPC). This allows for simple cross model comparisons. Additionally, users have the flexibility to zoom in/out, roam, and interrogate individual grid point values. Another useful functionality of the NBM Viewer is the ability to plot a time series for any one of the over 1300 CONUS sites (Fig. 2). This allows for comparisons at a particular site across projections. In addition to the NBM Viewer having the capability of displaying real-time data images, one also has the option of verifying monthly forecasts or near real-time forecasts for episodic events.

The NBM Viewer provides several types of verification metrics to allow the user to interrogate the quality of forecasts in a variety of ways. The two most commonly used metrics are the mean absolute error (MAE) and bias, where URMA is used as the proxy for truth. For example, Fig. 3 is the daytime maximum temperature bias for each of the corresponding panels shown in Fig. 2. Individual grid point values or a CONUS-wide bias average value can be displayed. One also has the option to assess the forecast performance of each system in time series form as a function of projection relative to the verifying observation (Fig. 4). Visualizing the time series forecasts in this manner not only allows for cross-system comparisons, but more importantly, enables one to see if/when a particular forecasting system converges to a particular solution. Many of the visualization enhancements (e.g., the addition of OCONUS domains and clickable verification plots) and verification capabilities that have been in place thus far are currently being enhanced with the latest technologies. Over the past year, two separate NBM display and verification programs are being developed with newer technologies allowing for more data interrogation and streamlining MDL's daily and monthly verification processing. By 2020, we expect the older NBM Viewer will be phased out in favor of these newer technologies. In any case, NWS forecasters and NBM developers who are the primary customers of the NBM Viewer have found the NBM Viewer technology an invaluable resource in identifying NBM issues during both the development and product evaluation phases. The NBM Viewer has also been heavily used in situations where a new NBM version is under development and 1) is not yet available to NWS forecasters for download, and 2) for when users whose AWIPS machines are not yet configured to ingest downloadable NBM data.

4. NBM METHODOLOGY

At the most fundamental level the NBM blending technique is relatively straightforward and can be broken down into three primary steps: (1) Collating model input data, (2) calibrating each model's input using the most recent URMA observations, and (3) finally blending the bias corrected guidance usually through objective weights (Fig. 5).

Currently, the NBM uses almost 30 different model inputs ranging from the global scale to mesoscale from a variety of Meteorological Centers (Fig. 6) and runs hourly. When model data arrives, the NBM processes that data and it is absorbed in the next hour's NBM solution. Given the sheer number of input models there are times of the day where several models are processed for any particular hour, while at other hours only two or three short-term models may be processed. For this reason there may be some NBM cycles where NBM guidance beyond a specific time horizon is not updated.

For many of the NBM weather elements, a decaying average bias correction algorithm (Cui et al. 2012) is used to calibrate the input model data prior to the blending process (with one notable exception —NBM QMD precipitation products). This algorithm works by comparing a model's recent past performance with the verifying URMA observation and adjusts the bias correction factor accordingly. These bias correction factors are updated daily as a function of model, cycle, weather element, and projection. This same methodology is also applied when generating MAE-factors used in objectively weighting each model's contribution to the NBM's final blended solution. Many of the continuous weather elements are bias corrected and objectively weighted in this manner. However, for those non-Gaussian weather elements (e.g., ceiling height and visibility) which are not suited to be bias corrected in a linear fashion, expert weights are used. These expert weights have been predetermined through various retrospective tests and are likewise a function of model, cycle, weather element, and projection. Following the blending process, select weather elements are quality control checked for consistency, such as the temperature always being equal to or greater than the dew point temperature. Care has also been taken to minimize temporal inconsistencies in NBM guidance by temporally interpolating model data into hours for which no model data is available. For more information on the scientific techniques employed in the NBM, the reader is referred to Craven et al. (in press); Hamill et al. 2017; Hamill and Scheuerer 2018.

5. NBM VERSION PRODUCT HISTORY

5.1 NBM v1.0 and v2.0

The first generation NBM, NBM v1.0, was implemented in NCO's job stream on January 6, 2016 and leveraged just three global models and two gridded MOS products covering the CONUS at a 2.5-km spatial resolution (Fig. 7); the deterministic Global Forecast Model (GFS), Ensemble Global Forecast Model (GEFS), Canadian Meteorological Center Ensemble Model (GEPS), Gridded GFS MOS (GMOS), and Ensemble Kernel Density MOS (EKDMOS). NBM v1.0 provided guidance twice a day (0000 and 1200 UTC) at 3-hour projections through 264 hours for a limited number of weather elements including temperature; dew point temperature; daytime maximum temperature; nighttime minimum temperature; wind speed; wind gust; wind direction; sky cover; relative humidity; and apparent temperature. It is important to note that since some individual NBM model inputs were not available for specific NBM weather elements, the maximum number of possible blended models was not always used (e.g., wind gusts). At the most basic level, this was obviously detrimental to the accuracy of guidance for that particular weather element. Additionally, this posed a second problem with inter-element consistency most notably between the weather elements of wind speed and wind gusts. To this end, post-processing checks were put into place to remove these inconsistencies. As several more models and weather elements have been added to the NBM since v1.0, the number of post-processing checks have grown in kind.

With the operational release of NBM v2.0 on November 15, 2016, five additional models were added; the Short-Range Ensemble Forecast (SREF), North American Mesoscale Forecast System [(NAM) high and low resolution)], Environment Canada Global deterministic (GPS) [for PoP12 and QPF06 only] and Gridded Localized Aviation MOS Program (GLMP). Five new weather elements were introduced into the CONUS domain with this implementation including 12-hour Probability of Precipitation (PoP12), 6-hour quantile mapped Quantitative Precipitation Forecasts (QPF06), Snow amount, Precipitation Type (Rain, Snow, Ice, Rain-Snow Mix), and Predominant Weather. Equally as important to these CONUS additions was the expansion of the number of NBM domains outside the CONUS (OCONUS) to include Alaska, Hawaii, Puerto Rico, and a majority of the Pacific and Atlantic Oceanic basins (Fig. 7). The NBM v2.0 weather elements populated in the OCONUS domains were limited to the weather elements implemented in NBM v1.0 noted above. Limited staffing along with incomplete and/or corrupt observational data sets were limiting factors in identically populating the OCONUS regions with those weather elements in the CONUS domain.

