1.2 Methods for estimating air traffic capacity reductions due to convective weather for verification

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1. Introduction

In the realm of forecast verification, it has been increasingly clear that the metrics used must tie back to the user perspective as much as possible. This is especially the case for forecasts used for traffic flow management (TFM) in the aviation community. The users of these forecasts are not trained meteorologists and require a forecast product that is simple, yet has the capability to inform them on which decisions to enact to effectively manage traffic on a rather large scale. Their current operational forecast product is the Collaborative Convective Forecast Product (CCFP) produced by forecasters at the Aviation Weather Center (AWC). Recently, there has been a push to display additional information that can be used to supplement the CCFP coarser polygons in terms of structure. These candidate forecasts must have skill in detecting structure in the important regions of the National Air Space (NAS). Therefore, to assess the structural information added by the candidate forecast a verification metric must be derived that takes into account the user's decision process. Namely, the users are affected by the permeability of the air space at sector levels for tactical decisions and at Air Route Traffic Control Center (ARTCC) scales for strategic decisions (Figure 1). The underlying theme of evaluating forecasts for air traffic flow planning is the reliability of the forecast in identifying convective structure, location, and intensity. A solid linear convective system is significantly more challenging for air traffic management, whereas a linear convective system with gaps between convective cores is slightly more manageable. As current plans for Next Generation Air Transportation System's (NextGen) initial operating capability (IOC) in 2013 do not drastically alter how the air space is currently managed it is necessary to keep the current NAS structure in the verification scheme yet make it flexible enough to handle future NextGen directions.

Two schemes were developed by the Forecast Verification Section (FVS) within NOAA/ESRL/GSD to address the issue of convective structure, namely the Euclidean Distance and Mincut Bottleneck approach. The schemes were developed using slightly different methodology, but yield similar results. Both schemes share common background information such as underlying historical air traffic data, jetway corridor information, and similar methodologies of overlaying hazardous convective weather. It is important to note that the metrics produced attempt to assess the permeability and porosity of the airspace for verification purposes and in doing so is simply a relative comparison of the forecast to the observation. This is not an attempt to address actual complex flow of the NAS.

Section 2 will outline the steps in assessing the permeability of the airspace. Section 3 of this paper will outline the background air traffic information necessary in both approaches. As the Mincut Bottleneck approach will be the focus of this paper, Section 4 will explain the basics of the approach. Section 5 will outline advancements in the algorithm for NextGen applications. Section 6 will examine some of the metrics pulled from the Mincut

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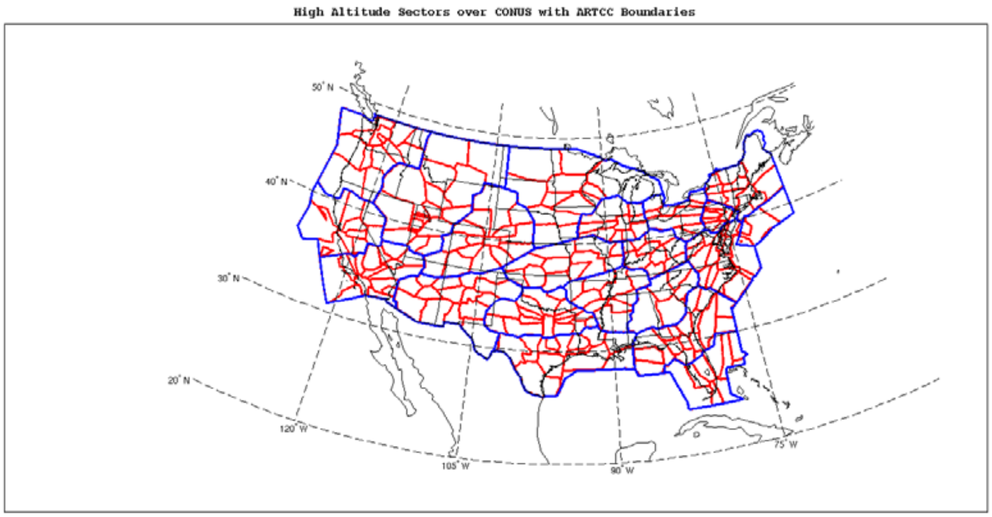


Figure 1. En route (ultra high altitude) sectors (red) over CONUS with ARTCC boundaries blue).

