2.1 IMPROVED THUNDERSTORM WEATHER INFORMATION FOR PILOTS THROUGH GROUND AND SATELLITE BASED OBSERVING SYSTEMS

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Abstract

Within FLYSAFE, a European Commission funded project running from 2005 to 2009, a ground based thunderstorm weather information and management system has been developed which uses remote sensing information from radar, satellite and lightning detection systems. It has successfully been employed and demonstrated during flight trials carried out in summer 2009 over Central Europe. The aim of the paper is to demonstrate that the information provided by such a system could help pilots in gaining a better overview of the weather situation as compared to what can be provided by nowadays onboard systems. This in turn could help pilots in decision making, e.g. which route to take when passing through a thunderstorm line. For the study a number of aircraft accidents and incidents related to thunderstorm activity has been selected for demonstrating the usefulness of such a ground based weather information system. In each case, thunderstorm positions as detected by the ground based system are compared with actual aircraft positions and tracks where known. Finally, the possible up-link of the ground-based weather information to the cockpit is addressed by referring to ongoing and future activities in this direction.

1. INTRODUCTION

Today's weather information for pilots on thunderstorm conditions on their flight is insufficient. Weather charts provided by the World Area Forecasting Centres and taken onboard by pilots before take-off are based on forecasts of large scale weather models which are initialized only four times a day. These models have high predictive skill in forecasting the large scale weather situation, i.e., the distribution of high and low pressure areas together with synoptic scale fronts for the next days and precipitation for about one day in advance. Thunderstorms however, whose time and space scales typically range from tens of minutes up to an hour and from hundreds of meters to some kilometres in diameter, cannot be deterministically forecast by these models. On the one hand the model's grid resolution is insufficient to resolve these weather features hence these features can only be treated in parameterized form. On the other hand predicting thunderstorms would require predicting the genesis of thunderstorms in the first place, which is difficult as it depends on a subtle interplay of various factors, among which are low level moisture supply; a conditionally unstable air mass and a forcing mechanism which provides the necessary lift of buoyant air parcels. Furthermore, the fine detail of these necessary ingredients are not measured by the routine observational network with the effect that such observations are not available in the initial data of the model forecasts.

These factors taken together implies that the information given in the weather charts with respect to thunderstorm occurrence cannot be accurate, rather such information provides only a broadscale picture of the spatial extent over a period of time and does not express the situation in terms of the granularity, intensity and duration.

For the instantaneous picture in flight, pilots have information on thunderstorm activity through onboard radar equipment. The radar provides a good indication on thunderstorm activity within the close range ahead of the aircraft, about 50 miles or so, provided there is precipitation within the convective up-droughts, strong enough to give radar returns. However, when precipitation cells are large and intense, or several cells lie behind one another, the radar pulses are strongly attenuated. In such cases information about the situation is incomplete which makes it difficult for pilots to choose a proper path around thunderstorm cells or through a thunderstorm line. In addition there are cases where thunderstorm cells are just about to develop with weak or no returns on the radar, yet they can produce convective turbulence which can propagate to levels above the developing cells (Lane et al., 2003). In that case the aircraft might experience sudden turbulence without any forewarning.

In contrast to onboard radar, remote sensing by ground based radar, satellite and lightning detectors can provide a more complete picture of the thunderstorm situation. Ground based systems have been developed which use this data to inspect cells from above, below and multiple viewing angles thereby being able to provide a more complete picture of the thunderstorm situation (e.g. Mueller et al, 2003). Thunderstorms can be detected from satellite observations due to their cold cloud tops and characteristic cloud properties; the precipitation they produce can be detected by radar and lightning discharges by lightning detectors. For the middle European area data retrieved by the Meteosat

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Second Generation satellites operated by EUMETSAT, radar data from the European radar network organized by the national weather services and lightning data from networks operated by EUCLID and LINET (Betz et al., 2004) can be used in expert systems to deduce and nowcast hazards brought about by thunderstorms. Utilising these sources of data a thunderstorm weather information and management system - Cb WIMS (Tafferner et al., 2008; details in section 3.1) was set up within the course of the FLYSAFE project, which was part funded by the European Commission (EU-FLYSAFE, 2005).

FLYSAFE aimed at defining and testing new tools and systems contributing to the safety of flights for all aircraft. It focused on the development of new on-board systems and ground-based systems to feed them with the information that they require. The project was structured upon the three “threats” which play a major role in aircraft accidents: collision with other aircraft, collision with terrain and adverse atmospheric conditions. For the latter, specialised ground based weather information management systems (WIMS) have been developed for the weather hazards icing, clear air turbulence, wake vortex turbulence and thunderstorms. These systems provided met data, in the form of feature objects, on the individual weather hazards over a defined area ranging from high resolution short-range on a local scale to long-range forecasts on a global scale. A summary on FLYSAFE achievements as regards to the use of weather objects for aviation activities is given in Mirza (2009b), as regards to weather data fusion in the cockpit see Verbeek et al. (2009).

In this paper four cases of aircraft incidents with severe turbulence and hail encounter and one accident are investigated with the new tools. The aim is to demonstrate the improved situation awareness pilots would gain once the thunderstorm analyses and forecasts of the ground based systems are uplinked to the cockpit during flight.

Figure 1: Nose and wind shield damage of two aircraft hit by hail stones during passage of thunderstorms. Left: Easy Jet Boeing 737 after take-off from Geneva, 15 August 2003. Right: WindJet A319 near Catania on Oct 1st 2009 (The Aviation Herald, Photo: ATRDRIVER)

2. THUNDERSTORM HAZARDS FOR AIRCRFAFT

Thunderstorms are complex weather features. They appear in all shapes and sizes and their lifetime can last from 15 minutes to several hours. Aircraft flying through thunderstorms are exposed to a number of hazards: turbulence, icing, hail, heavy rain, wind shear, lightning and reduced visibility. These hazards can act in combination and their strength is dependent on the type and intensity of a particular thunderstorm, the height at which the aircraft is passing through it, the duration of exposure, the type of aircraft and the flight phase. Figure 1 shows two examples where aircraft have been hit by hail when passing through a thunderstorm. In both cases the aircraft’s nose has been heavily damaged, and in one case also the wind shield has been cracked.

