Incidents in Air Transport

Wind Gradients and Turbulence

N° 5
December 2006

This edition presents four events linked to meteorological phenomena, strong winds at altitude or convective movements associated with cumulonimbus. Although different in nature, these examples have some common points: the sudden deterioration of the conditions, late detection, sometimes inappropriate reactions, lack of information transfer within flight crews (PIREP). Since they are difficult to characterize in flight and meteorological forecasts are often inaccurate, these phenomena can be underestimated and poorly managed. Making those involved more aware, in-flight updating of information allowing for better anticipation and increased vigilance when approaching areas of risk can all help flight crews to avoid or to reduce the effects. Other cases can be found on the BEA website (www.bea.aero) such as the report on the F-GITF accident (1996).

Wind gradient on entering a jet stream

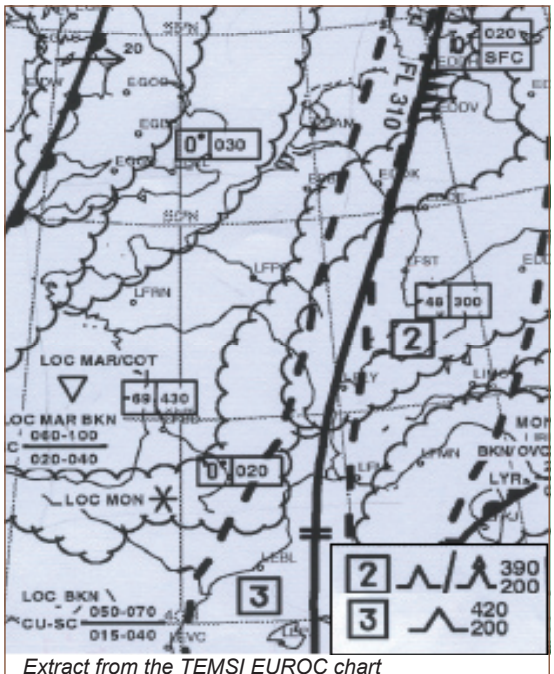
History of flight

► Preparation

At the end of December, the crew of a Boeing 737-500 was preparing the second leg of the day, between Lyon Saint-Exupéry and Paris Charles-de-Gaulle.

The meteorological situation over France was characterized by an airflow from the north, to which a jet stream of about 160 kt at FL310 was associated, above the Rhône Valley. Some zones of clear-air turbulence were associated with this jet stream.

On the TEMSI EUROC chart (valid 1 h 30 later) the crew noted that the planned route entered an area of moderate turbulence that extended from FL200 to FL420, centred on the jet stream.



Extract from the TEMSI EUROC chart

The forecast charts showed a wind from the northern sector, weak on the surface, about 30 kt at FL100, 110 kt at FL180 and 145 kt at FL300. A SIGMET contained in the flight dossier mentioned moderate to severe turbulence between FL180 and FL380 on the route. It was valid until the time of take-off.

► Climb

The co-pilot was PF. A short time after take-off, facing north, the Captain told the cabin crew that they could unfasten their seatbelts.

During the climb, the crew heard the controller make a remark to the crew of another airplane that had reached FL220, although it was only cleared to climb to FL200 so as not to interfere with the arrivals at Geneva. This crew explained that the autopilot had not captured FL200.

After having passed through FL100, still facing north and climbing towards FL200, the co-pilot activated the autopilot in LNAV and VNAV modes and entered the accelerated speed climb value of 325 kt in the FMS.

While the airplane was flying in clear air, passing through FL170, the Captain performed a visual check of the circuits and instruments. He noted that the speed was approaching VMO (340 kt), and that it was about 15 kt above the selected speed. He informed the co-pilot and made a nose-up input on the control column, causing the selection of CWS Pitch mode, which he saw on the FMA and which he called out. Despite this action, the speed remained abnormally high, still increasing and turbulence was felt.

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At FL191, the altitude warning indicated that the airplane was approaching the level selected. Pitch was then 17° nose-up and the vertical speed about 11 000 ft/min. Immediately, the Captain pushed forward the control column, selected the recommended speed of 280 kt in turbulent atmosphere on the Mode Control Panel and moved the thrust levers towards the rear stop. The airplane crossed FL200 with a 14° nose-up pitch.

The Captain applied further pitch-down inputs, leading to a vertical acceleration of -0.15 g. Three flight attendants at the aft of the airplane were lifted, struck the cabin ceiling and fell down, injuring themselves slightly. The passengers' seatbelts had remained fastened. The airplane descended after having reached FL207. This sequence lasted 28 seconds. The co-pilot alerted the controller of the level bust, which he attributed to turbulence.

