3.1 WHERE IS MY THUNDERSTORM FORECAST? THE SHIFTING PARADIGMS OF NEXT GENERATION AIR TRANSPORTATION SYSTEM (NEXTGEN) WEATHER INFORMATION

Cheryl G. Souders *
Tom Kays
Frances Bayne
Federal Aviation Administration, Washington, District of Columbia

Robert Showalter
James Tauss
Lorraine Leonard
CSSI, Inc., Washington, District of Columbia

Jack May
AvMet Applications, Inc., Reston, Virginia

1. INTRODUCTION

Aviation weather information today are available from numerous government and commercial sources, in textual formats (e.g., aviation meteorological reports (METARs), Terminal Aerodrome Forecasts, bulletins, watches, and warnings) and graphical depictions via displays (e.g., Next Generation Weather Radar or combined products from many sensor types, assembled by the Integrated Terminal Weather System). Weather information, from various sources and in different formats is often inconsistent, leading air transportation decisionmakers to interpret what each product means when taken in combination with potential adverse impacts to their decision. This may cause conflicting courses of action that frequently bring about reduced capacity or less efficient use of the National Airspace System (NAS). However, in the Next Generation Air Transportation System (NextGen) era, the majority of weather information will be digital data from a common source as necessary input to decision support tools (DST) used to help decisionmakers better determine flight constraints due to weather. This integration of digital weather information, in common format, into DSTs significantly improves decisionmaking, particularly in a dynamically changing weather, reducing congestion and delays.

Weather plays an important part in everyday life, so much so that major television stations vie for viewership by gathering their own Doppler weather radar information and hiring professional meteorologists. They use animated graphical displays of thunderstorm forecasts or snowfall amounts to explain in a minute of airtime the impact of weather to people across the country.

While current aviation weather depictions fail to keep pace with these popular, visual advancements, the operational improvement required by NextGen goes well beyond TV weather. In NextGen, moving streams of aircraft through shifting weather over time requires a four-dimensional workspace. Just seeing a static, two-dimensional, color display of forecast thunderstorm activity, e.g., expected areas of radar reflectivity or turbulence or in-flight icing, is insufficient. Continued use of aviation impact surrogates due to convection as a way to find and show where flight hazards may exist, such as satellite images, or radar reflectivity and echo tops will not be sufficient to support NextGen operations. The current paradigm for convective depictions of hazards tends to overly restrict potentially useable airspace and foster conflicting meteorological interpretation of impacting weather by Air Traffic Controllers and Traffic Flow Managers who need to focus on moving aircraft and not guessing about the weather. With the increased efficiency and demand expected of the future NAS, traffic flow management (TFM) and air traffic specialist automation systems (DSTs) must access common, gridded observation data and forecast model output to gather attributes that make up a thunderstorm. In this manner, the DSTs simplify the multitude of forecast weather variables, events, and thresholds and do so with probabilities and thus, be able to better discern when and where NAS airspace is available, impassable, or flow is constrained.

The "weather forecast" paradigm shift in the NextGen era is that, while stand-alone graphical displays of weather readily convey more information than text, they are no longer adequate. Required is the merging of more accurate probabilistic weather forecasts in gridded format with expected aircraft positions enabling DST algorithms to determine air traffic 'throughput' in and around forecast weather.

With the advent of Trajectory Based Operations (TBO), the cornerstone of NextGen, a paradigm shift is required in the way weather information is requested, accessed, depicted, and integrated into DSTs. To support the capabilities that will enable TBO, all digital weather elements are atmospheric values only and are user threshold independent. Their interpretation and

* *Corresponding author address:* Cheryl G. Souders, FAA, 800 Independence Ave, SW, Washington DC 20591; e-mail: *Cheryl.Souders@faa.gov*

ultimate aviation impact is to be determined by the users' DSTs. Impacts, for example, may be in the form of reroutes or sections of airspace throughput based on traffic loads and aircraft performance characteristics.

To enable the NextGen paradigm shift, the Federal Aviation Administration (FAA) developed draft performance requirements for the NextGen portfolio of weather services. These requirements will be allocated across multiple agencies as a future Joint Planning and Development Office (JPDO) task.