Aircraft can be hit by lightning but can also trigger lightning; normally with no damage to the airframe as the interior of the plane acts like a Faraday cage so long as its frame is made of metal.

However, lightning strikes cause electronic equipment to malfunction which might affect safety. Figure 2 shows a lightning stroke which was probably triggered by the aircraft itself after take off from a Japanese Air Force Base as described in Uman and Rakov (2003).

Figure 2: Aircraft hit by lighting. Photograph found on the internet. Reprinted and discussed by Uman and Rakov (2003).

Wind shear can be a great hazard for an aircraft especially on approach to land when passing through the up- and downdraft regions of a thunderstorm. Figure 3 illustrates the situation. First the aircraft experiences a lift increase when it encounters the outflow boundary of the thunderstorm; thereafter it enters the downdraft region where it encounters a downward force which is of course dangerous on approach to landing.

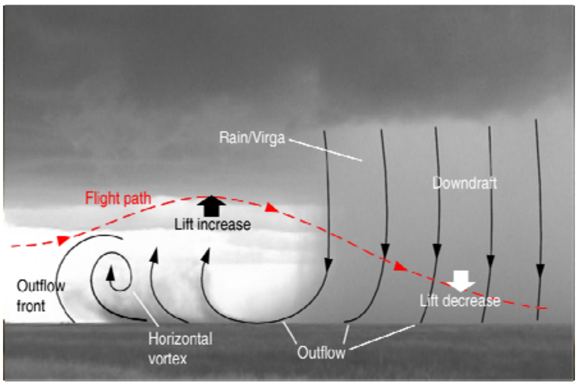

Figure 3: Lift increase and decrease for an aircraft which passes through a thunderstorm at low levels (FLYSAFE)

Thunderstorms can create an environment with great potential for icing which can pose a severe threat, depending on which parts of the aircraft are affected. For example, figure 4 shows the DLR hosted Dornier 228 after a flight in icing conditions. Icing is on the windshield and on the underside of the wing, i.e. those parts which are not protected by heating or boots for this type of the aircraft.

The high vertical velocities within the updraft part of the thunderstorm rapidly transport liquid water up to high altitudes, where atmospheric temperatures drop below freezing level creating conditions for super-cooled liquid water to exist even down to temperatures as low as -40° C (Hauf et al, 2003). During the EURICE measurement campaign (Amendola et al., 1998) super-cooled liquid drops up to a size of 8 mm have been found with a research aircraft (Sanchez et al., 1998).

Figure 4: wind shield and wing icing after a flight of the DLR Dornier 228 aircraft in severe icing conditions.

There have been numerous incidents and also a few accidents due to aircraft icing, e.g the ATR-72 crash near Chicago 1994 (Sand and Biter, 2000). Icing of the Pitot tubes can result in wrong speed indications for the pilots or the onboard computer. In two cases of unintended descent within the upper parts of two independent thunderstorms a complete freezing of the Pitot tubes was observed even though the anti-ice (heating) systems were activated (Hauf et al., 1999). Figure 5 shows icing accretion on the Pitot tubes of the DLR Dornier 228 after landing.

Turbulence in thunderstorms can force changes in vertical velocity of about +50 m/s to -25 m/s on short distances, which can impart corresponding changes in vertical accelerations to the aircraft which in turn can lead to injuries of flight personnel if not securely fastened to their seats.

Figure 5: Icing of Pitot tubes, picture taken after landing of a flight of the DLR Dornier 228 aircraft in severe icing conditions.

In extreme cases the forces can surmount the structural limits of the airframe (e.g. NLM Fokker F-28, Cityhopper crash, 6.10.81, Moerdijk NL).

Heavy rain in thunderstorms can in extreme cases cause flame out of the engines (e.g. May 24, 1988, a Salvadoran Boeing 737 arriving from Belize picking its way among thunderstorms ringing New Orleans). Another threat heavy rain can cause is skidding and eventually overshooting the runway during landing (e.g. Kingston, Jamaica Dec 23, 2009, a Boeing 737-800).

3. GROUND AND SATELLITE BASED OBSERVING SYSTEMS

3.1 *CB WIMS - Thunderstorm weather information and management system*

As mentioned above (section 1) various tools and systems have been developed within the research community to detect and nowcast thunderstorms. As part of the FLYSAFE project, a weather-information and management system was set-up for thunder-storms (CB-WIMS). DLR led the team and co-ordinated the contributions from Météo France, the UK Met Office, ONERA, the University of Hanover and DLR.

A set of requirements of pilots were obtained from a questionnaire and from discussions held at meetings, Pilots had expressed clearly that they do not wish to be confronted with a picture of the full complexity of a particular thunderstorm, which they would have to interpret themselves with regard to their flight, rather they would have the weather experts to define hazardous regions and tell the pilots where they can or where they cannot go. To fulfil this requirement the thunderstorm forecasts output from CB-WIMS are reexpressed as weather object, which define hazard volumes representing thunderstorm threats for aircraft. The aim of the weather object is to reduce then complexity of the weather feature. Figure 6 illustrates the concept.

In Figure 6, hazard volumes are depicted as cylinders for simplicity, however, in practice polygons are used. A thunderstorm object is composed of a "top volume" and a "bottom volume." The nested bottom objects define volumes where the thunderstorm hazards of wind shear, turbulence, heavy rain, hail, icing and lightning can occur within the lower tropospheric part of a thunderstorm cell which present a hazard to aircraft flying at low levels, especially during landing and take-off.

The bottom volumes are constructed by use of 3D-radar and lighting data using Météo-France' CONO algorithm (Hering et al., 2005) with severity defined by radar reflectivity thresholds 33 and 41 dBZ. The volume of each cylinder, in this case, represent the severity levels "moderate" and "severe" respectively.

