Tradeoffs for Routing Flights in View of Multiple Weather Hazards

Manuela Sauer, Matthias Steiner, Robert D. Sharman, James O. Pinto, and Wiebke K. Deierling

National Center for Atmospheric Research, Boulder, Colorado 80301

DOI: 10.2514/1.D0124

Adverse weather impacts the safety and efficiency of aviation. Convective storms, turbulence, and icing are aviation weather hazards that can lead to unpleasant rides and, in the worst case scenario, pose safety risks. Commercial flight route planning tools are largely based on wind optimization, and the daily air traffic flow discussion is heavily focused on avoidance of deep convective storms. Other hazards such as icing (mostly an issue for general aviation) and turbulence have to be manually accounted for by a dispatcher. Routing solutions favoring avoidance of convective storms can result in undesired outcomes such as significant encounters or extended duration of turbulence. This study examines various flight routing approaches, taking into account multiple weather hazards for a range of decision time horizons. A range of time horizons (that is, look-ahead distances) is used to assess the potential benefits of using weather uplinks (for example, onto an electronic flight bag) as compared to the limited information available through the onboard radar. The paper provides a glance at how to improve trajectory-based operations for safe, efficient, and comfortable airborne travel in the future.

I. Introduction

Safety and efficiency are key factors in air traffic management. Both are strongly dependent on the environment aviation is operating in and may be impacted by disruptions caused by adverse weather or other airspace constraints. Airlines try to minimize operational costs by aiming for tight schedules and optimal flight routes. Today’s commercial flight planning tools are optimizing trajectories based on wind as the primary weather information, especially for long-distance flights. In some regions, like the United States, where intense thunderstorms are common, the avoidance of expected large-scale convective storm activity is considered in the daily planning process of air traffic flows. Ground delay programs in response to weather-impacted destination airports as well as prevalidated large-scale reroutings along so-called playbook routes for en route weather avoidance are activated as part of the Federal Aviation Administration (FAA) severe weather avoidance plan to ensure smooth traffic flows [1,2]. Small-scale convective storms, which are inherently difficult to predict, are usually avoided on a tactical level during flight execution by using what is seen on the onboard radar or based on nowcast information accessible via the electronic flight bag (EFB). Other weather hazards such as turbulence and icing are typically avoided once encountered.

This study explores a variety of approaches and outcomes when considering zero to multiple weather hazards in the flight routing process. We examine exposure versus detox tradeoffs for various scenarios by nudging a flight en route as weather hazards are encountered, albeit with some simplifications, as will be discussed later. Results are shown for a combination of multiple city pairs and four distance flights. In some regions, like the United States, where intense thunderstorms are common, the avoidance of expected large-scale convective storm activity is considered in the daily planning process of air traffic flows. Ground delay programs in response to weather-impacted destination airports as well as prevalidated large-scale reroutings along so-called playbook routes for en route weather avoidance are activated as part of the Federal Aviation Administration (FAA) severe weather avoidance plan to ensure smooth traffic flows [1,2]. Small-scale convective storms, which are inherently difficult to predict, are usually avoided on a tactical level during flight execution by using what is seen on the onboard radar or based on nowcast information accessible via the electronic flight bag (EFB). Other weather hazards such as turbulence and icing are typically avoided once encountered.

This study explores a variety of approaches and outcomes when considering zero to multiple weather hazards in the flight routing process. We examine exposure versus detox tradeoffs for various scenarios by nudging a flight en route as weather hazards are encountered, albeit with some simplifications, as will be discussed later. Results are shown for a combination of multiple city pairs and four typical weather situations that can affect the U.S. National Airspace System (NAS). These weather situations cover the spectrum from large-scale frontal system cases that feature several aviation hazards of interest to scattered convective storms on a summer day. Characteristic effects will be evaluated and discussed. The results are expressed in terms of distance flown and duration of exposure to weather hazards that have not been considered in the flight planning or execution.

Information on operational weather avoidance practice is discussed in Sec. II. Weather data available to the aviation industry and applied here are introduced in Sec. III together with a description of the examined weather situations. Section IV provides insights into the routing tool and methodologies applied for this study, including a perspective on other approaches documented in the literature. Results of the performed simulations and analyses are discussed in Sec. V. A summary of key insights gained together with concluding remarks about future work is presented in Sec. VI.

II. Weather Avoidance in Today’s Operations

Certain atmospheric conditions pose a risk to safe aircraft operations, and thus require avoidance. Convective storms are accompanied by several other hazards, including turbulence and icing that may occur below, within, around, and above the visible cloud. Convective storms usually block the entire atmospheric column (i.e., all typical flight levels), as can be seen in Fig. 1, which demands a lateral circumnavigation by aircraft. To avoid convective storm hazards, international regulations of the FAA and the U.K. National Air Traffic Services (NATS) recommend staying clear of deep convection by at least 20 n miles (10 n miles below 20,000 ft) [3,4]. The pilot is usually able to detect convective cells by eye (in daylight and based on illumination by lightning or moonshine at night) and with the onboard radar that provides additional information about the intensity of storms (note that the signal strongly depends on the range and sensitivity the radar is set to). For tactical navigation through or around areas of convective storm hazards, pilots mostly rely on the onboard radar information despite its limited range (40–180 n miles), beam attenuation, and often nonoptimal use of tilt angle [5]. Although convective storms and their precipitating hydrometeors are detectable with the onboard radar, hazards like turbulence or icing that can occur significant distances away or completely detached from the intense convective storm cells are not. These hazards often occur in layers of substantial horizontal extent but with limited vertical depth (see Fig. 1). This latter characteristic may allow for vertical avoidance if feasible (e.g., climb rate enables reaching a hazard-clear flight level) or possible based on the phase of flight (en route) and other traffic nearby. However, any notable deviation from the flight plan, such as a heading change for lateral avoidance or a flight level (FL) change, needs to be coordinated with and cleared by air traffic control (ATC) to ensure safe operations. ATC may also be able to give routing advice based upon ground-based radar coverage and pilot reports (PIREPs) from preceding aircraft. Vertical maneuvers might be preferred by the
airlines, but their coordination will increase a controller’s workload because air traffic approaching from different directions at flight levels to be crossed must be accounted for.

