5.2 Situational Awareness about Thunderstorms On-board an Aircraft

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Thunderstorms are top-ranked by pilots as weather situations compromising the flight safety. The information for pilots about adverse weather like thunderstorms today is, if at all, based on significant weather charts. Such services, however, do not give the required information for a particular flight in a particular circumstance because thunderstorms are relatively short-living phenomena. Information is required in the time-scale of up to about one hour with frequent updates clearly outlining the dangerous areas which should be avoided. Tools and products are descried which deliver that information tailored along the aircraft's trajectory. The information is produced on ground by weather expert systems and delivered to and stored in a ground-based weather processor which serves as a data base and interface between the expert system and the aircraft. Concepts and first tests are described where the information on thunderstorms is up-linked from the data base to the aircraft.

The FLYSAFE Project

The worldwide growing air traffic raises an unprecedented challenge for its safety. New tools have to be invented and implemented, in particular on-board aircraft, to maintain the current low level of accidents in aviation. In that perspective, 36 partners from industry, research centres, weather services, universities, and small and medium enterprises together with the European Commission in its 6th Research and Development Framework Programme launched and run the integrated project FLYSAFE from 2005 to 2009 (http://www.eu-flysafe.org/Project.html). The project focused on the areas identified as the main causes of accidents around the world: loss of control, controlled flight into terrain, approach and landing, and addressed three types of threats: traffic collision, ground collision, and adverse weather conditions. FLYSAFE developed new systems and functions, both on board and on ground, allowing the most comprehensive and accurate awareness of the aircraft safety situation during all phases of flight. These functions included situational awareness, advance warning, and new human-machine interface [Fabreguettes, 2010].

To raise the situational awareness of flight crews for atmospheric disturbances, weather expert systems for wake vortices, thunderstorms, in-flight icing and clear-air turbulence have been designed and developed, see Figure 1. In the project, DLR was responsible for the weather expert systems for aircraft wake vortices and thunderstorms. The expert system for thunderstorms provided forecasts on a local (TMA) scale, a regional (continental) scale (both derived from systems developed at Météo France and DLR), and a global scale (provided by output from the Unified Model of the UK Met Office). These scale products differ in terms of area covered, spatial resolution and time between updates. Moving from global via continental to local scale, they provide increasingly more high-resolution forecasts and at a faster rate, while reducing the area covered. According to their designation, the global product covers (nearly) the whole earth surface, the continental product covers an area such as that of Europe in this case, while the local (TMA) product is limited to roughly 100 km around an airport.

The products are delivered to a ground weather processor (developed by the UK Met Office) as thunderstorm bottom and top volumes (see below), representing a hazard in the airport vicinity or en-route, respectively. In case of a request by an aircraft the ground weather processor selects the product with the finest resolution and up-links relevant data for the flight corridor of the aircraft into the cockpit. The workflow is depicted in Figure 2. The functionality of delivering the products from the thunderstorm expert system to the weather data base and further on to the cockpit has been demonstrated during a FLYSAFE demonstration and validation effort, which included a full flight simulator and flight tests with an operational data link from ground to the test aircraft.

