THE JOURNAL OF
AIR TRAFFIC CONTROL
OFFICIAL PUBLICATION OF THE AIR TRAFFIC CONTROL ASSOCIATION, INC.
Winter 2016 | VOLUME 58, NO. 4

Flight Planning and Execution With Multiple Weather Hazards

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Today's flight planning aims for safety and efficiency based on the airspace structure, available air routes, and weather. For long-distance flights, wind is of primary interest (e.g., riding a tailwind versus avoiding headwinds) and large-scale convective weather systems (e.g., hurricanes) will be avoided. Daily flight planning in the United States considers strategically routing aircraft around areas that are or expected to be convectively active, but other weather hazards, like turbulence and inflight icing, are mostly dealt with tactically.

We explore the potential benefits of considering multiple weather hazards for optimizing routes. We examine tradeoffs for various scenarios of making a route decision before takeoff versus nudging a flight en route as weather hazards present themselves. Results are shown for a combination of multiple city pairs (Figure 1) on a typical early winter day with a large-scale frontal system (Figure 2) affecting the United States airspace. This significant weather system included deep convective storms and notable areas of turbulence and icing hazards. The results are expressed in terms of distance flown and time exposed to weather hazards that have not been considered in the flight planning or execution.

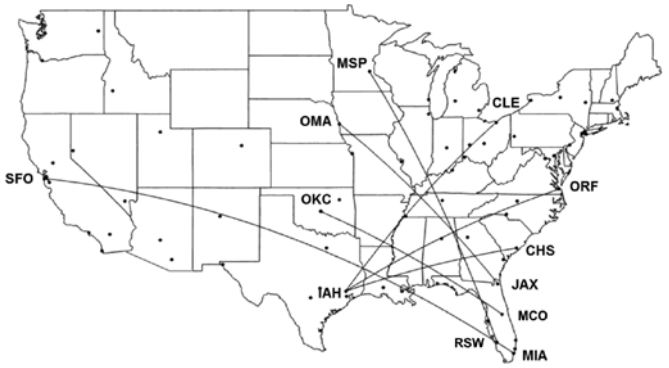

Figure 1. Great circle (direct) trajectories between seven city pairs used in the present study.

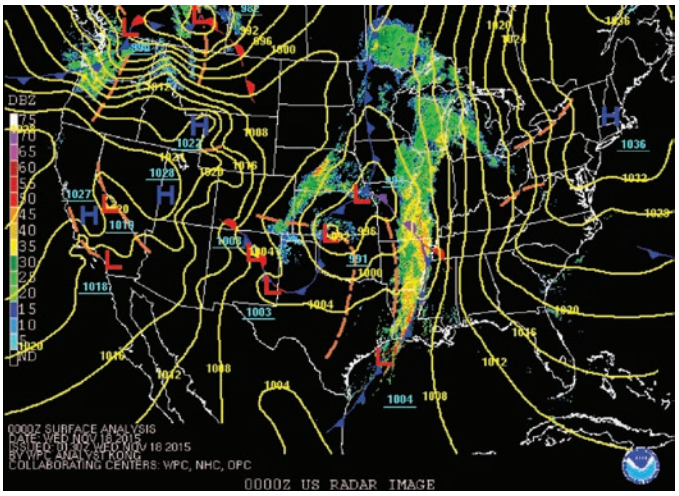

Figure 2. Synoptic weather situation for 0000 UTC on 18 November 2015 and associated areas of low pressure and radar precipitation echoes.

Weather Avoidance

The nature of convective storms and associated hazards below, within, and above a cumulonimbus cloud demand a lateral circumnavigation by aircraft in all phases of flight (Figure 3). Turbulence and icing hazards, in contrast, often occur in layers with limited vertical extent, possibly covering substantial horizontal areas, that may allow for vertical avoidance if feasable (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.

Whether a maneuver is necessary or practical may also depend on airline policies and procedures and aircraft capabilities. Passing shortly through a moderate or greater turbulent cloud layer during departure or arrival is mostly unavoidable. In level flight, package carriers may not be concerned about some level of turbulence, while commercial airlines may try to minimize turbulent encounters for passenger and crew safety and comfort.