Whether a maneuver is necessary or practical may also depend on airline policies and procedures, as well as aircraft capabilities. Passing through a turbulent cloud layer of moderate or greater intensity during departure or arrival for a short time is mostly unavoidable. En route, the level of acceptance, however, is likely to vary. Cargo carriers are not concerned with levels of turbulence that commercial airlines may try to avoid for passenger and crew safety, as well as ride comfort.

For icing conditions, aircraft certification strictly specifies whether or not an aircraft is allowed to encounter regions of icing [6]. During departure, flights usually climb fast and pass through hazardous icing layers quickly. Arrival traffic within the terminal maneuvering area of an airport, however, may transit slowly through such layers. Especially in the case of required holding, aircraft may remain in atmospheric conditions conducive to serious airframe icing for a significant amount of time (tens of minutes). Recognition of hazardous icing conditions by ATC is key to avoid setting up a significant amount of time (tens of minutes). Recognition of hazardous icing conditions by ATC is key to avoid setting up potentially dangerous holding patterns for arriving flights unable to transit slowly through such layers.

Adjustments typically made by air traffic managers and controllers include transition of flights to icing-free holding areas or not an aircraft is allowed to encounter regions of icing [6]. During departure, flights usually climb fast and pass through hazardous icing layers quickly. Arrival traffic within the terminal maneuvering area of an airport, however, may transit slowly through such layers. Especially in the case of required holding, aircraft may remain in atmospheric conditions conducive to serious airframe icing for a significant amount of time (tens of minutes). Recognition of hazardous icing conditions by ATC is key to avoid setting up potentially dangerous holding patterns for arriving flights unable to transit slowly through such layers. Especially in the case of required holding, aircraft may remain in atmospheric conditions conducive to serious airframe icing for a significant amount of time (tens of minutes). Recognition of hazardous icing conditions by ATC is key to avoid setting up potentially dangerous holding patterns for arriving flights unable to transit slowly through such layers.

For icing conditions, aircraft certification strictly specifies whether or not an aircraft is allowed to encounter regions of icing [6]. During departure, flights usually climb fast and pass through hazardous icing layers quickly. Arrival traffic within the terminal maneuvering area of an airport, however, may transit slowly through such layers. Especially in the case of required holding, aircraft may remain in atmospheric conditions conducive to serious airframe icing for a significant amount of time (tens of minutes). Recognition of hazardous icing conditions by ATC is key to avoid setting up potentially dangerous holding patterns for arriving flights unable to transit slowly through such layers. Especially in the case of required holding, aircraft may remain in atmospheric conditions conducive to serious airframe icing for a significant amount of time (tens of minutes). Recognition of hazardous icing conditions by ATC is key to avoid setting up potentially dangerous holding patterns for arriving flights unable to transit slowly through such layers.

III. Weather Data and Situations Studied

Timely and accurate information about rapidly changing weather conditions is crucial for safe and efficient aircraft operations. Detailed information about the magnitude, spatial extent, and evolution of different weather hazards is essential for planning efficient routes, crew and passenger safety, and ride comfort. Here, we use convective storm, turbulence, and inflight icing hazard guidance from the Consolidated Storm Prediction for Aviation (CoSPA) [7–9], the Graphical Turbulence Guidance (GTG) [10, 11], and the Current Icing Product (CIP)/Forecast Icing Product (FIP) [12], respectively.

Wind data are taken from the National Oceanic and Atmospheric Administration’s (NOAA’s) Rapid Refresh (RR) model [13]. The RR is NOAA’s continental-scale assimilation system and numerical forecast model. It provides hourly updated forecasts for North America with a 13 km horizontal grid resolution and 50 vertical levels. Winds appropriate for a given flight level are taken from the 2 h RR forecasts (accounting for latency of when the model output becomes available) to determine aircraft ground speeds.

CoSPA provides an analysis and forecast of vertically integrated liquid (VIL; a proxy for storm intensity) and echo top heights with an outlook period of 8 h in time increments of 15 min. The analysis is based on the Massachusetts Institute of Technology Lincoln Laboratory’s Corridor Integrated Weather System (CIWS) VIL and echo top mosaics, whereas the forecasts are a blend of CIWS extrapolation and the NOAA’s High-Resolution Rapid Refresh (HRRR) model forecasts. The convective storm hazards can be derived from either the VIL or echo top heights. For the purpose of this study, we identify moderate and severe (labeled mod and sev, respectively, in the figures) convective storms by areas with analyzed echo tops (defined by the maximum height exhibiting radar reflectivity greater than 18 decibel (dBZ)) exceeding flight levels 250 and 300, respectively.