The top volumes represent the hazards: turbulence, icing, and lightning and are detected from satellite data using DLR's Cb-TRAM algorithm (Zinner et al., 2008). Here the "severe" threshold is selected based on lightning density, an additional data source from the LINET network (Betz et al., 2004). A detailed description of the thunderstorms objects and their attributes is found in Tafferner et al. (2008).

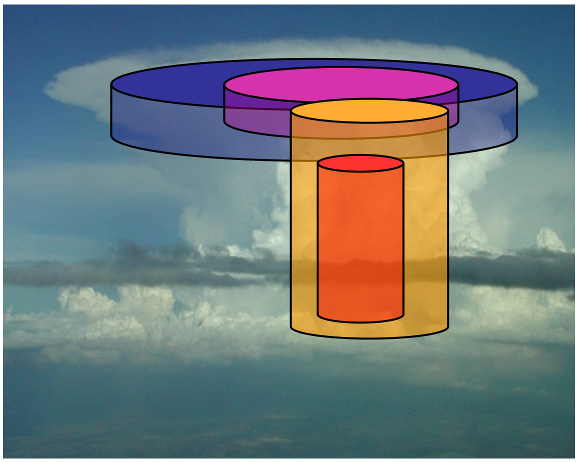

Figure 6: Bottom and top volumes representing hazard volumes for aircraft in two severity levels.

3.2 *Results from research flights carried out during FLYSAFE*

Evaluation from research flights carried out during FLYSAFE (Senesi et al., 2009) demonstrated that nowcast objects from CB WIMS could provide additional and valuable information on thunderstorm activity to the pilots. As part of the off-line evaluation contours of Nowcast weather objects were overlaid on the radar display, which was recorded to video during research flights. This evaluation found that:

- Thunderstorms can be represented by relatively simple bottom and top volumes in a meaningful way for aviation users (pilots and controllers)

- WIMS CB data are especially useful at the strategic time scale, namely beyond 10 minutes and in combination with Strategic Data Consolidation and Conflict Detection & Solution functions on-board an aircraft
- There is a real potential of the WIMS CB concept for safety in aviation since:
  - it surveys a much larger area than a single radar on-board the aircraft
  - it fuses data from lightning, satellite (multiple channels), polarimetric C and S band radar and atmospheric analyses from ground with on-board information
  - it provides a more "complete" picture of the hazard

As an example, we reprint here, figure 7, a snapshot of the radar display recorded during an experimental flight (figure 14 of Sénési et al. ,2009). The CB Weather objects from the WMS are shown as outlines in figure 7. CB bottom objects are pink and yellow representing severe and moderate hazards. CB Tops are orange and represent a moderate hazard. The spatial distribution of the CB weather objects agree well with the close range radar depiction to the forward right of the aircraft position (near the 50 nm range circle). However, beyond the close range, Cb weather objects indicate additional thunderstorm activity and also another cell further away (beyond the 100 nm range circle). Both these Cb cells are later confirmed after 10 and 20 minutes respectively by the onboard radar as the flight continues. Note that the radar returns on the left side beyond 50 nm are due to ground clutter and therefore not confirmed by CB WIMS as thunderstorm activity.

Figure 7: On board radar image for 14h05 UT on 19th August 2008. WIMS CB objects for 14h05 shown in yellow and pink for bottom objects moderate and severe plus orange contours showing CB top objects.

For the incidents and accidents reported upon in the next section we do not have onboard radar data available, nevertheless it will be demonstrated that thunderstorm information from the ground and satellite based observing systems provided to the pilots would most probably have helped raise their situation awareness with respect to the weather hazards they may encounter.

4. WEATHER RELATED AIRCRAFT INCIDENTS AS SEEN FROM GROUND AND SATELLITE BASED OBSERVING SYSTEMS

4.1 *European (continental) cases*

a) Incident of 9 May 2009: a quickly developing cell on the right flank of a major system

On 9 May 2009 a thunderstorm system originated in northern Switzerland and moved north-eastward over Lake Constance. At 1755 UT it is located north of the lake and partly over the river Danube (Fig. 8a). The red contour marks the upper level thunderstorm “top object” as determined from Meteosat satellite data by the DLR cloud tracker Cb-TAM (Zinner et al., 2009). The top object encircles the strongest updraft region. The figure sequence exhibits the rapid development of a new thunderstorm cell on the right flank of the mature cell, detected as convective initiation on 1800 UT (yellow contour in Fig. 8b) and rapid development at 1805 UT (orange contour in Fig. 8c). During the initiation phase an Airbus A321 enroute from Munich to Lisbon hit the related convective updraft. Severe turbulence was reported by the pilots, as a result two flight attendants and thirteen passengers were injured. The flight data recorder shows at 1753 UT a vertical acceleration of +1,85 g immediately followed by -0.5 g (BFU, 2009). The ground based radar observation from the European composite (Hafner, DWD) shows reflectivity values below 37 dBZ in the region of the yellow contour at 1800 UT and outside the thunderstorm bottom objects (figure 9). The latter are determined by DLR’s radar tracker Rad-TRAM (Kober and Tafferner, 2009). The radar image is composed of measurements from different radars such that at any point in space the reflectivity value is that of the lowest value within the set of scans and therefore is not representative of the convective precipitation processes in the whole vertical column. Indeed, inspecting the cross section along the flight track constructed from the full 3-dimensional radar scan from the Türkheim radar (48.06° N, 10.64° E), we find a small but intense reflectivity cell between about 5 and 7 km height reaching 30 dBZ just underneath the flight track at around 1750 UTC (Fig. 10). The flight track in the figure is marked by pink line segments. Note that the time stamp of the radar image in figure 10, 1746 UT, is the start time of the radar scan and it takes a few minutes to scan the full volume. It is probable that these observations correspond to the convective cell which produced the turbulence at the height of the flight track, at about 9 km, when the aircraft passed over it. As reported by the pilots there were indications of precipitation but without echoes on the radar display. This can be explained in the following way.