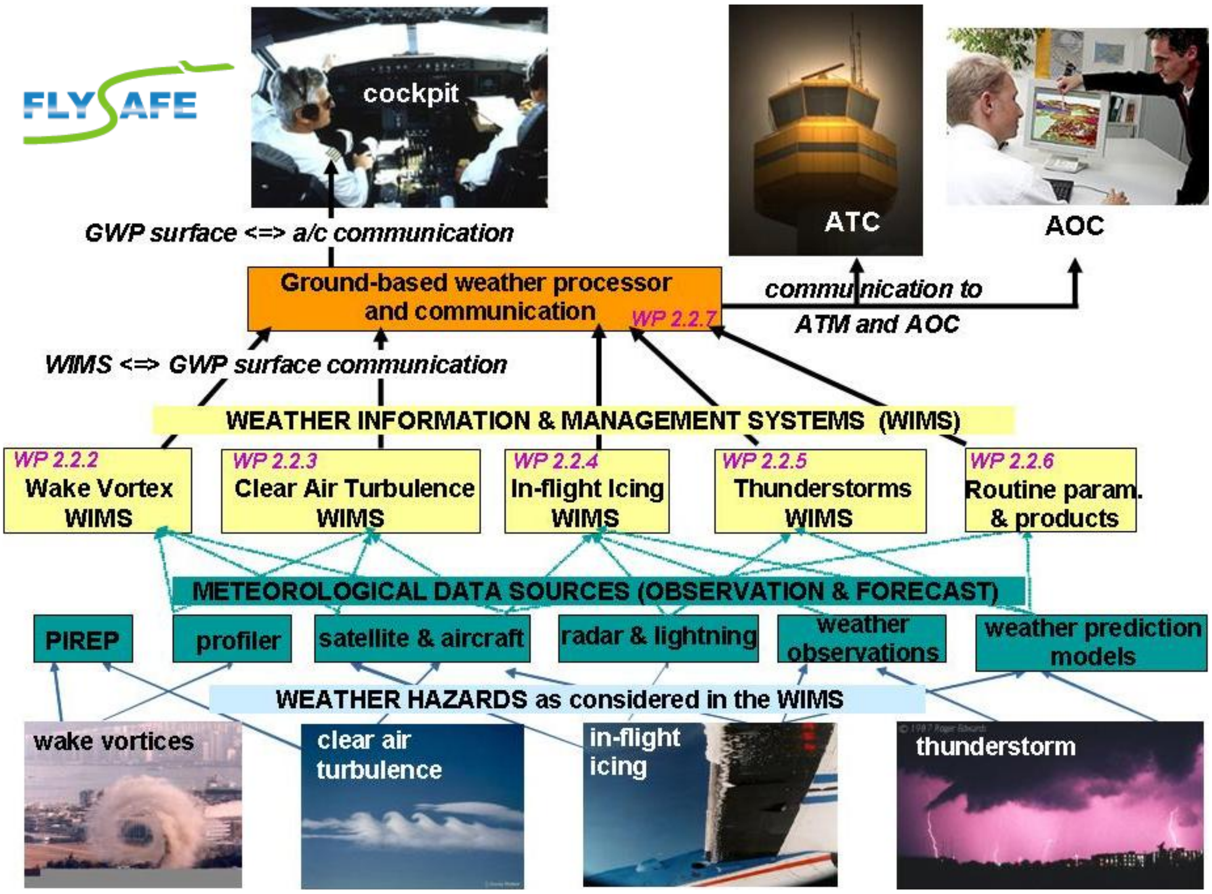

Figure 1. Provision of consistent, timely and tailored information on hazards like wake vortex, clear-air turbulence, in-flight icing and thunderstorm through ground-based weather expert systems, named WIMS, to the ground-based weather processor and communication platform from where the data are sent to cockpits as well as air traffic controllers (ATC), airline operating centres (AOC) and airports.