For icing conditions, aircraft certification strictly specifies whether or not an aircraft is allowed to encounter icing regions. 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. This is especially the case for a required holding pattern, when aircraft may remain in atmospheric conditions conducive to serious airframe icing for a significant amount of time (tens of minutes). ATC's recognition of hazardous icing conditions is key to avoid setting up potentially dangerous holding patterns for arriving flights unable to land right away due to airspace congestion or runway capacity limitations. Adjustments typically made by air traffic managers and controllers include transition of flights to icing-free holding areas and/or slowing down traffic into the area which may minimize the need for holding.

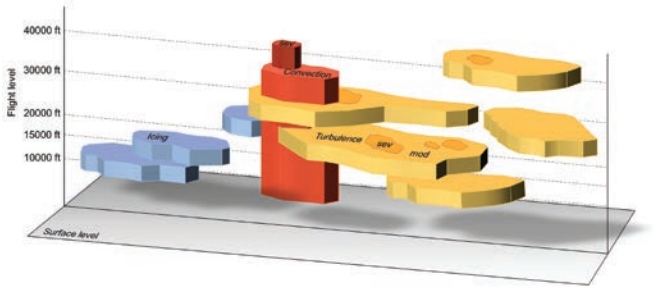

Figure 3. Schematic of the typical column-like occurrence of convection (red), and layered phenomena like icing (blue) and turbulence (yellow/orange).

Any deviation, whether horizontal or vertical, needs to be coordinated with and cleared by ATC to ensure safe operations. While airlines might prefer vertical maneuvers (e.g., for turbulence avoidance), their coordination may increase a controller's workload, as traffic from different directions accross flight levels has to be accounted for.

Simulation Environment and Weather Data

Weather avoidance is modeled using a research-quality simulation tool, DIVMET (i.e., divert meteorology), developed at the Leibniz Universität Hannover, Germany.[1] In its present configuration, DIVMET routes aircraft horizontally through two-dimensional fields of adverse weather that evolve with time and may include uncertainty information. Future enhancements will include vertical deviations as well. Adverse weather is represented as no-fly polygons that can be determined based on current and forecast gridded weather hazard information for a given flight level (e.g., based on intensity thresholds applied to weather hazard fields). In previous work, convective forecast information and associated uncertainties were used as input for the automated flight planning tool.[2] Here, in order to simplify analyses for multiple hazards, the uncertainty element is eliminated by using observations of aviation hazards in the analysis. Future work will utilize forecasts of multiple aviation hazards and associated uncertainties in the flight planning tool.

In the DIVMET tool, deep convective storms are avoided laterally based on a user-selectable minimum distance to the hazardous area–we use a 10 nautical mile separation distance, as recommended by the FAA and NATS.[3],[4] The decision of which side to circumnavigate a hazardous area is made based on the hazard object's lateral extent left and right of the planned route. The aircraft motion is implemented using basic kinematics and a constant ground speed of 250 m/s, and the simulated position gets updated every minute. The weather information is synchronized with the aircraft location at time steps of 15 minutes (consistent with the resolution of the weather data used).

Today's strategic flight planning in the United States is largely guided by avoiding areas of convective storms, especially during the spring and summer seasons.

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Timely and accurate information about rapidly changing weather conditions is crucial for safe and efficient aircraft operations. Detailed information about the magnitude and spatial extent of different weather hazards is essential. Here we use convective, turbulence, and inflight icing hazard guidance from the Consolidated Storm Prediction for Aviation (CoSPA),[5],[6] the Graphical Turbulence Guidance (GTG),[7] and the Current/Forecast Icing Product (CIP/FIP),[8] respectively.

