11.2 CLASSIFICATION OF WEATHER TRANSLATION MODELS FOR NEXTGEN

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1. ABSTRACT

In past work, we have surveyed the state-of-the-art in weather translation models and Air Traffic Management (ATM) impact models for the Next Generation Air Transportation System (NextGen). We have found that the literature often blurs the distinction between weather translation and ATM impact models, and to this end, we have in this paper explored a more rigorous definition and classification of fundamental weather translation and integration technologies for NextGen.

2. BACKGROUND

NextGen [JPDO08, JPDO09, JPDO10] has built a transformational concept of operations for the aviation weather system required to support capabilities such as Trajectory Based Operations (TBO) and Super Density Operations (SDO). NextGen offers a complete change in the roles and responsibilities of today's "actors" (pilots, controllers, dispatchers, weather providers, etc.) in the future. NextGen will provide consistent weather information, and more consistent and proactive decisions based on that information, to the point that system behavior with respect to weather information can be better predicted across the scales of the operational decisions made at any given moment, whether tactical or strategic. Decision makers will hold a common understanding of the ATM impact caused by the weather, rather than an understanding of the weather itself.

Figure 1 describes a stepwise process for the integration of weather information into NextGen decision making – one of the key tenets of the NextGen weather-ATM integration concept. **Figure 1** was designed [BP11] to communicate several ideas: 1) each module, could be developed as a separate Service Oriented Architecture (SOA) process (discouraging the development of end to end horizontal processes each with separate weather processing units), 2) the concept assigns responsibilities for the development of SOA modules to NextGen stakeholders, and 3) the concept delineates the sources of funding/research targeted against those modules. The paradigm shift here is to reduce the need for the actors to know how to understand the detailed meteorology, and increase the understanding of the impact of the meteorology on ATM. Facilitated by weather translation models, the operational actors can spend more time focusing on ATM impacts and the decisions at hand, utilizing more consistent interpreted data.

This stepwise process of **Figure 1** consists of four steps: 1) the production of consistent weather state information (i.e., nowcasts and/or forecasts), 2) the translation of that weather state information into data which describes in a generic sense the expected reduction in ATM resources due to weather, 3) comparing the translation data against specific system demand to determine when and where there are imbalances, and 4) automated tools to assist decision makers in how best to overcome those imbalances.

Figure 2 provides more detailed view of the inputs, processing steps, and outputs produced by each of the steps of the weather integration process outlined in **Figure 1. Figure 2** shows that the weather translation step takes several inputs, including weather state information, modeling and adaptation data, operational standards and procedures, baseline resource performance characteristics, and hypothetical (possible historical) demand. Some weather translation models require all of these inputs and others require only a subset of them.

Weather state information (nowcasts and/or forecasts) is first processed by an Input Weather Data Manager to extract relevant weather information required by a translation model (e.g., Vertically Integrated Liquid (VIL) values and echo top heights) and convert it to the input format required by the model. Translation Models and Algorithms then take this properly formatted weather inputs combined with other inputs to produce one or more types of outputs:

- Threshold events [BP11],
- Characterizations of weather-related National Airspace System (NAS) constraints [BP11], and
- Expected resource performance characteristics.

In general, all output types produced by Weather Translation are expressed in non-meteorological terms and reflect how pilots, controllers, or airlines respond to weather phenomena, independent of the ATM operational state and ATM application.

Given the ATM operational state defined by demand on resources produced by Demand Estimator, Air Traffic Control (ATC) operational constraints (e.g., staffing, equipment outages), and Special Airspace Activity (SAA) schedules, ATM impact conversion models (called below weather impact models) use outputs produced by weather translation models to derive the impacts of weather on ATM resources. These include resource performance estimates (e.g., weather-impacted sector capacities) and potential demand-capacity imbalances, which define Operational NAS Constraints. Decision Support Tools (DSTs) use outputs produced by weather translation and ATM impact models to generate mitigation plans (strategic Traffic Flow Management (TFM) plans and Traffic Management Initiatives (TMIs) and tactical trajectory adjustments) aimed at resolving imbalances.