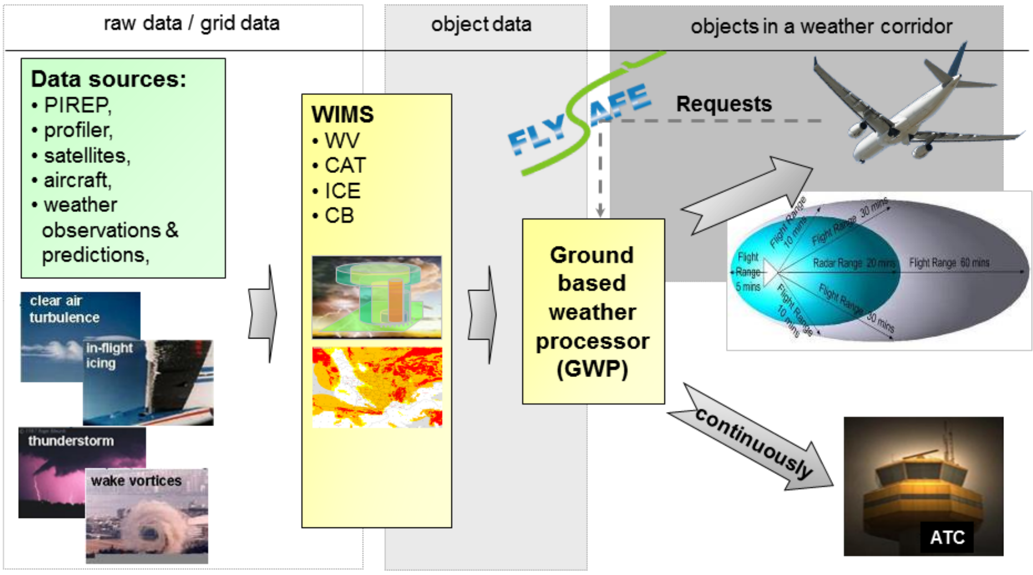

Figure 2. The workflow: Concatenating the weather data from various sources, producing simple products in the weather expert systems WIMS, transferring these products into a data base of the ground-based weather processor, and sending the relevant and tailored information to the aviation partners.

Reducing physical complexity to simple hazard areas

Thunderstorms can appear in various sizes from small convective cells to meso-scale convective systems and convective lines with corresponding life times from a few minutes to several hours. Remote sensing with satellite, radar, and lightning measurements gives detailed information on initiation, life cycle and dissipation of thunderstorms, but this detailed information is not very useful for air traffic controllers, airline dispatchers or pilots for decision making. Therefore, the strategy is not to describe thunderstorms to any observable detail, but reduce them to simplified weather objects representing the hazard levels "moderate" (avoid, if possible) and "severe" (no go area) for aircraft. This is the job of the weather expert system WIMS. Figure 3a shows a photo of a real thunderstorm with its idealized simplification as cylinder contours. The top volume represents the upper anvil part of the thunderstorm with the hazards turbulence and lightning; the bottom volume covers the hazards wind shear, heavy rain, hail, and lightning at mid-tropospheric and near ground levels. Outer and inner volumes indicate the hazard levels "moderate" and "severe", respectively. The top volume can be identified by using the Cumulonimbus tracking and monitoring (Cb-TRAM) algorithm which is based on satellite data (see Section 2.3 and Forster et al. [2008]) in combination with lightning data [Betz et al. 2004]. Cb-TRAM detects and nowcasts the outer top volume, i.e. turbulent areas within the anvil, while the lightning density exceeding a certain threshold marks the inner severe part of the top volume. Bottom volumes describing two severity levels can be detected with the aid of radar data exceeding certain thresholds, e.g. 33 and 41 dBZ as has been used in the CONO software [Hering et al., 2005] by Météo-France during the FLYSAFE campaign [Tafferner et al., 2008, 2009, Pradier et al., 2009]. If polarimetric radar information and/or lightning data are available in addition, the detection of the severe part can be refined as regards to occurrence of hail and/or lightning. The horizontal shapes of the top and bottom volumes do not have to be circular or elliptical, but can be polygon shaped as indicated in Figure 3b which displays the top and bottom volumes as detected for a real situation. Note that the three smaller pillars are convective cells which have not yet produced the characteristic thunderstorm cloud anvil, therefore they appear without top volume.