5.2 NBM v3.0 and v3.1

NBM Version v3.0, which was released on July 27th, 2017, incorporated additional global and mesoscale models for the CONUS, OCONUS, and Oceanic domains along with running hourly and providing 1-36 hour forecasts at hourly resolutions. Of notable mention was the HRRR (High Resolution Rapid Refresh), HiResWindow ARW NCEP [High-Resolution Window Forecast System (HIRESW)], HiResWindow NMMB NCEP [High-Resolution Window Forecast, System (HIRESW)], and Gridded LAMP (GLMP Localized Aviation MOS Product) models. With the introduction of higher resolution models, weather elements, such as ceiling height, visibility, and precipitation type forecasts could now be generated and in some instances by employing the same techniques at WFOs. One such example was leveraging several layers found in the high resolution models to calculate Bourgouin positive and negative energies to be used in calculating the probability of various precipitation types. Over the Oceanic domain strides were made to utilize individual ensemble members for the weather element of wind speed. Cumulative distribution functions were now being produced for the 10 m wind speeds at the 10th, 25th, 50th, 75th, and 90th percentiles.

NBM v3.1, implemented in October 2018, incorporated additional global models [i.e., ECMWF (deterministic and ensemble)] and mesoscale models [i.e., HRRR-Extended (1-36h guidance)] into its suite of model guidance covering the CONUS, OCONUS, and Oceanic domains. This upgrade enabled the NBM to fill existing product gaps requested by the Aviation, Fire Weather, Water Resources, and Marine NWS Service Programs. Prior to v3.1, NBM data was packaged in GRIB2 and only provided forecasts at grid points. NBM v3.1 introduced a new text product (similar to MOS-station bulletins) that provides NBM forecasts at stations. The data in these bulletins are the NBM's nearest grid point forecast to the corresponding station. Four individual NBM text bulletin products are generated every hour, each covering different forecast horizons.

5.3 NBM v3.2

NBM v3.2, which is scheduled to be implemented in December 2019, will continue to fill existing product gaps requested by the Aviation, Fire Weather, Water Resources, and Marine NWS Service Programs. This version leverages 31 possible model inputs at any given cycle and projection originating from five different NWP Centers and include: NCEP (19), Canada (4), Navy FNMOC (4), ECMWF (2), BoM Australia (2). Fig. 6 lists a majority of these models which are global and mesoscale based. A sufficient number of mesoscale models is included in the short term to provide mesoscale detail, especially for the weather elements of QPF, temperature, and wind speeds. With the exception of (P)QPF and Oceanic guidance, the ensemble mean is used in the blending process and not the individual members. This was done purposefully in order to emulate the effectual blending procedures used in the WFOs. If the reader would like greater detail into the blending science of several of the key NBM v3.2 weather elements NBM see Craven et al. (in press). NBM v3.2 is run hourly and leverages the most recent model guidance available in NCO's operational data stream. Because the NBM is run at the top of each hour and that hour's mesoscale data is never available for processing (let alone global model data), the NBM does not contain any model guidance at that hour. So, for example, the 1200 UTC NBM run contains 1100 UTC Gridded LAMP guidance and 1000 UTC HRRR guidance. NBM issuance time is defined as just that —Issuance time –and in no way reflects the model cycle times used in that particular NBM run. In keeping with this definition, all model guidance is therefore married to the same valid time (period) prior to being blended. As one might well imagine, this projection aligning, multi-dimensional matrix is elaborate.

With v3.2 the NBM continues to make great strides in the realm of providing probabilistic guidance. Most notably these include scientific advancements in the area of QMD probabilistic quantitative precipitation forecasts (PQPF) (especially in the mountainous West) and the addition of calibrated PQPF guidance for the Alaska and Puerto Rico domains. All QPF06, QPF12, and QPF24 percentile values (1 through 99) are available for the CONUS along with a variety of exceedance thresholds. 24-hour snowfall and ice amounts (CONUS and Alaska) select percentile and exceedance thresholds are also available along with uncertainty information in the form of standard deviations for daytime maximum temperature, nighttime minimum temperature, 10 m wind speeds, and 10 m Wind Gusts for the CONUS and OCONUS domains; Other NBM v3.2 highlights albeit not deterministic in nature include extending ceiling height and visibility guidance from 36 hours to 84 hours over the CONUS and Alaska domains for daily airport operational planning and adding the Guam domain that contains temperature, wind, and QPF guidance. Table 1 is a list of many of the weather elements available in NBM v3.2.

6. NBM WEB PAGE

The NBM Home Page (Fig. 8) is a "one-stop-source" for NBM product services that provides background information and data for both operational and experimental NBM guidance. This portal provides links to the most recent operational GRIB2 data and their unique identifying descriptors, and links to both the experimental and operational text bulletins (which look very similar to the traditional GFS MOS text bulletins). Text bulletins spanning various horizons (hourly, medium, and extended range) can be parsed by individual stations or combined into a set and then viewed or downloaded. The user will also find on this page a "Quick Viewer" to visualize the most recent NBM guidance for a host of weather elements for the 0000, 0700, 1200, and 1900 UTC cycles. One can display images for the CONUS, Alaska, Hawaii, and Puerto Rico domains. This visualization tool allows users to loop through projections for various NBM weather elements and with preselected NBM guidance values overlaid at select stations. While this is a very useful site, it must be pointed out that it is not operationally supported 24/7 and is not available from time-to-time due to planned and un-planned server outages. One final desirable feature added to v3.2 is the inter-comparison of individual model weights used in the blending process for select weather elements (Fig. 9). The distribution of these objective weights is yet another way of adding confidence to a forecaster's choice for a select use of models in the forecast process.

If the user requires an uninterrupted data feed of NBM operational guidance (GRIB2 files and/or text bulletins) he/she is encouraged to use NCO's NOMADS and ftp servers (hyperlinks provided in Appendix B). These data are also publicly available like those provided on the NBM Web Page. NBM data retention on NCO's sites are on the order of a couple of days. Therefore, if one wishes to create an archive of operational NBM data he/she is encouraged to create an automated process to pull the data.

Since one of the primary customers of NBM data is the NWS forecaster, the author would be remiss not to address some of the challenges associated with NBM data delivery and AWIPS data ingestion. As noted in Section 5, the NBM generates tens of weather elements every hour for six domains. This translates into approximately 2 terabytes (TB) of new data every hour. Disseminating this large volume of data to WFOs via the Satellite Broadcast Network (SBN) on an hourly basis is impossible given SBN capacity. Given these SBN limitations and WFO and NCEP forecast preparation deadlines, the largest volume of NBM data is only disseminated four times a day (0100, 0700, 1300, and 1900 UTC). Lower volumes of NBM data are disseminated at the 20 remaining cycle times. Nonetheless, NWS Regional Offices are still investigating alternative data delivery methods to regularly pull large volumes of NBM data throughout the day. On a related note, the NBM will receive a designated SBN dissemination channel to address competing data feeds inside AWIPS. While this will not solve the overall SBN saturated bandwidth issues, it will likely allow other models, such as the GFS, to load more quickly into AWIPS.

