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SUMMARY OF WEATHER-ATM INTEGRATION TECHNOLOGY

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1. INTRODUCTION

Air Traffic Management (ATM) is a significant driver for meteorological forecast technologies. In this paper, we present a literature survey for weather-ATM integration technology, identifying the methodologies for translating weather information into ATM impacts in the National Airspace System (NAS). Emphasis is given in the discussion on the ATM impact requirements and needs of the Next Generation Air Transportation System (NextGen).

2. BACKGROUND

The NextGen Concept of Operations [JPDO08, JPDO09a, SM06] and NextGen Weather Concept of Operations [JPDO06] describe how weather hazard mitigation is envisioned for the future of the NAS. The literature survey reported here was conducted for the Joint Planning and Development Office's (JPDO's) ATM-Weather Integration Plan [JPDO09b], and was the result of a collaboration of many researchers providing information about their research efforts. A more detailed survey is contained in Appendix B of the ATM-Weather Integration Plan [JPDO09b].

Figure 1 depicts an abstract decomposition of the components for NextGen Weather-ATM integration. In NextGen, it is envisioned that automated Decision Support Tools (DSTs) will fully integrate weather information into ATM planning processes. Data exchange and forecast dissemination will be handled by infrastructure developed by a NextGen Network Enabled Weather (NNEW) program, utilizing a virtual four-dimensional (4D) Weather Data Cube (Figure 1; left) as a "one-stop-shopping place" for weather information. A subset of that data repository, the Single Authoritative Source (SAS), will contain the primary weather information for ATM decision making. The primary government agency responsible for the 4D Weather Data Cube is the National Weather Service (NWS).

Weather translation models (Figure 1; middle) will transform weather data from the 4D Weather Data Cube into aviation constraints and trigger events. In general, weather translation models reflect how aircraft, pilots, or airlines respond to weather phenomena, independent of the time of day or location in the NAS (that is, independent of the ATM operational state). The primary government agency responsible for the development of weather translation models is FAA Meteorology.

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ATM translation models (Figure 1; right) provide information to compute the ATM impact of the forecasted weather. In general, these may be pixel- or point-based impacts, region-based impact, sector-based impacts, or route-based impacts, as illustrated in Figure 2. Given the ATM operational state (e.g., demand on an ATM resource) and ATM structured elements (airport, runway, and fix locations, routes, sector and center boundaries, etc), the ATM translation models are used to derive the ATM impact. The primary government agency responsible for the development of ATM impact models is FAA ATM.

In the NAS, en route Traffic Flow Management (TFM) balances air traffic demand against available capacity, to ensure a safe and expeditious flow of aircraft. TFM resources may be expressed in terms of airspace availability; this includes fix availability, route availability, and airspace availability (e.g., grid cell, hex cell, sector, center, or Flow Constrained Area (FCA)). Airspace availability is often expressed in terms of the airspace capacity, which is the focus of the majority of the models in this literature survey. TFM resources also include airport resources, including Airport Arrival Rate (AAR), Airport Departure Rate (ADR), runway availability, runway configuration, and others. All these resources are important, and are managed by predicting the weather-ATM impact on each resource.

The ATM impacts are input to ATM Decision Support (Figure 1; right), for use in reasoning about ATM impact mitigation options. TFM initiatives, for instance, Ground Delay Programs (GDPs) and Airspace Flow Programs (AFPs), may then be used to resolve imbalances between demand and capacity during severe weather events in the NAS, given the estimated ATM impact for terminal airport conditions (e.g., controlling the demand to match estimated AARs via GDPs) or given the estimated ATM impact for en route conditions (e.g., how to evenly distribute flights over acceptable en route weather avoidance routing options given en route FCAs). In NextGen, weather constraints will be assimilated into TFM DST technologies for use by humans and automation in controlling the NAS. The primary government agency responsible for the development of ATM decision support is FAA ATM.

3. WEATHER PHENOMENA AFFECTING AVIATION

Weather constraints stem from a variety of weather phenomena that affect either the passenger, crew, airframe, or ATM system [KM07, Kr10]: fog, haze, smoke, clouds, thunderstorms, lightning, hail, heavy rain, frozen precipitation at the surface, in flight icing, wind, wind shears, gusts, Convection-Induced Turbulence (CIT), Clear Air Turbulence (CAT), Mountain Wave Turbulence (MWT), microbursts, tornadoes, waterspouts, snow, volcanic ash, and space weather.

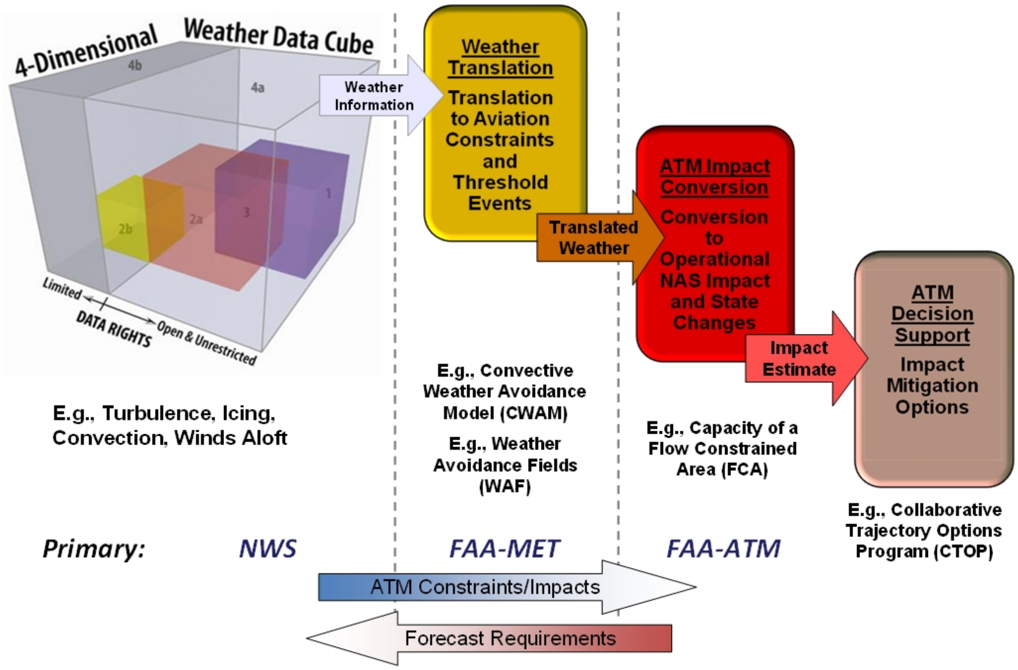


Figure 1: NextGen weather integration concept and primary federal agencies responsible for components.

Some of these aviation weather impacts affect individual flights and possibly could end in a fatal accident, while others are widespread and affect the performance of the entire NAS. This paper does not investigate each of these specific impacts in detail; however, it focuses on those areas where ATM impacts significantly affect NAS performance, anticipating that a Traffic Management Initiative (TMI) may be necessary at the national scale. Related literature [Bu78, AIM08, Le07, Pa94, Tu95] provides for pilot guidance and guidelines for addressing aviation weather hazards in the NAS.

In general, this literature survey addresses the following weather phenomena categories:

- Convective Weather
- Turbulence
- Terminal Area Weather
- Winter Weather
- Oceanic/Remote Weather
- Volcanic Ash
- Space Weather

The organization of this paper is centered along each of these weather categories in the order given above.