Bottleneck approach that are used in the verification effort. Section 7 will address future directions.

2. Assessing Air Space Permeability

The permeability of the airspace is determined by a five step process. The first step is to determine a geometry of aggregation, which can include ARTCC or sector polygons as well as arbitrarily shaped polygons. Air traffic corridors are then identified through the selected geometry. These corridors are based on observed aircraft behavior. The third step is weighting the corridor, which is accomplished through examining historical air traffic densities based on the Aircraft Situation Display (ASD) database. Corridors may also be weighted equally for some sensitivity studies. Convective obstructions to air traffic flow are then overlaid on the geometry of aggregation. These obstructions can be based on radar reflectivity, vertically integrated liquid (VIL), echo tops, or any derived convective field. Obstructions may also be probabilistic in nature. Finally, a metric is chosen to evaluate the permeability of the airspace, namely the Mincut Bottleneck approach or the Euclidean distance approach.

The Mincut Bottleneck approach estimates potential capacity by calculating the minimum distance across a given airspace geometry from a source and sink node (perpendicular to the corridor of air traffic flow) using convective objects as nodes. The minimum distance found from the forecast and observation for the particular geometry is then compared to the minimum distance without convective hazards overlaid. The convective objects may be dilated to estimate an air traffic avoidance field. The Mincut Bottleneck methodology for capacity reduction estimations is derived from proposed air space management for NextGen applications (Krozel et al. 2004).

The Euclidean distance approach estimates potential capacity by examining geometrical disturbances within the defined corridor. Euclidean distance is simply the calculated distance from a pixel to the nearest non-zero pixel (convective blob or corridor boundary). Convection is overlaid in the corridor of interest and the maximum Euclidean distance is calculated for that corridor and is compared to the maximum Euclidean distance when no convection is present. This is also done using the area of the Euclidean distance greater than some threshold to simulate an avoidance field. Complete blockage occurs when there is no connection between the entrance and exit points of the corridor in the Euclidean distance field (the Euclidean distance field must be greater than 0 and contiguous from entrance to exit).

3. Use of Air Traffic Data

The primary way to attach skill of forecasts to the aviation community is to examine how a given forecast performs in regions where TFM is more complex, usually meaning regions where air traffic has a higher density. The crux of understanding the permeability of the air space as it pertains to capacity is to apply actual air traffic information. The data used for the Mincut Bottleneck or Euclidean Distance schemes come from the ASD database which keeps records of air traffic over the NAS. This includes but is not limited to: aircraft type, arrival, destination, route (jetways and waypoints), and altitude information. The ASD data are used to create a system of air traffic corridors based on historical (previous season) flight routes to be applied to specific defined regions (in the current case ARTCCs or high altitude sectors).

The air traffic data include jetway information from the ASD database for the en route air traffic problem overlaid on the geometry of importance to the user (i.e. high altitude sectors, ARTCCs, or arbitrary polygons). There are 2 major types of jetways, low-altitude victor (designated with a V) and high altitude air jetways (designated J). There are additional jetways that specify special and international routes. For most studies we are concerned primarily with air jetways as most commercial flights are considered high altitude (above 27 kft in cruising altitude). These jetways overlaid onto sector or ARTCC geometries are then weighted according to air traffic density. The data are summarized by averaging the previous season's actual air traffic along a specific jetway by time of day to come up with hourly air traffic densities. It is well known that current air traffic has a weekly variation depending upon day of week, but the historical average density for a specific hour for all days is considered adequate for identifying primary routes through high altitude sectors. This weighting of the jetways within a sector or ARTCC becomes important when calculating the potential blockage of airspace when convection is overlaid.