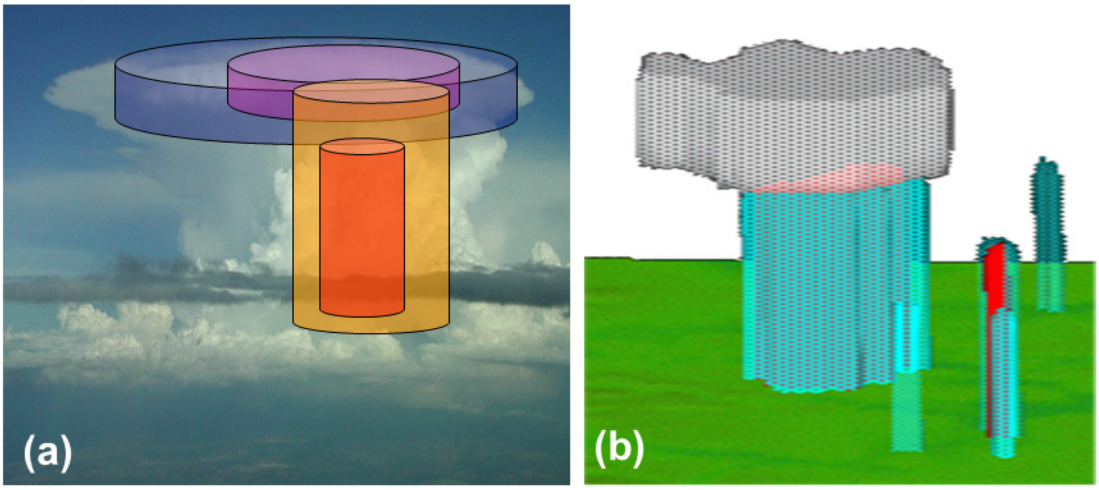

Figure 3. A thunderstorm rendered as a weather object with top and bottom volumes. (a) Photography of a thunderstorm with its idealized objects; (b) 3-dimensional view of objects as produced from a real thunderstorm by using detection algorithms based on satellite and radar data. Grey indicates top volumes, bluish colours indicate bottom volumes with level "severe" in red. Green is the ground surface.

Up-link of Data and Fusion with On-board Information

When the weather objects indicate and predict the hazardous volumes around thunderstorms simply and unambiguously, they are stored as ASCII files in standard XML format in a data base of the weather processor on ground. Upon request and depending on the flight trajectory of an aircraft, the weather processor takes the relevant XML coded objects for the flight corridor from the data base and transfers just those to the cockpit. This keeps data uplink costs to a minimum. In the cockpit the ground data can be displayed on electronic flights bags or fused with data from the on-board weather radar to get a comprehensive view of the situation. Figure 4 sketches that process of tailoring, up-linking, fusing and displaying.

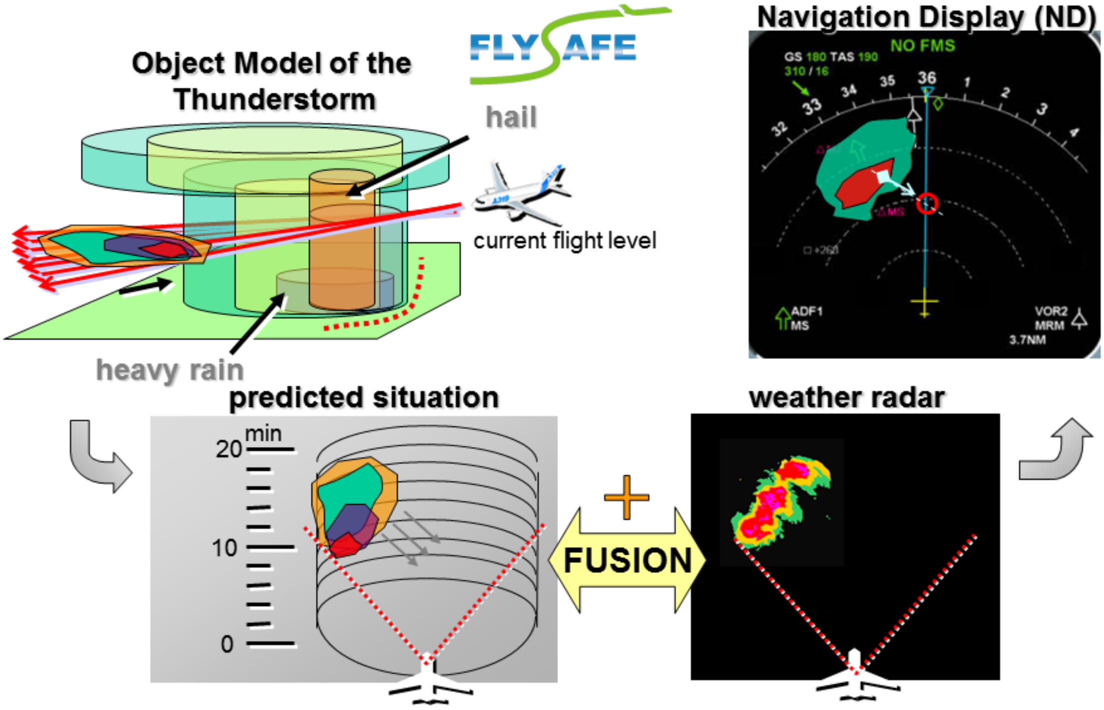

Figure 4. Sketch of the process of tailoring, up-linking, fusing and displaying the thunderstorm objects from the weather expert system on ground to the navigational display in the cockpit.

