Time Relevance of Convective Weather Forecasts for Air Traffic Automation

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Introduction

The Federal Aviation Administration (FAA) is handling nearly 120,000 flights a day through its Air Traffic Management (ATM) system[1] and air traffic congestion is expected to increase substantially over the next 20 years[2]. Weather-induced impacts to throughput and efficiency are the leading cause of flight delays accounting for 70% of all delays with convective weather accounting for 60% of all weather related delays[3].

To support the Next Generation Air Traffic System[2] goal of operating at 3X current capacity in the NAS, ATC decision support tools are being developed to create advisories to assist controllers in all weather constraints. Initial development of these decision support tools did not integrate information regarding weather constraints such as thunderstorms and relied on an additional system to provide that information[3]. Future Decision Support Tools should move towards an integrated system where weather constraints are factored into the advisory of a Decision Support Tool (DST).

Several groups such at NASA-Ames, Lincoln Laboratories, and MITRE are integrating convective weather data with DSTs. A survey of current convective weather forecast and observation data show they span a wide range of temporal and spatial resolutions. Short range convective observations can be obtained every 5 mins with longer range forecasts out to several days updated every 6 hrs. Today, the short range forecasts of less than 2 hours have a temporal resolution of 5 mins. Beyond 2 hours, forecasts have much lower temporal resolution of typically 1 hour. Spatial resolutions vary from 1km for short range to 40km for longer range forecasts. Improving the accuracy of long range convective forecasts is a major challenge. A report published by the National Research Council states improvements for convective forecasts for the 2 to 6 hour time frame will only be achieved for a limited set of convective phenomona in the next 5 to 10 years. Improved longer range forecasts will be probabilistic as opposed to the deterministic shorter range forecasts. Despite the known low level of confidence with respect to long range convective forecasts[4], these data are still useful to a DST routing algorithm. It is better to develop an aircraft route using the best information available than no information. The temporally coarse long range forecast data needs to be interpolated to be useful to a DST. A DST uses aircraft trajectory predictions that need to be evaluated for impacts by convective storms. Each time-step of a trajectory prediction needs to be checked against weather data. For the case of coarse temporal data, there needs to be a method fill in weather data where there is none. Simply using the coarse weather data without any interpolation can result in DST routes that are impacted by regions of strong convection. Increasing the temporal resolution of these data can be achieved but result in a large dataset that may prove to be an operational challenge in transmission and loading by a DST. Currently, it takes about 7mins retrieve a 7mb RUC2 forecast file from NOAA at NASA-Ames Research Center. A prototype NCWF6 1 hour forecast is about 3mb in size. A Six hour NCWF6 forecast with a 1hr forecast time-step will be about 18mb (6 x 3mb). A 6 hour NCWF6 forecast with a 15min forecast time-step will be about 7mb (24 x 3mb). Based on the time it takes to retrieve a 7mb RUC2 forecast, it will take approximately 70mins to retrieve a 6 hour NCWF forecast with 15min time-steps. Until those issues are addressed, there is a need to develop an algorithm that interpolates between these temporally coarse long range forecasts.

This paper describes a method of how to use low temporal resolution probabilistic weather forecasts in a DST. The beginning of this paper is a description of some convective weather forecast and observation products followed by an example of how weather data are used by a DST. The subsequent sections will describe probabilistic forecasts followed by a description of a method to use low temporal resolution probabilistic weather forecasts by providing a relevance value to these data outside of their valid times.

Description of Weather Data

Weather data can be grouped into observation or forecast products. Observation data can be from a radar that provides information about the current state of the atmosphere. Forecast products predict a future state of the atmosphere and can either be deterministic or probabilistic. Deterministic forecasts provide only one solution of the state of the atmosphere. Currently, forecasts of some phenomenon are quite accurate up to an hour that they can be deterministic. After that, there is enough uncertainty in the forecasts that probabilistic information should be included. Convective forecasts are both deterministic and probabilistic.