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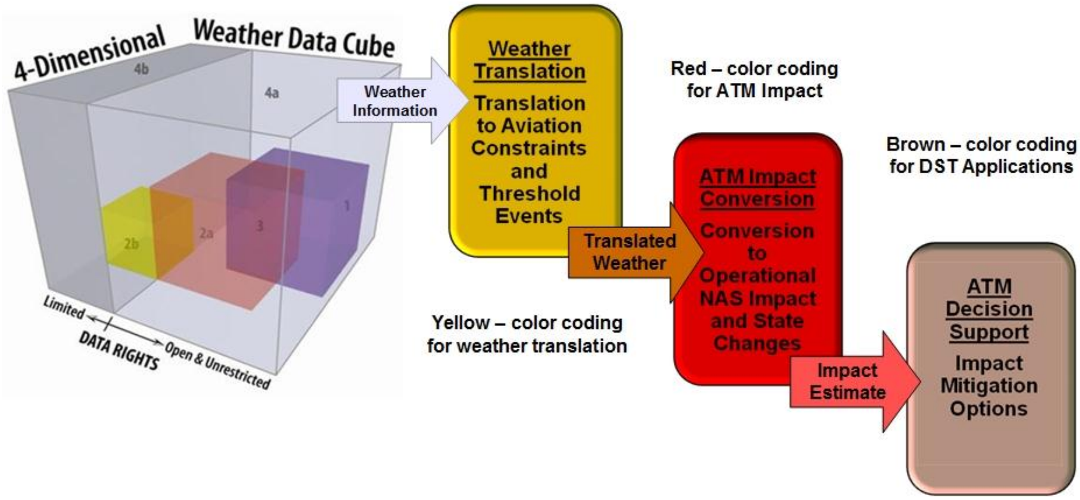


Figure 1: NextGen weather integration concept.