Furthermore, this survey includes the classification of each model into the airspace domain where the weather and model are appropriate:

- Surface – those areas involved in gate and tower operations, taxiways, and runways, including non-movement areas.
- Terminal/Transition – We combine the terminal and transition airspace into one domain, even though transitional airspace is typically classified as en route airspace. Terminal airspace is the area delegated to the Terminal Radar Approach Control (TRACON) for the provision of approach and departure sequencing, typically within the range of a "fast-sweep" radar (around 40 to 60 miles). Transitional airspace includes the en route phase of flight where aircraft are climbing out of or descending into airports.
- En Route – En route airspace controls the traffic between terminals, where aircraft are in cruise or transitional phase of flight. In this survey, we only consider the cruise phase of flight for the en route domain.

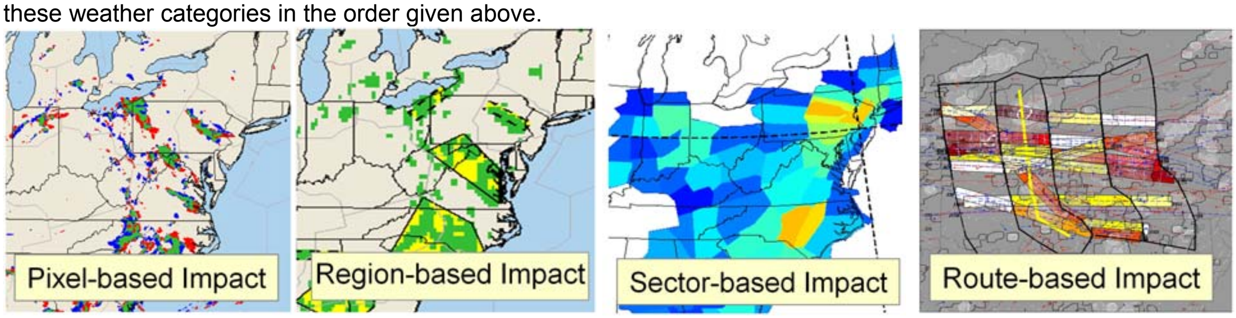


Figure 2: ATM impacts at different levels of ATM-relevant locations.

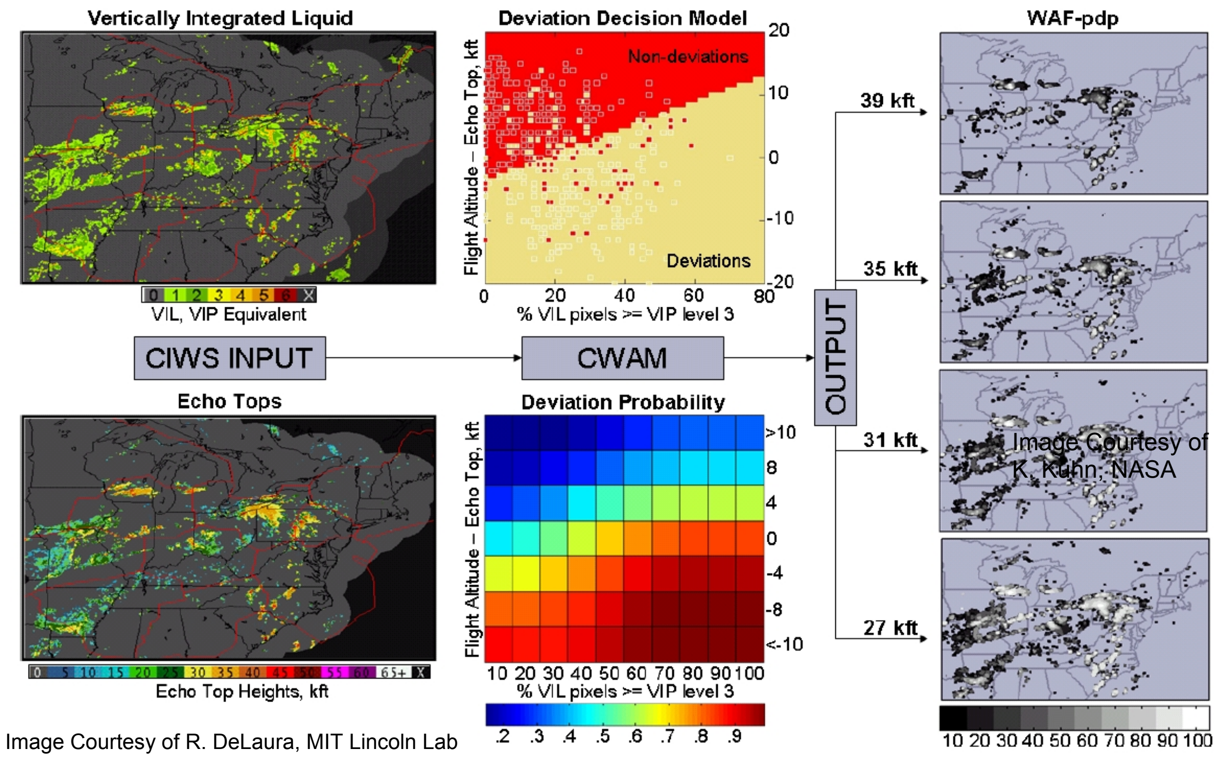


Figure 3: The translation of convective weather into Weather Avoidance Fields (WAFs).

- Oceanic – Oceanic airspace, where the major distinction is the absence of direct surveillance of aircraft, requiring procedural (non-radar) control. In this domain, we also include flight over polar regions, even though such flights may not be over oceanic airspace.

4. LITERATURE SURVEY

Next, we present a survey of ATM-weather impact models, organized according to weather category.

4.1 Convective Weather

There are generally two categories of models being researched for convective weather:

1. En Route, and
2. Terminal/Transition.

Often, these models are referred to as a Convective Weather Avoidance Model (CWAM).

En route CWAM. This model addresses how convective weather impacts traffic in en route airspace. The CWAM model was built by analyzing historical traffic and weather data to determine when pilots choose to deviate verses penetrate convective weather constraints. Both precipitation intensity as well as echo tops data are important factors in the decision. Weather Avoidance Fields (WAFs) are computed as a function of observed and/or forecasted weather (Figure 3) to determine 2D or 3D grids retaining either a probability of deviation (0% to 100%) or a binary deviation decision value (0 or 1). Two approaches have been taken to model and validate weather-avoiding deviations using trajectory and weather data: trajectory classification [RKP02, DE06, DRP08, DRE08, CRD07] and spatial cross-correlation [PBB02, Ku08].

When applying CWAM in a DST, the WAF is thresholded at a particular value (e.g., WAF = 0.7 or 0.8) to define the weather hazard constraint regions where deviations are expected. Recent work on CWAM involves the evaluation/assessment of CWAM for NAS operations [CDM10, MD10a, MD10b, RD10]. In [RD10], a method is presented to extend the CWAM obstacle polygon downwind from the thunderstorm, in order to capture the potential for CIT.

For NextGen, further research is still needed to mature the en route CWAM model. For instance, CIT influences how pilots respond to the moderate and severe turbulence encounters that occur both in and around convective weather [KRB09], and thus, needs to be included in CWAM modeling (as discussed in [RD10]). Today's CWAM models have been developed using only ground-based weather radar data analysis, while most pilot decisions are made based on airborne weather radar, which includes attenuation of the signal. Since current CWAM are based on ground-based weather radar, they do not readily discriminate between relatively benign decaying convection and stratiform rain and turbulence downwind from thunderstorms, both of which are equally characterized by echo tops in the 30-40 kft range and moderate precipitation intensities [DCF09]. In NextGen, data fusion techniques will likely create more detailed 4D short term forecast information about the WAF convective weather hazard by fusing together satellite, winds aloft, CIT estimates [CML04] and other factors. This information can be data linked to pilots to eliminate the attenuation of weather radar returns, and to better differentiate between benign and hazardous weather regions and thus, influence a more informed decision and better convective weather avoidance route choice.