2. NEXTGEN GOALS AND OBJECTIVES

To meet NextGen goals and objectives, a transformed air transportation system must include improved weather operation (JPDO, 2010), as follows:

- The integration of weather information, combined with the use of probabilistic forecasts to address weather uncertainty and improved forecast accuracy, minimizes the effects of weather on operations.
- Improved communications and information sharing allows all stakeholders access to a single authoritative weather source. Weather data is translated by users' DSTs into information presented to NAS users and service providers, such as the likelihood of flight deviation, airspace permeability, and capacity impacts.
- Users see weather information integrated with decision-oriented automation and human decisionmaking processes as opposed to separate data viewed on a "stand-alone" display.

In support of the NAS operational decisionmakers (JPDO, 2010):

- The primary role of weather information is to enable the identification of optimal trajectories that meet the safety, comfort, schedule, efficiency, and environmental impact requirements of all NAS users
- The increased precision and resolution of weather information supports decisionmaking by the Air Navigation Service Provider (ANSP) and also provides a basis for shared situational awareness for collaboration such as cooperative Air Traffic Management (ATM) among the ANSP, flight operators, and other stakeholders
- Weather information is designed to integrate with and support decision-oriented products with automation capabilities that enhance user safety within the NAS
- Weather information is supported by a set of consistent, reliable, probabilistic forecasts, covering location (three-dimensional space), timing, intensity, and the probability of all possible outcomes, each with an associated likelihood of occurrence
- The update frequency of weather information is commensurate with the need to respond to rapidly changing circumstances; in addition, these weather capabilities allow rapid notification (automation-to-automation) of changing weather situations to strategic and tactical decisionmakers.

Therefore, the bottom line is that NextGen NAS users need improved weather information with:

- High spatial resolution
- High update rate
- Probabilistic weather forecast elements
- A common weather picture
- A format that is fully integrable into functions that translate weather into potential NAS constraints

3. FOUR-DIMENSIONAL GRIDDED DATA

Through inter-agency agreement and based on FAA requirements, the JPDO designated the National Oceanic and Atmospheric Administration (NOAA) to develop the Four-Dimensional Weather Data Cube (4-D Wx Data Cube) and the associated "common weather picture," the Four-Dimensional Weather Single Authoritative Source (4-D Wx SAS) capability. The 4-D Wx Data Cube provides access to weather information and services. This includes weather information such as aviation-relevant observations, analyses, forecasts (including probability), space weather information, and climatology organized by three-dimensional (3-D) spatial (latitude, longitude, altitude), and time components.

The 4-D Wx SAS is a subset of the 4-D Wx Data Cube and supports the civil ANSP ATM decisions. By Final Operational Capability (FOC, circa 2025), the 4-D Wx SAS will (1) provide the optimal representation of all ANSP-used weather information that is consistent in time, space, and among weather elements, (2) be accessible to all, (3) be the sole source of weather information for the ANSP's ATM decisions, (4) be specified by the ANSP, and (5) be network-enabled as part of the 4-D Wx Data Cube.

4. FAA NEXTGEN WEATHER REQUIREMENTS DEVELOPMENT BACKGROUND

In January 2008, a JPDO study team produced drafts of functional requirements distributed for comment. Following this effort, the FAA led a multi-agency NextGen Weather Performance Requirements Team (NWPRT) to produce draft performance requirements for a subset of the NAS, the high-density terminal airspace, which were distributed for comment in October of 2009. More recently, performance requirements for the remaining NAS airspaces were sent out for review in February, 2011. These draft FAA 4-D Wx SAS performance requirements will, in part, form the basis for determining which JPDO concepts and FAA investment packages are viable and will best satisfy all NextGen NAS aviation weather users' requirements.

Initial teams, starting with little more than the NextGen Concept of Operations (ConOps), proposed weather requirements based on the long term needs of the ANSPs. In fact, the 4-D Wx SAS requirements were developed primarily based on the needs of the ANSP to support trajectory based operations, integrated arrival and departure, and integrated surface movement management. Requirements for the non-ANSP decisionmakers, which were allocated to the 4-D Wx Data Cube, will be developed in 2012.

During the requirements development process, use of weather information in NextGen was not envisioned as today, where it is independently considered and evaluated by decisionmakers. Useful weather information, by the year 2025, is envisioned as highly granular, mostly probabilistic, highly accurate and reliable, and fully integrated into automated tools (DSTs) that will use weather-related potential constraints to develop NAS impact assessments and recommend impact mitigation strategies to NextGen decisionmakers. These decisionmakers must effectively manage the amount of operational risk due to weather, enabling them to maximize airspace efficiency and safety of flight. The weather performance requirements must encompass the needs of the 4-D Wx SAS for observed and forecast weather parameters.