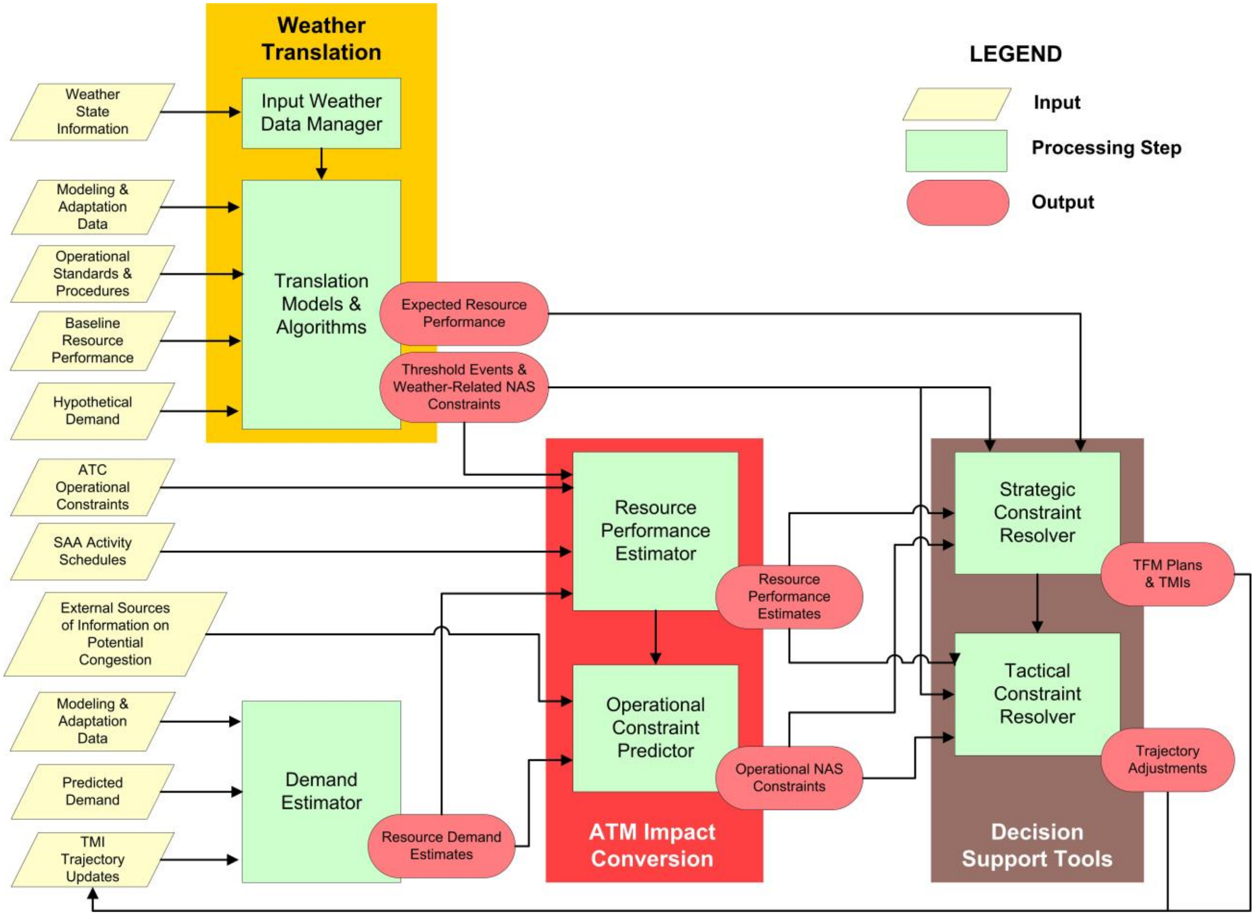


Figure 2: Functional Component Analysis supporting NextGen weather integration concept.

Figure 2 shows that specific knowledge of NAS operations and the NAS plans for the day are not required for weather translation models, whereas weather impact models must incorporate this information. This delineation allows for focused research, potentially by different sponsors or communities of interest, to occur and brings the expertise of these different communities (meteorologists/operations) to bear on the respective problem(s). Identification of various models into these “yellow”, “red”, and “brown” modules, therefore, have become a priority.

In summary, NextGen, weather translation models will be at the root of transforming raw weather forecast "data" into high level ATM-relevant "information". This ATM-relevant information is combined with operational data by weather impact models to support ATM decision makers and their DSTs to control the NAS in NextGen. Since different government agencies are researching and building different components of this system (e.g., the NOAA is developing the 4D weather data cube, while the FAA has separate organizations researching, building, and deploying weather translation models, ATM impact models, and DSTs), it is important to have well-defined boundaries between these system components for funding, research and development, and transfer of technology reasons.

3. DEFINITIONS AND MOTIVATING EXAMPLES

3.1 Definitions

In this section we provide definitions of terms and concepts used when describing and classifying weather integration technologies.

Threshold Event - "A situation in which a non-hazardous atmospheric parameter crosses a regulatory or operational threshold and may result in an associated change in the state of the affected NAS element" [BP11].

Weather-Related NAS Constraint – Spatially and temporally relevant 4D representations of meteorological phenomena which are potentially hazardous to aircraft. Such representations are defined in non-meteorological terms and expressed using weather avoidance fields [BP11].

Expected Resource Performance – An estimate of the loss of operational performance of a specified NAS component (or combination of components) due to the effects of weather. The loss is measured from a baseline performance estimate for a "perfect" weather day.

Hypothetical Demand – Air traffic demand defined by: 1) historical demand that characterizes the particular demand that was experienced on a given day at a given time for a given NAS resource, or 2) a synthetic demand generated to characterize idealized conditions for the demand on a resource. For instance, a synthetic demand may be for all aircraft to have the same Required Navigation Performance (RNP) level, or to all be of the same aircraft type, or for all aircraft to be flying in a common flow direction (e.g., the cardinal directions of North, East, South, or West).

Actual Demand – Actual air traffic demand is determined by the 4D Trajectories (4DTs) specified by filed flight plans, flight plan amendments, or projections of 4DTs in NextGen.

Airspace Permeability – Determines the throughput of an airspace, given a definition of a weather hazard and requirements for safe passage of traffic through the airspace. (For instance, a minimum gap size between weather hazards, a safety margin around weather hazards, and/or horizontal and vertical separation requirements between aircraft may be defined). Airspace permeability is a property of the weather hazards, and not dependent on pilot or controller workload limits or the ATM operational state.

Airspace Capacity - An estimate of the maximal operational performance of a specified NAS component (or combination of components). It depends on a given ATM operational state, workload limits, and actual demand expected to use this NAS component.

Operational NAS Constraint – Spatially and temporally relevant 4D representation of an airspace region in which actual demand is expected to exceed the available airspace capacity. The degree to which demand exceeds capacity defines the imbalance of the constraint.

Weather Translation – This is a process to "operationalize" weather information, whether observation or forecast, into meaningful information for an operational decision maker. This translation process provides estimates of the expected performance of NAS components and/or the entire NAS as a result of weather effects, without understanding or utilizing actual system intent information.

Weather ATM Impact – After a weather translation process has identified potential areas or NAS components whose operational performance will likely be negatively affected, the impact process then matches that translation estimate against the actual system desires for a given time frame. If the system desires to use a component at a higher level than what the translated weather performance suggests that the component will be able to achieve in the face of the weather, an imbalance is identified as a potential operational NAS constraint which will require some form of mitigation.