Terminal/Transition CWAM. This model is being researched to address how convective weather impacts terminal/transition airspace arrival and departure traffic. Each WAF grid point is assigned a probability (0% to 100%) and/or a binary value (0 or 1) that represents that likelihood that pilots will choose to avoid convective weather at a point location in the terminal/transition airspace. Terminal/transition area WAFs must model the fact that nominal ascending or descending trajectories for arrivals and departures do not allow for pilots to fly over hazardous weather cells – as is the case for en route CWAM. Pilots flying at low altitudes in the terminal area appear to penetrate weather that en route traffic generally avoids [RP99, RBB00, Ku08]. The willingness of pilots to penetrate severe weather on arrival increases as they approach the ground [RP99].

CWAM models for arrivals differ from CWAM models for departures. For instance, arrivals have a limited amount of remaining fuel so their pilots feel pressure to avoid excessive delays and holding while avoiding weather cells. On the other hand, departures can wait on the ground until the weather is more favorable. While departures typically climb out at full power and hence have little opportunity to deviate to avoid weather in the first few minutes of flight, arrivals have flexibility to maneuver until the final approach. Finally, arrivals descending from above the cloud base have less visual information about the severity of the weather below than departures climbing up from the ground.

For NextGen, terminal/transition CWAM research is needed both to understand the factors that affect pilot decision making during departures and arrivals, to identify the set of weather characteristics that correlate best with observed weather avoidance in the terminal/transition airspace, and to understand how unstructured routing and Required Navigation Performance (RNP) in NextGen may change the characteristics of terminal/transition airspace throughputs. A number of constraints are being considered by several researchers studying terminal weather avoidance mathematical modeling [KPM08, DA03, DRT08, KLM99, KWH97, RDE08, RDU09, TSM10].

Empirical Methods of Measuring Impacts of Convective Weather. Empirical methods are often used to model convective weather impacts. For instance, as illustrated in Figure 4 empirical data analyses [Ku08] reveal how weather impacts aircraft trajectories on an aggregate level. Large sets of historical data may be analyzed in order to discover potentially complex relationships among weather and aircraft trajectory related variables. For instance, precipitation intensity (Vertically Integrated Liquid (VIL) levels), storm cell height (radar echo top heights), and flight level (altitude) are important variables in predicting pilot behavior in the presence of thunderstorm activity. From empirical analysis, pilots generally avoid airspace within 5-km of storm activity, but frequently fly 5-km to 20-km away from severe storm activity [Ku08]. This often results in higher densities of air traffic in regions clear of hazardous weather, compared to clear weather day densities, as Figure 4 points out. From historical data, researchers observe that the sector occupancy counts go down to zero as the percentage of the sector covered by hazardous weather (NWS Level 3+) is 50% or more [KD07].

Rational Methods of Measuring Impacts of Convective Weather. In this approach [HRS05], the sector capacity reduction is evaluated according to percentage of flight plans that are blocked by hazardous convective weather. This evaluation may consider different levels of rerouting (from conservative to aggressive, with a variety of safety margins representing pilot and airline preferences) to evaluate a range of impacts of the weather on the nominal capacity of the sector. Controller and/or pilot workload constraints are modeled as appropriate.

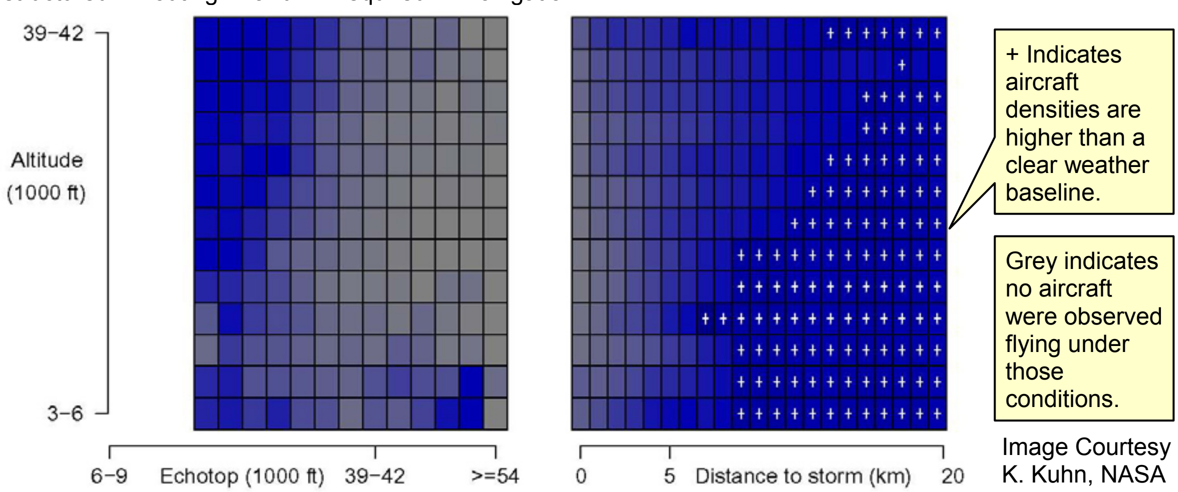


Image Courtesy of K. Kuhn, NASA

(a) Distance to VIL 4+, echo 35k+ Storm Cells (b) By altitude and VIL level in VIL 4+ conditions

Figure 4: Aircraft counts by altitude, VIL, echo top height, and distance relative to clear weather day counts.

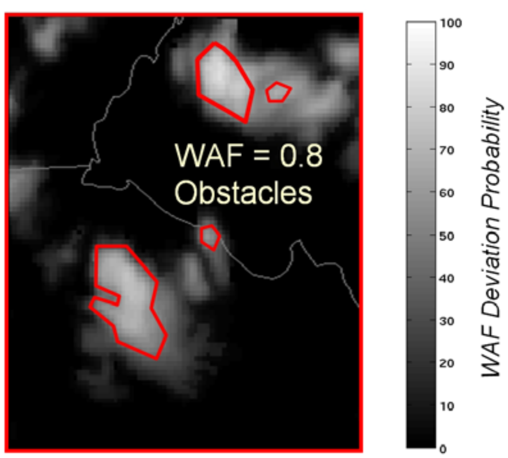
Weather-Weighted Periodic Auto Regressive (PAR) Models for Sector Demand Prediction. Since weather forecast uncertainties cause errors in sector count predictions [KRG02, WCG03], traditional deterministic methods only reliably predict the behavior of NAS for short time durations – up to 20 to 30 minutes. Strategic predictions may be pursued by a PAR model and its variants [Lj99, FP03] to evaluate the performance of various demand prediction models considering both the historical traffic flows to capture the mid-term trend, and flows in the near past to capture transient responses. A component of the model captures weather impacts on sector demand. Only convective weather with echo tops above the lower flight level of the sector are considered in weather hazard modeling. Results indicate improvements over traditional sector demand models [CS09]. Additional information on PAR models is in [CS08, SC08, SC09].

Mincut Algorithms to determine Maximum Capacity. For NextGen, when jet routes can be dynamically redefined to adjust flows of traffic around weather constraints, the maximum capacity of an airspace region may be determined using extensions of MaxFlow/Mincut Theory [AMO93, Mi90, KMP07a]. The network MaxFlow/Mincut Theorem has been extended to a continuous version of the maximum flow problem [Mi90, Ir79, St83], which is suitable for estimating the maximum throughput across an en route airspace given a traffic flow pattern [SWG08], a uniform distribution of flow monotonically traversing in a standard direction (e.g., East-to-West) [ZKK09], or random, Free Flight conditions [KMP07a, KMP07b]. The maximum capacity of transition airspace may be determined by transforming the problem into an analysis over an ascent or descent cone modeling terminal/transition airspace for arrival and departure flows [KPM08]. Mincut algorithms apply to several aviation applications [KMZ09, Ki10, LL10, Z10]. A comparison of the performance of Mincut techniques for estimating capacity compared to other capacity estimation methods is presented in [SWG08].