7. FUTURE NBM PLANS

As the NBM continues to evolve towards probabilistic guidance, several of the current NBM v3.2 deterministic products will be transitioned to a probabilistic space. Some of the more notable weather elements that are scheduled to become probabilistic include daytime maximum temperature, nighttime minimum temperature, wind speed, wind gust, ceiling height, visibility, maximum and minimum relative humidity, and snow level. At this point in time, the SAG is exploring a variety of statistical methods ranging from CDF creation by the inclusion of additional ensemble members that are not currently leveraged in v3.2 to advanced artificial intelligence (AI) techniques. Because it is highly unlikely that any one technique will perform equally on all the diverse set of weather elements noted above, NBM retrospective testing will be necessary to determine the best options moving forward. Ultimately, perhaps as early as 2023, we expect most, if not all NBM products to be probabilistic in nature.

Future NBM versions will also focus on techniques related to the blending of tropical cyclones. The NBM Team is currently working with NHC to develop a sophisticated feature-matching technique that incorporates inputs from the HWRF, HMON, and wTCM (Mattocks et al. 2018) hurricane models using the NBM as the background field. The primary challenge is to generate one tropical cyclone that best captures the combined spatial features and areal extent of these models. A secondary challenge includes the coalescing and smoothing of features along the blended tropical cyclone and wTCM tropical cyclone boundaries. Significant progress has already been made in these two areas, and we fully expect that this new product will be part of NBM v4.0. As the NBM development team continues to make strides in these innovative scientific blending techniques, MDL will continue to work with various NWS cross-cutting teams to ensure that all NBM product services continue to improve and play an important role in improving the NWS's IDSS.

8. ACKNOWLEDGEMENTS

The Author would like to personally thank several individuals for their contribution and review of this manuscript in no specific order. Jeff Craven, Dave Myrick, Dr. Harry Glahn, Bruce Veenhuis, Andy Just, Jerry Weidenfeld, and Robert James. The information they provided very much helped place the various NWS field blending activities and the NBM vision at NWS Headquarters into a linear historical context.

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Temperature	**Moisture**	**Precipitation**	**Wind**	**Winter Weather**	**Fire Weather**	**Aviation**	**Marine**
Temperature	Relative Humidity (RH)	1-h Quantitative Precipitation Forecasts (QPF)	10-m Wind Direction and Speed	1-h Snow Amount	Haines Index	Sky Cover	Significant Wave Height
Daytime Maximum Temperature	Maximum RH	6-h QPF	10-m Wind Gust	6-h Snow Amount	Fosberg Index	Ceiling Height	Freezing Spray
Nighttime Minimum Temperature	Minimum RH	12-h QPF	30-m Wind Speed	24-h Snow Amount	Solar Radiation	Visibility	Mean Sea Level Pressure
Apparent Temperature	Dew Point Temperature	24-h QPF	80-m Wind Speed	1-h Ice Amount	Mixing Height	Lowest Cloud Base	
Water Temperature		Precipitation Duration		6-h Ice Amount	Transport Wind	Echo Tops	
		1-h Probability of Precipitation (PoP)		24-h Ice Amount	Ventilation Rate	Vertically Integrated Liquid	
		6-h PoP		Conditional Prob. of Snow	3-h Prob. of Thunder	Maximum Hourly Reflectivity	
		12-h PoP		Conditional Prob. of Rain		Low Level Wind Shear (LLWS) Direction and Speed	
		Predominant Weather		Conditional Prob. of Sleet		LLWS Height	
				Conditional Prob. of Freezing Rain		Elrod Index	
				Cond Prob. of Refreezing Sleet		Mountain Wave Turbulence	
				Prob. of Ice Present		Surface-based CAPE	
				Maximum Wet-bulb Temperature (Tw) Aloft		1-h Prob. of Thunder	
				Positive Energy of Warm Layer (Bourgouin)		3-h Prob. of Thunder	
				Negative Energy of Cold Layer (Bourgouin)		12-h Prob. of Thunder	
				Snow Level			
				Snow to Liquid Ratio			

Table 1. Listing of weather elements available in NBM v3.2.