During that particular flight phase when the aircraft approached the thunderstorm region from the east, the aircraft was ascending (refer to the pink line in Fig. 10). Provided the radar only performed a horizontal scan without tilting, it probably did not detect the small cell because it was

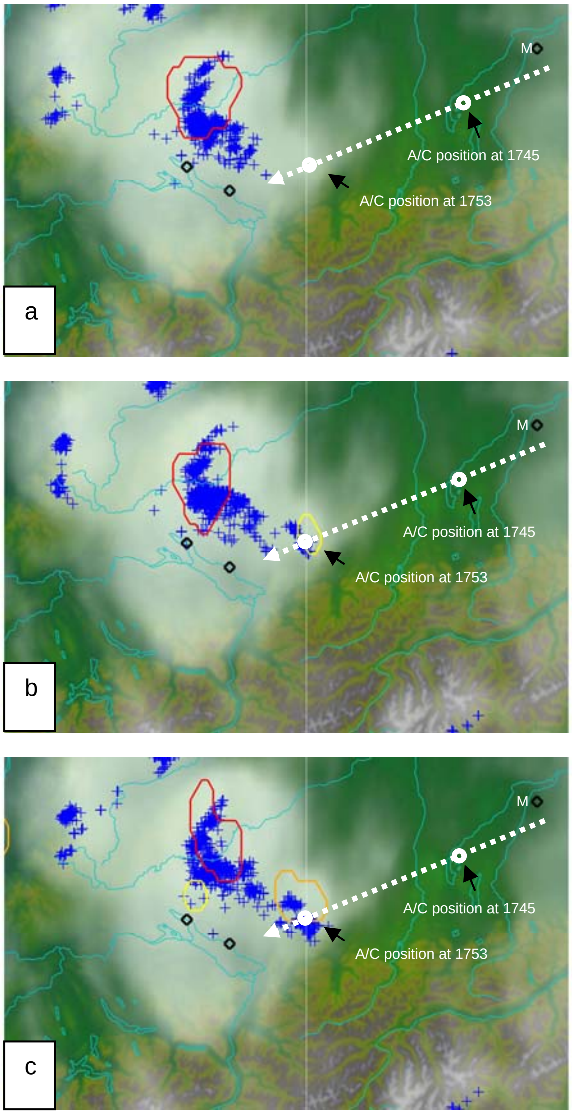

Figure 8: Thunderstorm cell development from 1755 (a) over 1800 (b) to 1805 UT (c). Marked in red: Cb top, yellow: convection initiation, orange: rapid development; blue: lightning observations during past 5 minutes (from LINET, Betz et al., 2004). Infrared satellite image in grey transparent shading. Flight track starting from Munich marked by dotted line, also a/c position at 1753 UT.

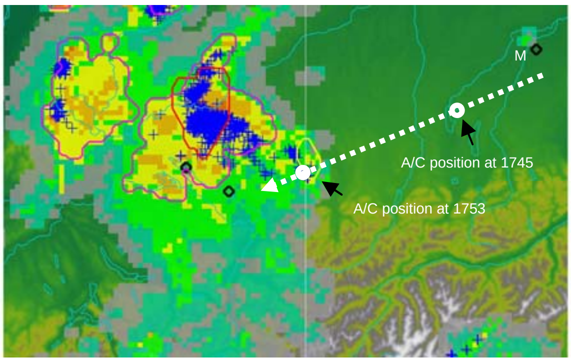

Figure 9: Same situation as in Fig. 8 at 1800 UT, but with radar reflectivity instead of satellite image and with violet contour marking the Cb bottom objects (by use of a 37 dBZ reflectivity threshold) in addition to the top object.

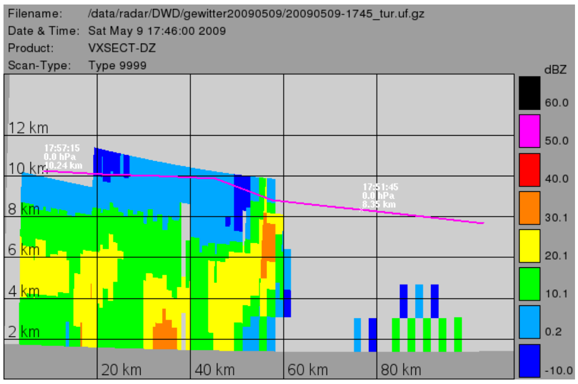

Figure 10: Vertical section through the radar reflectivity field as gained from the Türkheim radar at about 1748 UT along the flight path (pink line). Aircraft positions marked for 1751 and 1757 UTC.

below the lowest scan line of the radar. It is also possible that the gain switch was set at a too high value because of the strong thunderstorm cell to the north which the pilots wanted to avoid, again with the consequence that the small cell beneath did not show up on the screen. Finally, whilst flying over the cell, there were indications of precipitation to the pilots (perhaps on the wind shield). In accord with this note the vertical cross-section of the reflectivity pattern which indicates precipitation particles intersecting with the aircraft track (Fig. 10). At about the same time, the convective initiation is noticeable by lighting detections in that region (Fig. 8b). Note that these figures present lightning observations during the past 5 minutes before 1800 UTC.

In conclusion, this analysis shows that it was certainly difficult for the pilots to receive a clear early warning from their onboard equipment. In the BFU report it is also noted that the pilots decided to make a change in track by 5° to the south, possibly in order to avoid the mature thunderstorm system to the north (which they saw using the onboard radar).