GTG provides forecasts of turbulence with outlook of up to 18 h. We are using the nowcast version of GTG (equivalent of an analysis) that blends the most recent turbulence observations with a short-term GTG forecast based on the RR output and updates every 15 min. Turbulence observations used to generate the analysis product include in situ measurements of the eddy dissipation rate (EDR), turbulence PIREPs, and output from the National Center for Atmospheric Research’s turbulence detection algorithm that derives EDR values from the Next Generation Weather Radar (known as NEXRAD) Doppler weather radars. As suggested by Sharman and Pearson [10], areas of moderate and severe turbulence are identified by EDR $\geq 0.22 \text{ m}^{2/3} \text{ s}^{-1}$ and EDR $\geq 0.35 \text{ m}^{2/3} \text{ s}^{-1}$, respectively, for flight levels 100, 200, 300, and 400.

The CIP and FIP provide hourly updated current and forecast (up to 18 h) icing conditions that are diagnosed from RR model output. The CIP and FIP include a probability of icing, supercooled large droplet potential, and categorical icing severity. Areas of heavy icing indicated by the CIP categorical icing severity field are used in this study for flight levels 100, 150, and 200.

Representative snapshots of four typical weather situations used to examine the impact of accounting for multiple weather hazards during flight planning are shown in Fig. 2. Although the weather phenomena producing these hazard fields differ quite a bit, all four situations feature convective storm (red) and turbulent (orange) hazard areas of both intensities and in several flight levels (color coded as in Fig. 1). Additionally, icing conditions (blue colors) occur in all four cases but are not evident in most of the images because they coincide with the turbulence and/or convective hazard fields.

Figure 2a shows the line-shaped hazards associated with a cold front extending south from an area of low pressure centered over Iowa at 0600 hrs Coordinated Universal Time (UTC) on 18 November 2015. The cold front, which featured moderate and intense convective storms as well as turbulence, moved eastward over the course of the day. Icing conditions at levels 150 and 200 are also evident on the back edge of the frontal system. A second widespread turbulence area is associated with another frontal system in the Pacific Northwest of the United States. In this situation, turbulence is found throughout the atmospheric column but mostly collocated with the areas of convective storms.

Figure 2b depicts a typical summertime situation in which the hazards are more widely spaced and dominated by smaller areas of convective storms spread throughout the eastern two-thirds of the United States. In this situation, turbulence is found throughout the atmospheric column but mostly collocated with the areas of convective storms. Figure 2c depicts atmospheric hazards associated with a rapidly decaying wintertime cold front that is dominated by turbulence hazards. Turbulence prevails in lower atmospheric levels up to FL 300. There is also some turbulence associated with mountain waves over Colorado. Finally, in Fig. 2d, a springtime case is shown characterizing impacts of convective storm hazards and turbulence associated with a north–south-oriented cold front along the Mississippi River Valley and upper-level jet-induced turbulence over the Great Plains. The turbulence associated with the frontal system extended throughout much of the troposphere, whereas turbulence over the Great Plains was mostly contained within flight levels 300 through 400.

IV. Methodology

A. Perspective on Hazard Avoidance Methodologies

The problem of directing an aircraft through a field of constraints (e.g., time-varying weather hazards, congested or restricted airspace)
Fig. 2 Sample weather situations, with hazard areas color coded according to the legend in Fig. 1, overlaid on great-circle routes connecting seven city pairs (San Francisco International Airport (SFO)-Miami International Airport (MIA), George Bush Intercontinental Airport Houston (IAH)-Cleveland Hopkins International Airport (CLE), IAH-Norfolk International Airport (ORF), IAH-Charleston International Airport (CHS), Will Rogers World Airport Oklahoma City (OKC)-Orlando International Airport (MCO), Eppley Airfield Omaha Airport (OMA)-Jacksonville International Airport (JAX), Minneapolis–Saint Paul International Airport (MSP)-Southwest Florida International Airport (RSW)).

Over the past decades, NASA and others have been developing a variety of tools to examine novel air traffic management concepts focused on individual flights, traffic flows, or the entire NAS [38]. For example, the Dynamic Weather Routing (DWR) tool [39] enables identification of efficient flight paths around dynamically evolving convective weather by evaluating and proposing viable routing options with the ability to deconflict weather and air traffic downstream while considering actual airspace structures. DWR has been tested in real-world traffic operations at American Airlines’ Integrated Operations Control Center in Fort Worth, Texas since July 2012 and shown to realize significant time and fuel savings, including the potential to reduce congestion [40].

Because of its significant impacts on aviation, avoidance of convective storms has been extensively addressed, as exemplified by the aforementioned studies. More recently, Kim et al. [41,42] and Cheung [43] examined the combined effects of wind optimization and anticipated turbulence impacts on routing decisions. However, the authors knew of no prior study that had scrutinized the tradeoffs of flight routing in light of multiple constraints imposed by wind, convective storms, turbulence, and inflight icing combined, as is done in the present study.