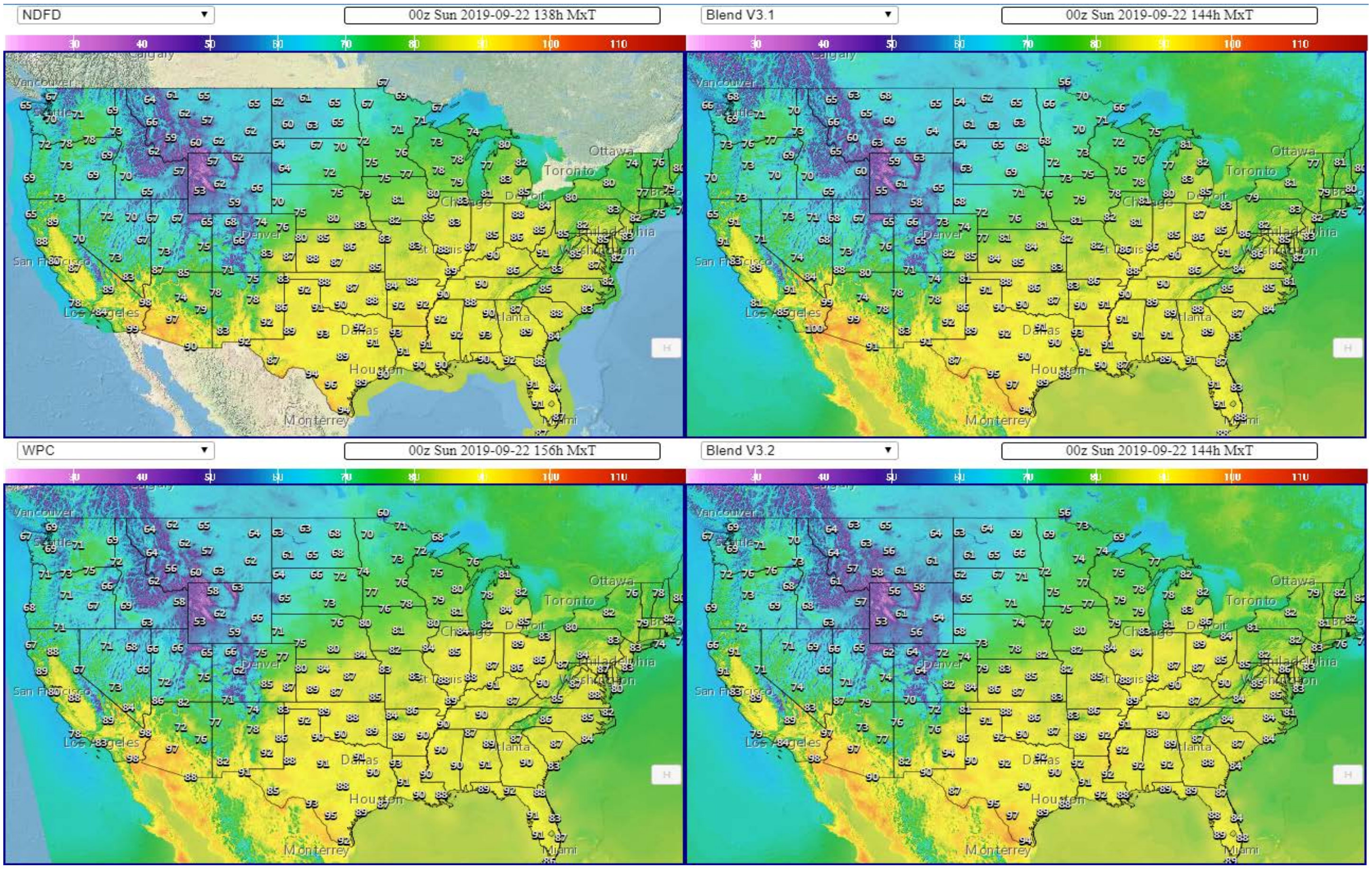

Figure 1. Four panel display of 120-h Maximum Daytime Temperature forecasts valid for 0000 UTC, 23 March 2019 for NDFD (upper left), NBM v3.1, (upper right), NBM v3.2 (lower right), and the Weather Prediction Center (WPC) (lower left).

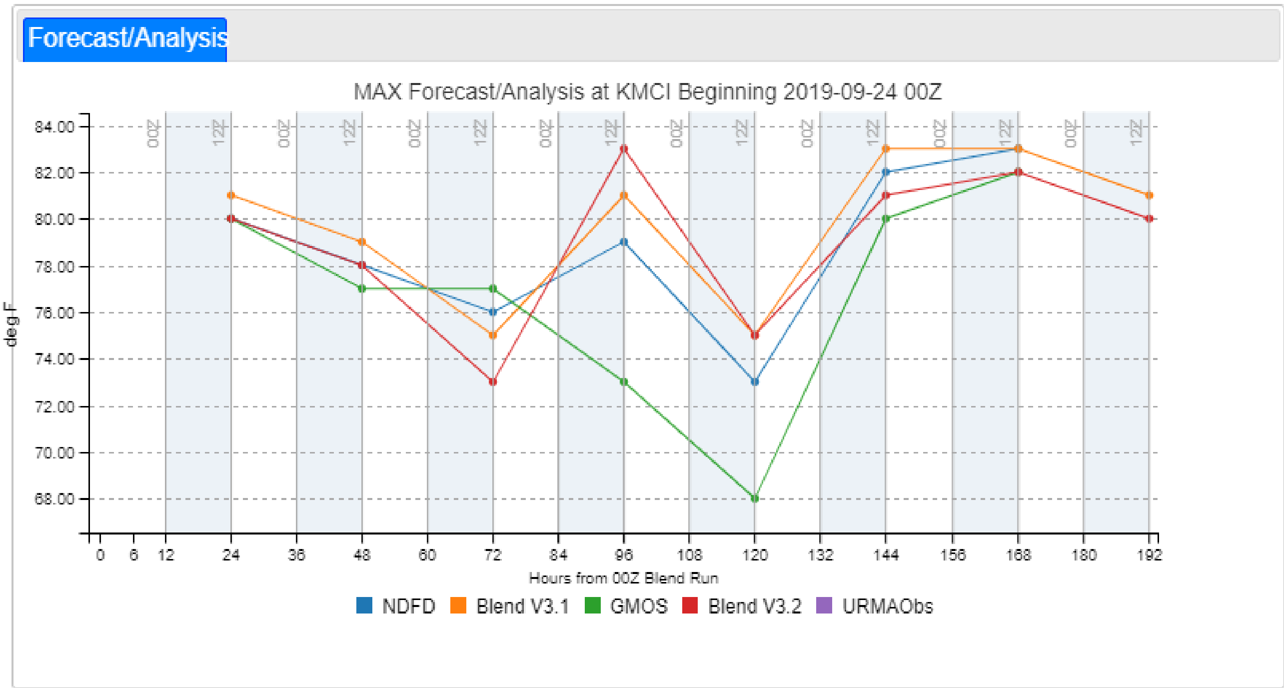

Figure 2. Daytime maximum temperature time series for Kansas City International Airport (KMCI) showing NDFD, NBM v3.1, NBM v3.2, GMOS, and URMA verifying observation.