However, it has to be stated that even the use of the ground and satellite based systems it would have been difficult to issue a timely warning in this case due to the rapid development of the convective cell. It is not uncommon that cold air outflows from mature thunderstorms provide convergence and the necessary lift for triggering new cells ahead of the existing systems. For detecting these mesoscale processes a combination of all available remote sensing data together with wind observations and numerical model forecast data is necessary within an integrated system with the aim to enable timely warnings. What can be done in the case of observable thunderstorms has been demonstrated in the course of the FLYSAFE project (Tafferner et al., 2009). Research is also underway to make it possible to nowcast convective initiation, i.e. to correctly predict time and location where a thunderstorm will develop. This is a still difficult task however, especially when considering not only the time needed to collect and process the data, which can be reduced to some minutes, but also the time needed to bring the information to the cockpit.

b) Incident of 5 June 2008

On 5 June 2008, an Airbus A319 aircraft during the descent to Munich experienced turbulence about 3 nm north of the way point LANDU at flight level 110 at 1637 UTC (BFU 2008). The approximate position is indicated in figure 11 by the dotted white oval.

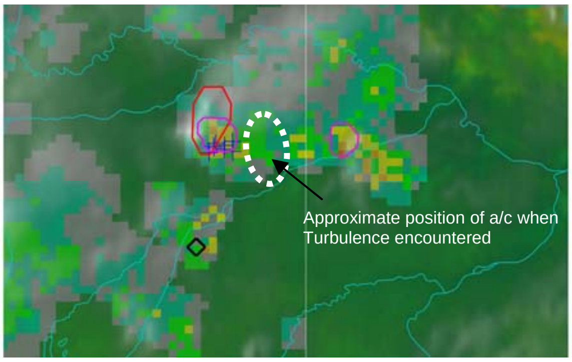

Figure 11: Radar reflectivity and Cb bottom volumes (pink contours) over southern Germany at time 1645; MSG rapid scan HRV image (transparent grey) and Cb top volume (red) at time 1640; approximate aircraft position indicated when turbulence encountered at 1637 UT. The black diamond marks the position of Munich airport.

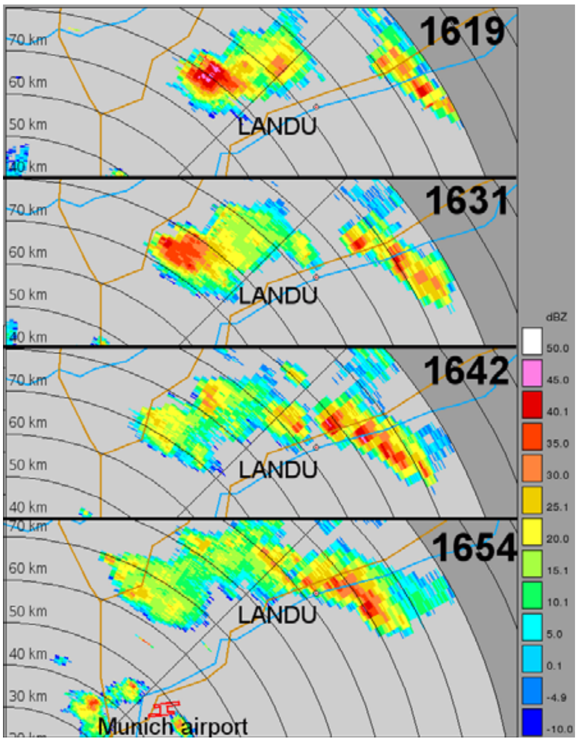

Figure 12: Radar reflectivity at four different times on 5 June 2008 from DLR polarimetric radar at a height of 3100m AMSL. The little dot at the crossing of the river Isar and the 80 km range circle marks the way point LANDU.

According to the BFU report, the pilots saw two cumulus clouds left and right of the flight path which were also apparent on the navigation display. In the figure, these are obviously the two cells marked by coloured contours on both sides of the aircraft position.

Like in the previous case, the intensity values in the radar composite are below 37 dBZ in the region of the aircraft. However, a detailed inspection of radar data from the DLR operated polarimetric radar POLDIRAD in the form of a constant altitude plan position indicator (CAPPI) at 3.1 km, somewhat below the height where the descending aircraft was at that time, shows the growth of small cells of high reflectivity up to 40 dBZ just north of waypoint LANDU between 1631 and 1642 UTC (figure 12). It is plausible that the aircraft approaching from north hit one of these cells with the turbulence encounter.

Again, as in the previous case, forecasting these events of convective activity is a very demanding task.

c) Encounter of severe turbulence and hail near Catania on Oct 1st 2009:

By the time of this writing it is not quite clear where and when then incident exactly happened. In a report from the website of The Aviation Herald (The Aviation Herald, 1) dated 13 October 2009 which refers to Italy's "*Agenzia Nazionale per la Sicurezza del Volo*" (ANSV) the following description of an incident was given.

"The crew of a Windjet Airbus A319-100, registration EI-ECX performing flight IV-283 from Forli to Palermo (Italy), decided to divert to Catania 90 nm southeast of Palermo due to adverse weather conditions in Palermo. During the approach to Catania the airplane encountered severe turbulence and hail. The crew continued for a safe landing in Catania. No injuries occurred."

A photograph taken after landing (figure 1, right) shows a hole in the aircraft's radome due to hail encounter. Also it is noted in the Aviation Herald page by referring to a report from a mechanics after landing that "*the airplane experienced wind shear of +50/-50 knots on final approach to Palermo prompting the crew to initiate a go-around. The airplane did not climb until after passing the runway at very low height despite the engines at full thrust*".

On the internet (Aviation Safety Network**,** 2009) the report of a passenger is published, who states among other things: "*From the sound and the frequency of impact of the ice lumps, the hailstones must have been at least 10cm in diameter. The hail shower lasted for about one minute. After landing at Catania one could see the destroyed radome (see photo. Fig 1), dents on the forward edges of wings and tail, and an opening in the vertical rudder surface*." The time of the incident is given as "about 17:00".

The METAR from Palermo, available around the time of the incident, reports at 1450 UT a 20° Wind with 26 knots with lowest visibility of 4000m, thunderstorm as present weather. The Cb-TRAM analysis for about this time is shown in figure 13.