Weather performance requirements (which assign measurable values to each function) were developed using a set of assumptions and rationale based on the team's understanding of NextGen concepts, as well as the capabilities and the underlying functionalities that will enable them. The ATM and operational user community must help validate these assumptions and rationale. Their feedback will lead to a better understanding of user needs with the weather functionality to provide it. Weather performance requirements are also subject to change as our understanding of both the mid-term and far-term operations increases over time.

5. CHANGING DEFINITIONS AND SHIFTING PARADIGMS

Weather requirements necessary to achieve the NextGen FOC were drafted as "solution-independent" entities, so as not to confuse the imperfect technological solutions of today with true weather requirements. For example, representing convective storms today, we may use a two-dimensional map (Figure 1) of radar reflectivity to show a moving and shifting three-dimensional volume of convective weather hazards. However, NAS decisionmakers need less weather displays; they need to know where the aviation hazards are expected to exceed operational thresholds of flight associated with convection/thunderstorms, e.g., hail, in-flight icing, low-level wind shear, low ceiling/visibility, downdrafts, high wind gusts, etc. In addition, a three-dimensional (not two-dimensional) perspective of these hazards, or attributes, is needed so that weather avoidance planning can be undertaken.

In an effort to determine the true components of convective weather hazards that the decisionmakers' DSTs would run against aircraft or decision-specific thresholds, the team identified as requirements each weather hazard (attribute) caused by convection, including those hazards often existing outside regions of high reflectivity such as turbulence, gust fronts, lightning, and tornadoes.

Both teams took on the challenge to develop weather requirements for operations that do not yet exist and that are not limited to the context of how weather information is used today. The result is stated within the context of NextGen operations and with a concerted effort to identify the true nature of aviation weather needs. These requirements were stated in the context of NextGen in a concerted effort to identify the true nature of aviation weather needs.

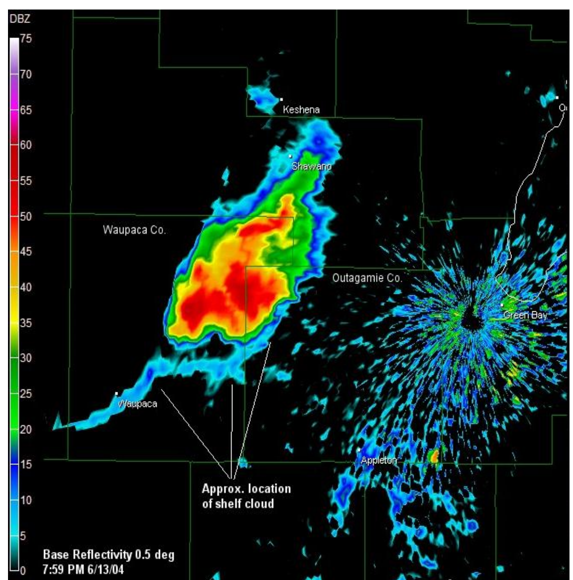

Figure 1. Two-dimensional depiction of radar reflectivity.

6. "WHERE'S MY THUNDERSTORM?"

The term thunderstorm is commonly used to refer to a 3-D portion of the NAS where hazards associated with thunderstorms exist. Those hazards include:

- Moderate or greater turbulence and areas of widespread vertical motion

- Low-level wind shear and gusty surface winds
- Large hail
- Moderate or greater in-flight icing
- Mesocyclones, tornadoes, funnel clouds, and waterspouts
- Lightning
- Low visibility and ceiling due to heavy precipitation