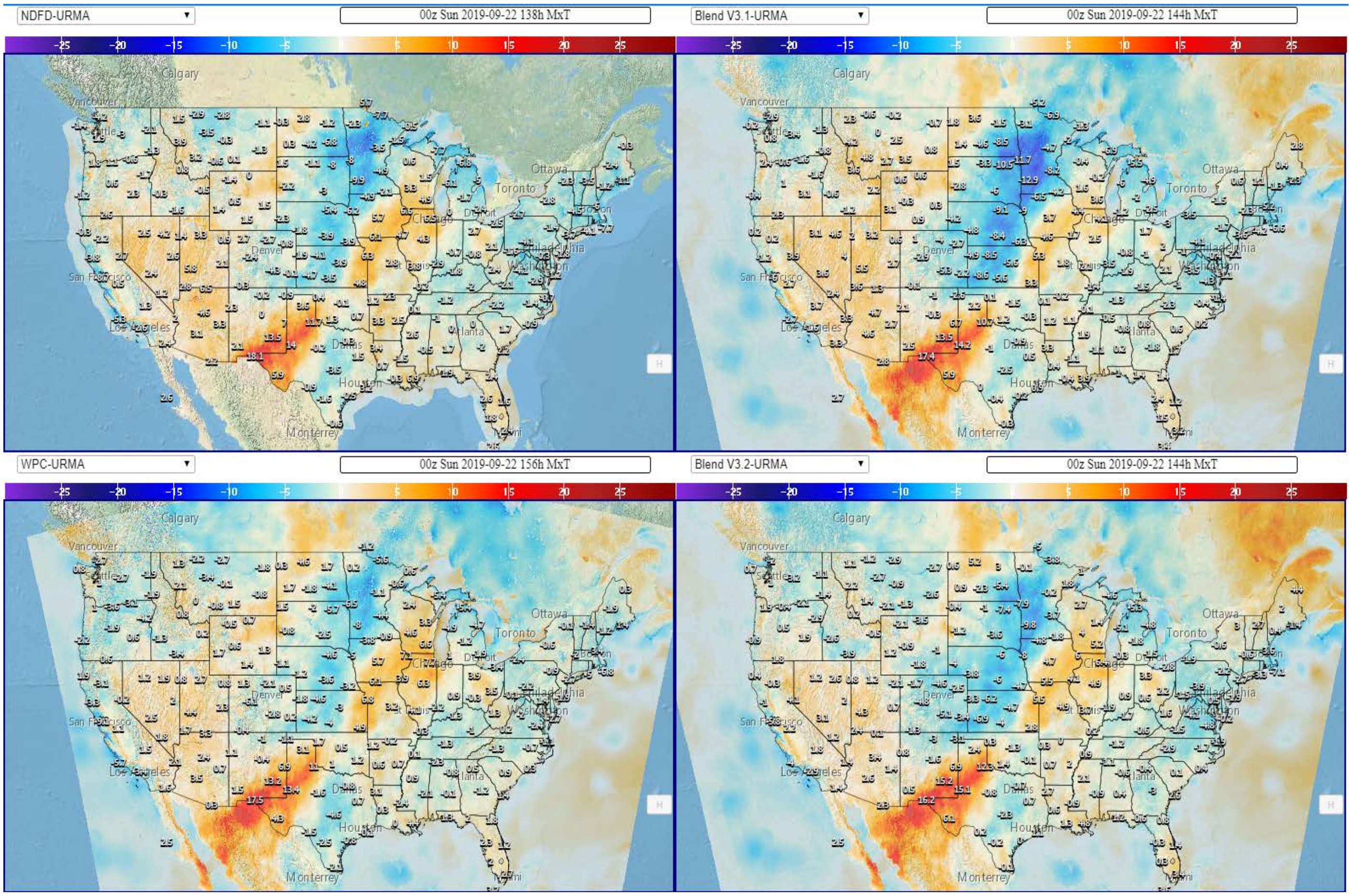

Figure 3. Bias of daytime maximum temperature shown Fig. 1 using URMA as the gridded analysis.

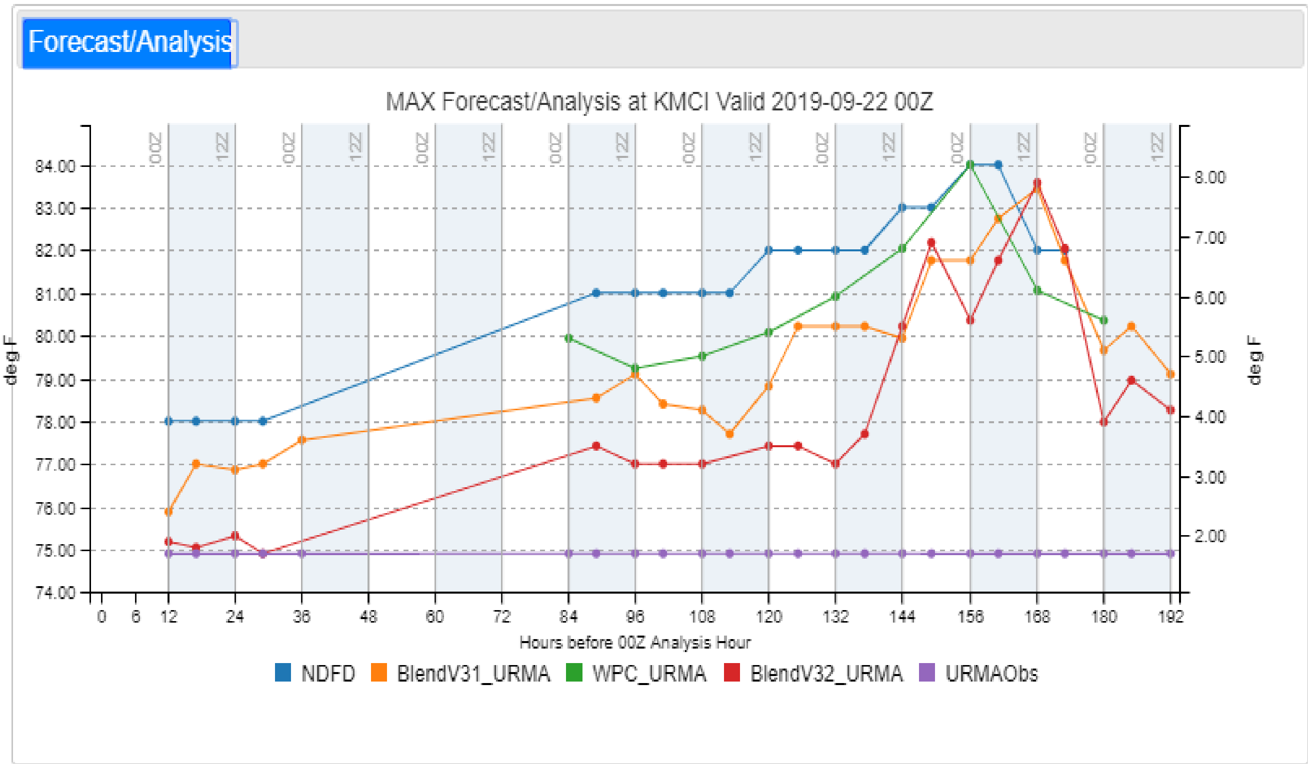

Figure 4. Verification of NDFD and WPC forecasts along with NBM v3.1, NBM v3.2, WPC guidance issued at various projection hours (abscissas) prior to the verifying time of 0000 UTC, 22 September 2019.