There is a wide time range of weather forecast data so there is a product that is more appropriate for particular ATM initiatives. Table 1 lists some weather products that can be used to determine areas of strong convection that are associated with strong thunderstorms. Most of these products provide thunderstorm forecasts with the National Convective Weather Forecast (NCWF) and Convective Weather Forecast (CWF) providing 1 or 2 hours forecasts every 15mins to the Convective Outlook predicting out to 73hrs into the future every 6 hours. NCWF is produced by the National Centers for Atmospheric Research. The CWF is part of the MIT/LL Corridor Integrated Weather System (CIWS) and Integrated Terminal Weather System (ITWS). The NCWF and CWF are currently used for short range route planning. The Convective Outlook product is used for general guidance and is very coarse. Following these are numerical weather prediction models that do not explicitly forecast thunderstorms and provide precipitation, wind, temperature and pressure forecasts. Table 1 presents a short summary of these weather products. Detailed descriptions can be found in the Appendix.

Product	Resolution	Forecast Range	Updates	Domain
SURVEILLANCE				
NEXRAD	1km	N/A	5mins	CONUS
FORECASTS				
Convective Weather Forecast/Corridor Integrated Weather System & Integrated Terminal Weather System	1km/1000ft	15min – 2 hrs	5 mins	NE CONUS& TERMINAL
National Convective Weather Forecast - 6	4km	1 - 6hr	15mins	CONUS
RUC Convective Probabilistic Forecast	20km	1 - 6hr	1hr	CONUS
Collaborative Convective Forecast Product	Coarse	2 –6 hrs	2hrs	CONUS
Convective Outlook	Coarse	6 - 73 hrs	3hrs – 12hrs	CONUS
North American Mesoscale	32km/45	6 – 84hrs	6hrs	North America
Global Forecast System	40km/64	6 – 384hrs	6hrs	Global

Table 1 – Summary of some convective weather products

Figure 1 shows ATM initiatives and the time range they are typically invoked in the bottom half of the figure and the forecast time range of weather products in the top. On one side of the ATM initiative spectrum, separation assurance maneuvers are typically used to control aircraft routes up to 20 minutes into the future while Airspace Planning is used to control routes from 6 hours and beyond. Short range planning limited to under 1hour can use observation and deterministic forecast thunderstorm forecasts. NEXRAD radar data provides a current state of the atmosphere and is updated every 5 mins. After 5mins, CWF forecast data can be used to evaluate routes up to 2hours into the future. Beyond 1 hr, there are a variety of deterministic and probabilistic forecast products available. According to Mueller[4], convective forecasting accuracy dramatically decreases after 2hrs due to rapid storm and non-linear storm evolution. As such, there is a need for improved convective forecasts with echo (thunderstorm) tops longer than 2 hrs to meet the NGATS vision of providing aircraft routing management to at least 6 hours into the future. Knowledge of thunderstorm tops is important in determining en-route re-routing strategies as shown by DeLaura and Evans[5]. Currently, only the CWF provides a forecast of thunderstorm tops.