Decision Support Tools – DSTs can utilize information from the 4D Weather Cube, weather translation estimates, and identified ATM impacts to inform operational decision makers that a problem may exist, suggest options for how to mitigate the problem, and assist in the execution of the mitigation strategy chosen by the decision maker.

3.2 Examples

Next, we discuss several examples showing how various weather integration technologies can be classified as weather translation or weather impact models. We also identify how weather translation models may be categorized by domain as either airport or airspace translation models.

In general, airport translation models include the translation of weather forecast data into airport Instrument Meteorological Conditions (IMC), Visual Meteorological Conditions (VMC), runway usability, runway configuration usability, Airport Departure Rate (ADR), or Airport Arrival Rate (AAR). On the other hand, airspace weather translation models include pilot behavior models, which identify how a pilot will respond to a given weather state, in particular, a weather state that constitutes a safety hazard.

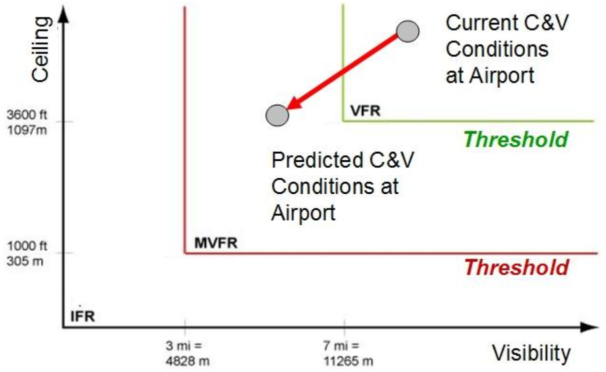


Figure 3: Thresholds between IFR, MVFR, and VFR.

For instance, **Figure 3** illustrates the threshold events associated with changes from Instrument Flight Rules (IFR) to Marginal Visual Flight Rules (MVFR) to Visual Flight Rules (VFR) at an airport, based on Ceiling and Visibility (C&V) weather data.

Pilot behavior models apply to convective weather avoidance, turbulence avoidance, in-flight icing avoidance, volcanic ash avoidance, as well as to space weather avoidance (**Figure 4**). Weather Avoidance Fields (WAFs), for instance as illustrated in **Figure 5**, result from the transformation of the weather forecast data through pilot-behavior models – the Convective Weather Avoidance Model (CWAM) being one of the most popular. While WAFs are a weather translation output, they may be further processed (translated) to create Route Availability (RA) (conversely, Route Blockage (RB)) and airspace permeability information.

In our classification of a weather translation and impact models, we make a distinction between when a model processes a generic or historical demand versus when the weather integration model processes the specific traffic demand characteristics and operational conditions of a given time and date. In doing so, we are able to classify a directional capacity concept to be a weather translation model if it simply describes the permeability of the weather system in terms of cardinal directions (north, east, south, or west), however, if it specifically addresses the directional capacity given the actual demand flowing in a particular direction, then we classify it as an ATM impact model.

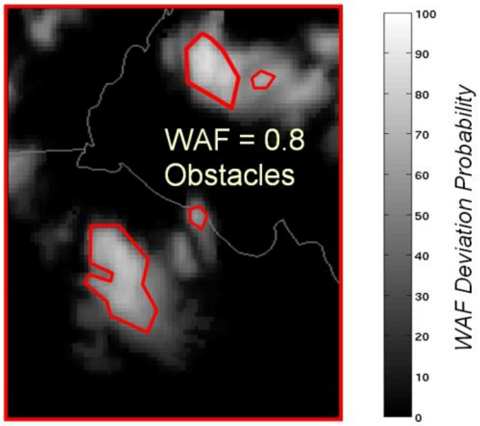


Figure 5: WAF defining a deviation probability and weather obstacles defined by a WAF threshold of 0.8.

Figure 6 illustrates how convective weather data can be analyzed in terms of four cardinal directions by a directional capacity concept to determine a permeability estimate in each of these directions without knowledge of the actual demand in any particular direction. The permeability in this example is calculated in terms of a mincut throughput (see [ZKK09]). These permeability values can be compared to clear-weather permeability values to determine the reduction in airspace capacity that may result, as illustrated in **Figure 7**. This translation would result in: "Sector XYZ will likely only allow 6 aircraft (vice a normal 10 on a clear weather day) based on the forecast weather and a hypothetical demand (and flow direction)." As shown in in **Figure 7**, capacity reduction maps do not consider the actual traffic demand; they only consider the comparison of the maximum throughput on a clear weather day compared to the throughput estimate for the given weather forecast, assuming a traffic flow direction.