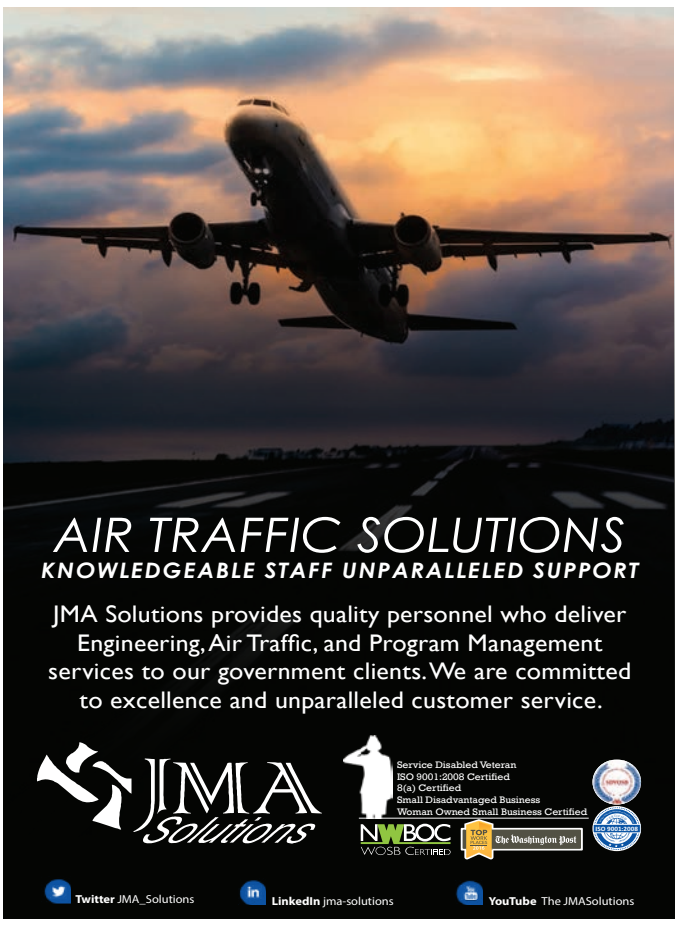
CoSPA provides analysis and convective hazard forecasts with a maximum outlook of eight hours in time increments of 15 minutes. The hazard depiction consists of a vertically integrated liquid (an indicator of storm intensity) and echo top height. For the purpose of this study, we identify moderate and severe convection by areas with analyzed echo tops (defined by 18 dBZ radar reflectivity) exceeding flight levels 250 and 300, respectively.

GTG provides turbulence forecasts with outlook of up to 18 hours. We are using the nowcast version of GTG (equivalent of an analysis), which blends the most recent turbulence observations with a short-term GTG forecast and updates every 15 minutes. The observations include in situ measurements of the eddy dissipation rate (EDR), turbulence pilot reports (PIREPs), and output from the NCAR Turbulence Detection Algorithm (NTDA) that derives EDR values from NEXRAD Doppler weather radars. Areas of moderate and severe turbulence are identified by EDR ≥ 0.3 and EDR ≥ 0.5 $m^{2/3} s^{-1}$, respectively, for flight levels 100, 200, 300, and 400. The values used here are somewhat larger than the 0.22 (moderate) and 0.35 (severe) $m^{2/3} s^{-1}$ thresholds suggested by Sharman et al.[9] Using the lower values would increase distances flown for turbulence avoidance.

CIP and FIP provide hourly updated diagnosed and forecasted (up to 18 hours) icing situations, depicting the icing probability, supercooled large droplet (SLD) potential, and categorical icing severity. Areas of heavy icing indicated by the CIP categorial field are used for flight levels 100, 150, and 200.

Route Optimization

We exercise various scenarios for route optimization. A great-circle trajectory provides the shortest distance between each city pair. This is the basic scenario without considering any weather hazards along the flight path (i.e., hazard ignorance). If one knows exactly how the weather unfolds (i.e., perfect forecast), one could optimize the route before takeoff and reach the destination without encountering any weather hazards of concern. More likely, a flight will take off along the great-circle trajectory and then start avoiding weather hazards as they are encountered within a 30-minute look-ahead time (i.e., adaptive nudging). These three modes are visualized in Figure 4 for an example flight from San Francisco, California (SFO), to Miami, Florida (MIA).