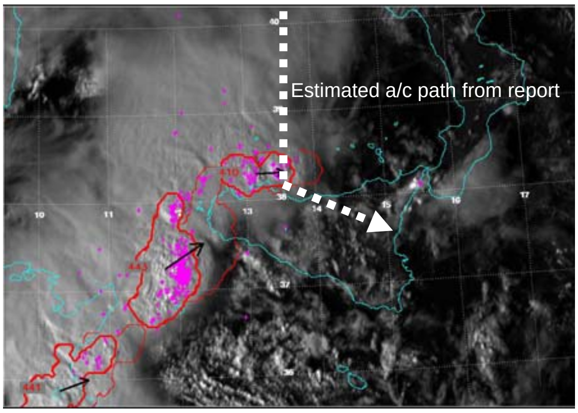

Figure 13: High resolution visible satellite image in grey transparent shading and mature thunderstorm cells at 1455 UT marked by thick red contours, thin red contours indicate one hour nowcasts of the cells. Lightning observations recorded during past 5 minutes before 1455 UT marked by pink dots (from LINET observation system). Dotted line segments mark direction from Forli to Palermo and from Palermo to Catania.

The satellite image from Meteosat in the high reso-lution visible channel shows an approaching thunder-storm front towards the island of Sicily. The heavy convection cells, marked in red, and the lightning activity in the frontral line, observations from the LINET network, can be traced back for more than three hours before this time. Most probably the aircraft flew into the foremost convective cell (labelled with 410) just off the coast of Palermo, where the black arrow indicates its progression. Note also that the one hour nowcast of that cell indicates propagation to the east. There are also lightning observations in that cell.

This is clearly an event where the satellite based analysis and nowcast could have been used to issue a thunderstorm warning for the region of Palermo at least half an hour before the aircraft entered the dangerous region. This information brought to the cockpit in time would have indicated the approaching hazard to the pilot long before he can notice it on the radar display which again would help in strategic planning.

4.2 Oceanic cases

a) Accident of 1 June 2009

On Sunday 31 May 2009 at 22 h 29 UTC (19 h 29 Rio time), the Airbus A330-203 registered F-GZCP, operated by Air France under flight number AF447, took off from Rio de Janeiro Galeão airport bound for Paris Charles de Gaulle. The airplane was carrying 216 passengers of 32 nationalities as well as 12 crew members. Around 3 h 45 minutes after take-off, the airplane crashed into the Atlantic Ocean about 435 nautical miles north-north-east of Fernando de Noronha Island, in the middle of the night and without any emergency message being sent. The last contact between the airplane and Brazilian Air Traffic Control (ATC) had been made around 35 minutes previously (BEA, Dec. 2009).

Soon after the accident a detailed meteorological analysis was presented by Vasquez (2009) on the internet. From all possible weather phenomena which could have threatened the aircraft, i.e. turbulence, lightning, icing, precipitation, hail and warm sink, he explained that severe turbulence at flight level could have played a major role; all other contributors were most likely of minor to no importance. Finally he concluded: "*Overall what we know for sure is weather was a factor and the flight definitely crossed through a thunderstorm complex. There is a definite correlation of weather with the crash. However the analysis indicates that the weather is not anything particularly exceptional in terms of instability or storm structure*". Currently there is no definite answer to what caused the crash (also because the blackbox recorder has not been found). However, there are speculations of whether icing of the Pitot tubes (related links also in Vasquez' report) might have enforced wrong speed measurements and consequently loss of flight control. From experiences gained through research flights over Germany carried out by DLR (Hauf et., 1999) in 1999, this cannot completely be ruled out. On those flights the DLR operated DORNIER aircraft DO-328 descended into high cumulus tops with concurrent icing of the Pitot tubes at an air temperature around -40° C, about the same temperature value at the height where AF447 was flying (according to Vasquez' analysis). On the one hand this shows that aircraft icing is possible at temperatures as low as -40° C at least in continental convective clouds, but on the other hand it is not clear whether this is possible also in tropical maritime convective clouds where cloud physical processes are different, e.g due to different temperature and humidity profiles and different aerosol content.

Figure 14 shows the convective situation over the Atlantic at two different times, i.e. 0000 and 0130 UTC, from the satellite cloud analysis. Red contours mark again the convective updrafts as detected by Cb-TRAM. The flight track is indicated by a white line combining the way points INTOL and TASIL. The convective cloud feature which is traversed by the flight route is seen to grow remarkably during this time span of ninety minutes. For the time 0130 UTC when the aircraft reported waypoint INTOL to ATC an approximate radar range of 80 nm is drawn as a yellow circle around the aircraft. This is to demonstrate that at this time the pilots could not foresee the strong convective activity on their future track from the on-board radar detection (also a longer range would not change the situation). Also, just from looking out of the window it was probably impossible for them to recognize the thunderstorm complexes in the far distance due to the midnight darkness. Furthermore there are no lightning discharges observed from the networks for this region at this time (noted by Vasquez' report) which could have warned the pilots. Half an hour later, at 0200 UTC, when the aircraft was close to the major convective complex (figure 15a), the onboard radar should have detected the cells, but now indicating convective activity almost everywhere in front of the aircraft which makes it difficult for the pilot to decide whether to penetrate the system or to go around and in which direction. This is complicated by the fact that the onboard radar signal is strongly attenuated by precipitation, due to its short wave length of 3cm (as compared to ground based radars) with the effect not being able to render the real extension of the storm. In this case the pilots obviously chose to go through the convective complex. Figure 15b shows the aircraft in its last known position when it had almost crossed the major storm cell at 0210 UTC.