Analysis from the Flight Tests

During the flight trials we could demonstrate the functionality of the data up-link in real time. Data fusion or a common display with the on-board weather radar data could only be achieved *a-posteriori* when analysing the flights. Nevertheless, it could be shown that the delivered and up-linked objects compare well to the weather radar depiction on board the test aircraft. Most importantly, the ground data complete the picture of the weather hazard on board the aircraft as they survey a much larger area than the on-board radar and combine data from several observational sources.

How the situational awareness of the pilots could be significantly enhanced is outlined in Figure 5. It shows snapshots of the radar display recorded during a test flight over south-easterly France on 19th of August 2008 in a 10 min sequence [Sénési et al., 2009]. Objects from Cb-TRAM and the heavy precipitation cells for two different precipitation intensities are indicated as coloured contours. The spatial distribution of the thunderstorm objects agrees well with what the on-board radar sees on the right side of the intended flight track near the 50 nautical miles range circle (Figure 5 a). However, beyond that range, the on-board radar sees much less reflectivity although the expert system indicates additional thunderstorm activity (blue circle in Figure 5 a); and even a third cell is indicated by the objects beyond the 100 nautical miles range circle (red rectangle). Both cells cannot be seen by the radar at 14:05 UTC because the radar beam is attenuated by the first and closest cell and 100 nautical miles is about the detectable distance of that radar. After 10 and 20 minutes, though, these cells indicated by the objects already at 14:05 get confirmed by the on-board radar as the flight continues (Figure 5 b/c at 14:15 / 14:25 UTC, respectively). Note that the radar returns on the left side of the intended flight track (red circle in Figure 5 a) are not corroborated by the expert system. Figure 5 d reveals that these returns are not from thunderstorm activity but stem from the reflecting ground of the mountain region (so-called ground clutter).