B. Present Routing Approach

Routing simulations in this study are done using the research-quality weather avoidance model DIVMET (which stands for divert meteorology) [44], originally developed at the Leibniz Universität in Hannover, Germany and based on a geometrical approach similar to a pilot’s visual decision making. DIVMET routes aircraft horizontally through layered two-dimensional fields of adverse weather that evolve with time, and it accounts for the wind speed at a respective flight level. The weather hazards are represented as no-fly polygons using either current or forecast data for a given flight level (e.g., based on intensity thresholds applied to weather hazard fields as explained in Sec. III). In previous work [45], convective storm forecast
The weather impact on planned flights is evaluated and hazard avoidance modeled based on a set of great-circle connections of seven city pairs, as shown in Fig. 2. Each flight profile consists of a continuous climb to (and eventual descent from) either cruise level FL 300 or FL 400 and a corresponding linear airspeed profile that gets modified by winds as described by Sauer et al. [46]. In the simulation, a flight departs from each airport at the top of the hour between 0000 and 2000 hrs UTC [1800 hrs UTC at Miami International Airport (MIA) in Florida and at San Francisco International Airport (SFO) in California], resulting in 290 planned flights. As a baseline for comparison, these flights are first executed along the planned great-circle route through all weather encountered along the way without deviations (ignorance scenario). The amount of time spent within weather hazards is computed by summing the number of minutes spent within the hazard polygons during execution of all the flights. In a second step, DIVMET is used to avoid (i.e., divert around) the hazard represented by a set of hazards as summarized in Table 1. The scenarios are determined based on hazard type and its severity. For example, scenario $sC$ represents common operating procedures in a typical setting of the onboard radar range for a dispatch perspective or larger situational awareness if using EFBs.

### Table 1 Routing scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Considered hazard(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignorance</td>
<td>None</td>
</tr>
<tr>
<td>$sC$</td>
<td>Severe convection</td>
</tr>
<tr>
<td>$msC$</td>
<td>Moderate/severe convection</td>
</tr>
<tr>
<td>$sCST$</td>
<td>Severe convection + severe turbulence</td>
</tr>
<tr>
<td>$msCST$</td>
<td>Moderate/severe convection + severe turbulence</td>
</tr>
</tbody>
</table>

#### Fig. 3
Weather avoidance routing solutions for four different scenarios for a flight from Houston to Norfolk, Virginia (ORF) with departure at 1300 hrs UTC on 18 November 2015.

The analyses of these trajectory simulations focus on the impact of the aircraft encounter times with hazards not considered in the deviation scenario and additional distance flown because of a detour (i.e., actual flown distance minus planned great-circle distance) for the full set of routing scenarios (Table 1). A comparison of trajectory characteristics allows for detection of systematic changes caused by avoidance routing under different scenarios and specifications.

### V. Results

#### A. Weather Impact on Planned Flights

To build a baseline for the avoidance routing evaluation, the weather hazards encountered during flights following a planned great-circle trajectory between city pairs are determined (ignorance scenario). The aircraft position is updated every minute and checked for overlap with and exposure to coincident weather hazards. For each flight, a running count is kept of times the aircraft position is found to be within a specific hazard polygon. Figure 4 summarizes the results of this analysis for the 290 planned flights and four common weather impact cases (Fig. 2). The box and whiskers plots (upper graph in each panel) provide details on the time exposed to hazards, whereas the bar charts (lower graph in panel) indicate the percentage of flights impacted by weather hazards for the ignorance scenario. Starting from the left in the upper graphs, the first two box plots (gray for FL 300, and white for FL 400) give the exposure to any kind of weather hazard and intensity. The next couple of box plots indicates exposure to severe hazards only, followed by the distributions for each individual hazard type and intensity. Although

---

*Sauer ETAL.* 73

---

**Fig. 3** Weather avoidance routing solutions for four different scenarios for a flight from Houston to Norfolk, Virginia (ORF) with departure at 1300 hrs UTC on 18 November 2015.
icing was tracked also, it turned out that none of the planned flights encountered this hazard type.

In the case of the large-scale frontal weather system on 18 November 2015 (shown in Fig. 4a), all 290 flights (100%) in FL 300 and 285 flights in FL 400 encountered at least 1 min of flight time in moderate or greater weather hazards. About 80% (50%) of the flights encountered severe hazards at FL 300 (FL 400), with severe turbulence encounters (75% of the flights at FL300) about three times as often as severe convective storm encounters. There was significantly less severe turbulence (more comparable to severe convective storms) experienced at FL 400 during this case. The majority of flights encountered some moderate convective storms or moderate turbulence at either flight level. The median and average durations of severe hazard encounters for a flight at FL 400 were very small on this day, although some flights experienced notable exposure times. Severe turbulence encounters were of longer duration at FL 300: typically around 5–10 min with outliers exceeding half an hour; encounters of severe convective storms were very small at FL 300. Exposure to moderate convective storms or moderate turbulence was typically on the order of about 10 min, although the distribution of turbulence exposure was highly skewed with maximum encounters way beyond half an hour (even beyond 1 h at FL 400).

In the summer case with scattered thunderstorm cells on 14 July 2016 (Fig. 4b), about two-thirds of the flights encountered some moderate or greater weather hazard along their flight path, whereas about one-third of the flights were not affected. Most flights encountered some moderate convective storms or moderate turbulence (90% at FL 300 and 85% at FL 400). The mean duration of convection storm exposure was typically small: that is, less than 10 min for moderate-intensity levels and less than 5 min for severe-intensity levels. The mean exposure for a flight to severe turbulence was negligible, but moderate turbulence was experienced on average during about 10 min (somewhat less at FL 400).