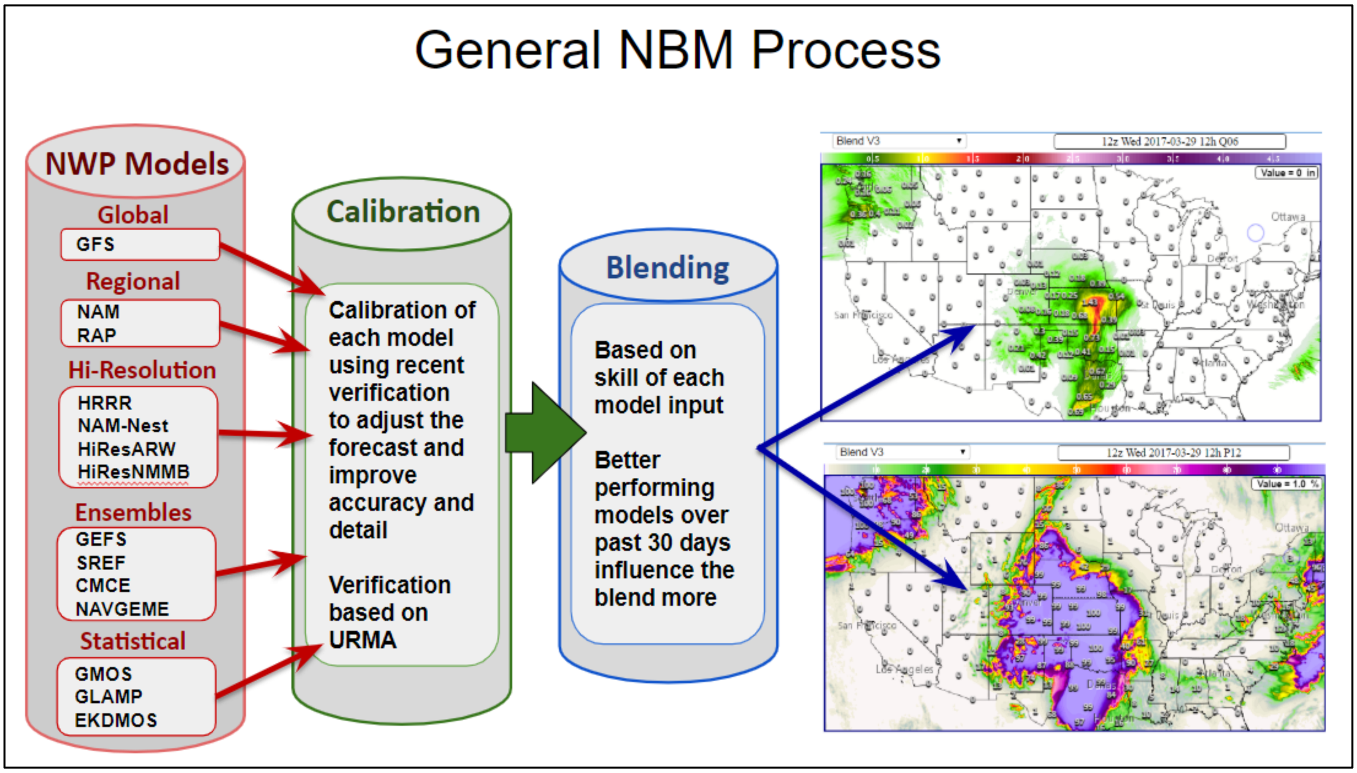

Figure 5. Schematic diagram showing the three primary steps used in the NBM Blending process.

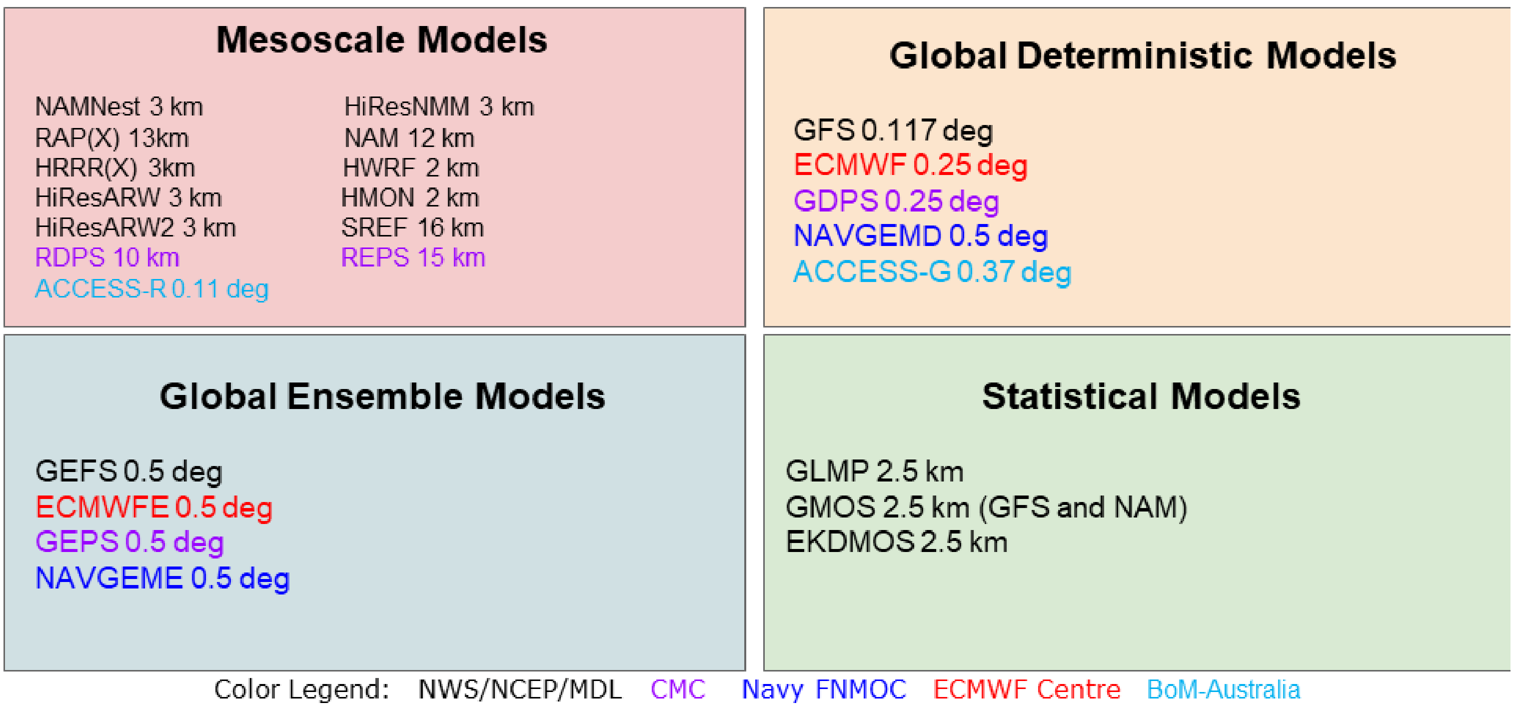

Figure 6. NBM v3.2 NWS and non-NWS model inputs delineated by model type.