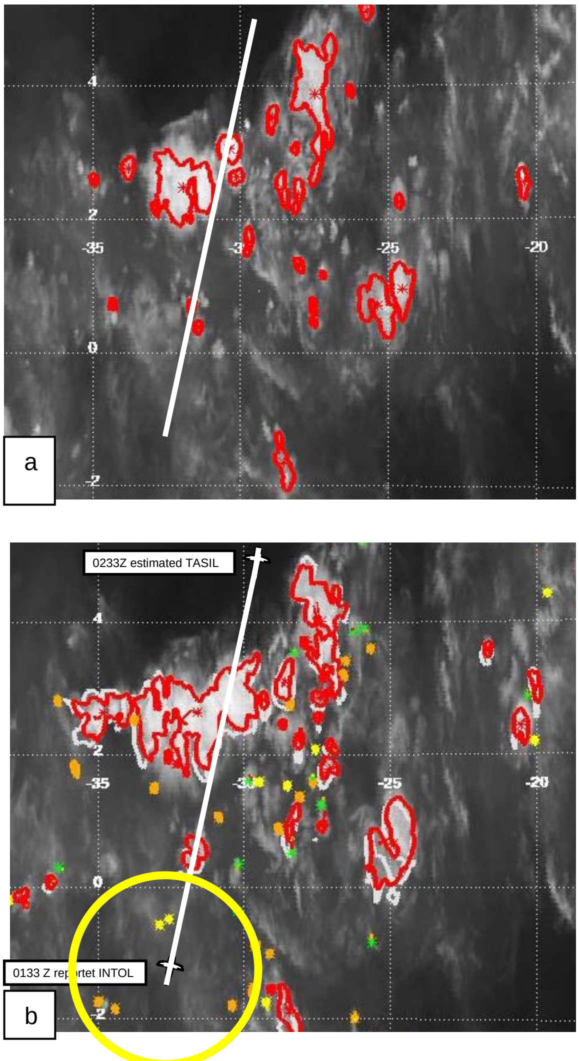

Figure 14: Meteosat infrared image over the Atlantic east of Brasil together with convective clusters (red contours) as identified from the Cb-TRAM cloud analysis on 1 June 2009 for time 000 UTC (a) and 0130 UTC (b). Also marked is the flight route between the way points INTOL and TASIL. The yellow circle indicates a radar range of about 80nm. Yellow, orange and green little patches mark initial developments not relevant for this analysis and not discussed.

What can and what cannot be seen on the onboard radar deserves more attention, especially for aircraft flying through tropical convective complexes at high altitudes. From an investigation undertaken by Air France (Flightglobal, 2009) it looks like that the setting of the sensitivity, i.e. the gain switch, has a great influence on what is seen on the navigational display. In that report it is stated: "*Several other flights - ahead of, and trailing, AF447 at about the same altitude - altered course to avoid cloud masses. Those included another Air France A330 operating the AF459 service from Sao Paulo to Paris. That crew crossed a turbulent area that had not been detected on weather radar and, as a result, increased the sensitivity - subsequently avoiding a "much worse" area of turbulence*." And further in the report it is noted that: "*France's Bureau d'Enquetes et d'Analyses says the crew of AF459, which had been 37min behind AF447, detected echoes on the weather radar which 'differed significantly' depending on the radar setting*."

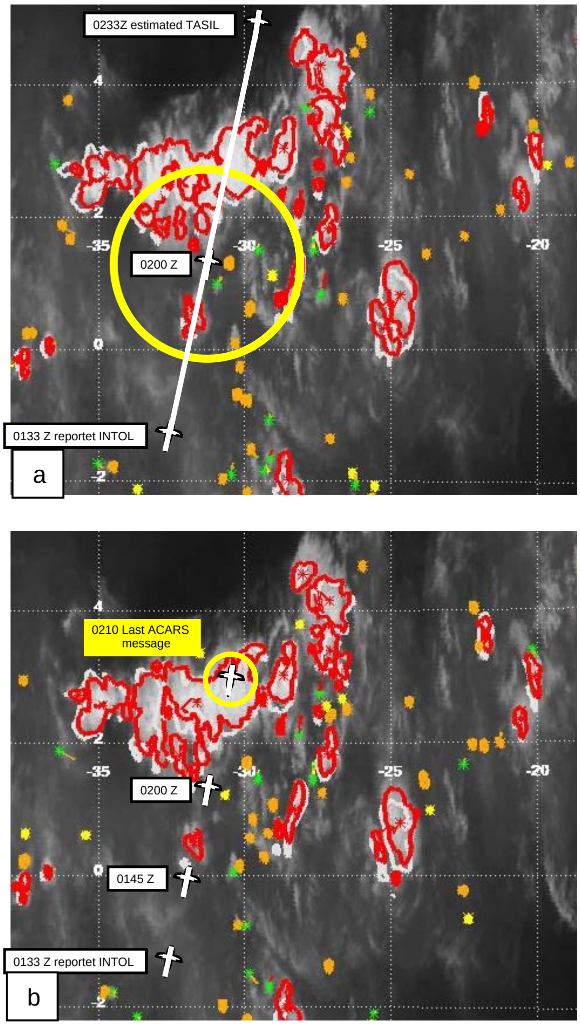

Figure 15: as in figure 14, but for 0200 UTC (a) and 0210 UTC (b)

When searching for a physical explanation one could speculate that the droplet size and precipitation particles at the height where aircraft fly through these tropical storms are quite small and are therefore not detectable or only with weaker return signals by the onboard radar (Rosenfeld, pers. comm. with one of the co-authors).

Regardless whether strong or weak returns can be seen on the navigational display by the pilot, the sequence of figures 14 and 15 makes clear that the ground based information is able to represent the real situation about the convective activity and that this information, when brought to the cockpit, would help pilots in making decisions, especially when the planned route is impacted by thunderstorms. Ideally an alternative route in a given situation would be proposed by the ground based systems, e.g. as indicated by the dotted line in figure 16. This is not to say that the indicated route would have been possible for flight AF447. There might be restrictions due to ATC, prescribed air routes or fuel uptake which would not allow such a detour. Furthermore, it is known that often aircraft fly through these storms without any problems. Obviously, it is not only the mere presence and location of these storms that is relevant but also their evolution; whether they are growing in size or depth, their movement and possibly more elaborate attitudes like height, precipitation rate and type, lightning activity and turbulence level. Some of which have been addressed in the FLYSAFE Cb WIMS.