The third weather case, featuring a narrow cold front on 18 December 2016 (Fig. 4c), shows the fewest flights affected by moderate or greater weather hazards. About 15 flights encountered severe convective storms, and maybe twice that many flights experienced moderate convective storms. The average encounter was typically of very short duration (a few minutes), although some flights spent more than 30 min in convective storm areas. Severe turbulence encounters were rare and minimal in duration; however, there was notable exposure to moderate turbulence levels. About half the flights at FL 300 experienced moderate turbulence of several-minute durations, whereas some flights endured substantial time in moderate turbulence (a maximum of 2 h was observed). Long turbulence exposure happened for flights traveling along the cold front, such as seen for flights between airports in Houston, Texas (IAH) and Cleveland, Ohio (CLE) on that day (e.g., somewhat earlier than shown in Fig. 2c). Clearly, the organization of a weather system and its orientation relative to the direction of flight, plus the timing and location of both the weather and flight, matter in terms of what weather impact will be experienced along the route. Flights parallel to a front may either experience not many weather hazards at all, if they are offset from the front, or have to endure a lot of impacts while flying along and particularly within the front. On the other hand, flights perpendicular to a front will experience pronounced weather impacts (albeit of limited duration) when crossing the front.

The fourth case, a large-scale frontal system observed on 30 April 2017 (Fig. 4d), was similar to the November case (Fig. 4a) discussed previously, but the convective storms in the southeastern
United States were much more substantial in extent and intensity. This resulted in many more flights experiencing severe convective storms and severe turbulence, and the time spent in severe weather hazards was typically on the order of 10 min for convective storms and 5 min for turbulence, with maximum exposure reaching half an hour. A second area of large-scale turbulence further north is associated with the occlusion and the warm front. Overall, almost all flights were impacted by some kind of weather hazard and more than 75% by severe convection and/or turbulence. Because of the sizes of these hazard areas in this case, the characteristic values, such as mean and median, of all the encounter distributions are higher than in the other weather situations discussed here.

Clearly, ignoring weather hazards results in significant encounters along a direct flight route that will affect the ride comfort and possibly jeopardize the safety of the crew and passengers. Therefore, the subsequent discussion will focus on weather hazard avoidance. We exemplify simulation results for FL 300 only because the results for FL 400 are comparable.

B. Weather Avoidance

Weather avoidance in today’s operations primarily means avoiding significant convective storms, as discussed in Sec. II. Avoiding areas of severe convective storms, however, does not automatically imply that other weather hazards such as significant turbulence may have been avoided as well. In fact, many times, reroutes around convective storms may result in increased encounters of turbulence, as our simulations show. We exemplify this based on an analysis of the 30 April 2017 weather case (Figs. 2d and 4d). There were four cancellations and three 15 min departure delays in our simulations due to severe convection on top of an airport on this particular day.

Figure 5 summarizes the difference between Fig. 4d (ignorance scenario) and how Fig. 4d would look if severe convective storms were avoided (i.e., scenario sC in Table 1). The four panels of Fig. 5 focus on encounters of a particular hazard, like severe convective storms (Fig. 5a), moderate convective storms (Fig. 5b), severe turbulence (Fig. 5c), and moderate turbulence (Fig. 5d), for flights executed under the scenario of avoiding severe convective storms (sC in Table 1). The box in the upper left corner of a panel lists the number of flights with no weather hazard encounters (e.g., no severe convection in Fig. 5a), subdivided into how many flights had zero encounters previously under the ignorance scenario (labeled no change) and how many flights now have zero encounters based on avoiding severe convective storms (labeled new). The cancellations are counted in the new category. Adding up the no change and new numbers, plus the number of flights that still encountered some weather hazard (shown across the top of a panel) during their flight, accounts for all 290 flights of the simulation.

Ideally, avoidance of severe convective storms should have yielded zero flights that encountered any severe convection during their travel in Fig. 5a. Indeed, 207 out of 220 originally impacted flights
successfully resolved the conflict with this hazard; however, there were 13 flights that still experienced some severe convection for reasons of temporal resolution in the weather updates. I.e., these encounters are mostly due to discretization effects when a new weather object overlaps with the current aircraft position after a weather update. For these flights, the histogram in Fig. 5a shows how much of the original exposure time has been reduced (there, for 10 flights), remained the same (zero), or increased (for three flights) if the effect went in the other direction. The green/red histogram shows the distribution of the number of flights counted in bins of 5 min increments, where negative time (green side) indicates a reduction in hazard exposure duration and positive time (red side) indicates an increase in hazard exposure duration. The lower graph (downward gray bars) shows the average remaining exposure duration of the flights counted in that bin.

Clearly, one would hope that most of the still affected flights would show up on the green side of the distribution, such that hazard avoidance generally yields a positive outcome. Figure 5a shows that 10 of the 13 flights affected by severe convection had significant reductions in exposure (from 5 to 45 min), mostly to levels of little to no exposure. However, for 2 of these 10 flights (the one in the 15–20 min exposure reduction bin) the exposure was still about 20 min of severe convective storms. The simulations yielded three flights with slightly longer exposure to severe storms, but the average exposure was clearly less than 5 min. Of these three flights (i.e., the number shown in parentheses), however, did not encounter severe convection previously under the ignorance scenario, but the flight passed close to a severe convective cell such that the severe convection avoidance scenario caught this flight inside the applied buffer zone; in addition, the flight ran into an occasional discretization issue with the weather updates in which avoidance became impossible.