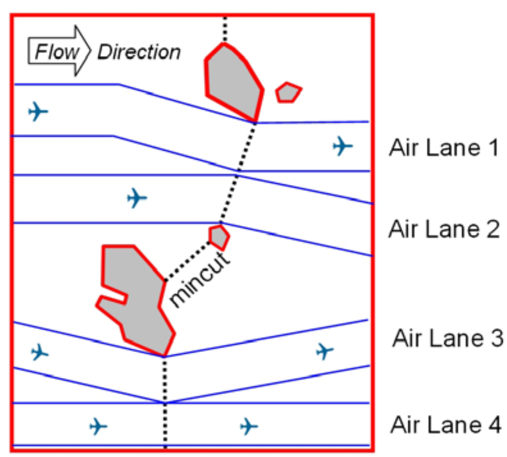
Figure 5 illustrates the model [MPK06]. Given convective weather constraints and a method of defining the weather hazard (e.g., the appropriate en route or terminal CWAM model and WAF threshold), a geometric hazard map is determined. Next, one defines the width of an air lane (equivalently, the required gap size between adjacent hazardous weather cells) that is required for a flow of traffic passing through the airspace (a sector, FCA, grid cell, or hex cell) in a given period of time. The required gap size between weather constraints may be expressed in terms of RNP requirements for air lanes. In one version of the problem, mixed air lane widths are used to represent a non-uniform RNP equipage and/or a set of preferences by aircraft arriving into the airspace [KPM08]. An algorithmic solution identifies the Mincut bottleneck – this Mincut line determines the maximum capacity in terms of the maximum number of air lanes that can pass through the gaps between weather hazards. The maximum number of air lanes can be determined by analyzing weather constraints as a function of time given a weather forecast.

For NextGen, complexity and human workload (controller and/or pilot) limitations must be taken into account for determining the capacity of an airspace.

Sector Capacity considering CWAM and Flow Structure. Sector capacity is limited by controller workload, which is not only a function of the number of aircraft present in a sector, but also a function of traffic complexity. In today's NAS, traffic complexity may be characterized by the traffic flow patterns [SWG06] within a sector; each sector exhibits a small set of typical traffic flow patterns, each of which corresponds to a different level of traffic complexity. Thus, in higher complexity traffic conditions, it takes fewer flights to generate high workload for a controller team, and hence the sector capacity must contain fewer flights.



(a) The weather hazard obstacle is defined by thresholding the WAF data



(b) The Mincut bottleneck is computed to determine the maximum number of lanes of traffic that may pass through the airspace region

Figure 5: The translation of convective weather WAF data into maximum ATM throughput.

In this method, the weather-impacted sector capacity considers CWAM as well as flow structure [SWG06, SWG07a, SWG07b, SWG08, SWG09]. The size, shape, and location of convective weather cells in a sector determine a Weather Avoidance Altitude Field (WAAF), a 3D version of the CWAM WAF. Using clustered flow features [SWG06], the future traffic flow pattern in the sector is predicted and described with sector transit triplets. The available flow capacity ratio of each flow in the predicted traffic flow pattern is then determined using MaxFlow/Mincut Theory. The available sector capacity ratio is the weighted average of the available flow capacity ratio of all the flows in the predicted traffic flow pattern. The weather-impacted sector capacity is the available sector capacity ratio times the normal sector capacity given the predicted traffic flow pattern. The flow-based available sector capacity ratio has a strong linear correlation with the estimated actual sector capacity for the sectors with dominant flows [SWG08].

Route Availability (RA) in Convective Weather. The RA model assess the convective weather impacts on jet routes in the NAS. The analysis is spatially confined to lateral regions (left and right of the centerline) around a jet route. This applies to terminal/transition arrival and departure routes as well as en route routes.

RA methods invoke CWAM modeling, WAF generation, MaxFlow/Mincut and/or Route Blockage (RB) techniques in order to assess the impact that convective weather has on a jet route [KPP04, MED06, WEW06, KPP07, Ma07, MWD09, DRD10, TSM10]. The appropriate terminal/transition CWAM or en route CWAM model is applied based on the airspace domain of interest. RA and route capacity are related to the number, required width (gap size between hazardous weather cells), and complexity of paths identified. The route capacity is the rate of traffic flow that an available route can support. Capacity estimates must account for the workload and uncertainty involved in flying the weather-avoiding trajectories that they identify.

RB uses a probabilistic partition of airspace, in which each pixel is assigned a probability of deviation around the pixel. RB finds the best path that traverses the space, defined as the widest path that encounters the minimum probability of deviation in the traversal. RB is a weighted average of all pixels in the space with deviation probabilities greater than the minimum probability encountered by the best path. RB differs from MaxFlow/Mincut in that it identifies a single path that traverses the airspace, and it takes into account the nature of the weather that trajectories are likely to encounter on their traversal of the airspace.

Weather Impacted Traffic Index (WITI). WITI measures the number of flights impacted by weather constraints across NAS resource locations. WITI was first developed to quantify en route convective weather impacts; however, the approach is now applied to other weather hazard types as well and to the terminal domain. Given a weather grid *W*, the WITI metric assigns to each grid cell in *W* a value of 1 if above a severe weather threshold and 0 otherwise. For a given look ahead time, the number of aircraft predicted to use each grid cell of *W* determines a traffic count *T* for the grid cell. The WITI metric simply sums over all grid cells the product $W \cdot T$ for the grid cell, which can then be computed for any time period [CDC01, Kl05].

The WITI-B variant evaluates the extent to which a flight must reroute in order to avoid severe weather [KCW08b]. If a planned trajectory is projected to encounter severe weather, WITI-B finds the closest point void of weather in a perpendicular direction to the trajectory. The WITI-B score for that route is weighted by the number of cells between the original constrained cell and the unconstrained cell found for the reroute.

WITI traffic counts can be determined in several ways: (1) actual flight tracks from good weather days [CS04], (2) current day flight plans [PBB02], or (3) great circle routes between origin and destination airports [KJL07]. Scheduled flight frequencies for the day in question are used. The En route WITI (E-WITI) for a flow is the product of its hourly flight frequency and the amount of convective reports in a rectangular or hexagonal grid. This can be aggregated to the NAS level, to a 24-hour day, as well as to a center, sector, or general airspace geometry. E-WITI measures may also be allocated to origin and destination airports. While en route delays may not be due to local airport weather, the resulting delays are considered to originate and/or eventuate at the departure or arrival airports. A grid cell's WITI score for a flow is apportioned to each airport proportional to the square root of the distance from the cell to those airports, assigning a larger WITI score the closer a hazardous weather cell is to an airport. This provides a national WITI score recorded by airport – consistent with how NAS delays are recorded in today's Aviation System Performance Metrics (ASPM) [KJL07]. A strong correlation exists between the WITI metric and NAS delays [Sr06].

Further research into WITI metrics considers other factors, such as the number of cancellations, diversions, and excess miles flown in reroutes [Kl05]. Types of weather include local convection, terminal area winds (direction, severity, and altitude), freezing precipitation, low Ceiling and Visibility (C&V), as well as the impact of turbulence on en route flows [CWK09]. The correlation between the WITI and delays [AGE01,CS04, Sr06, SC08, SC09, SrK09] has improved as additional types of weather besides en route convection have been considered. The Terminal WITI (T-WITI) considers terminal area weather, ranked by severity of impact, and weights it by the departures and arrivals at an airport.