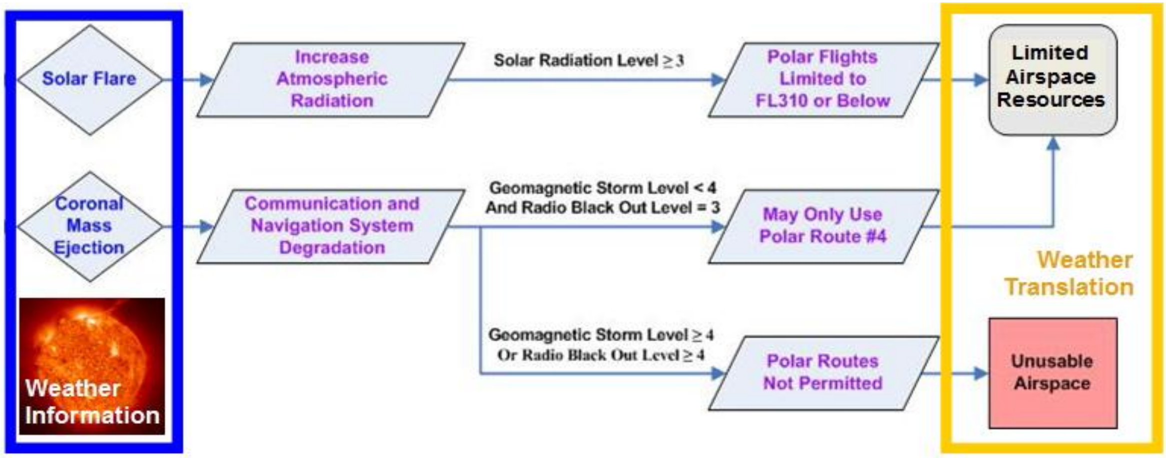
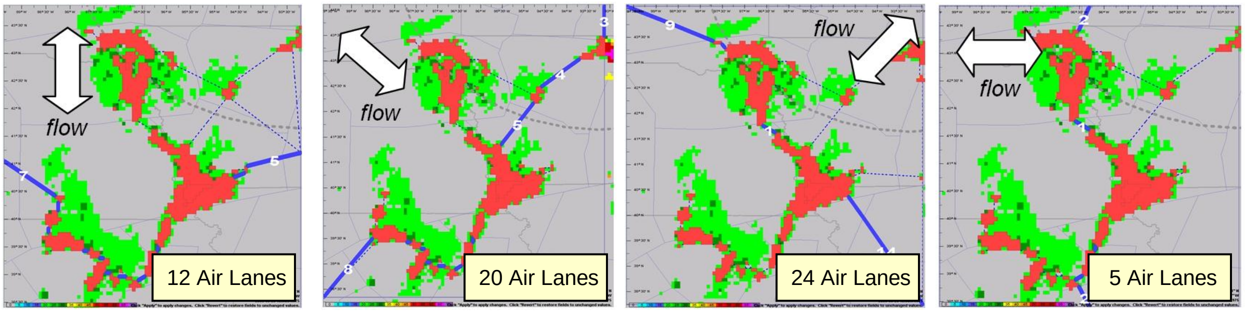
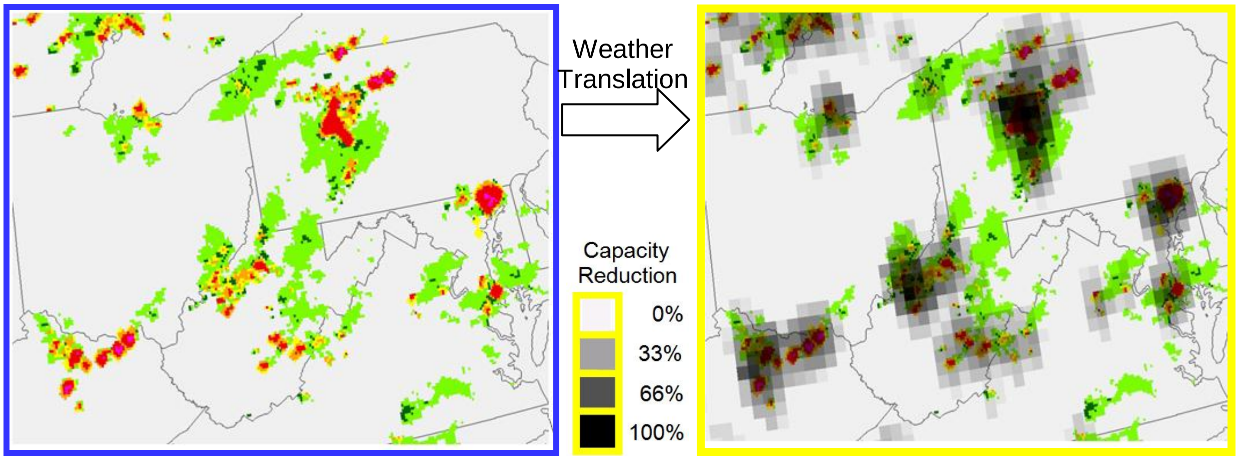