Avoiding severe convective storms may include avoiding some of the moderate convection as well. Figure 5b shows that for 93 out of the 262 originally affected flights avoiding severe convective storms resulted in complete avoidance of moderate convection. In addition, 129 of the remaining affected flights benefitted from a significant reduction in exposure (mostly from 5 to 25 min, plus a few up to 55 min) to moderate convection, reducing the time spent in moderate convective storms to mostly 10 min or less. For 26 flights, avoiding severe convective storms did not change the exposure to moderate convection. Moreover, for 14 flights, the avoidance rerouting increased the time spent in moderate convection by 5–15 min, and 3 out of these 14 negatively affected flights did not previously fly through moderate convection under the ignorance scenario. Avoiding severe convection does not necessarily remove severe turbulence encounters, as demonstrated in Fig. 5c. For 90 flights, this was the case, but there were 128 flights that still endured severe turbulence. For 43 of those flights, avoiding severe convection increased exposure to severe turbulence; in fact, for one flight, this resulted in an extended encounter of severe turbulence (more than 20 min). Unfortunately, 7 of those 43 flights did not originally experience severe turbulence under the ignorance scenario. For 28 flights, avoiding severe convection made no difference with regard to encountering severe turbulence, whereas 57 flights benefited from a significant reduction (from 5 to 25 min) in time exposed to severe turbulence, with the remaining time spent in severe turbulence typically less than 5 min.

Lastly, avoiding severe convective storms does little to resolve encounters with moderate turbulence; only 17 of the 240 originally affected flights benefitted from that. For the remaining 223 flights, 79 benefitted from at least some reduction of exposure to moderate turbulence, whereas for 74 flights, the moderate turbulence encounter actually increased; for one flight, this increase was 30 min for a total of about 50 min spent in moderate turbulence. Also, 14 flights did not previously encounter moderate turbulence under the direct great-circle trajectory (ignorance scenario). The average flight exposure to moderate turbulence at FL 300 was maybe 10–20 min; although, for several flights, the exposure lasted notably longer.

Results from all four weather cases are summarized in Table 2. Routing around severe convective storms (scenario sC in Table 1) avoids most severe convection hazards successfully. The remaining conflicts (less than 5%) are due to discretization effects, as alluded to previously. Avoiding severe convective storms, however, does not necessarily resolve conflicts with either moderate convection or moderate and severe turbulence. In two of the cases (14 July 2016 and 30 April 2017), routing around severe convective storms did help in avoiding moderate convection, or at least notably reduced exposure duration. For turbulence, in some circumstances, the hazard encounters were reduced; whereas at other times, the exposure increased. In fact, there were many situations in which routing around severe convective storms yielded notable new encounters of severe turbulence that were not seen under the ignorance scenario. Clearly, if one would like to avoid specific weather hazards, one needs to explicitly target rerouting around them (or avoid layered hazards by changing flight levels, which we did not explore in this study).

| Table 2 Number of flights encountering weather hazards for the severe convective storm avoidance scenario sC |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  |                 |                 |                 |                 |
|                  | No encounter    |                 |                 |                 |
| Hazard           | Case            | Same | Resolved | Total | Less | Same | More | (New) | Total |
| Severe convection| 20151118        | 208  | 76     | 284   | 2    | 3    | 1    | (1)   | 6     |
|                  | 20160714        | 144  | 131    | 275   | 14   | 1    | 0    | (0)   | 15    |
|                  | 20161218        | 244  | 42     | 286   | 3    | 0    | 3    | (0)   | 4     |
|                  | 20170430        | 70   | 207    | 277   | 10   | 0    | 3    | (1)   | 13    |
| Moderate convection| 20151118      | 36   | 4      | 40    | 52   | 149  | 49   | (1)   | 250   |
|                  | 20160714        | 121  | 105    | 226   | 49   | 10   | 5    | (0)   | 64    |
|                  | 20161218        | 184  | 19     | 203   | 30   | 47   | 10   | (0)   | 87    |
|                  | 20170430        | 28   | 93     | 121   | 129  | 26   | 14   | (3)   | 169   |
| Severe turbulence| 20151118        | 64   | 16     | 80    | 32   | 153  | 25   | (6)   | 210   |
|                  | 20160714        | 241  | 32     | 273   | 2    | 5    | 10   | (8)   | 17    |
|                  | 20161218        | 271  | 8      | 279   | 2    | 6    | 3    | (1)   | 11    |
|                  | 20170430        | 72   | 90     | 162   | 57   | 28   | 43   | (7)   | 128   |
| Moderate turbulence| 20151118      | 98   | 1      | 99    | 12   | 140  | 39   | (2)   | 191   |
|                  | 20160714        | 111  | 38     | 149   | 94   | 27   | 20   | (0)   | 141   |
|                  | 20161218        | 129  | 11     | 140   | 35   | 99   | 16   | (0)   | 150   |
|                  | 20170430        | 50   | 17     | 67    | 79   | 70   | 74   | (14)  | 223   |

Avoided 95–99% | Encountered 1–5%
Avoided 14–78% | Encountered 22–86%
Avoided 26–96% | Encountered 4–72%
Avoided 23–51% | Encountered 49–77%
Every deviation from the planned direct great-circle trajectory results in a detour and extra distance flown (determined as the actually flown route minus the direct trajectory), which ultimately adds costs for extra fuel, incurred schedule delays, and possibly missed passenger or crew connections. Figure 6 summarizes key distributions of the individual detours (box-and-whisker plots, left ordinate) and daily cumulative detour (gray bars, right ordinate) for flights at FL 300 under different hazard consideration scenarios (Table 1) and all four weather situations (Fig. 2). Scenario sC in Fig. 6d shows the detours associated with avoiding severe convective storms on 30 April 2017, as discussed previously in Fig. 5. The median (mean) detour flown for this avoidance scenario is about 30 (50) n miles, but several flights incurred detours in excess of 200 n miles. The cumulative detour flown by all 290 flights that day was approximately 14,000 n miles. Clearly, 30 April 2017 exhibited the most significant and organized convective storms (Fig. 2d) that caused substantial rerouting actions as compared to the other three days examined. The narrow cold front on 18 December 2016 (Fig. 2c) yielded the shortest detours (and least cumulative total) because of minimal convective storms that day. The other two days fell somewhere in between these two examples. Avoiding areas of moderate or greater intensity convective storms (scenario msC) led to longer individual detours and cumulative extra distance flown, as expected. In the November case, almost all aircraft deviated. More than 75% of all flights travelled at least an additional 75 n miles, and individual flights experienced detours in excess of 600 n miles. The detours were generally more limited on 14 July 2016 (Fig. 2b) and 18 December 2016 (Fig. 2c) because the weather was less organized or widespread, enabling some flights to pass through gaps or fly mostly parallel to the hazardous weather. Despite that, there were some flights that incurred substantial individual deviations comparable to those of the other two impact weather days.