Finally, the National Weather Index (NWX) implements the WITI for the FAA. In addition to calculating E-WITI and T-WITI, it considers the additional delays due to queuing during periods where demand exceeds capacity, both en route and at airports. The 4-component NWX is referred to as the NWX4 [CWK09]. Current research is now exploring the use of the WITI for airline route evaluation, departure and arrival fix evaluation at TRACONs, and principal fix evaluation in ATM centers [KMK09].

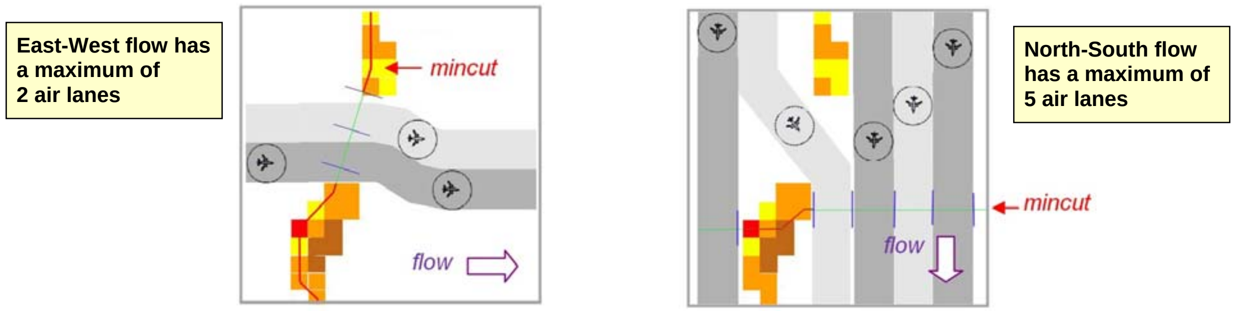


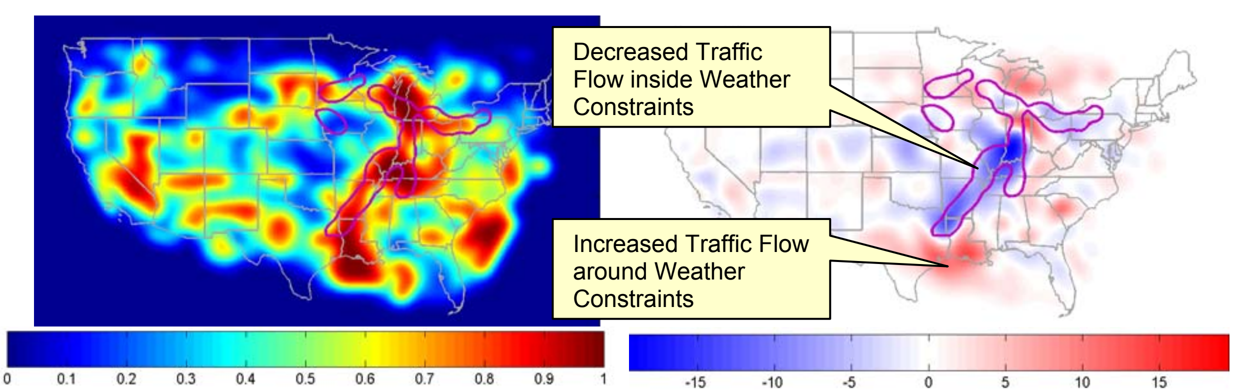
Figure 6: The directional capacity of a squall line with respect to two directions of traffic flow.

Directional Demand and Directional Capacity. In addition to capacity being a function of flow pattern for a given airspace, airborne separation, RNP requirements, and convective weather impacting an airspace, capacity is also a function of traffic demand, both spatial and temporal. Since traffic flow patterns are directional, capacity is also directional. If the majority of traffic in a given period of time wants to traverse a center in the east-west direction and the center airspace capacity cannot accommodate this demand, the fact that the center might have, in principle, plenty of capacity to accommodate north-south traffic does not help. Consider the case of a squall line (e.g. Figure 6), and traffic flow trying to pass through gaps in the squall line. Queuing delays will ensue when the capacity is limited in a particular direction, and upstream traffic will be forced to deviate around the constraint or be held upstream or back at origin airports.

The capacity of an airspace can be estimated [ZKK09] for a series of cardinal directions, e.g., North (N), East (E), South (S), West (W) (e.g., Figure 6) and the diagonals NE, NW, SE, and SW. Also, directions can be quantified every θ degrees (e.g., θ=20°), spaced around a given NAS resource, for instance, around an airport, metroplex, fix location, or within a section of airspace [KPM08, KCW08a, KCW08b, KCW09]. For a given angle, the maximum capacity for traffic arriving from or traveling in that direction may be established. MaxFlow/Mincut techniques [ZKK09, KPM08] as well as scan line techniques [KCW08a, KCW09] and Raycast techniques [PK10] have been demonstrated for this purpose. The maximum capacity for a particular airspace oriented along a given angle quantifies the permeability of the weather with respect to traffic arriving from [KPM08] or traveling in [KCW08a, KCW08b, KCW09] that direction. The permeability can be calculated using pre-defined thresholds [SSM07] that indicate at what probability or actual intensity of convective weather will most aircraft be likely to deviate (or plan the flight around the weather in the first place).

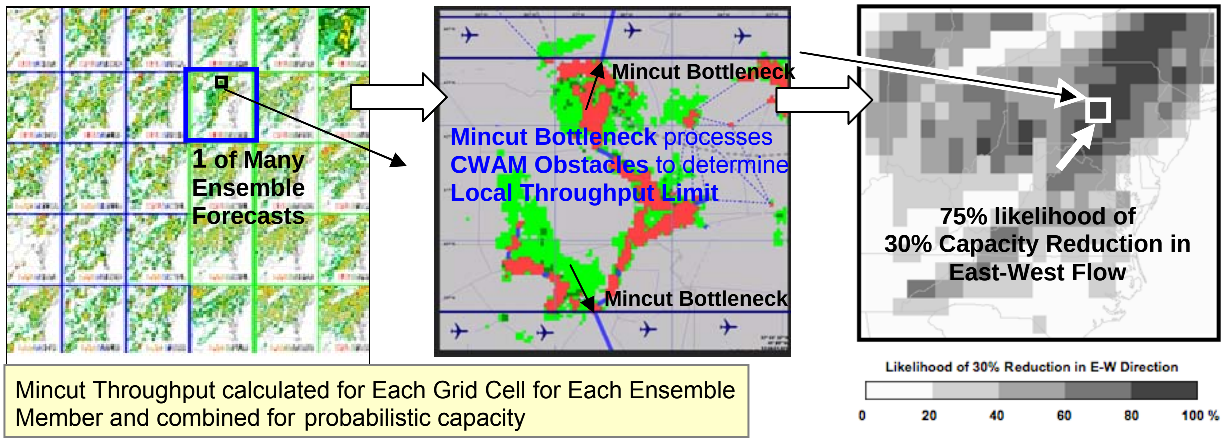
Capacity reductions in a given direction may determine the number of aircraft that can be accepted from or can travel to a particular direction. This may be expressed in units relative to the maximum capacity for the airspace when no weather is present. Directional demand can also be calculated in each direction using the primary direction a flight will take within a given unit of airspace (grid cell, hex cell, sector, center, FCA, etc.).

Impact of Convective Weather on NAS Traffic Flow Distributions. A few models address the strategic adaptation of traffic flows in the NAS due to en route weather constraints. These models estimate the level of congestion that may result as weather constraints reduce the capacity in certain parts of the NAS which causes increased capacity elsewhere (e.g., Figure 7). Two different approaches are based on congestion grids [J05], which consider individual aircraft trajectories and how they may populate space-time grids, and network flow models [MK08], which consider aggregate traffic flow adjustments instead of individual reroutes.



(a) Predicted Traffic Flow relative to Available Capacity (b) Predicted change in traffic counts due to weather

Figure 7: Redistribution of traffic demand due to convective weather constraints.