Figure 4: Space weather avoidance translation model.



(a) North-South (b) South-East (c) North-East (d) East-West

Figure 6: Mincut Algorithm applied to four cardinal directions; courtesy of [ZKK09].



(a) Weather Forecast – information in standard weather units; useful for a wide variety of aviation as well as non-aviation applications

(b) Expected Airspace Resource Performance – data overlays the weather forecast and displays information relevant to NAS operations

Figure 7: Expected Airspace Resource Performance Map (based on mincut analysis); courtesy of [ZKK09].

Other examples are in the airport domain. While we classify a technology that evaluates the usability of a runway or runway configuration as a weather translation model, we classify a runway configuration prediction or airport throughput algorithm as an ATM impact model – a subtle distinction being that in order to predict the runway configuration that is going to be used or throughput that will result requires operational data (e.g., actual demand and aircraft types) beyond just the weather state. If the forecast is for a wind shift, which would then force an airport operational configuration change, thereby reducing (or increasing) acceptance/departure rates, this answer is a translation.

The boundary line between translation and impact offers many different shades of grey. Depending on how these techniques are bundled (which is discouraged in a SOA architecture) these techniques can assess hypothetical resource performance and its reduction (translation) or actual resource performance and its reduction given planned system demand (impact). In evaluating these techniques we found many which could support the translation and impact functions depending on how we envisioned their operational use and architecture. For instance, calculating an AAR may generate a value which says given the forecast weather the best possible rate is X for various hypothetical demand scenarios (translation). However, when actual demand is used to calculate AAR, then the model is performing an ATM impact function. In cases when the computation of AAR uses the knowledge of active and predicted runway configurations or local decisions regarding operations, then the model is performing an ATM impact function. However, if hypothetical or historically used runway configurations are used to calculate the AAR, the model performs a translation function.

In order to define the line between translation and impact, it is helpful to understand what question is being answered. If the question is “what is the potential impact to a NAS resource (sector, route, terminal, etc.) if the weather forecast was to verify?”, then the interpretation is this is a translation model. A question of “what is the impact on a NAS resource given the weather and the planned actual use of the system by specific aircraft (and their planned/scheduled intent)?” then the technique is deriving an ATM impact answer, because the “potential” impact has been further assessed against an actual demand of the system.

Several other examples below attempt to clear this delineation. For convective forecasts, we use the WAF which has embedded within its logic an understanding of the behavior of the “typical” or “average” pilot. A convective forecast is generated, the WAF model is used to define typical pilot avoidance areas, which can then be evaluated against a NAS resource. The end result is an estimate of potential degradation in the specific NAS resource given a generic convective forecast.

The Route Availability Planning Tool (RAPT) [DRT08] is another example. RAPT's output includes an estimate of the route availability (or blockage) based on typical pilot behavior and a weather forecast. It has no knowledge as to whether a specific aircraft desires to use that route. However, if we then put actual aircraft desires into the calculation and determine specific aircraft are requesting routes which will likely be blocked, then the "answer" has become an ATM impact assessment, cueing a downstream DST to deal with the conflict.

The message here is that in many cases, a technique cannot be binned solely into translation or impact without knowing the desired or planned operational utilization of the technique and the answer the process is attempting to answer. In our evaluation of the techniques we had to ask ourselves whether the technique was associated with a specific process or not. If so, we could better determine the classification. If not, we then envisioned potential uses of the technique to assist our classification task.

Table 1: Characteristics and color coding for classifying weather integration technologies.