C. Sensitivity to Avoidance Decision Horizon

The previously discussed results were obtained with a decision horizon of 200 n miles, meaning that the flight started deviating once a hazardous weather conflict was encountered within this distance. It is assumed that the pilot would make a decision as soon as an object appeared at the outer edge of the onboard radar field of view set to the maximum range (although, for rerouting purposes, the entire object and not only the part detected by weather radar is considered here). However, in operations, the radar range is often set to much shorter distances (80–100 n miles). Also, because the information available to the pilot is mostly limited to what is shown in the onboard radar display, it is unlikely that the pilot would make a decision immediately after convective storm hazards appeared somewhere along the outer edge. Instead, the flight would continue on the planned path for the time being to monitor the situation as it unfolds on the radar scope.

The impact of a shorter decision horizon on the length of deviation around convective storms is shown in Fig. 7a. The results indicate that detours tend to be notably longer when the decision to deviate is made avoiding moderate or greater turbulence plus moderate or greater convection (scenario msCmsT) yields by far the longest individual detours and cumulative extra distance flown, as expected. In the November case, almost all aircraft deviated. More than 75% of all flights travelled at least an additional 75 n miles, and individual flights experienced detours in excess of 600 n miles. The detours were generally more limited on 14 July 2016 (Fig. 2b) and 18 December 2016 (Fig. 2c) because the weather was less organized or widespread, enabling some flights to pass through gaps or fly mostly parallel to the hazardous weather. Despite that, there were some flights that incurred substantial individual deviations comparable to those of the other two impact weather days.

C. Sensitivity to Avoidance Decision Horizon

The previously discussed results were obtained with a decision horizon of 200 n miles, meaning that the flight started deviating once a hazardous weather conflict was encountered within this distance. It is assumed that the pilot would make a decision as soon as an object appeared at the outer edge of the onboard radar field of view set to the maximum range (although, for rerouting purposes, the entire object and not only the part detected by weather radar is considered here). However, in operations, the radar range is often set to much shorter distances (80–100 n miles). Also, because the information available to the pilot is mostly limited to what is shown in the onboard radar display, it is unlikely that the pilot would make a decision immediately after convective storm hazards appeared somewhere along the outer edge. Instead, the flight would continue on the planned path for the time being to monitor the situation as it unfolds on the radar scope.

The impact of a shorter decision horizon on the length of deviation around convective storms is shown in Fig. 7a. The results indicate that detours tend to be notably longer when the decision to deviate is made avoiding moderate or greater turbulence plus moderate or greater convection (scenario msCmsT) yields by far the longest individual detours and cumulative extra distance flown, as expected. In the November case, almost all aircraft deviated. More than 75% of all flights travelled at least an additional 75 n miles, and individual flights experienced detours in excess of 600 n miles. The detours were generally more limited on 14 July 2016 (Fig. 2b) and 18 December 2016 (Fig. 2c) because the weather was less organized or widespread, enabling some flights to pass through gaps or fly mostly parallel to the hazardous weather. Despite that, there were some flights that incurred substantial individual deviations comparable to those of the other two impact weather days.
much closer to the hazard (i.e., 100 vs 200-n-mile decision horizon). The distribution of detour distance changes is highly skewed toward longer distances flown (177 flights were negatively affected), although the tails of both the maximum extra distance and the distance reduction were comparable (~300 n miles). Twelve flights did not deviate in the reference scenario (i.e., moderate or greater convective storm avoidance msC), and an additional 12 flights did not need to deviate with a delayed decision while continuing to monitor the weather situation. For another 53 flights, a delayed decision also resulted in a reduced deviation.

With increasing use of EFBS, weather outlooks beyond the radar horizon become more widely available in the cockpit. This enables a greater situational awareness, and routing decisions can be made at an earlier stage. A comparison of detours with an outlook horizon of 400 n miles (equivalent to about a 50 min flight time at 250 m - s⁻¹) and the reference decision horizon of 200 n miles is provided in Fig. 7b. The distribution of detour changes is also notably skewed, but this time leaning in the direction of reduced distances flown to avoid moderate or greater convective weather hazards msC. The majority of the flights (214) did end up with reduced and smoother deviations than under a 200-n-mile decision horizon. The tails of the distribution were reduced as well.