(a) Ensemble of Forecasts (b) Local ATM impact per Grid Cell (c) ATM Impact Map

Figure 8: Translating ensemble weather forecasts into a probabilistic capacity map in terms of likelihood of a given capacity reduction.

Translation of Ensemble Weather Forecasts into Probabilistic ATM Impacts. In NextGen, in order to capture the uncertainties posed by long term weather forecasting, DSTs will integrate probabilistic weather forecast information into ATM impacts [SM08, SBM09]. The Numerical Weather Prediction (NWP) community is moving toward ensemble modeling techniques as a means to model forecast uncertainty [SBB07, SBM09, SK09, SBM10]. Figure 8 illustrates the process. A series of deterministic forecasts (i.e., members of an ensemble) are generated where each ensemble forecast represents a possible weather scenario that may emerge later in the day. Weather forecasts are in turn translated into ATM impacts with relative likelihoods and probability density functions (pdfs) depending on the ensemble configuration.

This process can be performed using tactical 1-hour as well as strategic 2-, 4-, and 6-hour forecasts processing anything from 2-member to 30-member (or more) ensemble weather forecasts, depending on the ATM application. The definition of a weather hazard could be for convection, turbulence, icing, or other aviation-relevant hazards, and any appropriate weather hazard model can be placed into the ensemble-translation process; for instance, the CWAM WAF for a given altitude range. The airspace capacity reduction could be directional, for instance, East-West, or in any particular direction where TFM plans to organize and direct traffic.

Translation of a Deterministic Weather Forecast into Probabilistic ATM Impacts. While the previously mentioned ensemble approach for characterizing uncertainty of forecasts is promising for long term weather forecasts, other methods may be useful in short look-ahead times. In NextGen, systems can benefit from understanding how a single deterministic forecast in a grid-based format, and some error bounds associated with the forecast, can translate into probabilistic ATM impacts for a given airspace region [KZM09, KPK10].

In this method, a single deterministic forecast is input, and variations on this forecast are created by considering error models that account for possible errors in timing, errors in coverage, translational errors, or echo top errors. Given a standard deviation that describes the potential error in each of these dimensions, a synthetic ensemble of forecasts is created that are similar (perturbations) to the input deterministic forecast. The intermediate ensemble of erroneous forecasts is then input into an ATM impact model, for instance, the RB method or CWAM model, and a set of ATM impacts is output. The ATM impacts may be quantified in terms of a cumulative distribution function (cdf), pdf, a set of scenarios or maps and associated metrics, or some other format.

The set of erroneous forecasts represents “what if” cases; “what if the weather system arrives early”, “what if it arrives late”, “what if it is larger than expected”, “what if it is smaller than expected”, etc. The underlying assumption is that the weather organization has been correctly forecasted, but the growth or decay or speed of weather cells may be in question.

This process will be adapted to the needs of the particular ATM application. This process can be performed using tactical 15-minute to 1-hour look ahead. At some point, true ensemble methods (ensembles of NWP forecasts) will perform better than this method of creating synthetic ensembles, so future research is needed to identify at what look-ahead time this method should be replaced with the processing of true ensemble forecasts. The benefit of the synthetic ensemble method is that it provides a well-defined sensitivity estimate of the ATM impact given errors in a single deterministic forecast.

Probabilistic Convective Weather Forecasts used to Assess Pilot Deviation Probability. Efforts have been made to determine how to use probabilistic weather forecasts in ATM automation where probabilities of convective weather need to be translated to ATM impact. An example probabilistic weather forecast is the National Convective Weather Product–6 (NCWP-6), which provides up to 6-hour forecasts of the probability of convection. One approach is to determine a correlation between aircraft position and NCWF-6 convective probability values [SSM07]. Using the correlation, a decision-maker could assess the NCWF-6 probability that aircraft are willing to traverse, and in turn, the risk associated with traveling in the vicinity of forecasted NCWF-6 probability contours. The Probability Cut-off Parameter (PCP) is the maximum NCWF-6 probability contour that correlates with a majority of aircraft positions based on historical analysis. With a 1-hour NCWF-6 forecast, the 80th percentile PCP value for all aircraft flying through the probability field across the CONUS is around 35% using four months of flight track and weather data [SSM07]. PCP values differ for longer forecast times. Also, PCP values can be established for a local scope, at center and sector levels [SAG09].

4.2 Turbulence

Next, we present turbulence impact models.

ATM Impact of Turbulence. The ATM impact of turbulence [KIK09, KKS10, LSK10, SKK11] results from pilots desiring to avoid or exit turbulent conditions for safety reasons. This may happen tactically or strategically. The descent maneuver is the most typical maneuver when pilots tactically encounter turbulence [KIK09, SKK11]. The exit strategy can be determined tactically, essentially as an aircraft experiences turbulence, or is warned that it is about to enter it, or strategically, with sufficient planning time to enter into a region of potential turbulence or to avoid such a region. Given a turbulence forecast for advance warning of potential Moderate-or-Greater (MoG) or of Severe-or-Greater (SoG) turbulence, a pilot or dispatcher can decide to enter into a region of potential MoG turbulence if acceptable to the pilot or airlines (a pilot decision or airline policy decision), or in the case of potential SoG, the region should be avoided.

Turbulence is capable of producing both workload and airspace utilization ATM impacts. Tactical information about actual turbulence encounters are conveyed through Pilot Reports (PIREPs). PIREPs are broadcast to controllers and then relayed to other pilots. Today, this occurs by voice communications; in NextGen this process is expected to be automated for many aircraft through electronic PIREPs (e-PIREPs). Processing of PIREPs increases pilot, flight dispatch, and controller workload but does not, strictly speaking, close airspace. MoG turbulence tends to close en route airspace flight levels given that passenger comfort and safety is a high priority for many airlines. However, there are some types of aircraft that may fly through MoG turbulence, for instance, cargo aircraft, ferry flights, or some business jets. Forecasted or reported SoG turbulence is an immediate safety hazard that closes airspace flight levels and, if encountered, may require diversion due to the likelihood of passenger/pilot injuries and/or required aircraft inspections.

The impacts of CAT turbulence in the NAS has been analyzed [SKK11] using both a sector-based approach and a trajectory-based approach. CAT turbulence-avoidance maneuver statistics can be classified by user class, weight class, physical class, aircraft type, as well as airline. Each of these factors plays a role in the maneuver chosen and magnitude of the CAT avoidance maneuver. General trends indicate that as the probability of SoG turbulence increases for the upcoming sector or for the upcoming portion of flight trajectory, there is an increasing likelihood that the aircraft will maneuver, and the maneuver is most typically a vertical descent maneuver, increasing in magnitude as the probability of severe turbulence is higher. The analyses also show that some aircraft classes - for instance, cargo aircraft - are less likely to maneuver in moderate or severe turbulence, compared to passenger-carrying commercial aircraft; some airlines exhibit a more pro-active policy than others; and small General Aviation (GA) jets respond more pro-actively than large GA jets.

Tactical Feedback of Automated Turbulence e-PIREPs. Currently turbulence encounters are reported from cockpit crews either verbally or by text data link. PIREPs are subjective, late (transmitted only when pilot or controller workload permits), and not easily disseminated to all users. Pilots need to know how turbulence will affect their aircraft in order to make route change decisions. Different aircraft respond to turbulence differently, therefore considerable inference is required on the part of crews to transform turbulence PIREPs from larger or smaller aircraft into the hazard to their own aircraft.

NextGen will likely automate the process of collecting and distributing turbulence (as well as other) PIREP information. Automated e-PIREPs, where human judgment on the magnitude of the turbulence encounter is replaced by an automatic measurement of the turbulence, will automatically and frequently report PIREPs by data link to controllers and to nearby aircraft. Essentially, all e-PIREP equipped aircraft become sensors in the sky for real-time turbulence information.