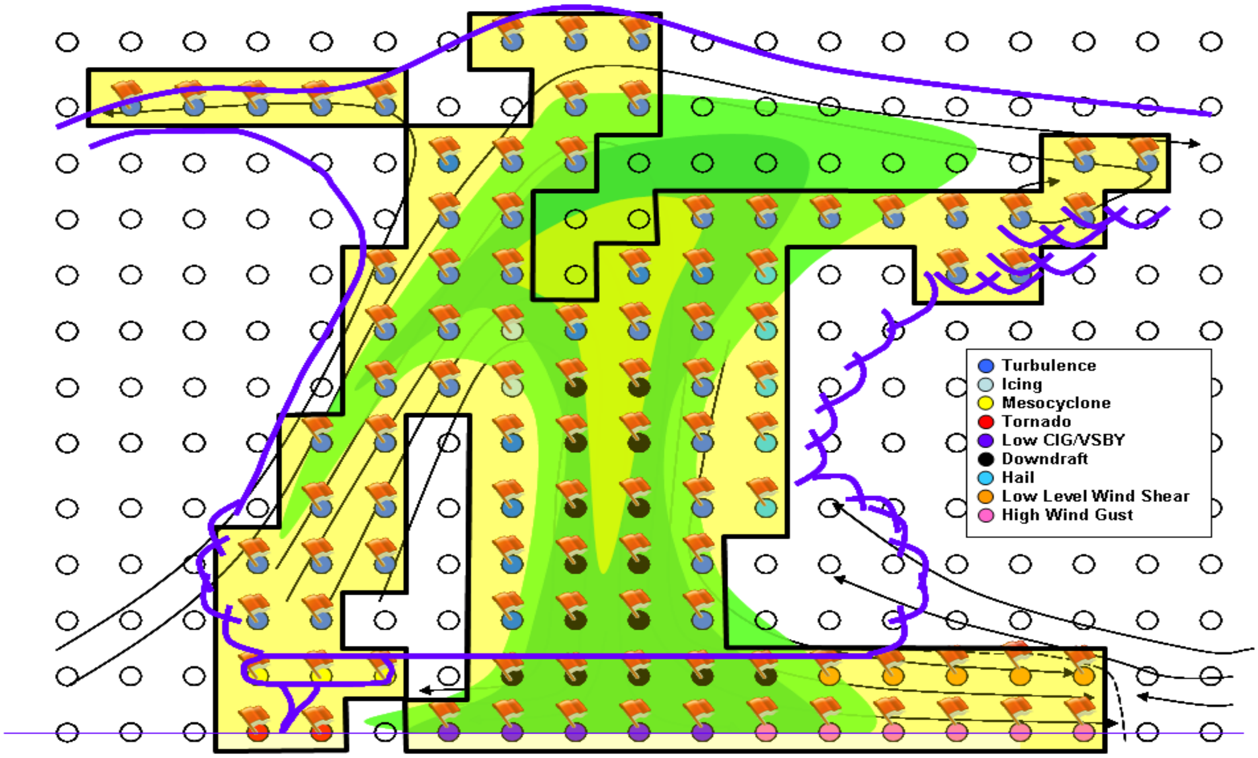

Figure 2. Convective Hazard Volume with Flags Representing Convective Hazards

Authoritative sources of information that define thunderstorms (e.g., FAA Order 7900.5, FMH-1, and the AMS Glossary) do so consistently using the term lightning and thunder. In these definitions, hazards other than lightning may or may not be present to be classified as a thunderstorm.

Although the term thunderstorm is commonly used in aviation, these definitions do not allow a precise, high-resolution description of the volume of airspace that contains its hazards. Lightning exists for just a flash, yet the hazards associated with thunderstorms can exist before, during, and after the flash. Lightning fills a relatively small column of air, yet the hazards associated with thunderstorms exist miles away from the lightning at great heights or along the ground, and can exist long after the last flash occurs. In the NextGen requirements effort, identifying the criteria needed to precisely circumscribe a volume of airspace that meets the condition of having a thunderstorm has been problematic if not vexing. Today, the technological solution depicting "thunderstorms," uses a two-dimensional depiction of radar reflectivity to represent a volume of convective weather hazards (e.g., composite reflectivity, vertically integrated liquid, and echo tops.)

What the decisionmakers' DSTs need to know is where *all* of the hazards associated with free buoyant convection (i.e., thunderstorms) are located. In an effort to determine the true components of convective weather hazards that the decisionmaker DSTs will use to run against aircraft or decision-specific thresholds, the team chose to identify as requirements each weather hazard caused by convection, including those hazards often existing outside regions of high radar reflectivity such as turbulence, gust fronts, wind shear, lightning, and tornadoes.