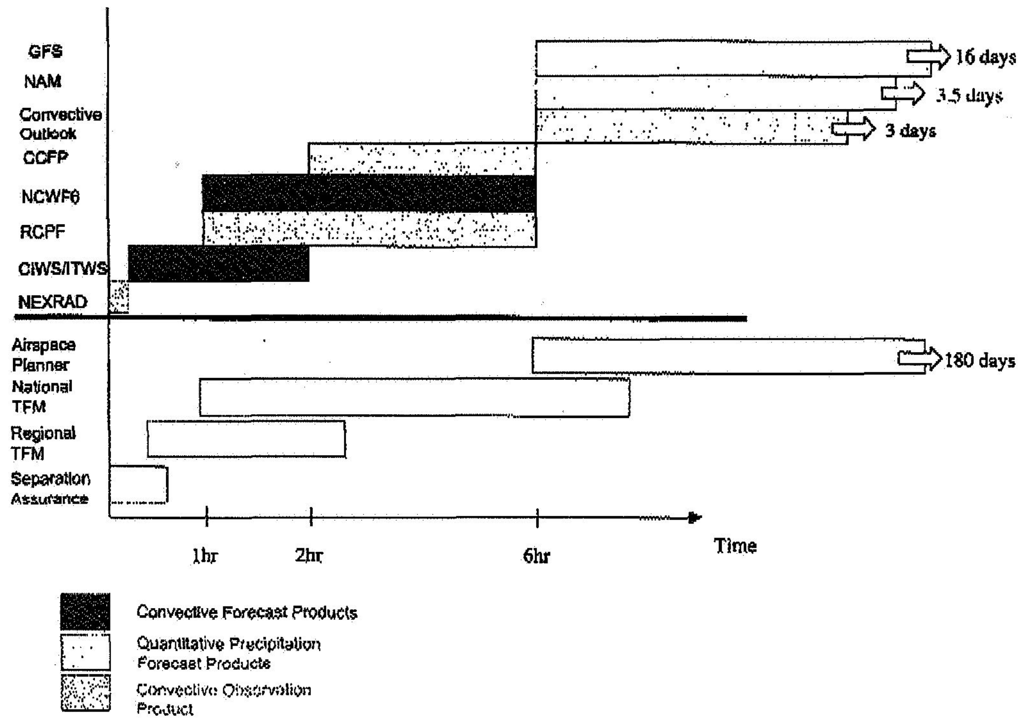


Figure 1 – Summary of some convective weather products and ATM initiatives.

According to the National Research Council report tilted "Weather Forecasting Accuracy for FAA Traffic Flow Management"[6], Meteorologists have recognized a deterministic 2 - 6hr convective forecast is extremely challenging and have started to produce probabilistic convective forecasts to fill this need. Probabilistic forecasts can be a deterministic forecast of thunderstorm intensity with a probability associated with it or an aggregate ensemble of many intensity forecasts with a probability associated with each scenario. Forecasts with probability information allow a DST to make more flexible advisories. A DST can create an advisory through a region where the probability of occurrence for a weather constraint is low or avoid it when the probability is high. In the case of probability scenarios, a DST can consider a route for each scenario. Following is a short discussion on two types of probabilistic forecasts.

Figure 2 is an illustration of NCWF6 with associated probability. The NCWF6 forecast extrapolates from surveillance what is most likely to happen. Figure 2 shows the probability of each VIL > 3 occurring at specific locations. It does not show another possible event that might include the dissipation of the entire line of convection above North and South Carolina.

Work by Davidson et al[7]. shows a probabilistic forecast product that aggregates the results of an ensemble forecast into distinct scenarios in Figure 3. Within each scenario can be a probability for each individual weather scene. To create these scenarios, typically an ensemble of forecasts is aggregated to reduce the number of scenarios. The degree of aggregation will depend on if these forecasts are solely for automation or the human user. A human user will require a handful of scenarios to make it easier to interpret while automation can use more scenarios. There are other techniques that are designed to have the automation use many probabilistic forecasts with no human interaction[7]. There are 3 possible outcomes for this forecast; 0% no thunderstorms, 10% severe thunderstorms, and 90% moderate thunderstorms. Within each scenario, there is a probability associated for each thunderstorm characterization. In this example, the moderate thunderstorm scenario shows a 20% probability of the thunderstorms being comprised of isolated cells, 20% squall line, and 60% a squall line with some gaps. For Fig 2, a routing algorithm can consider the probabilities of each VIL > 3 occurring at these locations and create routes around or through them. A probability associated with a deterministic forecast only shows the likelihood that each convective feature will develop for one scenario. However, a probabilistic scenario forecast will show other possible scenarios such as shown in Fig 3. A routing algorithm can consider all the possible scenarios in a probabilistic scenario forecast and route traffic proportionally to the probability of each scenario occurring or use another scheme.