With a collection of e-PIREP information reported at a wide variety of flight levels (null as well as hazard reports), turbulence information can be data linked directly to nearby aircraft or collected and distributed via a centralized database. Given turbulence data at or above a given threshold (note: the threshold differs based on aircraft type, velocity, altitude, and weight), crews can determine which regions of airspace may be a hazard and which are safe to traverse. Clusters of point e-PIREP data classified as hazardous can be identified, as well as clusters of clear air data (null or low magnitude reports). Thus, hazardous airspace as well as airspace clear of turbulence can be communicated to nearby aircraft that are soon to pass into such airspace. Since turbulence is a transient hazard, this process needs to be automated, a data link needs to quickly communicate information to nearby aircraft, and the process must repeat throughout the day for detecting CIT and CAT hazards. This tactical feedback process [KRB09] of where turbulence hazards actually exist will complement long term strategic forecasts of the potential for turbulence to exist.

4.3 Terminal Area Weather

Next, we present terminal area weather impact models.

Probabilistic Fog Burn Off Forecast and TFM Decision Making. For San Francisco International Airport (SFO), a model has been developed to integrate probabilistic weather forecasts into TFM decision making using only a single weather parameter [CW03, CW09, CI09] – the marine stratus (fog) burn off time – at a fixed geographical location (the SFO approach zone). Traffic managers initiate a GDP to reduce the inflow of aircraft when fog at SFO lingers well into the morning arrival rush, thereby reducing the AAR in half (because only one runway can be used for arrivals instead of two). The confidence of each of several forecasts is rated and empirical errors of historical forecasts are used to create a probabilistic forecast in terms of a cdf of clearing time [IB04, CIR06]. A weather translation model integrates SFO's probabilistic fog burn off forecast in with GDP algorithms [CI09].

A Monte-Carlo simulation approach can be used to find optimal GDP parameters based on the objectives of minimizing unnecessary delay and managing the risk of airborne holding [CW09]. The model samples multiple times from the cdf of the forecast of stratus clearing time, calculating the key measures for each possible GDP end time and scope. The mean value of each metric is calculated over all clearing time samples for each GDP scenario, providing the expected value of each metric given the uncertainty in the clearing time. An objective function uses these key metrics to select the GDP parameters that minimize cost. This model places a high importance on managing the risk of excessive airborne holding if the stratus clears later than anticipated.

Implementing a GDP under uncertainty in stratus clearance time at SFO is both stochastic and dynamic in nature. Decisions related to AAR, scope, and departure delays require revision in response to updated forecasts. Towards this, a parallel body of research is underway to develop an algorithm for setting AARs and allocating slots to flights, and dynamically revising those decisions based on updated forecasts [MHG09]. The primary input is a set of capacity scenarios and their probabilities, generated from forecasts. Given a distribution for the stratus clearing time, one algorithm applies a stochastic optimization model [BHO03] to decide on optimum AAR, following which a slot allocation algorithm is applied to assign landing slots to airlines [HBM07]. After airline substitutions and cancellations, the revised schedule and updated forecasts are fed back into the algorithm, which is re-applied in response to changing conditions.

Stochastic dynamic optimization models that simultaneously decide AARs and individual flight delays require more than just capacity scenarios as inputs [MH07]. Typically these models apply a wait-and-see policy where certain decisions are delayed until updated information on airport capacity becomes available. Such models could help in NextGen if weather forecasts provide a capacity scenario tree whose branching points provide information on when to expect updates in forecasts and the conditional probabilities of scenarios associated with those updates.

Forecasts for C&V and Obstructions to Visibility (OTV). The C&V and OTV impacts differ depending on the flight regime (surface, terminal, en route) and type of aircraft operation (Part 91 vs. Part 135 or Part 121). For the en route NAS, the ATM impact for IFR-equipped aircraft results from reduced AARs and Miles-in-Trail (MIT) restrictions that originate from the impacts of OTV on terminal airspace and airport ground areas. This impact can reduce air route capacity and may propagate from sector to sector as passback MIT restrictions. OTV impacts on terminal arrival and departure operations include restrictions on VFR operations, increased MIT requirements on final approach, increased missed approach potential, higher workload for pilots and controllers (e.g., PIREP communications), and restrictions on use of Land And Hold Short Operations (LAHSO). Impacts result from ground fog, low ceiling, low visibility due to precipitation, and smoke and haze. These conditions are further influenced by day/night effects and by viewing angle relative to solar angle. For ground operations, the OTV impacts come from ground fog, low visibility due to precipitation, blowing snow, plus day/night and viewing angle effects. For non-IFR equipped GA aircraft, the OTV impact to ATM is minimal; however, the safety impact to inadvertent penetration into IMC during VFR operations is significant.

A limited amount of airport-centric modeling has been pursued [Hu10, HR08a, HR08b, RH07]. However, assessment models must represent the system-wide impacts of propagating passback MIT restrictions, which result in impacts on air route capacity as well as reduced AARs, ground holds and departure delays at remote airports where OTV conditions are not present.

Improved Wind Forecasts to predict Runway Configuration Changes. The airport configuration is a primary factor in various airport characteristics such as arrival and departure capacities (AARs and ADRs) and terminal area traffic patterns. Since the airport configuration is largely dependent on airport wind conditions, an ATM impact model must translate the wind conditions (and other factors, in particular, to classify runways as operating under IFR or VFR) into AAR, ADR, and other impacts. One model [PA10] is based on information decision trees and the mapping of the weather state into tree branches based on the IFR or VFR conditions.

Today there is poor dissemination throughout the NAS of the airport configurations in use at each airport at any given time, with very little known about expected future configuration changes. AARs, ADRs, and terminal traffic patterns are central to a variety of ATM decisions, such as setting arrival restrictions to avoid airborne holding as well as the effects certain airport configurations have on nearby airport traffic flows and configurations. Consequently, the uncertainty from wind conditions translates into uncertainty about the current or future airport configuration.

In order to build a model for translating wind conditions into ATM impacts, both meteorological and ATM modeling need to be addressed. The wind speed and direction is essential in determining which runways are feasible. Terminal Aerodrome Forecasts (TAFs) do not currently predict wind conditions precisely enough or accurately enough to enable airport configuration prediction. NextGen weather forecast systems must correct this in order to assimilate weather into DSTs for airport surface operations as well as TFM decision making. Accurately predicting wind conditions at an airport is difficult, and viable automated methods are only now emerging due to recent scientific advances and gains in computer performance. Furthermore, TAFs are intended primarily to provide information for filing flight plans, so they are not required to include certain changes in wind speed or direction that may cause airport configuration changes.

As for modeling the ATM impact, research is needed to establish how controllers choose between viable configurations to meet airport arrival and departure demands. Controllers usually have 30 minutes or more leeway in the timing of a configuration change, while maintaining safety. This leeway is generally used to choose a time at which to implement a runway configuration change so as to minimize inefficiencies associated with making the change. The timing of the arrival and departure traffic demand, weather (winds as well as possibly convective weather constraints), and other factors need to be modeled. Furthermore, there is generally a preferred configuration that will be used if it is feasible for a sufficiently long period of time. NextGen needs a mathematical model that relates these factors to the forecasted weather and traffic conditions.

Weather Impacts on Airport Capacity. Terminal weather conditions, including C&V, surface winds, precipitation, snow, and convective activity, have significant direct (e.g., available runways) and indirect (e.g., aircraft separation requirements) impact on the available airport capacity. Approaches for estimating airport capacity as function of existing or forecast weather can be roughly divided into two groups: models predicting the impact based on trends observed in historical data [KJL07, HR08a, Sm08, Hu10, PSL10] and analytical airport capacity models explicitly incorporating weather parameters and their uncertainty into the modeling process [KMC09].