Instead of using the ambiguous term "thunderstorm" to describe the hazards associated with convection, the NWPRT team recommended a term that describes a thunderstorm with sufficient precision -- Convective Hazard Volume (CHV). CHV represents the volume of airspace containing thunderstorm-related phenomena associated with the convective characteristics of cumulonimbus clouds. See Figure 2 for a depiction of a CHV. This definition of CHV would include the following phenomena not necessarily included in the volume defined by radar—vertically integrated liquid (VIL) or composite reflectivity:

- Turbulence in the anvil portion of a cumulonimbus cloud far away from lightning flashes

- Moderate to strong low-level wind shear caused by outflow boundaries many miles away from lightning flashes

- A tornado funnel on the ground 30 miles from the heavy precipitation area of a thunderstorm (Lawrence, Kansas, 2006) (US DOC, 2006)

- Tropical storm convection that has little or no lightning

The CHV describes a volume containing thunderstorm hazards independent of the volume defined by high values of VIL or composite reflectivity. The CHV does not include turbulence within cumulus or towering cumulus clouds. Instead of determining performance requirements for a “thunderstorm,” the requirements were developed separately for each of the convective hazard elements. Table 1 lists the forecast information elements that will contribute towards construction of the CHV. For example, enhanced predictions of lightning will provide decision guidance for managing ground-based operations (e.g., baggage handling, re-fueling, etc.) as well as other airport, airline, and third-party operator asset management.

7. IMPROVEMENTS WITH CHVs

The concept of the CHV supports the decisionmakers need to have visual confirmation to support DST-provided guidance for trajectory modification prior to encountering the impacted airspace. Such trajectory modifications remain increasingly “closed,” in that updates based on conflicts, weather, or other emerging issues include a return of each aircraft to its preferred route as soon as practical to keep trajectory and conflict prediction accurate. The CHV concept supports advanced flight deck automation guidance for the provision of options for continued safe and efficient flight based on user preferences and aircraft performance. Other aircraft may be brought in over the top of the weather (meaning impact-specific weather and not just echo tops) and assigned a new arrival path segment. If sufficient gaps are identified then bi-directional operations and their guidance can be safely supported. In transitioning to the NextGen timeframe, the CHV also supports a decrease in potential workload for en route controllers due to reduced pilot requests for deviation. It supports more strategic inter and intra-flow control initiatives, based on gaps in convective impacts, into trajectory modifications (but still closed) for affected aircraft.

Lightning, Total (surface and aloft)	**Sky Condition (surface and aloft)**
Location of Lightning	Location of Clouds
Mesocyclones (aloft) Location of Mesocyclones	Vertical Visibility at Airports
Precipitation Liquid Water Equivalent Aloft Liquid Water Content Aloft Median Vol. Diameter of Liq. Water Droplets Aloft	**Tornadic Vortices** Location of Turbulence Intensity of Turbulence **Turbulence** Location of Turbulence Intensity of Turbulence
Type of Precipitation	
Liquid Precipitation **Rain** Location of Rain	**Visibility** Surface Prevailing Visibility Flight Visibility
Freezing Precipitation	
In-Flight Icing (Freezing Precipitation Aloft)	
Location of In-Flight Icing	
Solid Precipitation	
Hail	

Table 1 "Forecast Atmospheric Information Elements for a CHV

In the radar-sparse oceanic environment, the CHV would support the need to provide an expanded depiction of route availability, including coverage, into the oceanic portion of the global domains. This is especially needed over the North Atlantic Ocean to increase the predictive capacity/demand imbalances due to thunderstorms affecting European arrivals at eastern U.S. hubs. Of nearly equal priority is expanded coverage into the Canadian portion of the en route airspace domain, in order to better plan Canadian playbook routes.

8. NEXTGEN WEATHER PERFORMANCE REQUIREMENTS

FAA NextGen 4-D Wx SAS final draft Performance Requirements for the functions 'observe' and 'forecast' (including functional probability forecasts) will be provided for final review in February 2011. These requirements are specified for five NextGen airspace types. (See Figure 3 below.) The five types of NextGen airspace are: 1) high-density terminal airspace, 2) designated en route terminal airspace, 3) designated global terminal airspace, 4) en route airspace, and 5) global airspace. Note: "Terminal" airspace is centered at, and extends around primary airports (flight terminals), from the surface up to low altitudes where fast updates to discern mesoscale weather events changing on the order of seconds must be provided. "High Density" refers to the volume of air traffic operations conducted at a terminal that is among the top 35 airports. "En Route" airspace extends to high altitudes and fills in between terminal airspaces. "Designated En Route" airspace may extend down to the surface in between primary terminals, where fewer commercial flight operations are conducted. "Global" refers to international airspace beyond the United States air traffic control flight information regions. Higher capacity airspace will require finer resolution and shorter periods between updates. Some of these performance requirements will be allocated to the FAA and used to support NextGen weather capabilities.