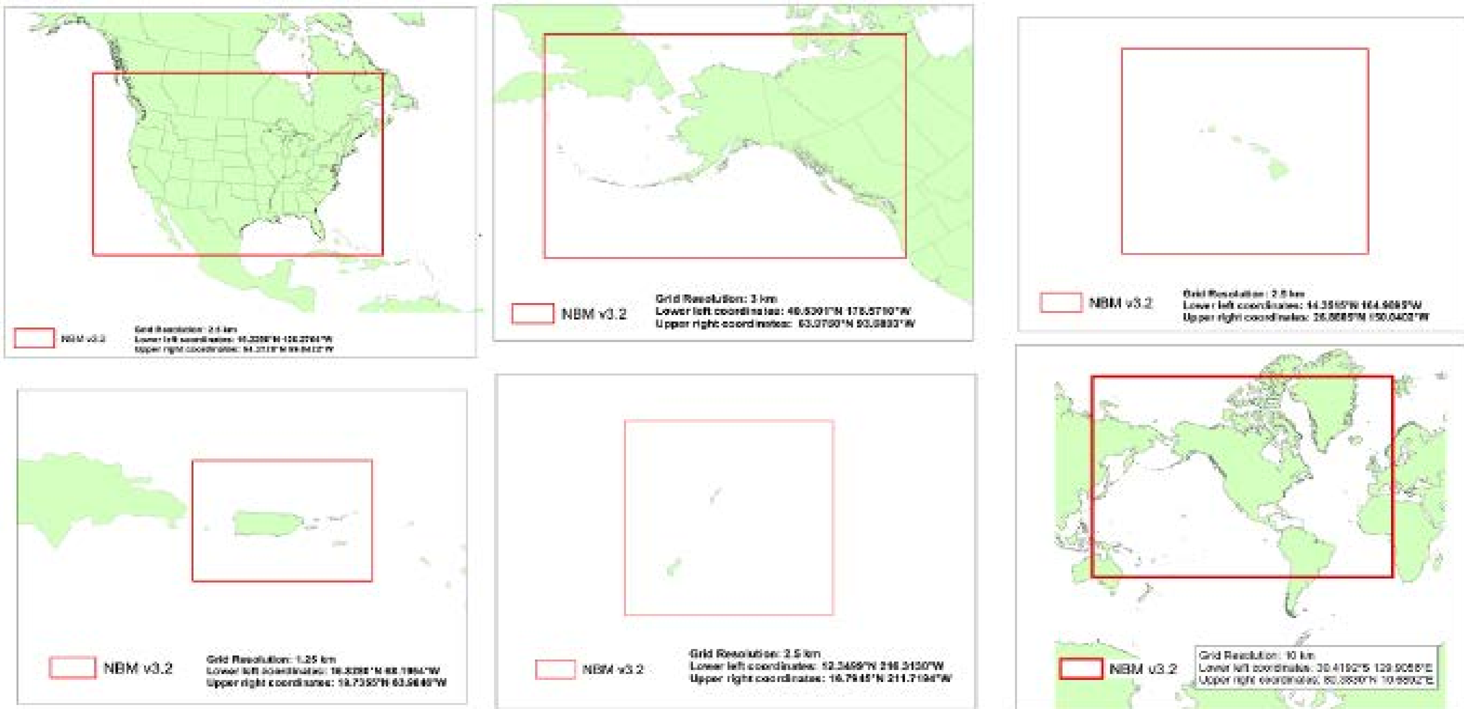

Figure 7. Six domains for which NBM guidance is available. CONUS (upper left), Alaska (upper center), Hawaii (upper right), Puerto Rico (lower left), Guam (lower center), and Oceanic (lower right).