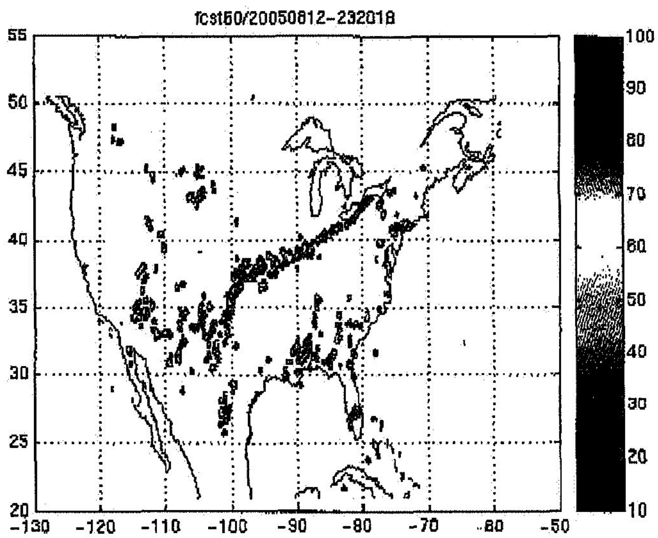


Figure 2 – 1hr NCWF6 probabilistic forecast. Probability are contoured according to the color legend. Data courtesy of the National Centers for Atmospheric Research, Boulder, Co.

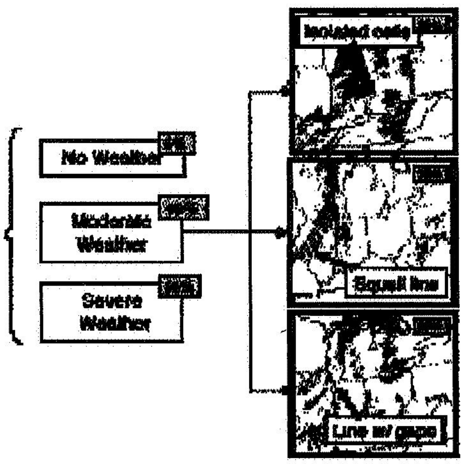


Figure 3 – Depiction of probabilistic scenario from Davidson et al.[14]

Weather Data in DST Route Building Algorithms

There is a time-range for which observation or forecast products are useful. For long-range advisories, a forecast becomes more important and observation less important at the far end of this advisory. However, forecasts can also be useful for some short-range advisories. A forecast may show a developing storm that is not yet detected by observation to appear in the near term. Conversely, an observation product is not very useful in creating an advisory to be invoked near 6hrs. However, all these data should be considered when creating an advisory. A route building algorithm should evaluate if any part of a DST trajectory prediction coincides with a weather constraint. This can be performed by evaluating the observation data and then evaluating the forecast data. The influence these data have on an advisory is dependent on how time relevant those data are to a specific advisory time horizon.

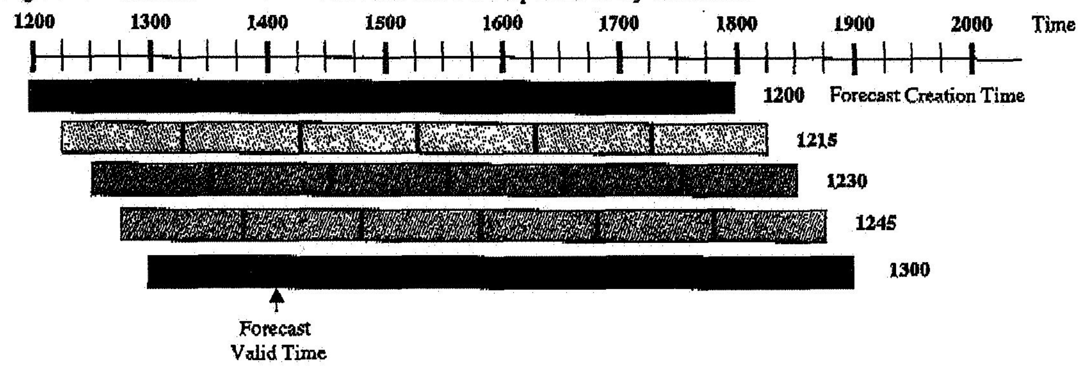
Figures 4a and Fib 4b will illustrate the use of weather data in a DST by showing how a DST can use surveillance and forecast weather data to create routes. This example shows a departing aircraft flying from SFO to the east in the presence of thunderstorms as a result of typical front moving east. Overlayed on Fig 4a are simplified thunderstorm forecasts and observations. Forecasts are unfilled polygons and observation data are filled. Colors indicate the intensity of the storm region. Green is least intense, yellow is moderate and red is most intense. For this example, the forecasts and observations are updated every 15 mins. Geographic and low sector boundaries of the ARTCC are also shown. Time steps along the aircraft advisory route or aircraft prediction are set at 15 minutes with the origination time set at 11:00am. Flight time of this turboprop to Lake Tahoe is approximately 1hr. Surveillance at 11:00am shows 2 individual storms to the north and one to the east of SFO. A short-range deterministic forecast that is valid at 11:15am (15 minutes into the future) shows the 3 storms moving south and the development of 2 currently undetected storms.