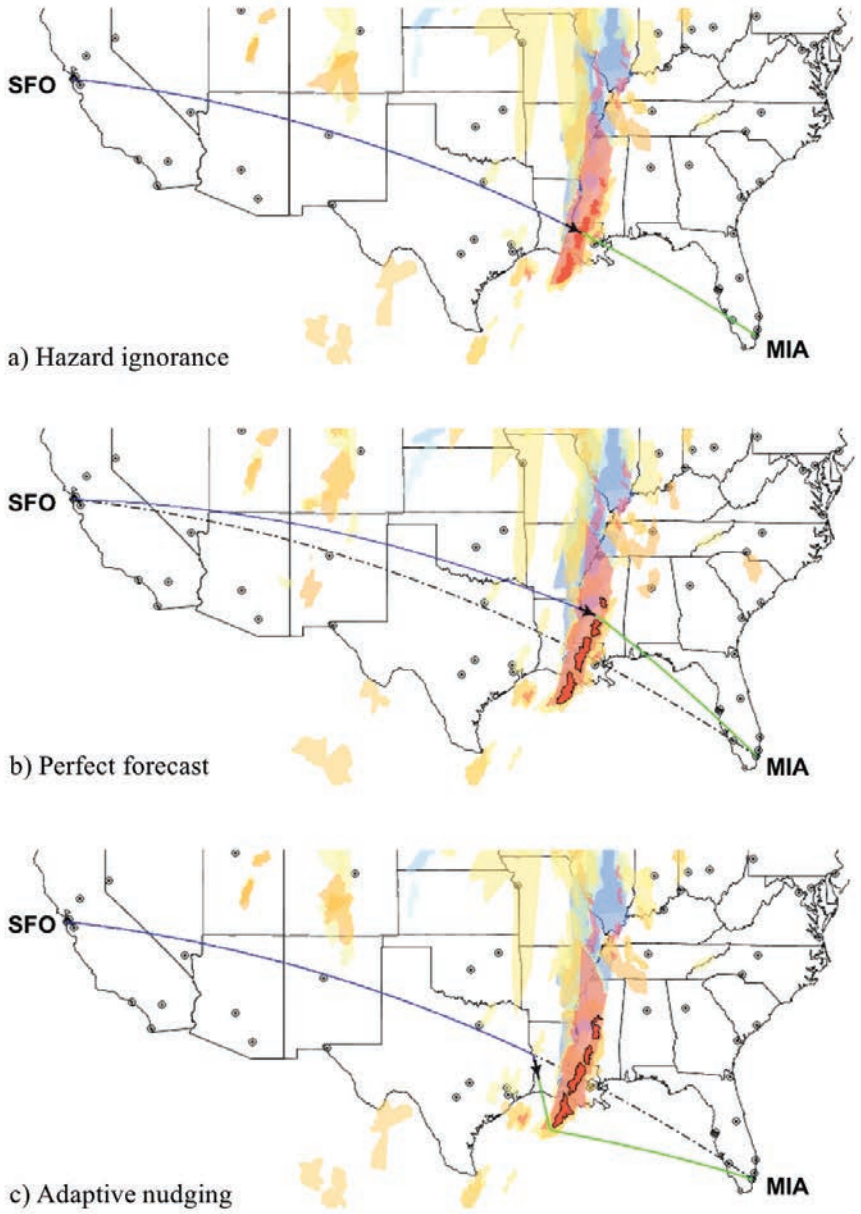


Figure 4. Effects of the applied simulation modes: a) hazard ignorance, b) perfect forecast, and c) adaptive nudging for a flight from SFO to MIA. The blue line indicates the already flown part of the trajectory; the green one is still to follow and might be adjusted to the updating situation in c). Hazards are color-shaded as in Figure 3.

For the purpose of this study, we consider convective storms and turbulence as weather hazards that should be avoided. Moreover, we examine two levels of hazard intensity (i.e., moderate and severe) as avoidance options. At this point, we are only monitoring icing hazard encounters, but do not avoid them, as they are generally experienced at lower flight levels either upon departure or arrival and are most often traversed rather quickly. Table 1 summarizes the 10 different scenarios that result from considering convective and turbulence hazards with two levels of hazard intensity for flight levels 300 and 400, plus one scenario where weather hazards are ignored.

Seven city pairs (Figure 1) provide the basis for the analyses discussed in this article, and flights moving in both directions. At every airport it is assumed flights depart at the top of the hour between 0000 and 2000 UTC (in SFO and MIA the last simulated flight is at 1800 UTC), and the weather data of November 18, 2015 is synchronized with the aircraft location. Moreover, we exercise all three simulation modes hazard ignorance, adaptive nudging, and perfect forecast. This yields a total of 6,090 flight simulations with DIVMET based on the 290 routes and 11 distinct scenarios (see Table 1), 10 of which (all except scenario 0) are simulated in two modes (adaptive nudging and perfect forecast).