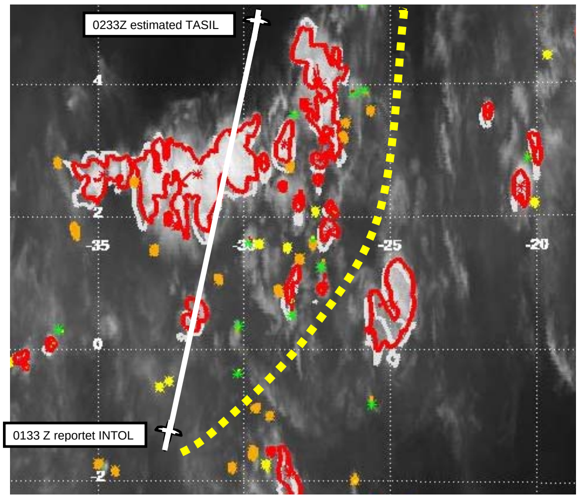

Figure 16: As in fig. 14b, with indication of alternative route marked by dotted line.

b) Incident of 30 November 2009

From Aviation Herald (Hradecky, 2009): *"An Air France Airbus A330-200, registration F-GZCK performing flight AF-445 (dep Nov 29th) from Rio de Janeiro Galeao, RJ (Brazil) to Paris Charles de Gaulle (France) with 203 passengers and 12 crew, was enroute at FL380 overhead the Atlantic on airway UN866 just before waypoint DEKON about 680nm northeast of Fortaleza,CE (Brazil) and 750nm southwest of Praia (Cape Verde), when the crew called Mayday on the international emergency frequency indicating, they encountered severe turbulence and were descending to a lower altitude."*

Later in the report it is noted that the airplane was at FL380 about 60nm ahead of DEKON on airway UN866 at time 0350 UTC. The Cb-TRAM analysis for this date and time is shown in figure 17 together with the airway and the approximate position when Mayday was called. Apparently the aircraft flew right through a major thunderstorm as seen clearly in the satellite image and marked by the red contour. From inspection of the development before and after this time (not shown) it is apparent that the convective cluster in this location originated around 0100 UTC and was still growing at the time of encounter. Also one can notice that additional convective clouds are on the

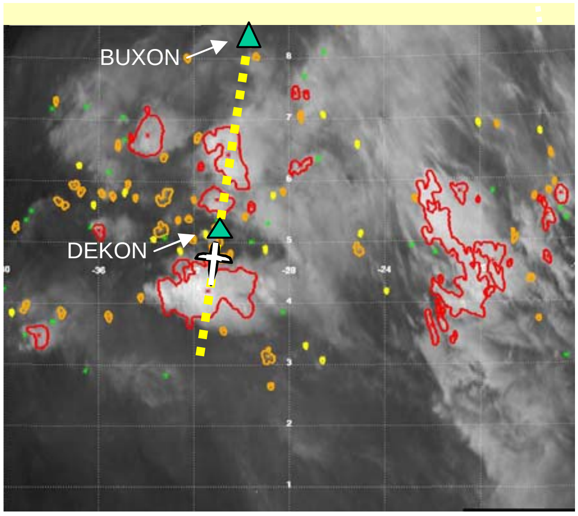

Figure 17: IR Meteosat 9 image on 30 November 2009 at 0350 UTC with mature convective cells (red contours) from Cb-TRAM analysis. Airway UN866 marked by yellow dotted line together with position of aircraft.

flight path further to the north between DEKON and BUXON way points (fig. 17). According to the report the turbulence lasted for about 30 minutes. It is not clear whether it would have been possible for the pilot to choose another route. The French Bureau d'Enquêtes et d'Analyses (BEA) reports that according to the air safety report weather forced the crew to divert from the airway and descend to FL360 employing oceanic contingency procedures after being unable to obtain clearance from ATC.

Some questions immediately arise again as in the previous case: would it have been possible to fly safer routes to the right or left of the clusters or were these options difficult/not possible due to ATC control regulations? Since the pilots did not receive ATC clearance, was the area under ATC control not? Would fuel considerations matter? In case detours are possible, then one could expect that a future uplink of weather data, e.g. a satellite image together with the Cb polygons, would be quite valuable to the pilots for early strategic planning. The weather data could be displayed e.g. on an electronic flight bag.

5. IMPROVED WEATHER INFORMATION FOR PILOTS THROUGH UPLINK

It was demonstrated through the FLYSAFE project that is possible to uplink weather information to the flight deck using industry standard internet technologies and current satellite data links (Intelsat) (Mirza et al, 2008, 2009a, Verbeck et al, 2009). It was also shown during flight simulations and scenario walkthroughs with domain experts that weather information presented in the form of weather objects on the navigation display was considered to be helpful, especially for strategic planning and raising the pilots' situation awareness. We suggest that our analysis of the case studies presented that uplink of rich weather information would be especially valuable for oceanic flights, where surface-based observations are limited or not available.

Currently incorporation of weather information into avionics systems is still within the domain of research and development, and many hurdles will need to be overcome before such systems are considered to be a part of the primary systems. Some the hurdles are not related to the technology but more related to institutional issues, such as certification, quality management and legal, etc. However, today it is noted that there is an increasing trend in the use of electronic flight books, which are preloaded with weather information; and for aircraft used for passenger transport, the availability of cabin internet services. Thus is it is not beyond the realms of possibility to foresee weather information being uplinked via the cabin internet services then subsequently routed to an electronic flight book; thereby affording the flight crew a greater awareness of the weather situation for their route. Until primary systems are in place services for weather information would have to be regarded as advisory.

The next two decades will witness a reformation of the management of the national airspace within the United States and Europe. This reformation is being spearheaded by two research and development programmes – SESAR and NextGen (SESAR,2007, JPDO, 2006, 2007a, 2007b, 2008). Both programmes envisage that weather information will become more readily available to all users via the concept of the 4-D Weather Cube (Eurocontrol, 2006a, 2006b, UCAR 2008). When such a facility is in place then information about thunderstorms could be made available on request or through publish and subscribe services, as could all the weather information developed during the FLYSAFE project.

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