For the first 15 minutes time-step, the current surveillance data is more relevant for this time-step and lower for the forecast data resulting in an advisory for the aircraft to fly south and graze the forecasted storm to the south. This forecasted storm to the south is not due to appear until after the aircraft has passed it so the DST may consider this an appropriate choice.

In Fig 4b, it is 11:15am and the surveillance shows the 2 forecasted developing storms have shown up. The forecast shows some storms moving to the south-east with the one near the California-Nevada border stalling. The northern most storm is forecasted to decay as shown with the decreasing forecasted intensity and smaller size. The forecast shows the storm north of Lake Tahoe moving south into the aircraft's planned path about 45 mins from the aircraft's current position. The DST creates an advisory that curves to the north avoiding this and the stalling storm near the state border but passing right over the current position of a storm north of Lake Tahoe. However, the current storm is predicted to move so the observation data are not as relevant to this time-step and higher for the prediction data.

between forecast data as shown in Fig. 5a and b. This figure shows five successive forecasts created at 1200, 1215, 1230, 1245 and 1300.

Figure 5a – Illustration of successive 6hr forecasts updated every 15minutes



Each forecast has forecast time-steps of 1hr that are indicated with a solid black line. For example, the 1200 forecast has forecasts that are valid at 1300, 1400, 1500, 1600, and 1700. Figure 5b shows the 1300 forecast can be augmented with previous forecasts. This time line shows a forecast at created at 1300 with

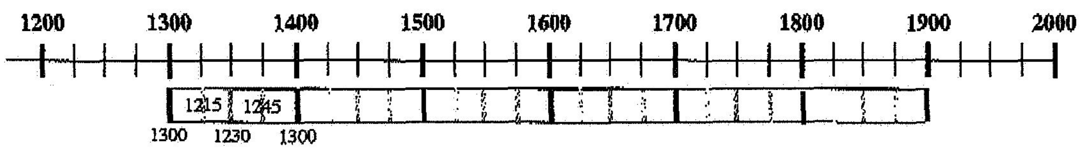


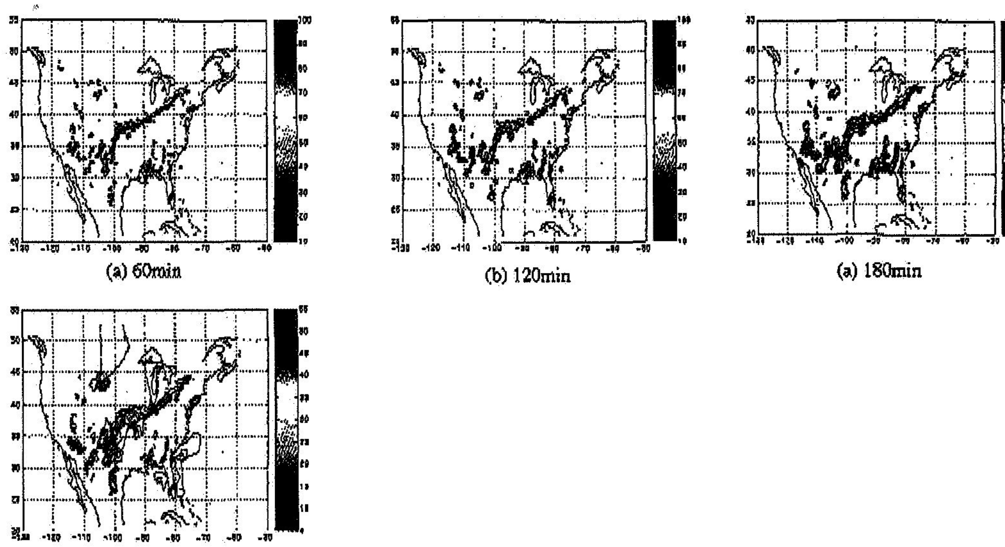
Figure 5b – Example of using previous forecasts to augment current forecast