The air traffic densities are updated after each season to keep up with changes in flow due to the increase or decrease in air traffic demand. It is also updated for different geometries selected for a particular study, whether it is how current air traffic flows in the NAS in sectors and ARTCCs or in arbitrary spaces such as a uniform hexagonal grid. Additional stratifications may also be used in the creation of the air traffic data such as altitude bands or aircraft type. This becomes increasingly important as forecasts of convection contain information of echo tops that may be used in greater detail by traffic flow management.

4. Current Mincut Approach

Mincut theory and subsequent advancements have been increasingly visible in the NextGen community for both air traffic planning and forecast evaluation (Song et al. 2009; Steiner et al. 2009). Mincut theory is derived from graph theory in which a sink and source node are connected to nodes within a domain; the resulting minimum cut is the sum of the shortest line segments (bottlenecks) from the sink and source nodes passing through the domain and any nodes within the domain. In the case of this exercise, convective hazards are the nodes inside the domain and the source and sink nodes are chosen to be perpendicular to the corridor. The Mincut technique is depicted in Figure 2, where the jetway representing flow is in green, the corridor is outlined in blue, the convective hazard is red, the bottleneck due to convection and due to the corridor geometry are labeled and appear in orange.

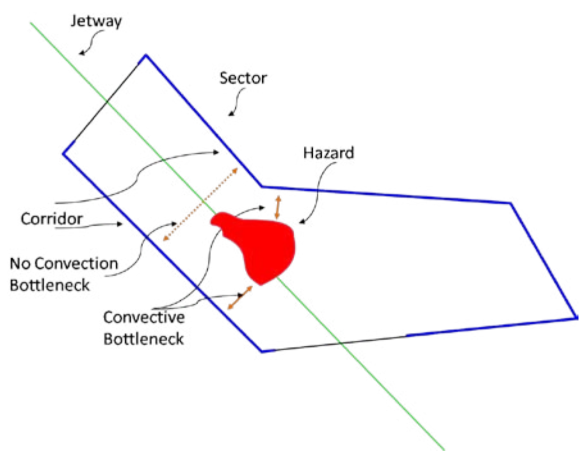


Figure 2: Illustration of the Mincut Bottleneck technique for a jetway,

The ratio of the bottlenecks become the basis of estimating the potential flow reduction in the sector or ARTCC and is given by (1). A flow reduction of 1 means the corridor is completely blocked by convection, where as 0 means the corridor is completely unblocked.

$$Flow\ Reduction = 1 - \frac{Mincut_{convection}}{Mincut_{corridor}} \quad \textbf{(1)}$$

Once the historical air traffic flow data are collected, this background information can be applied in calculating flow blockages due to convective hazards. Connecting to current TFM operations, at least through the IOC timeframe, sector and ARTCC geometries were used as geometries of interest to understand flow blockage due to convection (Figure 1). The first step of the Mincut Bottleneck approach is to overlay the non-zero flow jetways onto a given geometry (e.g. high altitude sectors). A flow corridor is defined by the jetway's entrance and exit points with the corridor width based on observed deviations from jetways. For each corridor through a sector or ARTCC, the bottleneck is calculated and then compared to the flow obtained without convection. The results are then weighted by the importance of the corridor due to the amount of traffic through that corridor at that specific time based on historical data.