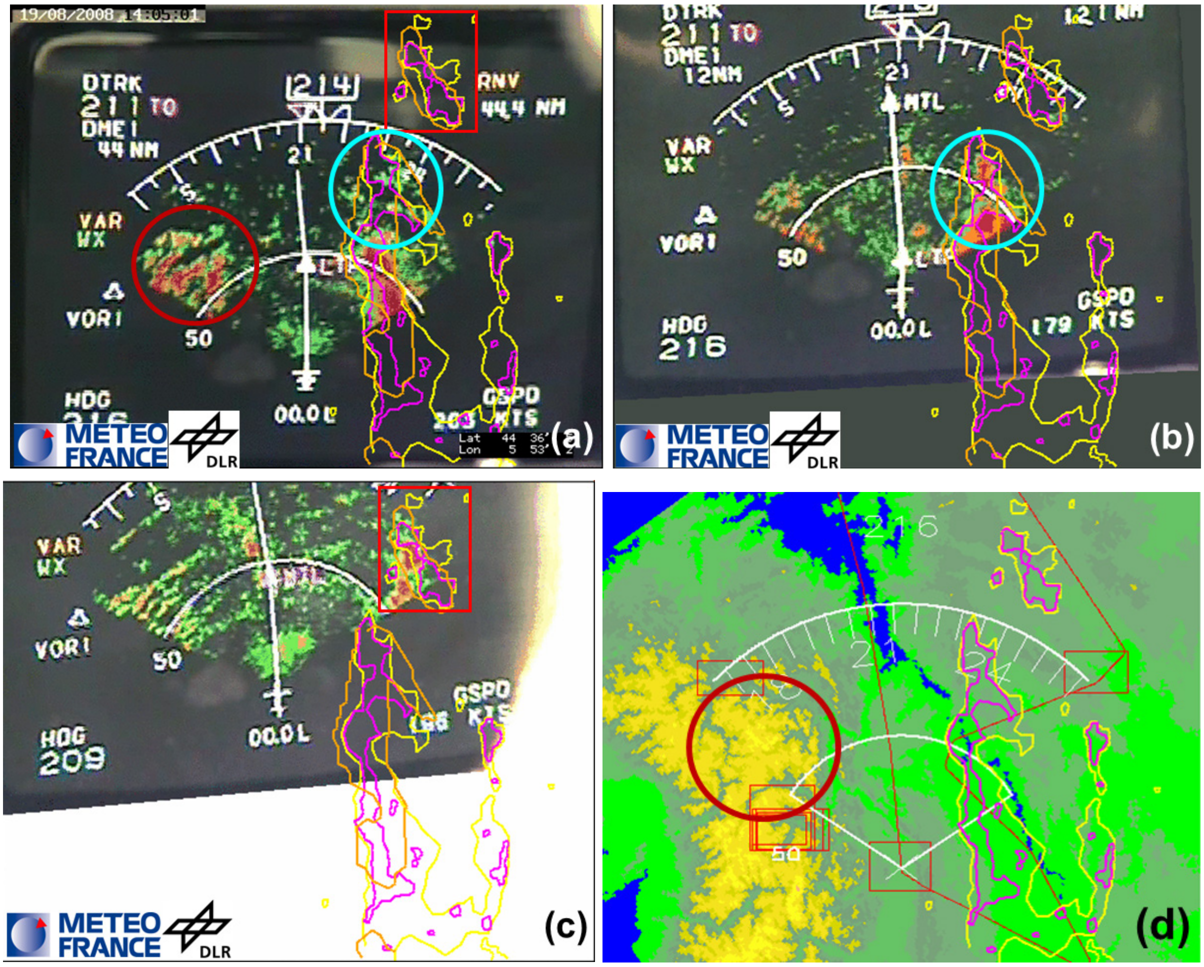

Figure 5. On-board weather radar images on 19th of August 2008 at (a) 14:05, (b) 14:15 and (c) 14:25 UTC with superimposed weather object contours from the ground system. Orange contours indicate Cb-TRAM objects, yellow and pink contours indicate heavy precipitation cells for two different intensities representing moderate and severe precipitation. (d) ground map of the flight area showing a mountain region in yellow.

Lacking Proper Weather Information in a Safety Critical Case

On Sunday 31 May 2009 at 22:29 UTC (19:29 Rio time), the Airbus A330-200 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 hours 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. Whatever the reason for the crash finally was, the flight definitely crossed through a thunderstorm complex. Figure 6 shows the convective situation over the Atlantic at four different times from the satellite cloud analysis [Tafferner et al. 2010]. Red contours mark 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 from 0 to

01:30 UTC. At that time when the aircraft reported waypoint INTOL to air traffic control an approximate radar range of 80 nautical miles 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 signal returns (also a longer-range radar would not change the situation).

Also, just from looking out of the window it was probably impossible for them to recognise the thunderstorm complexes in the far distance due to the darkness at night. 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 02:00 UTC, when the aircraft was close to the major convective complex (Figure 6 c), the on-board 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 on-board radar signal is strongly attenuated by precipitation, due to its short wave length of 3 cm (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 6 d shows the aircraft in its last known position when it had almost crossed the major storm cell at 02:10 UTC.