forecast time-steps at each hour. The timeline is segmented into 15 min increments. Fig 5b collapses all the valid forecasts prior to the most current 1300 forecast onto one time-line to illustrate how previous forecasts can be used to increase temporal resolution. At 1300, there is a valid forecast at each hour. In between these hours, previous forecasts can be used to provide data at 15min in between each hour. Colored lines coincide with the colors of the forecast times in Fig 5a and illustrate which previous data can be used to augment the 1300 forecast. At 1300, the forecast created at 1215 can provide data for 1315 and the forecast created at 1230 can provide data for 1330 and so on. The data for 1815Z is 45mins old at 1300Z so even with using previous forecasts, there exists a need for higher fidelity temporal forecasts.

NCWF-6 researchers believe a forecast with higher fidelity forecast time-steps of 15mins can be achieved. This will result in a large dataset resulting in longer transmission times and could pose to be an operational issue in loading these data into a DST. Until higher temporal fidelity forecast data are available, an algorithm in the DST can be developed to provide forecast data for times outside of the forecast time-intervals. The following section describes a method to provide forecast data for times outside of forecast time-intervals.

Time-Relevance of Convective Forecast Data

For any forecast, there are instances where there will be no forecast data for every time interval. In cases where the time intervals are fairly close, such as 15 minutes, using the forecast time closest to the time of interest may suffice. Forecasts with longer time intervals may require another technique to obtain the necessary forecast data. Interpolating forecast data is a common technique in providing data where none exist.[8,9] Wier[9] mentions some primary weather elements such as temperature and winds can be interpolated using a linear or polynomial methods. Temporally interpolating visibility data is tricky and he shows an example where no simple interpolation scheme could predict the correct visibility forecast. Visibility may degrade quickly in high visibility areas depending on the appearance of fog or other obstructions which may not always be brought in by advection. Convective forecasts are similar in that they also do not lend themselves to simple interpolation and care must be taken to temporally interpolate convective forecasts for similar reasons. Figure 6 illustrates the challenge in interpolating convective forecasts by using sample NCWF6 forecasts from 60 mins to 240 mins. The probability of VIL > 3 are contoured according to the color legend. For the longer range forecasts, the maximum probabilities are lower and there are more probable regions of convection. Interpolating between the 120min and 240min forecast to produce a 180min forecast would not produce the actual 180min forecast. At 120 min, there is a high probability a storm is present in south Florida and at 240min the probability of occurrence is very low. Simply interpolating between 120 mins and 240mins to create a forecast at 180mins will produce a forecast of a lower probability of strong convective activity than at 120mins. The actual 180min forecast shows a higher probability of strong convection; quite to the opposite of the interpolation result.



(a) 60min

(b) 120min

(a) 180min

(d) 240min

Figure 6. Example NCWF6 forecasts. Data courtesy of the National Centers for Atmospheric Research, Boulder, CO.

If interpolation does not always yield reliable results, then another method needs to be applied to best use whatever forecast data are available. The following describes a method that assumes forecast data are useful outside of their specified valid forecast time. There exists a time outside of a forecast's valid time that those data are useful. A forecast that is valid for 1200 may be useful at 1201 or 1210. This range of usefulness can depend on how fast that particular weather phenomena are changing. A usefulness or "time-relevance" (t_r) metric can be associated with each forecast time-step to be used in a re-routing algorithm. A high time relevance indicates the forecast data is highly relevant for that time. t_r can simply be based on the "nearest neighbor" approach where the forecast data closest to a particular time is used.