Past independent evaluations from the Forecast Verification Section (FVS) at NOAA/ESRL have used CCFP and the National Convective Weather Diagnostic (NCWD; described by Megenhardt et al. 2004) as the baseline forecast and observation, respectively (Kay et al. 2007). The current forecasts being evaluated as supplemental products to CCFP include the Localized Aviation MOS Program (LAMP) Thunderstorm Probability field (Charba and Liang, 2005) and the Consolidated Storm Prediction for Aviation (CoSPA) product (Wolfson et al. 2008). Dichotomous products such as NCWD and the CoSPA VIL or Echo Top fields are relatively easy to deal with in terms of calculating the permeability of a given airspace. Convective nodes can be defined simply by setting a threshold on the NCWD field (VIP 3 or equivalent) to create a convective hazard field which is overlaid onto a sector and its weighted corridors. Nodes can also be defined based on other fields such as a derived avoidance field. CCFP, which is defined as a combination of a range of convective coverage and a probabilistic confidence, and the probabilistic LAMP field requires additional effort in computing the permeability of a given airspace.

The primary mechanism of computing the permeability metric for probabilistic products relies on transforming the probabilistic field into a convective coverage field. Although the probabilistic field (such as LAMP) might not translate exactly into coverage by the product definition it is important to note that for convective planning this transformation is necessary. For example, LAMP probabilities calibrated for long term climatology reliability may score quite well, but decisions for strategic air traffic routing requires information on finer temporal scales.

CCFP although already defined as coverage (with additional high and low confidence stratifications) has been shown to have a human calibration from the actual definition of the product. This allows for a historical distribution of coverage to be put in place for CCFP polygons of different coverage and confidence combinations. For example, a sparse coverage, low confidence polygon defined as convective coverage ranging from 25-49% has a mean convective coverage over the last 5 years of ~3%. Using this calibration, a CCFP polygon of sparse coverage will increase the permeability of the sector more realistically.

Once convective coverage is determined for the specific products, the Mincut algorithm can be applied. This is accomplished by a neighborhood approach using the coverage percentages. For example, if a uniform CCFP polygon covers a sector completely the permeability reverts to inverse of the coverage.

5. Adaptations for NextGen

Although current geometries (ARTCCs and sectors) and associated strategic tools (Airspace Flow Programs, AFPs and Ground Delay Programs, GDPs) are not likely to change in the near future it is necessary to be flexible for new NextGen flight plan strategies. Ideas from flexible jetways to free flight have been explored as possible alternatives. One unique aspect of the Mincut Bottleneck or Euclidean distance approach is that they can adapt to any bounding shape that does not have to necessarily reflect TFM sectors and ARTCCs as they are known today. Additionally, it is possible to account for a flexible jetway approach by utilizing Bézier curves.

Bézier curves are used in image processing and font design for constructing smooth curves of varying degrees between a set of points. The number of points chosen refers to the degree of the Bézier curve. The method herein uses the quadratic Bézier curve for the creation of a flexible jetway. The illustration in Figure 2 is representative of using a defined corridor where air traffic along the jetway may deviate anywhere in the sector as long as the entrance and exit points are constant. This can be thought of an example of free flight within a sector and gives a good estimate of sector permeability. However, flow can be slightly more restrictive. There may be some degree of flexibility in the jetway which can be governed by the use of Bézier curves. Figure 3 shows an example of a jetway with a variety of “flexible” degrees which converges to the simplest, most restrictive flow form, a no-deviation jetway.