The NextGen 'observe' and 'forecast' weather requirements include only those elements directly observed and forecast. Most calculated and derived weather information is not included in these weather requirements. The NextGen forecast weather requirements set also did not include requirements associated with 3-D objects that could be constructed from forecast weather elements. Examples of 3-D objects (or constructions) not included are freezing level, cloud layers, cloud tops and thunderstorms. The NWPRT assumed these constructions and other value-added information would be created either by weather enterprise decision support services or by user DSTs. The FAA will use modelling and simulation studies with participation by a selected set of NAS decisionmakers as a final validation that the minimum set of requirements for every ANSP use have been defined. In 2012, the NWPRT will begin developing probabilistic forecast performance requirements, and performance requirements for functions other than Observe and Forecast.

9. SUMMARY

With the advent of TBO, the cornerstone of NextGen, a paradigm shift is required in the way weather information is requested, accessed, depicted, and integrated into DSTs. To support the capabilities that will enable TBO, all digital weather elements are atmospheric values only and are user threshold

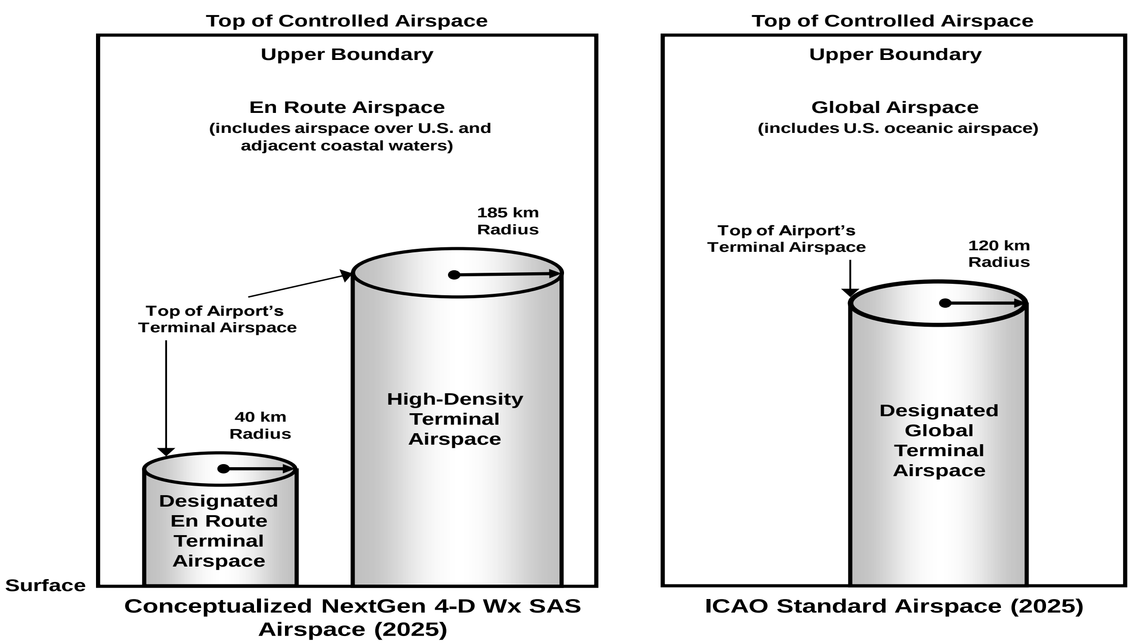

Figure 3. Airspace Categories for 2025 NextGen Weather Support NWPRT 2011

independent. Although there are a number of paradigm shifts in the NextGen era, the key one is that, current weather information will be inadequate. Instead, automated processing and merging (or integration) of more accurate probabilistic weather forecasts in gridded format with expected aircraft positions will be required and will enable DST algorithms to determine air traffic 'throughput' in and around forecast weather.

What the decisionmakers' DSTs need to know is where *all* of the hazards associated with free buoyant convection (i.e., thunderstorms) are located. In an effort to determine the true components of convective weather hazards that the decisionmaker DSTs will use to run against aircraft or decision-specific thresholds, the team chose to identify as requirements each weather hazard caused by convection, including those hazards often existing outside regions of high radar reflectivity such as turbulence, gust fronts, wind shear, lightning, and tornadoes. The NWPRT team recommended a term that describes a thunderstorm with sufficient precision – as a Convective Hazard Volume (CHV) that represents the volume of airspace containing thunderstorm-related phenomena associated with the convective characteristics of cumulonimbus clouds.

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10. REFERENCES

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