Figure 7 illustrates a function, other than "nearest neighbor" that can be used to describe the relevance of weather data outside of the forecast valid time. This time-relevance of weather function is shown as a function of time from the forecast valid time. At forecast valid time (t =0), the value of this forecast is the highest. Before and after this valid time, the value of this forecast is shown to decrease according to Eqn 1. Cole[10] showed the time-relevance of RUC data can be modeled with a similar equation.

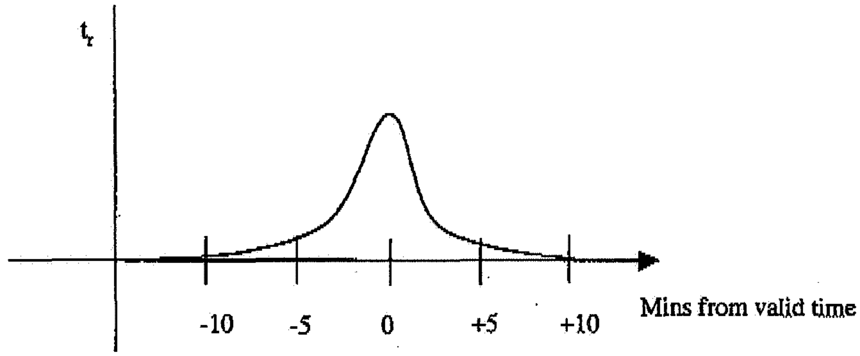


Figure 7. Time-relevance of weather data function

$$t_r = Ae^{-Btime^2}$$ **Equation 1**

$-\infty < time < \infty$ for forecast data

where A sets the maximum value of t_r and B affects the shape of the function. The application of the time-relevance function is shown in Figure 8. A 4hr forecast with 1hr forecast intervals created at 1200 is shown. Each tick in between the forecast intervals are 15 minutes. The time-value function is shown above the time-line. Maximum t_r is shown at each forecast interval and then is reduced to zero at the midpoint between the successive forecast time-interval. Clearly these time-relevance functions can overlap and each time step can be a combination of forecasts.

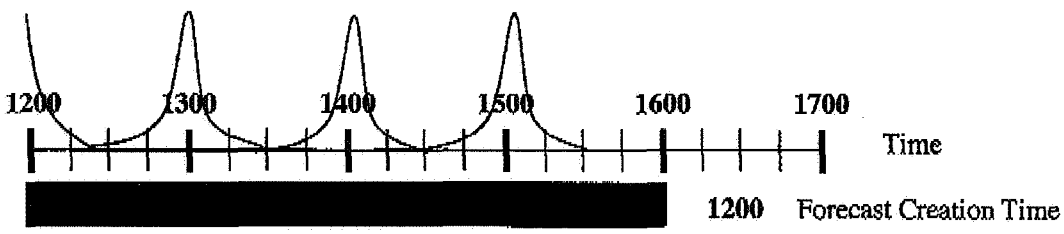


Figure 8. – Application of time-relevance function

The following section will show how the t_r is used in a Decision Support Tool for re-routing advisories.

Appendix

Convective Weather Forecast[11]

The Convective Weather Forecast (CWF) is developed by Lincoln Laboratories for use in the Integrated Terminal Weather System and Corridor Weather Integrated System. This product uses a multi-scale storm tracking algorithm that takes into account measured storm growth and decay trends and underlying models of how convection behaves. CWF is designed to track the envelope motion of large scale storms and the cell motion of smaller, isolated cell regions. It computes growing and decaying trends of precipitation (radar-based estimate of vertically integrated liquid water) over different time scales to make estimates of future storm strength and areal coverage. A significant aspect of this system is its categorization of weather type (line, stratiform, small or large isolated cell, etc.), used in applying the correct track vectors, growth and decay trends and storm evolution models to the forecast, and ultimately in predicting the impact of the forecasted weather on air traffic capacity

National Convective Weather Forecast-6[12]