Our assessment is based on the distance flown (will be longer than shortest distance obtained without weather avoidance) and the duration of weather hazard encounters (those not considered) along the flight path, including climb, en route, and descent phases.

Tradeoff Analysis

Figure 5 illustrates four intermediate routing solutions for scenarios sC, msC, sCmsT300, and msCmsT300 (see Table 1 for details) in the nudging mode for a flight from Houston, Texas (IAH), to

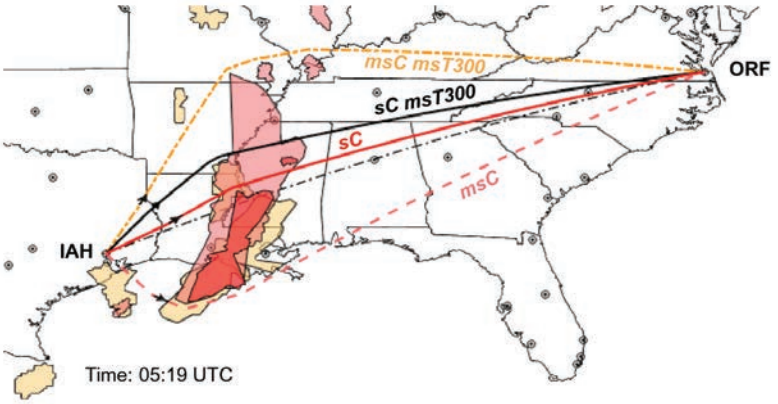


Figure 5. Routing solutions for select scenarios in the nudging mode for a flight departing at 0500 UTC from IAH heading for ORF. The aircraft position is depicted at 0519 UTC.

Norfolk, Virginia. (ORF). The routing solutions differ significantly in their shape, direction, and distance flown. The weather hazard avoidance detours generally increase with decreasing hazard intensity threshold, as the resulting objects exhibit an increasingly larger footprint.

The flight path avoiding severe convection (sC, red solid line) deviates only slightly to the north from the great-circle route, as most of the intense convection occurs south of the ideal direct route. But avoiding both moderate and severe convection (msC, red dashed line) results in a significantly larger detour going south all the way around the convection. Avoiding both severe convection plus moderate or greater turbulence (sCmsT300, black solid line) yields a somewhat larger detour to the north compared to avoiding severe convection only. The largest detour results from avoiding both moderate and severe convection plus moderate or greater turbulence (msCmsT300, orange dotted line), as the path south around the convection is not available due to the presence of turbulence hazards located just to the southeast of IAH.

Table 2 shows impact measures for the city pair routing and scenarios shown in Figure 5. Convection of moderate and severe intensity and moderate turbulence are encountered at flight level 300 along the great-circle direct route, if weather hazard avoidance is ignored. Exclusively accounting for severe convection with the adaptive nudging mode, the red route (sC) is 0.5 percent longer than the direct route. The maximum detour (14.3 percent) for this case emerges when considering moderate convection as well (msC). Gray shading in the lower part of Table 2 indicates considered hazards for the rerouting process. Severe convection is successfully avoided in all scenarios. If not explicitly accounted for, moderate convection and moderate turbulence are encountered–the latter for a longer period than the direct route with weather hazard ignorance would have produced. This example shows that accounting for convective hazards may result in undesired turbulence encounters.

Typically, considering avoidance of a particular weather hazard will be successful, unless a situation arises where, due to the discretization of the weather information (15 minute updates), a rapidly changing weather situation and limited turning options may yield some weather hazard encounters. Such an example is seen in Table 2 for msCmsT300, where six minutes of moderate convection are still encountered despite the avoidance criteria. A higher weather update rate would reduce or eliminate this problem.

The 290 simulated routes between the seven city pairs for that particular day amounted to 333,230 nautical miles (based on direct trajectories) or more than 40,000 minutes of flight. Without any weather hazard avoidance, more than 95 percent of the 290 great-circle trajectory flights were affected by at least one of the considered hazards. Figure 6 shows the individual impacts by phase of flight (climb, en route, and descent) and weather hazard (convection, turbulence, and inflight icing). Hazard encounters are summarized in

Table 1. Hazard scenarios for consideration in the rerouting process.

