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

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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 safely monitoring storms with Global Hawk?
  - *Want 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 obtained in 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:

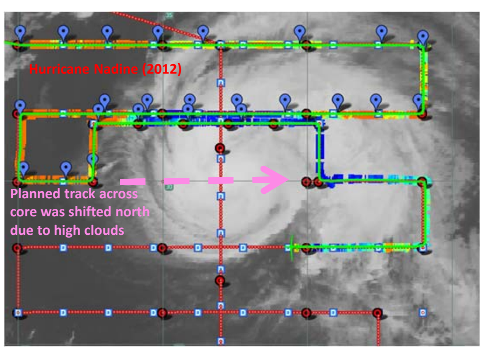
1) While flying at FL500 or below:
   - Do not approach thunderstorms (within 25 nmi)

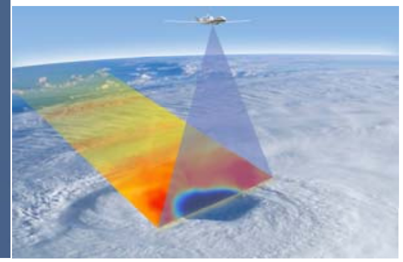
2) While flying above FL500:
   - Do not approach reported lightning within 25 nm in areas where cloud tops are reported at FL500 or higher.
   - Aircraft should maintain at least 10000 ft vertical separation from reported lightning if cloud tops are below FL500

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

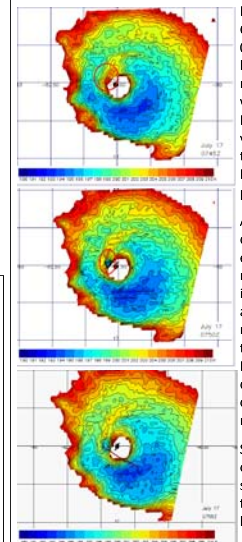
Date	Campaign	Plane	Storm	Notes
8/23/98	CAMEX-3	ER-2	Hurricane Bonnie	9/2 (Earl): Slight turbulence, did not impact flight
8/24/98	CAMEX-3	ER-2	Hurricane Bonnie	
8/26/98	CAMEX-3	ER-2	Hurricane Bonnie	
9/2/98	CAMEX-3	ER-2	Hurricane Earl	
9/21/98	CAMEX-3	ER-2	Hurricane Georges	9/25 (Georges): Considerable turbulence at 63 kft, smoothed out at 65 kft.
9/22/98	CAMEX-3	ER-2	Hurricane Georges	
9/25/98	CAMEX-3	ER-2	Hurricane Georges	
9/27/98	CAMEX-3	ER-2	Hurricane Georges	
8/20/01	CAMEX-4	ER-2	T.S. Chantal	Light turbulence 62-64 kft
9/10/01	CAMEX-4	ER-2	Hurricane Erin	Small bump over eye
9/19/01	CAMEX-4	ER-2	T.S. Gabrielle	9/19 (Gabrielle): Some bumps reported; towers up to 55 kft.
9/22/01	CAMEX-4	ER-2	T.S. Humberto	
9/23/01	CAMEX-4	ER-2	Hurricane Humberto	
9/24/01	CAMEX-4	ER-2	Hurricane Humberto	
7/5/05	TCSP	ER-2	T.D. #4	7/9 (Dennis): Turbulence and some overshooting tops (doming)
7/6/05	TCSP	ER-2	T.S. Dennis	
7/9/05	TCSP	ER-2	Hurricane Dennis	
7/15/05	TCSP	ER-2	Pre- T.S. Eugene	7/17 (Emily): Turbulence led to re-design of flight track
7/16/05	TCSP	ER-2	Pre- T.S. Eugene	
7/17/05	TCSP	ER-2	Hurricane Emily	
7/24/05	TCSP	ER-2	T.D. #7	
7/25/05	TCSP	ER-2	T.S. Gert	
8/28/10	GRIP	GH	T.S. Frank	
9/2/10	GRIP	GH	Pre-T.S. Earl	
9/12/10	GRIP	GH	Pre-T.S. Karl	
9/16/10	GRIP	GH	Hurricane Karl	
9/24/10	GRIP	GH	T.S. Matthew	

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.

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.