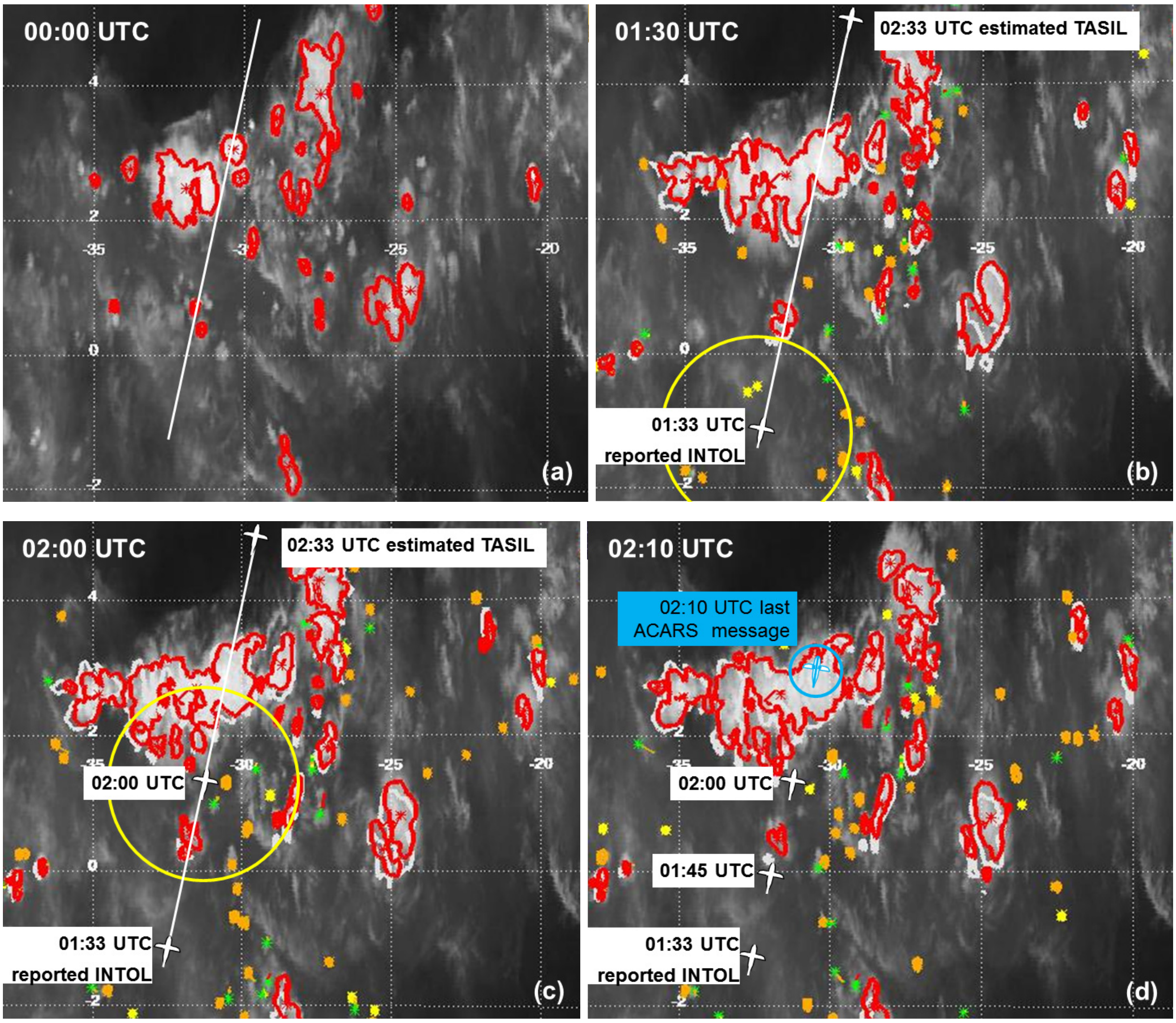

Figure 6. Meteosat infrared images over the Atlantic east of Brasil together with convective clusters (red contours) as identified from the Cb-TRAM cloud analysis on 1 June 2009 at four different time instants. Also marked is the flight route between the way points INTOL and TASIL. The yellow circle 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 on-board 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 37 min behind AF447, detected echoes on the weather radar which ‘differed significantly’ depending on the radar setting.”

It is also 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.

However, regardless whether strong or weak returns can be seen on the navigational display, the sequence of satellite images and object contours in Figure 6 elucidates that the information from ground-based weather expert systems 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. Ideally, an alternative route in a given situation would be proposed by the integrated surveillance system on board the aircraft, as was demonstrated in the FLYSAFE project. Such a surveillance system would propose a detour to the flight crew after considering all aspects of the flight and the airspace as fuel capacity and consumption, other traffic or further hazards.

Next steps

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 of 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 bags which are preloaded with weather information. For aircraft used for passenger transport, cabin internet services become more and more available. Thus, 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 bag. However, until primary systems are in place, services for weather information would have to be regarded as advisory.

On a European level research and development are underway in the ESA-co-funded project planet2 for a certified airborne collaborative network to exchange real-time atmospheric data and meteorological conditions from/to business and regional aircraft. The goal is to get in-flight information updates on weather conditions and hazards, and at the same time, to contribute to the global weather observations by providing complementary atmospheric measurements to the existing Aircraft Meteorological Data Relay system. The European Commission is co-funding the project ALICIA to develop new cockpit information systems applicable to multiple types of aircraft and helicopters and enabling robust worldwide operations in all weather conditions.

Acknowledgements

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