Scenario	Considered hazard
0	none
sC	sev Conv
msC	mod + sev Conv
sCsT300	sev Conv + sev Turb FL300
sCmsT300	sev Conv + mod/sev Turb FL300
msCsT300	mod/sev Conv + sev Turb FL300
msCmsT300	mod/sev Conv + mod/sev Turb FL300
sCsT400	sev Conv + sev Turb FL400
sCmsT400	sev Conv + mod/sev Turb FL400
msCsT400	mod/sev Conv + sev Turb FL400
msCmsT400	mod/sev Conv + mod/sev Turb FL400

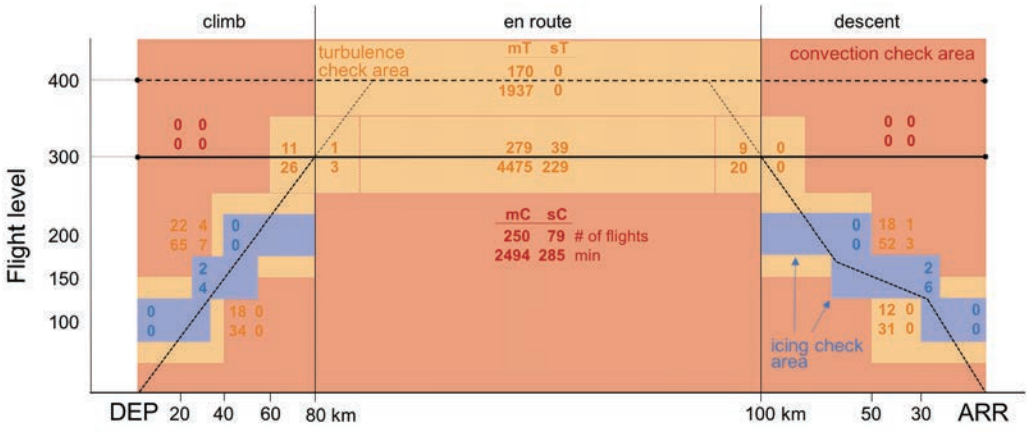


Figure 6. Hazard impacts under the ignorance scenario on 290 direct routes in the respective checking areas color-shaded as in Figure 3.

tabular form within the figure, where the left (right) column shows moderate (severe) convection or turbulence, and the upper row indicates the affected number of flights, while the lower row reveals the duration (in minutes) of the hazard encounter. For the inflight icing hazard, only category heavy icing encounters are shown; there were very few encounters, and all of them were at flight level 150.

On this particular day and for the chosen city pairs, there were no convective storms and very few moderate or greater turbulence encounters in the climb and descent areas. The majority of weather hazard encounters occurred in the en route checking area. Travel at flight level 300 was much bumpier than flying at level 400 and would have included some severe turbulence encounters. Moderate or greater turbulence encounters lasted for about 4,500 minutes for all simulated flights at flight level 300, and flights experienced moderate or greater convection for about 2,500 minutes.

Figure 7 summarizes the results based on considering multi-hazard avoidance using either the adaptive nudging (labeled 'n') or perfect forecast ('pf') mode. Shown are the distributions of percent increase in distance flown due to weather hazard avoidance maneuvers for the various scenarios listed in Table 1.

Because severe convection and turbulence encounters along the direct routes were very small on this particular day, the detours for those scenarios were marginal in most cases. Obviously, for safety reasons those hazards have to be avoided, yet the increased distances flown tend to be relatively small. Avoiding moderate or greater convection and turbulence notably increases the distances flown–the median increase was about 15 percent, but the maximum increase was about 85 percent. The detours tended to be longer at flight level 300 than level 400. In addition, the perfect forecast solutions were a bit shorter than the adaptive nudging solutions. Further study is warranted to better understand the utility of the different approaches to weather hazard avoidance in flight planning.