Color	Name	Description
Yellow	Weather Translation (TRA)	Pure weather translation models resulting in threshold events and/or characterizations of weather-related NAS constraints
Orange	Weather Translation and ATM Impact (TRA/IMP)	Can be used as both translation and ATM impact conversions models
Red	ATM Impact (IMP)	Pure ATM impact conversion model processing actual demand
Brown	DST Application (DST)	Assisting human in making decisions on identified operational NAS constraints

4. CLASSIFICATION

The ATM impacts associated with a wide variety of weather phenomena (terminal and en route winds, convection, turbulence, icing, volcanic ash, winter weather, space weather, and others) are being widely researched in the literature (see related surveys by Krozel [K10, K11]). In this section, we study weather integration models described in Appendix B of JPDO ATM-Weather Integration Plan [JPDO10] and identify the distinguishing characteristics which classify a technology into either translation (TRA), ATM impact (IMP), a combination of TRA/IMP, or a DST application (see **Table 1**).

Table 2 shows the results of our classification analysis for 42 weather integration technologies described in Appendix B of [JPDO10]. It shows that very few technologies can be classified as "pure" translation or "pure" impact models. On the contrary, 25 out of 42 technologies can be used as either translation or impact depending on the intent with which there are used and the input data provided to these models.

Table 2 also shows that there are several different types of weather translation approaches which fall into two primary categories. One category includes behavioral models, which attempt to explain and more importantly predict the decisions made by human actors, which include a wide constituency of roles including pilots, controllers, TFM managers, TRACONS, Airline Operations Centers (AOCs) and the like. The second category is more physics based, utilizing knowledge of current standards and regulations against physics to determine estimates of expected NAS performance. Ultimately, the outputs of both types of models provide an assessment of the degradation of performance of an analyzed piece of the NAS based on weather information. Note that once the weather has been translated, the human actor (in the future) may no longer need to "see" the weather information itself.

Behavioral models are very useful in the translation function. While it is not foreseen the future NAS will have the capability of fully understanding all of the decision making factors residing in a specific actor (for tactical decision assessments), a description of the "median" or "mean" actor allows for estimates of the types of decisions made across a larger area of analysis. These models are typically less complex and able to generate estimates of potential system impact with minimal computational power. Also, these models more often than physics-based models can be classified as "pure" translation models.

Physics-based models, on the other hand, allow for more tactical understanding and option development than the behavior models. These models often require higher degrees of resolution in input weather information and can take longer to produce near real time output, but offer greater precision in the estimates of weather influence on the airspace.

5. DISCUSSION

Figure 1 partitions technologies against three modules, all of which support a SOA concept of moving and sharing information across the spectrum of future NAS users. One aspect of this classification exercise reveals there is a wide distribution of technologies with many candidates in each of the three modules.

Table 2: NextGen weather translation and integration technologies (take from [JPDO10]).