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

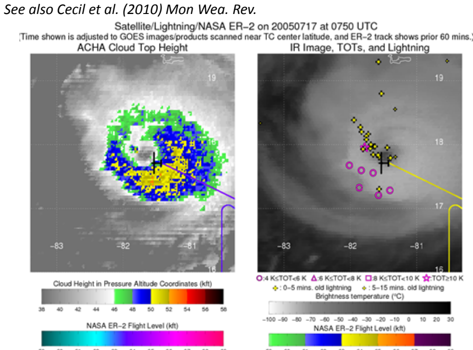


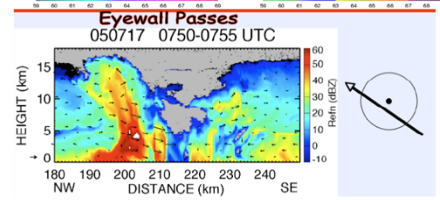
Hurricane Emily had just peaked at Category 5 intensity (140 kt, 929 hPa) at 00 UTC 17 July with the last recon flight before the ER-2 mission. Subsequent recon showed the hurricane had weakened during the night. The NASA ER-2 approached from the ESE, crossing very cold (~194 K), high (~51 kft) cloud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

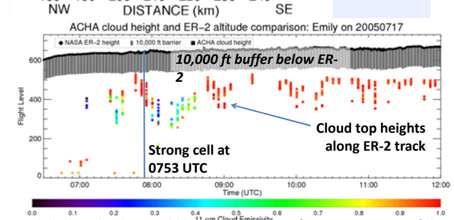
A new, intense convective cell was developing on the inner edge of the eyewall, just west of the center. This region looked innocuous in 0745 UTC IR imagery. The ER-2 crossed the new cell at 0753 UTC. Onboard radar / radiometer / lightning sensors indicate the strongest convection in any NASA ER-2 tropical 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.

IR imagery above from Quinlan (2008) M.S. Thesis (U. Alabama-Huntsville). See also Cecil et al. (2010) Mon Wea. Rev.

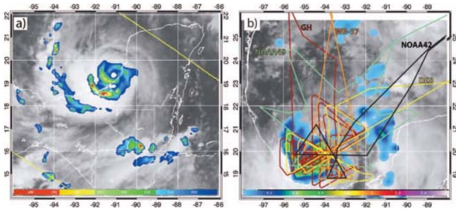






2012 Global Hawk rules would have kept us away from eastern part of the storm, where pilot did not encounter trouble. Rules would have allowed flight in western and northern parts of storm, until lightning and high clouds developed there. *Rules would have eliminated the safe part of storm.*

What We *Do Not* Want To Avoid: Hurricane Karl (2010) Global Hawk Example

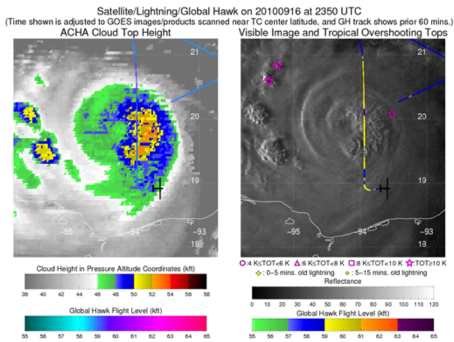


Hurricane Karl flight tracks, 16-17 Sep 2010, from Braun et al. 2013 BAMS.

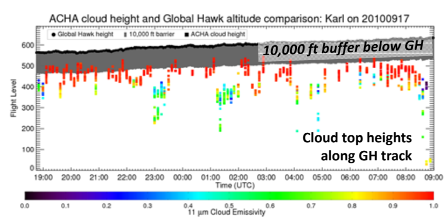
In Hurricane Karl (2010), Global Hawk AV-6 (red line in right panel) made 20 passes across the eye, some coordinated with other aircraft (denoted by other colors). No trouble was reported by the Global Hawk pilots.

Cloud tops frequently exceeded 50,000 ft, but there were no indicators of particularly strong convection (as distinct from deep convection). The flight rules cited at far left had not yet been established – this flight would have been in violation of those rules.

Some lightning had been noted near the eye, but the flash rates were low (unlike the Hurricane Emily case). Tropical Overshooting Tops were sporadic.

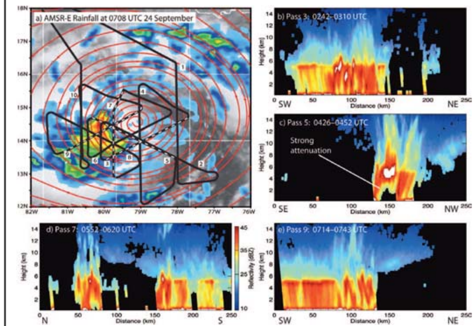


The type of display below was developed by U. Wisconsin / CIMSS for real-time hazard avoidance during the 2013 deployment of HS3. Applying it post hoc to the Hurricane Karl flight from GRIP shows that optically thick clouds (red symbols) frequently exceeded 50,000 ft height (in pressure coordinates, for compatibility with aircraft flight levels) and occasionally came within 5000 ft of the Global Hawk flight level.



