Safety and efficiency are key factors for air traffic management. Both are strongly dependent on the environment and may be impacted by any disruptions caused by adverse weather or other airspace constraints. Today’s management of air traffic is heavily geared towards wind-optimized trajectories, esp. for long-distance flights. In the United States, the avoidance of areas of expected large scale convective activity is considered in the daily flight planning process. Avoidance of small scale convection is usually handled on the tactical level. Other weather hazards such as turbulence and icing are not as prominently recognized but dealt with ad hoc during flight execution as needed.

For future trajectory-based operations, an overall four-dimensional integration of atmospheric hazards is required. The research-driven weather avoidance tool DIVMET (i.e. divert meteorology), which is applied here, allows for an evaluation of the aircraft exposure to several hazards along the trajectory. It features decision making support and builds a platform to study routing effects resulting from multiple hazard avoidance scenarios.

In this study, we examine tradeoffs between detour (i.e. extra flight distance) versus hazard encounters for various synchronized weather hazards considered for avoidance when encountered along the route. The DIVMET simulations are based on two different weather situations, a large-scale early winter frontal system (18 November 2015) and an air mass convection case (14 July 2016). Both cases include deep convection (line arrangement in the winter case vs. massive isolated storms in the summer case) as well as notable areas of turbulence and icing hazards.

The impact on the National Airspace System (NAS) is evaluated by a set of seven airport pairs whose great circle connections are likely to be affected by these weather situations as can be seen in Figure 1. Overlaid are the hazard situations at 0600 (left) and 1800 (right) UTC of both days, respectively, as identified by individual expert products, such as the Consolidated Storm Prediction for Aviation (CoSPA, convection, red),[2],[3] the Graphical Turbulence Guidance Nowcast (GTGN, turbulence, yellow/orange),[4],[5] and the Current/Forecast Icing Product (CIP/FIP, icing, blue).[6]

Departures at every designated airport are scheduled at the top of every hour between 0000 and 2000 UTC (MIA and SFO at 0000 to 1800 UTC) resulting in a set of 290 planned flights. These are simulated with seven different weather scenarios and two flight levels each resulting in 4060 trajectories to evaluate.

The metrics discussed here are the number of flights affected by weather hazards, encounter durations with such and detours resulting from avoiding those hazards.
I. Weather Avoidance

According to the nature of convective storms and associated hazards below, within, and above a cumulonimbus cloud this hazard blocks the whole atmospheric column and demands a lateral circumnavigation by aircraft in all phases of flight (red in Figure 2). Turbulence (yellow/orange) and icing (blue) hazards, in contrast, often occur in layers with limited vertical extent (although possibly covering substantial horizontal areas) that 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.

Whether a maneuver is tactically necessary is mainly decided by the individual pilot in correspondence with the responsible controller based on airline policies, procedures, and aircraft capabilities/certification. For strategic reroutings the airline dispatcher is involved. The pilot’s willingness to deviate from the planned route depends on their load, passengers or freight, and the intensity of the weather. Passing shortly through some layers of even intensive turbulence or icing conditions in the ascent is usually acceptable while cruising in such conditions for some time is not. Significant turbulence en route is often avoided by searching for a clear and turbulence free flight level. Icing conditions usually prevail in lower flight levels and can get dangerous in holding patterns for arriving flights unable to land right away due to traffic constraints. In such cases, 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 1 Great circle (direct) trajectories between seven city pairs overlaid with the color-coded weather hazards (see legend) at 0600 UTC on 18 November 2015 (left) and 1800 UTC on 14 July 2016 (right).

Figure 2 Schematic of vertical hazard levels color-coded as in Figure 1.
II. Methodology

Weather avoidance is modeled using the research-quality simulation tool DIVMET originally developed at the Leibniz Universität Hannover, Germany. While accounting for a simple vertical flight profile (continuous climb and descent), DIVMET routes aircraft horizontally through layered two-dimensional fields of adverse weather that evolve with time (15-minute update rate for convective and turbulence information, hourly for icing data) and is represented as no-fly polygons. These can be determined based on current and forecast gridded weather hazard information for a given flight level by applying individual intensity thresholds to the respective weather hazard fields provided by expert systems. Here, moderate and severe convection is considered by the 18 dBZ contours at 25,000 and 30,000 ft, respectively, in the CoSPA product. Turbulence of moderate and severe intensity is captured by eddy dissipation rates (EDR) equal or greater than 0.22 and 0.35 m²/³ s⁻¹ as provided by GTGN. Icing hazards are represented by the category ‘heavy’ in the CIP.

In the DIVMET tool, deep convective storms are avoided laterally based on a user-selectable minimum distance to the hazardous area—we use a 20 nautical mile (nmi) separation distance, as recommended by the FAA. The same is applied to severe turbulence. Moderate turbulence and icing hazards are avoided by 10 nmi distance, the latter, however, is not encountered at all in this study, and, thus, is not further taken into account here. The decision on which side to circumnavigate a hazardous area is made based on the hazard object’s cover area and lateral extent left and right of the planned route.

In case of a convective cell in the vicinity of the respective airport (20 nmi radius for severe convection, 10 nmi for moderate intensity) the departure is delayed by at least 15 minutes (update rate of convective information). The flight is cancelled if its delay is equal or larger than 60 minutes as the next scheduled flight departs then.

The aircraft movement along the trajectory follows a simplified airspeed profile which is modified by a four dimensional wind field obtained from the Rapid Refresh (RAP). The aircraft position and its status with regards to the hazard situation (i.e. hazard encounter) is updated every minute.