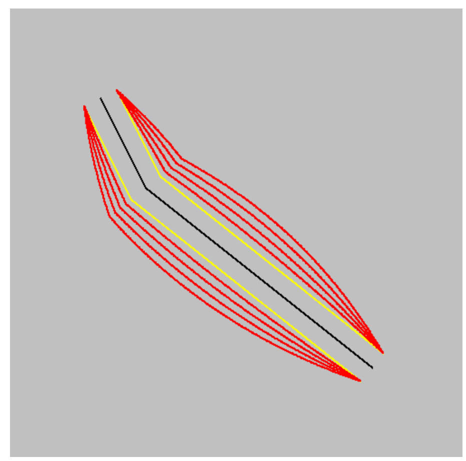
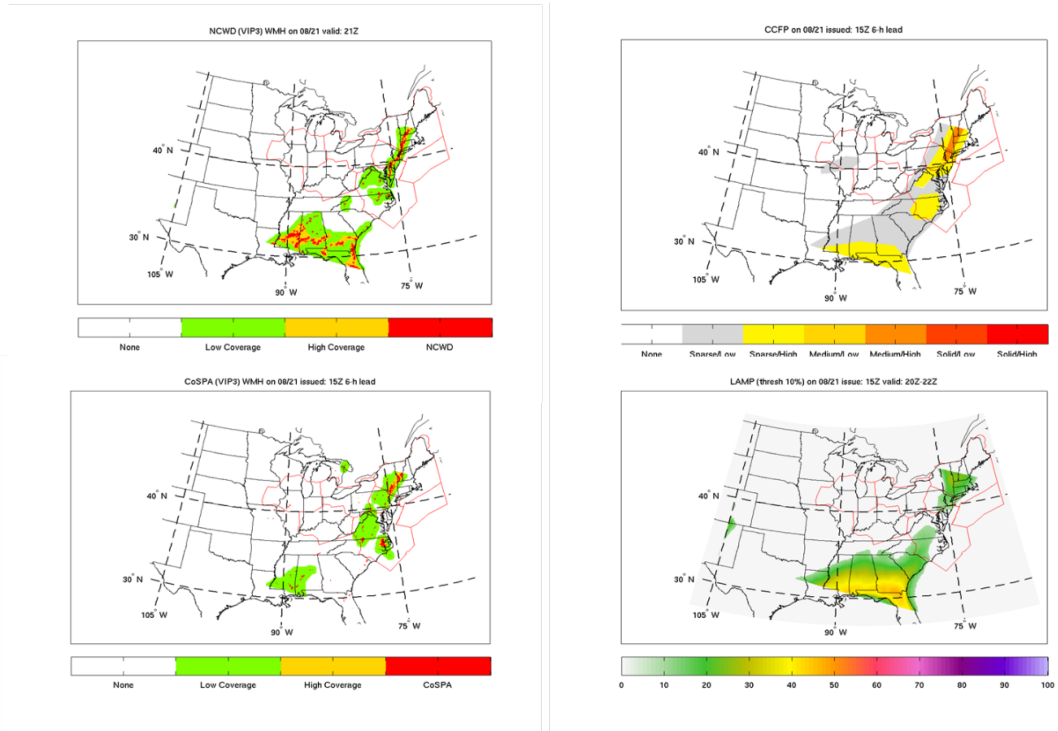


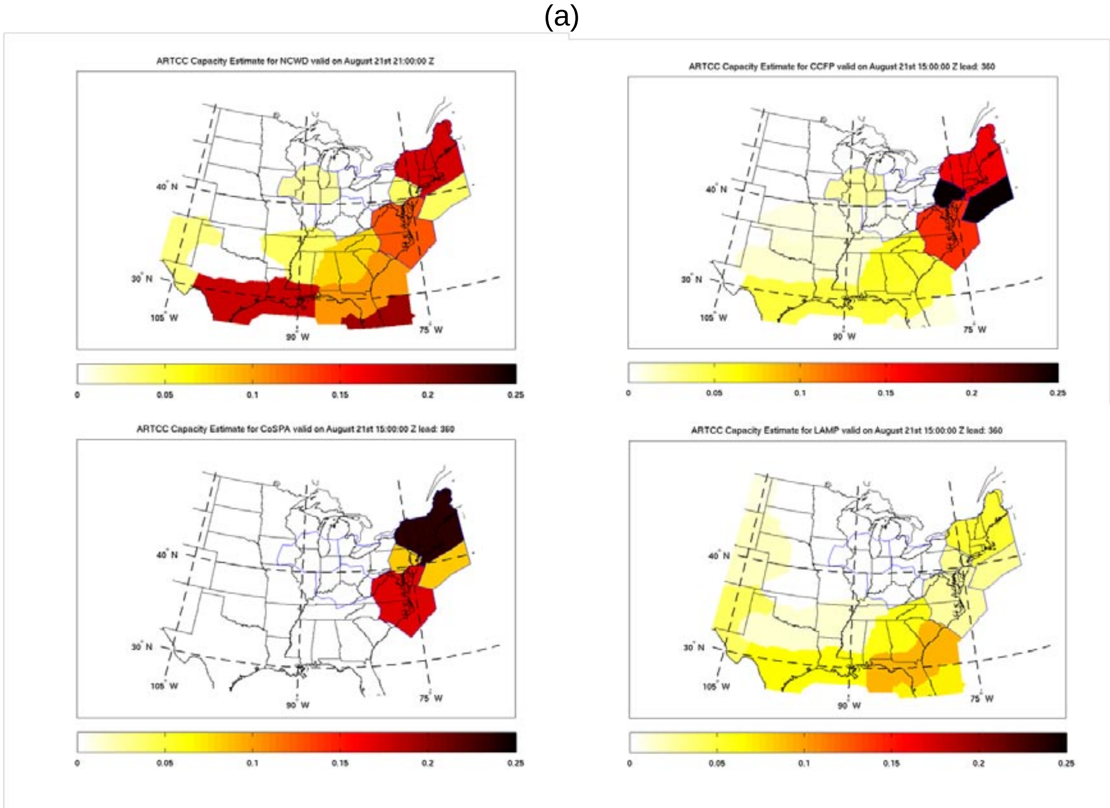
Figure 3. An example of “flexible” corridors with varying degrees of freedom (red lines) away from the route (black) with the original corridor (yellow).