For those wishing to view the entire flight periods for these 3 storm overflights, animations have been posted in the links at:
http://cimss.ssec.wisc.edu/~sarahm/ACHA_lightning_example_Emily.html
http://cimss.ssec.wisc.edu/~sarahm/ACHA_lightning_example_Emily_RSO.html
http://cimss.ssec.wisc.edu/~sarahm/ACHA_lightning_example_Matthew.html
http://cimss.ssec.wisc.edu/~sarahm/ACHA_lightning_example_Karl.html

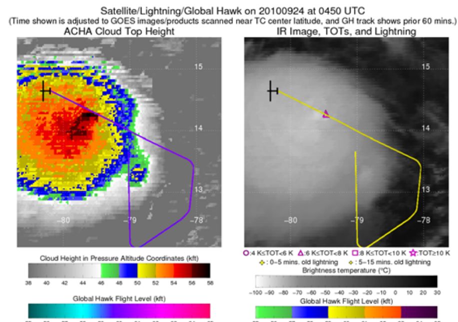
What We *Do Not* Want To Avoid: Tropical Storm Matthew (2010) Global Hawk Example



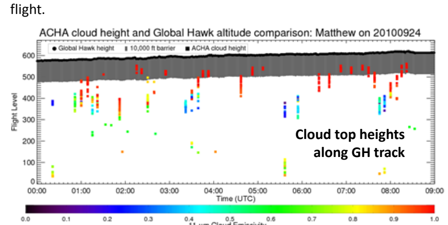
Tropical Storm Matthew Global Hawk flight tracks and nadir profiles of radar reflectivity, 24 Sep 2010, from Braun et al. 2013 BAMS.

In Tropical Storm Matthew (2010), Global Hawk AV-6 made 10 passes across the center. No trouble was reported by the Global Hawk pilots.

A region of cold, high (54-58,000 ft) cloud tops persisted northeast of the center for many hours. In the example shown below, a single Tropical Overshooting Top was detected with a high cold top at 0450 UTC where the Global Hawk had passed at about 0443 UTC, and a group of lightning flashes were detected in that same location at 0507 and 0537 UTC (not shown), but neither of these convective-intensity indicators reached the magnitude that they did for the Hurricane Emily event.



The ACHA (AWG Cloud Height Algorithm, from UW-CIMSS) derived cloud-top heights for TS Matthew were generally the coldest/highest of the 3 examples. Note the large number of cloud heights reaching 55-58 kft, coming within about 5000 ft (and sometimes closer) of the Global Hawk flight altitude periodically throughout the flight. Inspection of the detailed animations for Matthew demonstrates that there were occasional bursts of lightning for some limited regions, occasional groups of Tropical Overshooting Tops for some limited regions, but only rarely did these (independent) indicators of intense convection persist in the same region for more than about 30 minutes. The Global Hawk experienced no safety / turbulence problems during this flight.



Summary and Conlusions

- The current Global Hawk flight rules would probably not 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 strictly 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 of the updraft, at least 20 m/s (4000 ft/minute) at the time the ER-2 overflew it.
- Such a strong updraft can generate strong 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 kft 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 penetrate the stable layer at which surrounding cloud tops have spread out (anvil 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 anvil top.
- 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 cloud tops. 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 jet) is normally less than 5-10 minutes. This is significant because the TOT that was a 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 nmi)

2) Aircraft should maintain at least 5000 ft vertical separation from significant convective cloud tops *except*:
a) When cloud tops above FL500: Do not approach reported significant lightning activity or indicators of significant overshooting tops within 25 nmi.
b) When cloud tops are below FL500, maintain 10000 ft separation from reported significant lightning or indicators of significant overshooting tops.
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 proxy 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 stratiform regions (not considered a hazard), 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 adjusted with minutes notice in 2013, instead of days notice previously) (HS3 2013)	
More flexibility 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	*Solutions*: Lower freeze-point fuel is available. Heat bypass can be installed on AV-1, as already installed on AV-6
Issue: AV-1 has not attained desired altitude in HS3	*Solutions*: Altitude tests in Oct 2013 suggest take-off weight may be limiting the altitude. Payload weight will be reduced in 2014. Loading less fuel would also reduce weight. Other ways to shed weight being investigated. Future programs can use AV-6 for payload that requires highest altitude.
Issue: Global Hawk reliability related to navigation units	*Solution*: NASA DFRC reviewing current policy for automatic return when any of the 4 navigation units fails. New policy expected for adoption by USAF, Northrop Grumman, and DFRC to allow operations to continue with 3 of the 4 nav units functional.