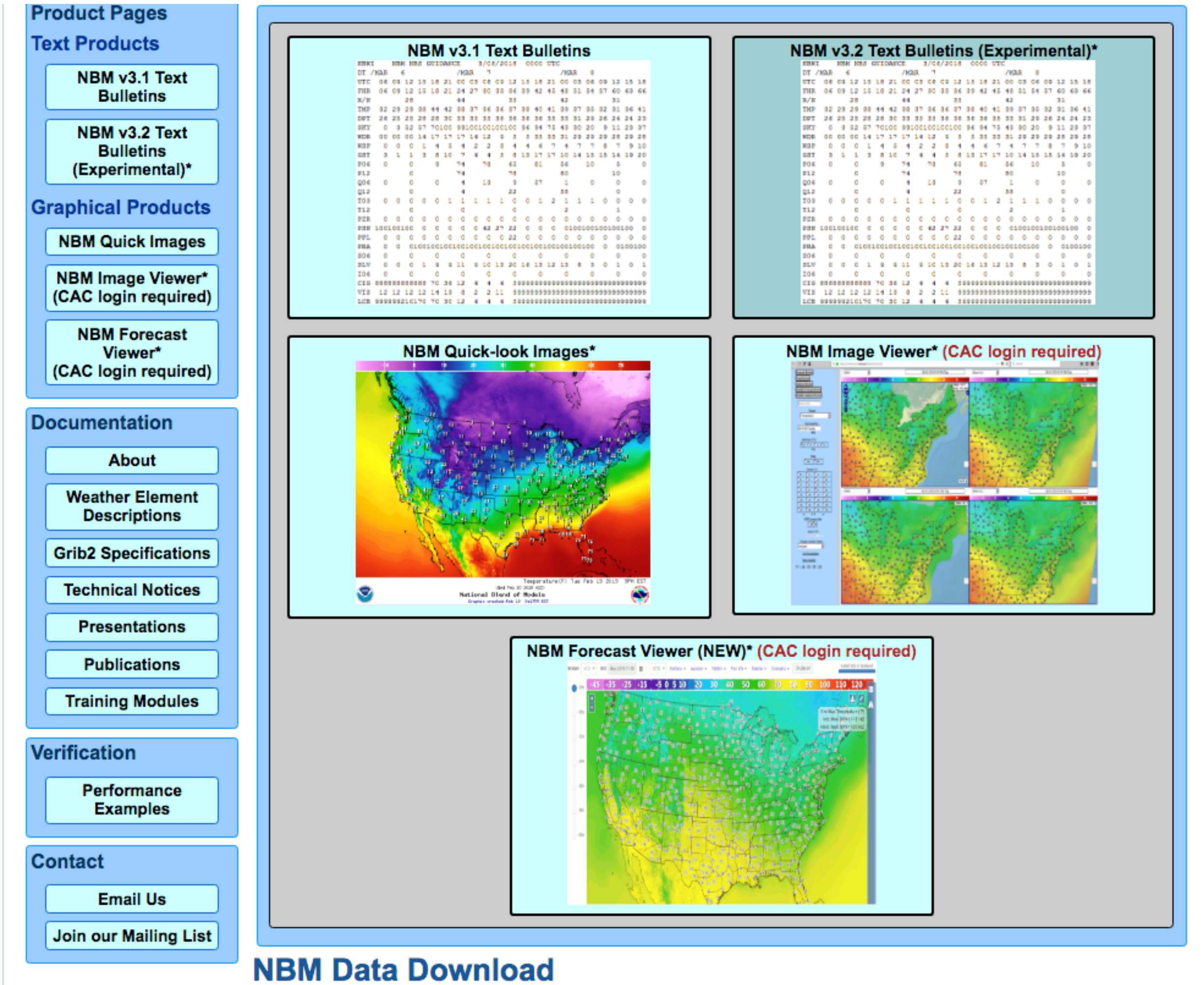

Figure 8. MDL's NBM Home Page contains images and links for data download.

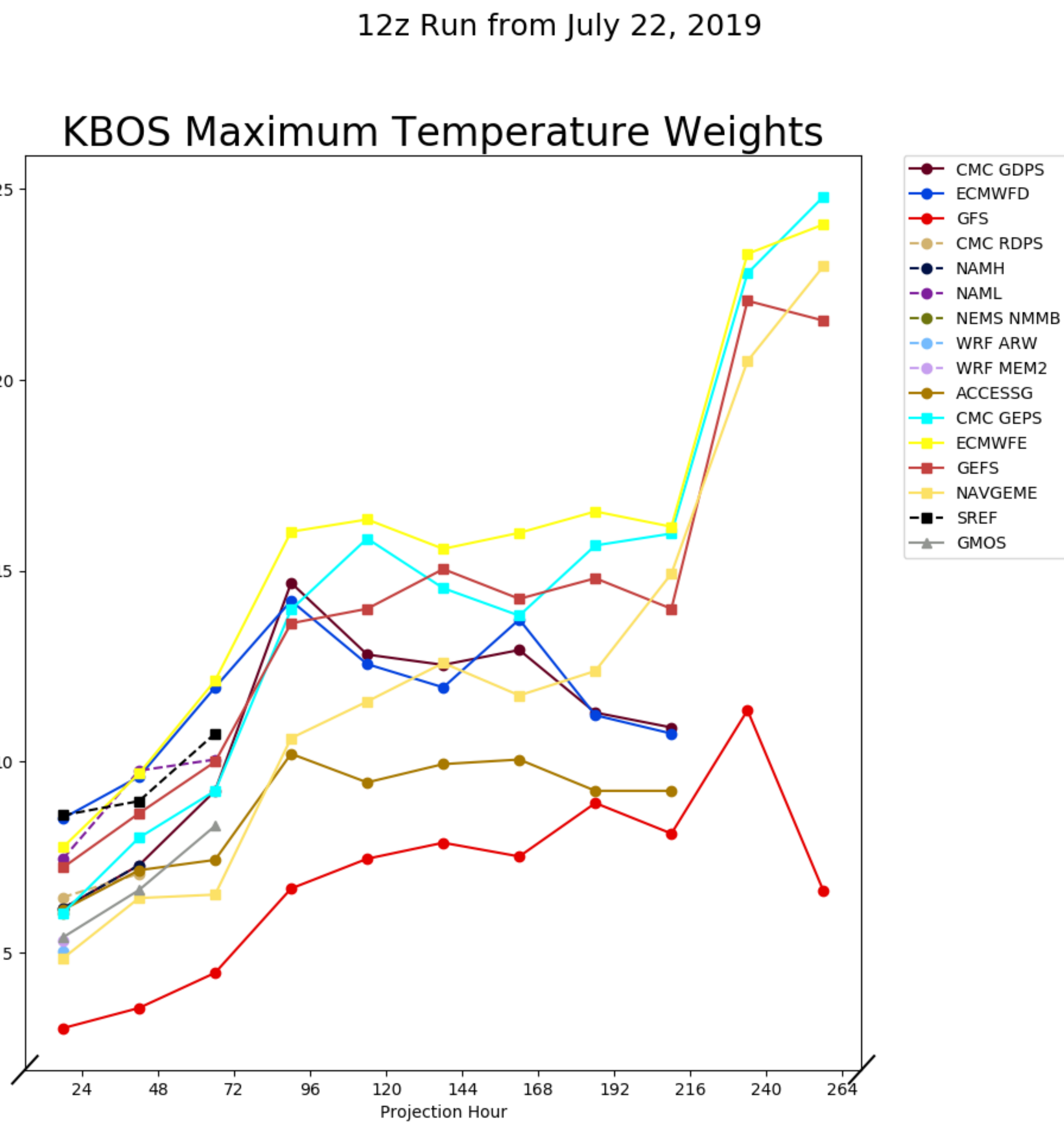

Figure 9. 1200 UTC, 22 July 2019, daytime maximum temperature MAE weights for various NBM model inputs for Boston, MA.

Appendix A

NBM Modules published by the COMET Program:

1) Introduction to the NWS National Blend of Global Models (2015), published by The COMET® Program.
2) Gridded Products in the NWS National Blend of Global Models (2016), published by The COMET® Program.
3) Verification Methods in the NWS National Blend of Global Models (2016), published by The COMET® Program.
4) Statistical Methods in the NWS National Blend of Global Models (2016), published by The COMET® Program.
5) Statistical Methods in the NWS National Blend of Global Models Part 2 (2017), published by the COMET® Program
6) Mesoscale Components of the National Blend of Models Version 3.0 (2018), published by the COMET® Program
7) What's New in the National Blend of Models version 3.1 (2018), published by the COMET® Program
8) National Blend of Models Version 3.2: Modified Blend Methods and New Model Components (2019), published by the COMET® Program
9) Unified Terrain in the National Blend of Models (2018), published by the COMET® Program
10) What's New in NBM v3.2 (2019), published by the COMET® Program
11) National Blend of Models Version 3.2: Winter Weather Guidance (2019), published by the COMET® Program
12) National Blend of Models Version 3.2: New Weather Elements (2019), published by the COMET® Program

Appendix B

Hyperlinks to NCO's uninterrupted data feed of NBM operational guidance:

1) http://nomads.ncep.noaa.gov/pub/data/nccf/com/blend/prod/
2) http://ftp.ncep.noaa.gov/data/nccf/com/blend/prod/
3) ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/blend/prod/
4) ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/blend/prod/