Simulations are run for two different cruise levels (FL300, FL400) with an outlook radius of 100 nmi (i.e. equivalent to a medium board radar range) where deviations for hazard avoidance are initiated. A set of seven scenarios that differ in terms of hazards considered in the rerouting process (see Table 1) is applied. An initial step is the simulation with the Ignorance case where the planned great circle path is followed no matter what hazard is encountered. By checking the aircraft surrounding and potential hazard encounters every minute (time step of aircraft movement) an evaluation of each flight’s exposure to risks along the planned trajectory is possible. Additionally, a number of combinations of moderate and/or severe convection and/or turbulence hazards is taken into account in the remaining scenarios. The routing solutions of such may vary as indicated in and discussed around Figure 3.

Characteristic impact measures, such as the detour length (i.e. actual flight distance minus planned great circle distance), exposure time to each hazard as well as metrics like the additional flight time and extra sector crossings as a consequence of the rerouting (not discussed here) can be determined for each flight and scenario to evaluate the optimal solution for the individual case. Here, however, an integrated analysis of all flights is presented.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Considered hazard(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignorance</td>
<td>none</td>
</tr>
<tr>
<td>0Conv</td>
<td>sev Conv</td>
</tr>
<tr>
<td>modConv</td>
<td>mod/sev Conv</td>
</tr>
<tr>
<td>0Conv0T</td>
<td>sev Conv + mod/sev Turb</td>
</tr>
<tr>
<td>0Conv0T0T</td>
<td>sev Conv + mod/sev Turb + sev Turb</td>
</tr>
<tr>
<td>mod0Conv0T</td>
<td>mod/sev Conv + mod/sev Turb</td>
</tr>
</tbody>
</table>

Table 1 Hazard scenarios.
Some insights in the analysis results

The routing solutions for a flight from A to B may differ significantly depending on the selection of hazards taken into account in the rerouting process as shown in Figure 3. Exclusive consideration of severe convection (dark red) in the sc scenario (black dashed trajectory) results in a marginal deviation from the initially planned great circle route (dashed-dotted). This solution only adds a small detour but encounters of moderate convection (light reddish) can be expected. When including moderate convection in the rerouting process (msC, red trajectory), in this sample case, the flight starts off as planned but deviates once it is within the 200 nmi decision horizon. The detour is larger than in the sc scenario and severe turbulence is encountered. Consideration of all hazards (msCmsT, solid black trajectory) results in an instantaneous rerouting right after departure.

First step in the analysis is an overall evaluation of the impact of both weather situations on the planned great circle routes. Figure 5 summarizes the number of planned flights at cruise level FL300 (solid box) and FL400 (contour only) affected by atmospheric hazards on 18 November 2015 (gray) and 14 July 2016 (blue). In the frontal system situation, most often flights at both levels are impacted by moderate hazards (mod Conv: 253 and 256 affected flights, mod Turb: 190 and 207 affected flights for FL300 and FL400, respectively) plus such in FL300 encounter severe turbulence (220 flights affected). Overall each of the 290 planned flights cruising at FL300 and all but 5 at FL400 encountered at least one hazard in moderate or greater intensity. Exposure to severe hazards is more often detected for flights in FL300 (because of severe turbulence).
In the summer case with air mass convection (blue bars) impacts were mainly caused by moderate/severe convection and moderate turbulence which mostly occurred altogether in those isolated storms (see Figure 1). About 65% (FL400: 63%) of all flights were affected by any hazard, 52% (FL400: 50%) by severe hazards.

An evaluation of the number of flights affected by severe hazards in the various simulation scenarios can be based on Figure 5. The leftmost block (Ignorance scenario) is the same as the second block in Figure 4) but includes information on the duration of such impacts (see legend). In the winter case, 90 flights (31%) cruising at FL300 spend at least 10 minutes in severe hazards when flying along the planned route. The effects of hazard encounters when accounting for hazard avoidance differ significantly in the studied weather situations. In the summer case, consideration of severe convection while accounting for a 20 nmi safety distance reduces the overall number of flights affected by severe hazards to 10% (6% ≥ 3min, 4% ≥ 5min, 1 ≥ 10min). The inclusion of severe turbulence or moderate hazards only adds a
marginal benefit. In contrast, in the frontal system case, severe convection is a hazard with minor impact. Thus, exclusive consideration of this hazard (or in combination with moderate convection) does not significantly reduce the number of affected flights. Instead, it is necessary to account for turbulence hazards in the rerouting process to reduce these numbers. Still, quite some flights are affected by severe hazards (even for encounters of 2–10 minutes). This is due to different reasons including discretization effects and model logic (e.g., continuing with present heading when having encountered a hazard [i.e. after a weather update]). Any weather avoidance or, in general, any deviation from the great circle route adds flight distance and, thus, cost (e.g., fuel, time, etc.). Especially in large scale weather situations (e.g., that of 18 November 2015), such detours are long. Figure 6 shows the distributions of all 290 flights per scenario. While the avoidance of severe convection adds minor flight distances (avg. 5 nmi, max. 156 nmi), the integration of moderate hazards (esp. turbulence) results in long detours with outliers between 600 and 1159 nmi and average additional flight distances ranging between 98 and 184 nmi.

The risk to encounter hazardous weather can be reduced mostly at the cost of extra flight distance (fuel, delay, etc.). In the context of TBO it is of high importance to integrate appropriate weather information in the planning process and visualize and update it during flight execution. DIVMET is a platform to study such processes, operational flights planning however should be left to more elaborated state of the art flight planning tools.

References