6. Verification Metrics

The focus of this paper is to use the Mincut Bottleneck approach (and corresponding Euclidean distance approach) to verify convective forecasts in the context of current operational planning while remaining flexible enough for NextGen planning. Current TFM relies on having sharp, accurate forecasts of convective weather in order to deploy playbooks to effectively route air traffic. This requires not



(a)



(b)

Figure 4. NCWD (top left), CCFP (top right), CoSPA (bottom left), and LAMP with a 10% threshold (bottom right) on 21 August 2009 6-h lead time valid at 21Z (a) with the same products ARTCC flow reductions (b).

only accurate meteorological information, but requires accurate meteorological information on the scales important to operations. This implies that current jetway information, along with ARTCC and sector geometries, be used and weighted by traffic flow estimates. Using historical traffic masks illustrates the need for high resolution convective forecasts in the NE US, where even isolated convection can cause massive delays due to the sheer volume of air traffic. Several ways of communicating results of the Mincut Bottleneck and Euclidean distance technique have been derived ranging from qualitative images to quantitative statistics based on aggregate measures. Images of sector capacity reductions on the ARTCC scale are shown in Figure 4. The ARTCC scale was used due to the fact that AFPs are traditionally issued on the ARTCC scale which is of high importance to the command center.

Forecasts are not considered useful to the strategic planning process if they are not considered sharp. Sharpness refers to the ability to forecast extreme events with relative frequency to that at which they occur. In this context, sharpness can be measured with the Mincut Bottleneck algorithm. If a particular forecast exhibits sharpness it is more apt to go out on a limb to predict high impactful events affecting a sector or ARTCC. Diagnosing sharpness has been accomplished by the use of a simple histogram of ARTCC permeability in past studies. It can be clearly seen that a climatologically driven forecast will not exhibit much sharpness as it hedges toward broad areas of probabilities. CCFP is considered a broad forecast containing little to no structural information. However, by issuing small or nested medium to high coverage polygons it does exhibit sharpness at important strategic decision points (e.g. 15 UTC telecon). An example of this sharpness histogram can be seen in Figure 5.