ID	Technology Name	Classification
B-1.1	En route Convective Weather Avoidance Modeling (CWAM)	TRA
B-1.2	Terminal Convective Weather Avoidance Modeling (CWAM)	TRA
B-1.3	Mincut Algorithms to determine Maximum Capacity for an Airspace	TRA,IMP
B-1.4	Weather-Impacted Sector Capacity considering CWAM and Flow Structure	TRA,IMP
B-1.5	Route Availability in Convective Weather	TRA,IMP
B-1.6	Directional Capacity and Directional Demand	TRA,IMP
B-1.7	ATM Impact based on the Weather Impacted Traffic Index	IMP
B-1.8	Weather-Weighted Periodic Auto Regressive Models for Sector Demand Prediction	IMP
B-1.9	ATM Impact in terms of a Stochastic Congestion Grid	IMP
B-1.10	ATM Impact in terms of Network Flow Adjustments	IMP
B-1.11	Translation of Ensemble Weather Forecasts into Probabilistic ATM Impacts	TRA,IMP
B-1.12	Translation of a Deterministic Weather Forecast into Probabilistic ATM Impacts	TRA,IMP
B-1.13	Sensitivity of NAS-wide ATM Performance to Weather Forecasting Uncertainty	IMP
B-1.14	Probabilistic Convective Weather Forecasts to Assess Pilot Deviation Probability	TRA
B-1.15	Integrated Forecast Quality Assessment with ATM Impacts for Aviation Applications	TRA
B-1.16	Conditioning ATM Impact Models into User-relevant Metrics	TRA,IMP
B-1.17	Integration of the Probabilistic Fog Burn Off Forecast into TFM Decision Making	TRA,IMP
B-1.18	Mincut Algorithms given Hard/Soft Constraints to determine Maximum Capacity	TRA,IMP
B-1.19	ATM Impact of Turbulence	TRA,IMP
B-1.20	Tactical Feedback of Automated Turbulence electronic Pilot Reports	TRA,IMP
B-1.21	ATM Impact of Winter Weather at Airports	TRA,IMP
B-1.22	Weather Impacts on Airport Capacity	TRA,IMP
B-1.23	ATM Impact of In-Flight Icing	TRA,IMP
B-1.24	ATM Impacts Derived From Probabilistic Forecasts for C&V and Obstructions to Visibility	TRA,IMP
B-1.25	Improved Wind Forecasts to predict Runway Configuration Changes	TRA,IMP
B-1.26	Improved Wind Forecasts to facilitate Wake Vortex Decision Support	TRA,IMP
B-1.27	Impact of Winds Aloft on the Compression of Terminal Area Traffic Flows	TRA,IMP
B-1.28	Oceanic/Remote Weather Integration	TRA,IMP
B-1.29	Translation of Volcanic Ash Plume Hazards onto Airspace and Airport Impacts	TRA,IMP
B-1.30	Translation of Atmospheric Effects into Environmental and ATM Impacts	TRA,IMP
B-1.31	ATM Impact of Space Weather	TRA,IMP
B-1.32	ATM Impact of Weather Constraints on General Aviation Access to the NAS	TRA,IMP
B-1-33	Weather-Impacts on Airport Capacity	TRA,IMP
B-1-34	NAS Traffic Flow Distribution Impacts due to Convective Weather	TRA,IMP
B-2.1	Sequential, Probabilistic Congestion Management for Addressing Weather Impacts	**DST**
B-2.2	Sequential Traffic Flow Optimization with Tactical Flight Control Heuristics	**DST**
B-2.3	Airspace Flow Programs to Address 4D Probabilistic Weather Constraints	**DST**
B-2.4	Ground Delay Program Planning under Capacity Uncertainty	**DST**
B-2.5	Contingency Planning w/ Ensemble Weather Forecasts & Probabilistic Decision Trees	**DST**
B-2.6	Probabilistic Traffic Flow Management	**DST**
B-2.7	Heuristic Search for Resolution Actions in Response to Weather Impacts	**DST**
B-2.8	Integrated Departure Route Planning with Weather Constraints	**DST**
B-2.9	Tactical Flow-based Rerouting	**DST**
B-2.10	Tactical On-Demand Coded Departure Routes (CDRs)	**DST**

While NextGen may discourage horizontal "end to end weather modules" for the ultimate desire to directly integrate weather information into operational decision making systems, it does increase the challenge of insuring synchronization across those modules towards this common goal. By classifying these particular technologies additional focus by the sponsoring communities can be realized. For instance, the 4D Weather Cube and some of the weather translation technologies are already sponsored with some research and programmatic actions underway, while many of the impact and DSTs have yet to receive significant attention. Additionally, while this may be a normal process of acquiring new weather processes within the overall NextGen context, it is important to realize the modules on the right side of **Figure 1** should and will "inform" the left modules of the types and characteristics of the required weather information itself, and therefore should also be identified as soon as possible.

Additional analysis underway and outside the scope of this paper utilizes the categorization of these techniques listed in **Table 2** to evaluate and potentially assign research funding priorities against these various techniques.

Finally, we note that the respective outputs, from a human-interpreted display point of view, are not relevant in assigning the technologies to the various modules. In a NextGen framework, each of these techniques is expected to generate information which can be easily transported and communication to different SOA modules. Even within a DST, the envisioned end displays will not be traditional weather graphics; instead, operational decisions will be influenced and recommended within and underlying the operational system displays.

6. CONCLUSION

In the design of NextGen and its supporting technology, a clear distinction must be made between the data, information, models, and algorithms that are included in the 4D Weather Data Cube, Weather Translation Modules, ATM Impact Conversion Modules, and Decision Support Modules. In order to avoid the duplication of effort and to build shared understanding of weather impact on ATM, NextGen must discourage end to end horizontal processes each with separate weather processing units, separate weather translation models, separate ATM impact models, and DSTs that make different assumptions about these modules. Instead, NextGen must progress to use a SOA approach for the design of these modules. NextGen must proceed to locate the data, information, models, and algorithms in unique locations within the SOA, allowing all modules that require data, information, models, and algorithms to use the same components. This will provide a common situational awareness for the DST end users, who will all be operating off of consistent data, information, weather translations, and ATM impacts, with a common basis for end user decision making in the NAS.

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