T- WITI [KJL07, KKL09] is an example of an airport capacity model utilizing historical trend data to determine the impact of weather on available capacity. It uses airport capacity degradation thresholds determined using historical data for airports to determine estimated capacity reduction as a function of C&V, winds, snow, precipitation, and convection. Weather events are prioritized in terms of severity of their impact on capacity reduction, and if multiple weather events exist or are predicted at the airport, then the estimated capacity reduction is assumed to be equal to the capacity reduction caused by the most severe weather event.

An alternate approach to estimate weather impact on available airport capacity is to use an analytical stochastic model which considers the impact of both terminal airspace and runway system constraints on airport capacity. Probabilistic airport capacity estimates can take into account weather nowcasts and forecasts for C&V, winds, precipitation and echo tops and utilize several weather translation and weather impact models (e.g., WAAF and MaxFlow/Mincut) and runway capacity models [SZO04] to analytically compute probabilistic ranges of estimated airport capacity as a function of forecast terminal weather.

4.4 Winter Weather

Next, we present winter weather impact models.

Winter Weather at Airports. The accumulation of ice on aircraft prior to takeoff is a significant safety hazard affecting aircraft. Research [RCM00] indicates that the icing hazard for aircraft directly corresponds to the amount of water in the snow, rather than visibility – the traditional metric used to determine de-icing and takeoff decisions. Results from field tests of de-icing fluids have identified the liquid-equivalent snowfall rate as the most important factor determining the holdover time (time until a fluid fails to protect against further ice build-up) [RVC99].

The ATM impact of decisions made regarding aircraft de-icing holdover times, de-icing fluid types, and application procedures have yet to be defined and integrated into a NextGen gate-to-gate concept of operations. From initial field evaluations using stand-alone DSTs, significant impacts to an airport occur from de-icing operations [RCM00], including airport ground congestion, decreased AARs, and decreased ADRs. Metrics affecting severity of impacts include precise timing of the snow event start and stop times, characterization of snowfall in terms of Liquid Water Equivalent (LWE), optimal deicer mix and temperature to maximize holdover times, and precise timing of the sequence of events from pushback, to de-icing, taxi, and takeoff to prevent additional de-icing. NextGen integration needs further DST requirements for winter weather impact in order to optimize gate-to-gate performance.

In-Flight Icing. For aircraft not certified for icing conditions, all known or forecast icing is prohibited airspace. An icing SIGMET is considered a hard constraint for *all* aircraft. Today, SIGMETs are typically valid for up to 4 hours and usually affect a large volume of airspace. Some situations have icing severity and aircraft equipage combined to define a “soft” constraint – some aircraft may penetrate the icing volume for limited exposure times [KrK09, LKM09, LSK10].

In-flight icing is typically a low altitude hazard, generally less than FL240 [KrK09]. Major ATM impacts, therefore, are seen for low-end GA and for all aircraft in the arrival/departure and terminal phases of flight [VH99, VH00, KrK09]. The national ATM impact can be significant when icing affects large airport metroplexes, especially when the icing hazard touches ground level [KrK09]. In modeling the ATM impact, the traffic density is significantly decreased by a SIGMET when compared to the same day a week before and a week after – the effect is strongest if the SIGMET has a lower altitude that reaches ground level. Holding patterns are established outside of the SIGMET volume to allow aircraft to descend below the SIGMET prior to arrival if the SIGMET does not extend to ground level. Other impacts include increased ground delays until the SIGMET is released, cancellations of flights scheduled to take off when the SIGMET is active, and aircraft forced to fly above or below the SIGMET altitude ranges, thus increasing densities above and below the SIGMET volume and increasing controller workload for those altitudes. No mathematical model has been published to date to describe how an icing forecast translates into these above mentioned impacts, and the expected magnitudes of the impacts.

4.5 Oceanic/Remote Weather

Oceanic/remote weather includes turbulence, volcanic ash, thunderstorms, and hurricanes. Oceanic/remote airspace is limited by the lack of surveillance information to monitor aircraft separations and the lack of detailed weather forecast information. Creative use of available data from satellites and other limited sources is required [DW06, Ni03]. While many of the oceanic tracks are over named fixes, some like the North Atlantic Organized Track System (NAT OTS) and routes across the North Pacific (NOPAC), do utilize a flexible track system that changes on a twice daily basis after consideration of jet stream and oceanic weather. If weather events (hurricanes, volcanic ash, and turbulence) are forecasted before tracks are published, the tracks are planned to avoid the weather. Aircraft going to the US from Europe experience headwinds caused by the jet stream. Aircraft going from the US to Europe use the jet stream to their advantage by routing along the strongest tailwinds. Prototype algorithms have been developed for regional use, but not integrated with ATM procedures. For instance, studies [GSC07, GSM07] demonstrate how wind data can help generate wind optimal oceanic routes, transitioning away from the fixed oceanic routes to user-preferred routes. While such routing takes advantage of the jet stream, it also must take into account MoG and SoG turbulence that can be found near the jet stream, which is an area of future research.

4.6 Volcanic Ash

Airborne volcanic ash clouds constitute an aviation hazard that can severely damage jet aircraft airframes, windshields, and engines through pitting, erosion, corrosion, and congestion. Volcanic ash contamination may render large volumes of airspace unusable, necessitating costly rerouting contingencies; degrade braking action at affected airports; and completely close contaminated airports [KMP08]. Advanced techniques are needed in NextGen to detect, forecast, and disseminate information on volcanic ash plume hazards, their movement in 4D, and how the hazards will affect ATM resources [ES93, Li04, GMW04, He04, CKK09]. There are no mathematical models in the literature that describe the ATM impacts as a function of the volcanic cloud state and forecasted movement.

4.7 Space Weather

The impacts of space weather on aviation are described in [AG10, Fi03, JB05, JB10, JC04, MT09, MW08]. Space weather includes phenomena such as solar flares and Coronal Mass Ejection (CME), which can impact aircraft flying on the northern polar routes. To quantify the weather state, the official descriptions for space weather conditions are defined by the Space Weather Prediction Center of NOAA.

Solar flares contribute to increased radiation exposure for passengers and crew (who have increased exposure due to frequent flying of polar flights), however, they do not cause a noticeable degradation in the performance of essential flight critical systems of aircraft. The flight crew has about 7 to 8 minutes to respond. If the severity of the radiation present meets or exceeds a given level, then flights are limited to FL310 or below on all polar routes. This requires the flight to have a tactical response which usually involves a flight path reroute. Flights generally are not cancelled or diverted due to any solar flare activity.

CME is the ejection of material from the sun as a result of a solar flare; it takes about 2-3 days to reach the earth. CME interferes with a flight’s communication and navigational systems degrading their performance. The response depends on the level of the Geomagnetic Storm Level (GSL) and the Radio Blackout Level (RBL). If GSL<4 and RBL=3, then all polar flights are restricted to only use Polar Route 4. However, if either GSL≥4 or RBL≥4, then no polar routes are permitted.

5. CONCLUSION

This literature survey highlights the many approaches being explored for modeling the impact of weather on Air Traffic Management in the National Airspace System. The majority of the models and the most mature models are for convective weather. Fewer and less mature models are available for modeling the effects of non-convective weather hazards. There is a lack of well-developed impact models for the areas of oceanic/remote weather, volcanic ash, and space weather. Most models are based on empirical methods, with a few based on rational methods. Given that only a few rational methods have been established for weather impact modeling, there is a need for fundamental research to derive rational models and to further connect the rational models with the empirical models. Further work is needed to integrate these weather impact models into the decision support tools for pilots, dispatchers, and air traffic controllers in the Next Generation Air Transportation System.

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