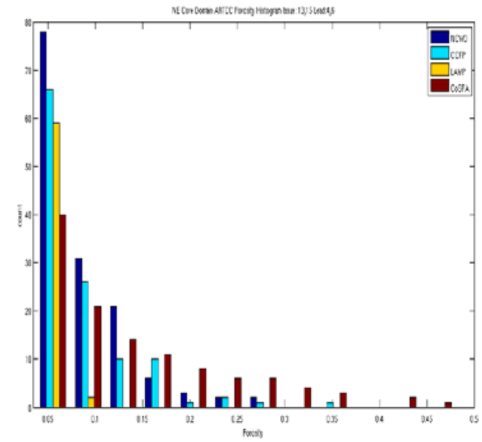


Figure 5. A sharpness histogram showing the frequency of forecasting extreme blockage events in the NE US in late summer 2009, NCWD (blue), CCFP (cyan), LAMP (yellow), CoSPA (red).

Although a forecast must exhibit sharpness, it also has to exhibit accuracy. For this, scatter plots are often useful in representing the skill of forecasting reductions in flow due to the presence of convection. A scatter plot that exhibits perfect skill will fall on the line y=x. Linear regression may be used as a first order comparison of the skill from one product to another. An example of such a scatter plot is shown in Figure 6.

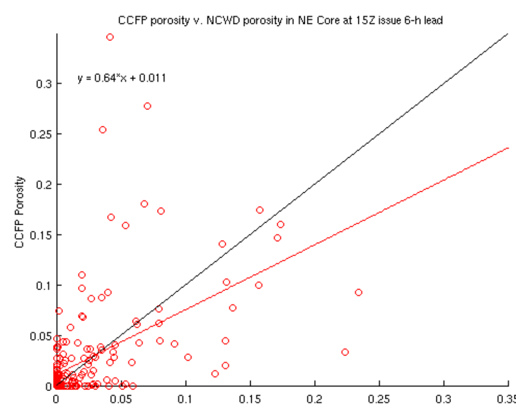


Figure 6. A scatter plot of CCFP flow reduction (y-axis) versus NCWD flow reduction (x-axis). With a regression line plotted.

Additional useful diagnostic plots come into play when examining products of higher temporal resolution as well as products that forecast beyond the 6-h lead time. These plots are referred to as planning point plots. These plots show the forecast of flow reduction through time using the products native temporal resolution while accounting for product latency to give an operational perspective. These plots can show the onset and cessation of important events in sectors or ARTCCs for a specific planning time, such as the important 15Z planning telcon. From these plots aggregate statistics can be generated that show the accuracy of the onset of events throughout the season as well as the cessation of events. High temporal resolution products have an advantage here as events may begin or decay at times between CCFP valid times. An example planning point plot is shown in Figure 7.

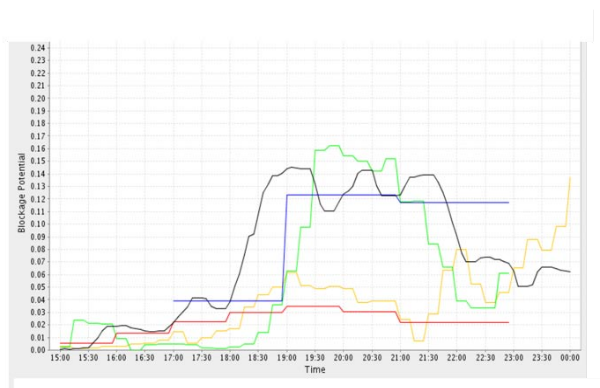


Figure 7. A planning point plot beginning at 15Z for ZDC on 21 August 2009. Black is the smoothed observation showing onset around 17:45Z. CCFP is shown (blue), LAMP (red), CoSPA (green), and the HRRR (yellow).

7. Future Work

Future work of the scheme will involve updating current traffic information from the ASD database. This can include stratifying based on altitude bands and aircraft type for the future application of using echo top fields in both CCFP and CoSPA. Additional work involves adapting the schemes for terminal impacts in addition to the current en route view. Work is ongoing in the transition of these metrics into the Network Enabled Verification Service developed at NOAA/ESRL (Madine et al. 2009). This will allow for the real time access of information to multiple users in the context of aviation planning.

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