The current National Convective Weather Forecast developed at the National Centers for Atmospheric Research (NCWF) provides an operational 2 hour forecast product and an experimental 6 hour product is being tested for operations in 2007. Both products are similar in their output with different forecast ranges. The National Convective Weather Forecast (NCWF) product, designed and implemented by the National Center for Atmospheric Research (NCAR), provides current convective hazards and 1-hour extrapolation forecasts of thunderstorm hazard locations. The hazard field and forecasts update every 5 minutes. The NCWF convective hazard field depicts areas of aviation hazard due to convective activity. The hazard field is based on National Radar Mosaics and National Lightning Detection Network cloud-to-ground data. The NCWF product provides a 1 hour extrapolation forecast which are most reliable for long lived mature multi-storm systems. However, the initiation and dissipation of these systems, as well as shorter lived isolated storms, are not well forecast at this time

Collaborative Convective Forecast Product[13]

The CCFP is prepared through a multistep collaborative process that begins with AWC forecasters, but includes participation from airline meteorologists and dispatchers, as well as meteorologists from the Center Weather Service Units (CWSUs) at the Air Route Traffic Control Centers (ARTCCs). A CCFP forecast is produced and issued every other hour from 3 AM to 11 PM Eastern Daylight Time, every day from early March to late October, and is the result of the collaboration of several meteorological facilities. Each issuance includes three forecasts; one with a lead time of +2 hours from the issue time, one with a +4 hour lead time and one with a +6 hour lead time. The domain of the forecast is the 48 contiguous United States, southern Ontario and southern Quebec, and certain adjacent areas. The forecast parameters are the expected location, coverage, tops and movement of thunderstorms The CCFP is used as a strategic decision aid by the decision-makers at the airlines and the Air Traffic Control System Command Center (ATCSCC) for rerouting air traffic around convective weather.

Convective Outlook[14]

Convective outlook is not a model but coarse manually developed guidance. The Storm Prediction Center is the National Weather Service's center of expertise for forecasting convection, especially for economically-disruptive weather events such as tornadoes, large hail, and damaging winds. The current SPC severe thunderstorm forecast product suite includes Convective Outlooks for today (Day 1), tomorrow (Day 2) and the day following (Day 3). According to the National Weather Service, a severe thunderstorm produces hail that is dime size, 0.75 inches in diameter or larger, and/or wind gusts to 58 mph or greater, and/or a tornado.

RUC Convective Forecast Product[15]

NOAA's Global Systems Division, formerly the Forecast Systems Laboratory, has developed a convective probability forecast product based on the Rapid Update Cycle (RUC) model (Benjamin et al 2004a,b). This product is not yet operational. The RUC Convective Probability Forecast (RCPF) was first tested in a real-time mode during the summer of 2003, with verification of 2-, 4-, and 6-h forecasts performed within the Real-Time Verification System (RTVS, Mahoney et al 2002).

North American Mesoscale[16]

Formally the ETA model until Jan 2005. The ETA model was named after the ETA coordinate system, which is a mathematical coordinate system that takes into account topographical features such as mountains. As a result of using this coordinate system and the higher resolution, the ETA model has a much more accurate picture of the terrain across the USA.

Global Forecast System[17]

The GFS incorporates all codes that support the production of the GFS suite of products, including a medium range forecast model (MRF) and a global data assimilation system (GDAS). We will generally use GFS to refer to both.

The predecessor to the GFS was developed experimentally during the late 1970s (Sela 1980) and implemented as the global forecast model at the National Meteorological Center (NMC, now the National

Centers for Environmental Prediction or NCEP) on 18 March 1981 at the following resolutions:

- Triangular truncation at 30 waves with 12 levels (T30L12)
- T24L12 from 48 to 84 hours
- T24L6 from 84 to 144 hours (TPBs 282A and 282B)

The 1981 global spectral model was developed as a result of increased computing power, which enabled spectral models to become competitive with global operational grid point models. In fact, the model replaced the seven-level, 191-km grid point primitive equation model used in various configurations since the late 1960s.

Major changes were made to the global spectral model in 1985 (TPB 351), at which point it was renamed the Medium Range Forecast (MRF) Model. These changes included new physics packages, an increase in the number of waves resolved to rhomboidal truncation at 40 waves (R40), and an increase in the number of equally spaced layers from 12 to 18.

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