Weather Avoidance Guidelines for NASA Global Hawk High-Altitude Unmanned Aircraft Systems (UAS)

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What We Want To Avoid:
Hurricane Emily (2005) ER-2 Example

Hurricane Emily had just peaked at Category 5 intensity (140 kt, 929 hPa) at 00 UTC 17 July with the last recon flight before the ER-2 mission. Subsequent recon flights showed hurricane had weakened during the night. The NASA ER-2 approached the eye from the southeast, crossing very cold (~194 kft, high (~51 kft) cloud tops on the inbound leg (~0745 UTC). Despite the high cloud tops, no problems were reported.

A new, intense convective cell was developing on the inner edge of the eyewall, just west of the center. This region looked innocuous in 0745 UTC IR imagery. The ER-2 crossed the new cell at 0735 UTC. Onboard radar / radiometric / lightning sensors indicate the strongest convection in any NASA ER-2 tropical cyclone flight. Pilot had difficulty with turbulence, but completed one more pass before requesting an alternate flight pattern.

Several lightning flashes and tropical overshooting tops (TOTs) are seen in subsequent analyses (below right). Note the location errors in lightning data are large in this part of the Caribbean.


The main example of what we want to avoid with the Global Hawk is the Hurricane Emily ER-2 flight (17 July 2005). The ER-2 pilot encountered turbulence on the first two passes across the hurricane. The pilot lined up for a third pass. Based on the previous turbulence and visual observation of high cloud tops and frequent lightning, the pilot judged that the pattern was not safe to continue. He requested an alternate pattern, and subsequently executed rectangular patterns just outside the eyewall.

The Hurricane Georges (25 Sep 1998) and TS Chantal (20 Aug 2001) flights listed above also had considerable lightning, as a clue that there may be turbulence.

Weather Avoidance

Background
- NASA operates two developmental-model Global Hawk unmanned aircraft systems (AV-1 and AV-6).
- Ceiling: ~65,000 ft
- Duration > 24 hours
- These aircraft are suitable for remote sensing, not storm- or cloud-penetration.
- Can almost think of them as gliders with jet engine
- Aircraft safety requirements include avoidance of clouds and turbulence.
- Science requirements can include overflight of clouds

What are the limits on safety monitoring storms with Global Hawk?

Went to be cautious without unnecessarily sacrificing science.

Hurricane and Severe Storm Sentinel (HS3) - 2012-2014

Both NASA Global Hawks operated from NASA Wallops (Virginia) in Aug-Sep Targets: Atlantic hurricanes, tropical storms, tropical disturbances with potential for subsequent development.

The HS3 science team is concerned that flight rules, if strictly interpreted, may lead to diverting around many deep cloud systems. This could unnecessarily sacrifice opportunities for obtaining important datasets. Experience, backed up with data from recent field programs, led us to suggest modification of the previous flight rules.

Hazards To Be Avoided:
Significant turbulence is by far the most probable hazard when flying the Global Hawk above tropical storms. That is the motivation for most of the flight rules below, and for the suggested modifications. Lightning and cloud top information is primarily used as a proxy for the threat of turbulence.

Weather Avoidance Rules used in 2012:
1) While flying at FL500 or below:
   - Do not approach thunderstorms (within 25 nm)
2) While flying above FL500:
   - Do not approach reported lightning within 25 nm in areas where cloud tops are reported at FL500 or higher.
   - Aircraft should maintain at least 10,000 ft vertical separation from reported lightning if cloud tops are below FL500
3) No overflight of cumulus tops that are higher than FL500
4) No flight into forecast or reported icing conditions
5) No flight into forecast or reported moderate or severe turbulence

The 3rd rule, prohibiting overflight of cumulus tops higher than FL500, is especially problematic. High cloud tops are much more common in tropical systems than are reports of turbulence or indicators of intense convection.

High cloud tops and some lightning caused a substantial diversion in the Sep 14-15 Hurricane Nadine (2012) flight (below), with the storm core subsequently avoided as a precaution.

From past experience with NASA high altitude aircraft over tropical cyclones, noteworthy turbulence is rare. ER-2 generally flies ~ FL650

<table>
<thead>
<tr>
<th>Date</th>
<th>Campaign</th>
<th>Plane</th>
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<th>Notes</th>
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<tr>
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<td>ER-2</td>
<td>Hurricane Bonnie</td>
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<td>9/2 (Earl): slight turbulence, did not impact flight</td>
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<td>CAMEX-3</td>
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<td>Hurricane Georges</td>
<td>9/25 (Georges): considerable turbulence at 63 kft, smoothed out at 65 kft</td>
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<td>T.S. Chantal</td>
<td>Light turbulence 62-64 kft</td>
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<td>7/9 (Dennis): turbulence and some overshooting tops (doming)</td>
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<td>T.S. Matthew</td>
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No noteworthy turbulence has been encountered by the Global Hawks during the HS3 flights (2012-13, not listed in the table), or during the GRIP flights.