Table 2. Routing effects of IAH to ORF flight shown in Figure 5 for the nudging mode. The upper part of the table shows the detour expressed as percentage of the great-circle distance (1043.8 nautical miles). The bottom part of the table shows time spent in moderate or severe convection and turbulence, respectively.

none	*sC*	*msC*	*sC msT300*	*msC msT300*	
0	0.5	14.3	7.1	13.1	Detour [%]
		Hazard exposure [min]			
16	15	0	8	6	mod Conv
5	0	0	0	0	sev Conv
6	10	13	0	0	mod Turb
0	0	0	0	0	sev Turb

Discussion

Today's strategic flight planning in the U.S. is largely guided by avoiding areas of convective storms, especially during the spring and summer seasons. Avoiding current or predicted convective storms, however, will not necessarily lead to avoidance of turbulence hazards. In fact, sometimes such avoidance maneuvers guide flights into turbulent areas, which is not a desired outcome and can lead to unpleasant (if not potentially harmful) rides, detours, increased fuel burn, and extra ATC workload.[10]

We have been exploring a planning tool that for the first time enables simultaneous consideration of multiple weather hazards for optimally routing flights. The analyses presented shed light on the tradeoffs between considering either zero, single, or multiple weather hazards, and whether the routing decision was made before takeoff or the flight adaptively nudged en route. The preliminary results discussed here look promising, but it is premature to draw conclusions or to provide guidance for modified approaches to flight planning and air traffic management (ATM).

Additional research and development is necessary to enhance the tool's realism of flight routing and hazard avoidance, and adding flight level wind information. In particular, we will add a vertical hazard avoidance option to reflect the common practice of avoiding layers of turbulence and inflight icing. Furthermore, incorporation of weather hazard forecasts and their uncertainty will enable an assessment of flight planning considering multiple weather hazards in an

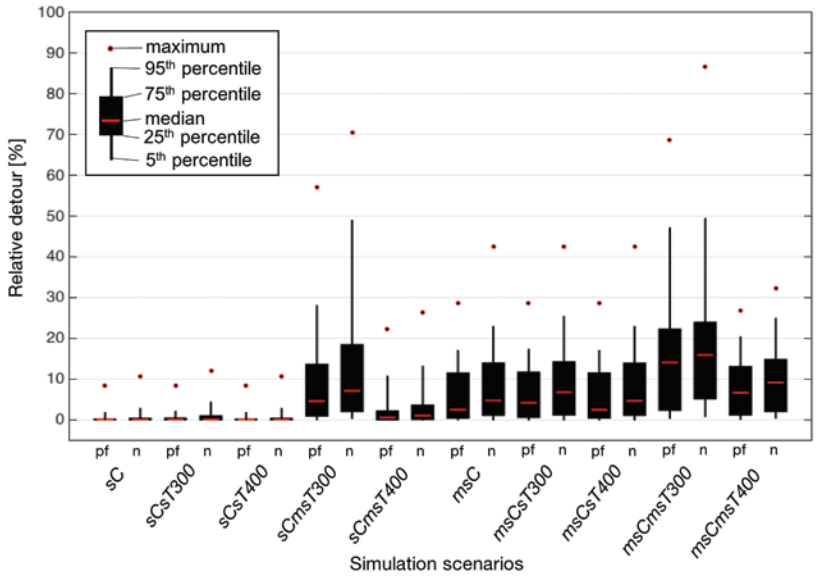


Figure 7. Relative detour distributions of the different simulation modes and scenarios.

operational environment. Recall that today's traffic management is using deterministic forecasts, but future applications will make use of probabilistic forecasts that capture prediction uncertainty. Inclusion of additional hazards like volcanic ash clouds or restricted air spaces could easily be accomodated as well.

The analyses to date have focused on hazard encounters (if they are not considered) and the extra distance flown due to hazard avoidance. Future assessments may conceive environmentally-friendly routes by minimizing contrail production and fuel burn, or maximizing passenger comfort and crew safety.

Ultimately, last but not least, since the weather avoidance tool is computationally efficient at producing hazard avoidance solutions, it can be used in real time for flight guidance.

Acknowledgements

The lead-author conducted the research presented here during a three-month stay at NCAR supported by the Halaby Graduate Student Fellowship. The results were generated using DIVMET software. Copyright © 2016 Leibniz Universität Hannover, by Professor Dr. Thomas Hauf, and MeteoSolutions GmbH. Partial support for this research came from the National Science Foundation (NSF) and the FAA. The views expressed are those of the authors and do not necessarily represent the official policy or position of the funding agencies.

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