D. Air Traffic Control Perspective

Deviations from a planned route require coordination and clearance with ATC, which increases the workload. Table 3 approximates the increase in ATC workload based on the daily total number of route adjustments at FL 300 (compared to a planned great-circle direct route), in which only heading changes greater than 3 deg are counted. Clearly, the amount of route adjustments depends on the weather situation and the hazard avoidance scenario. Avoiding only severe convective storm cells sC requires the fewest route adjustments, and thus an ATC workload increase. Avoiding severe convection and severe turbulence (i.e., scenario sCsT in Table 1) requires more route adjustments; but, only in one of the examined four cases (i.e., 18 November 2015), there were substantially more adjustments needed. Avoiding moderate intensity levels of either convective storms msC and/or turbulence mT substantially increases the number of required route adjustments. There is no clear trend in terms of adjustments needed (and thus ATC workload increase) as a function look-ahead horizon.

VI. Conclusions

Today’s flight planning and execution in the United States and elsewhere is largely guided by wind optimization and avoiding areas of convective storms. Yet, convective storms are associated with multiple weather hazards, such as strong winds, turbulence, icing, hail, and lightning; and rerouting around intense convective storm cells does not necessarily remove encounters of those other hazards. It is not uncommon that avoidance of severe convection may route flights into areas of significant turbulence, which is not a desired outcome.

In this study, the tradeoffs for flight routing were explored in view of multiple weather hazards. Convective storms, turbulence, and icing conditions were considered based on four typical impacting weather situations. The analyses were carried out using the DIVMET simulation tool that accounts for the environmental winds when routing flights. Seven city pairs were examined with hourly flight departures in both directions. Moreover, a range of hazard avoidance scenarios was studied, including consideration of no, single, or multiple weather hazards of various intensities.

Avoidance of weather hazards results in detours that are associated with increased distances flown and fuel burned. Because deviations from the planned, direct great-circle route require coordination and clearance with air traffic control (ATC), this increases workload as well. The current analyses demonstrate that considering increasing numbers of weather hazards and decreasing hazard intensity thresholds yield longer detours and higher ATC workload, as expected. However, the actual weather hazard avoidance routing and associated detours strongly depend on the particular weather conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Horizon</th>
<th>sC</th>
<th>msC</th>
<th>sCsT</th>
<th>msCsT</th>
</tr>
</thead>
<tbody>
<tr>
<td>20151118</td>
<td>100</td>
<td>475</td>
<td>1778</td>
<td>1650</td>
<td>2412</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>462</td>
<td>1779</td>
<td>1700</td>
<td>2493</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>505</td>
<td>1594</td>
<td>1788</td>
<td>2640</td>
</tr>
<tr>
<td>20160714</td>
<td>100</td>
<td>817</td>
<td>1048</td>
<td>876</td>
<td>1408</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>761</td>
<td>1033</td>
<td>823</td>
<td>1425</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>756</td>
<td>961</td>
<td>807</td>
<td>1322</td>
</tr>
<tr>
<td>20161218</td>
<td>100</td>
<td>273</td>
<td>618</td>
<td>295</td>
<td>809</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>235</td>
<td>551</td>
<td>259</td>
<td>810</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>253</td>
<td>551</td>
<td>294</td>
<td>755</td>
</tr>
<tr>
<td>20170430</td>
<td>100</td>
<td>1324</td>
<td>1871</td>
<td>1498</td>
<td>1432</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>1208</td>
<td>1690</td>
<td>1477</td>
<td>1491</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>1156</td>
<td>1496</td>
<td>1403</td>
<td>1561</td>
</tr>
</tbody>
</table>
situation, flight path, and chosen avoidance scenario. Larger and more organized weather systems generally yield longer detours, although it depends on the flight-path orientation relative to the weather and its organization. Sensitivity analyses based on different look-ahead distances, emulating a pilot’s perspective based on the onboard radar scope or a broader situational awareness using the electronic flight bag, did reveal a clear trend of shorter reroute distances flown with an increasing decision horizon, but the signal was unclear in terms of ATC workload impacts.

Further analyses are needed to more comprehensively examine the tradeoffs for flight routing in view of multiple weather hazards. These analyses will have to include an option for vertical hazard avoidance, such as is typically done with layered hazards like turbulence. Moreover, one should explore tradeoffs between acceptable hazard exposure duration if not avoided (e.g., for short-duration moderate turbulence encounters) versus fuel burn from the extra distance flown (or climb/descend to a different flight level) by avoiding the hazard. Also, it may be worth considering the wind-optimized route as the basis for comparison rather than the great-circle route.

Consideration of weather nowcast/forecast and associated uncertainty can yield valuable insights, as has been demonstrated in several studies on aircraft routing [28, 29, 46], air traffic flow management [23], and airspace congestion. Future research may also allow for penetration of larger moderate or greater areas of turbulence and icing hazards because severe levels of such hazards are usually intermittent. It is worth noting that the moderate or greater turbulence and icing hazard depiction of today’s guidance products may be somewhat overalerting as compared to in situ measurements and pilot observations (PIREPs).

Additional hazards like volcanic ash clouds, space weather impacts, or dynamically restricted airspaces can easily be included. Future flight operations may conceivably environmentally friendly routes by minimizing contrail production to reduce radiative forcing and fuel burn, or maximizing passenger comfort and crew safety.

Acknowledgments

This research was carried out with primary funding from the National Science Foundation and, in part, from the Federal Aviation Administration. The National Center for Atmospheric Research is funded by the National Science Foundation. The authors would like to thank Daniel Adriationsen for providing the inflight icing datasets used in this study and Eulalia Hernández Romero for valuable feedback on the paper. The thoughtful comments and suggestions by two anonymous reviewers and the Associate Editor, Craig Wanke, were much appreciated and helped improve the paper. The views expressed are those of the authors and do not necessarily represent the official policy or position of the funding agencies.

References


C. Wanke
Associate Editor