2012 Global Hawk Rules would have kept us away from eastern part of the storm, where pilot did not encounter trouble. Rules would have allowed flight in western and northern parts of storm, until lightning and high clouds developed there. Rules would have eliminated the safe part of storm.
Summary and Conclusions

• The current Global Hawk flight rules would not possibly have been effective in the single-event of greatest concern (the Emily encounter). The cloud top had not reached 50,000 ft until minutes before the encounter. The TOT and lightning data would not have been available until near the overflight time since this was a rapidly growing cell. This case would have required a last-minute diversion when lightning became frequent. Avoiding such a cell probably requires continual monitoring of the forward camera and storm scope, whether or not cloud tops have been exceeding specific limits.

• However, the current overflight rules as recently interpreted would have prohibited significant fractions of the successful Global Hawk overpasses of Karl and Matthew that proved not to be hazardous.

• Many other high altitude aircraft (ER-2 and Global Hawk) flights in NASA tropical cyclone field programs have successfully overflown deep convective clouds without incident.

• The convective cell that caused serious concern about the safety of the ER-2 in Emily was especially strong for a tropical cyclone environment, probably as strong or stronger than any that was overflown by the ER-2 in 20 previous flights over tropical cyclones.

• Specifically, what made that cell a safety concern was the magnitude of the vertical velocity above the tops at 10 km (3000 ft), and below that, at 3 km (10,000 ft) above the top.

• Such a strong updraft can create significant gravity waves at and above the tropopause, posing a potential danger to aircraft far above the maximum altitude of the updraft itself or its associated cloud top. Indeed, the ER-2 was probably at least 9000 ft above that cloud top.

• Cloud-top height, by itself, is not an especially good indicator of the intensity of convection and the likelihood of turbulence. Nor is overflying high cloud tops (i.e. > 50,000 ft) of particular concern unless there is other evidence of very strong convective updrafts beneath those tops in the path of the aircraft.

• Lightning, especially lightning with a high flash rate, is well correlated with convective intensity. Lightning with a minimal flash rate (say 1.3 flashes per minute) is indicative of updraft speeds of about 10 m/s in the mixed phase region where charge is being separated, generally at altitudes about 20-25 km in a hurricane. That is still stronger than typical updrafts (more like 5 m/s).

• An unresolved issue is whether there is a high and instantaneous correlation between vertical velocity in the middle troposphere (necessary for lightning generation) and near cloud top (more direct concern for overflights).

• Tropical overshooting tops (TOTs) indicate significant vertical velocity at a storm's cloud-top canopy that penetrates the stable layer at which surrounding cloud tops have spread out (envelop tops).

• An indirect indication of vertical velocity at cloud top is the magnitude of the brightness temperature difference between the coldest overshooting pixel (TOT) and the immediate surrounding anvils.

• One should be especially cautious about overflying TOTs with deficits of 8-10 degrees K or more for newer cells and smaller values when embedded in existing cold clouds. Such tops may indicate updraft speeds > 10-15 m/s.

• However, we need more research on the use of this convective indicator, because it is suggested that the time scale of an individual TOT (if it is more like a small bubble rather than a deep cell) is normally less than 5-10 minutes. This is significant because the TOT that was the problem for the Emily flight (Fig. 2) was only detected in available GOES imagery as a potential hazard 3 minutes before the encounter.

Weather Avoidance Rules Adopted in 2013:
1) While flying at FL500 or below:
   ...Do not approach thunderstorms (within 25 nm).
2) Aircraft should maintain at least 5000 ft vertical separation from significant convective cloud tops except:
   ...When cloud tops above FL500 do not approach significant lightning activity or indicators of significant overshooting tops within 25 nm.
3) No flight into forecasted or reported icing conditions.
4) No flight into forecasted or reported moderate or severe turbulence.

The key changes from the 2012 rules are that:
1) Cloud tops above FL500 can be overflown if there are no indications of strong convection.
2) Strong convection as a probe for turbulence is now interpreted having either significant lightning activity or significant overshooting tops. This recognizes that occasional lightning flashes may occur with relatively weak convection or stratostratus regions (not considered hazardous), and also that a region with numerous overshooting tops may be hazardous even if no lightning has been detected.

Other HS3 improvements to NASA Global Hawk operations, and further improvements identified for future programs

Deployment & operation of 2 NASA Global Hawks accomplished (HS3 2013)

NASA Global Hawks launched for science missions on three consecutive days, with <3-hour turnaround between landing and subsequent takeoff (HS3 2013)

Flexibility with dropsonde locations and advance notice locations adopted with HS3 2013

Further increase in flight planning advance notice, allowing initial flight plan to simply define a large box, with more detailed flight plan following 24 hr prior to flight (HS3 2013)

Issue: HS3 had some warnings for low AV-1 fuel temperature

Solution: Lower freestream fuel is available.

Note: Back-up canister is on AV-1, as already installed on AV-2.

Issue: AV-1 has not attained desired altitude in HS3

Solution: 2 AV-1's were not used in HS3, but instead 2 AV-2's were used, as always in past.

Issue: Global Hawk reliability related to navigation units

Solution: NASA DPC receiving new policy for automatic return when any of the 4 navigation units fails. New policy expected for adoption by USAP, MARSS, and DFRC to allow operations to continue with 3 of 4 navs functional.