Additional information

► Calculation of the equivalent headwind encountered

The headwind, recalculated on the basis of the recorded parameters, increased by 100 kt in 63 seconds, going from 40 kt to 140 kt between FL140 and FL190. This can be broken down into two phases: for 47 seconds the increase in the equivalent headwind was about a knot a second, and then it went up to three knots a second.

► Airplane Systems

Autopilot and autothrust

In VNAV mode the autopilot maintains speed by acting on the pitch, the engine thrust remaining regulated at the climb rate. The pilot can override the autopilot by using the flight controls. When he acts on the control column, the autopilot passes into Pitch CWS mode. The airplane is then flying manually in pitch[1].

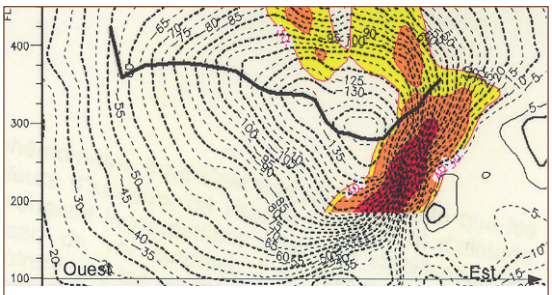
Vertical Speed Indicators (VSI)

The airplane's vertical speed indicators show the vertical speed as calculated by the IRS. The values shown are graduated from -6 000 ft/min to +6 000 ft/min. They were at upper limit level for eighteen seconds.

► Meteorological Forecasts

The TEMSI EUROC chart is prepared by a forecaster. Using computer software, he overlays different fields of meteorological parameters, established by forecast models, on the background of a geographical map.

He then positions the relevant graphic elements that encode the meteorological information.



Cross section of wind speeds forecast north of Lyon

When positioning the turbulence indicator field on the chart, the forecaster draws the various clear air turbulence zones above FL200. He then traces the jet streams analogically, overlaying the speed values of winds over 80 kt. On these tracks, he identifies the points that correspond to the extreme values, marked with the wind speed and the flight level.

In the area of the incident, the heart of the jet stream was at FL280, 3,000 feet below the level indicated on the TEMSI chart. Winds above 80 kt were forecast between FL160 and FL425, which corresponds to a depth of jet stream of 26,500 feet.

The comparison between the forecast wind values and those encountered by the airplane shows that the wind speed was underestimated by 20 kt on average by the computer model. The wind gradient was forecast.

The above entry indicates that the axis of the jet-stream is at FL350 and the 80 kt isotach (associated with the limits of the jet's envelope) is located between FL300 and FL380

Implementation at Météo France of amendment 73 to ICAO Annex 3

► Evolution of the presentation of information linked to a jet stream

Since 8 February 2005, the differences in minimum and maximum altitude in relation to the jet stream (speeds above 80 kt) are presented next to the strength symbols. This representation, which makes it possible to know the depth of the jet stream and to identify possible wind gradients, did not exist at the time of the incident. This evolution resulted from Amendment 74 to Annex 3 (ICAO – Meteorological Service for International Air Navigation[2]).

[1] If the AP is in CMD mode, with transparent pitch piloting (CWS P), the AP passes over to acquisition, then to altitude hold on approach to the selected level.

[2] The symbols used are decided on by pilots and meteorologists in ICAO working groups and submitted to the World Meteorological Organisation.

► Operator's procedures
The airplane's operations manual contains, amongst other things, the following procedures in the chapter on "Unfavourable meteorological conditions - flight in turbulent atmosphere":

– "Put on the permanent signs as soon as turbulence is encountered"
– "Engage autopilot in CWS in severe turbulence areas"
– "The AFS can be used in turbulence at the discretion of the crew. Short speed excursions of 10 kt to 15 kt can occur and the AFS can remain unless the performance is unacceptable…"
– "The recommended climb speed[3] for entering severe turbulence is 280 kt/M 0, 73…"
– " The horizon is the basic instrument to control the airplane's attitude. (…) Do not make sudden or high amplitude pitch corrections. React carefully, thoughtfully (…) Great variations in altitude are possible in very turbulent atmosphere. If the margins in relation to high ground allow it, these variations are permissible. Maintain airplane attitude at all costs, then correct the speed, the altitude and the heading …".

Lessons learned

This event is not directly linked to a turbulence phenomenon but to wind, which is often the cause. Information on turbulence can thus be useful to identify the presence of such gradients.

► Identification of a wind gradient
By the meteorological services
At the time of the event, it was difficult for the forecaster to make the extent of the vertical height of the jet stream appear clearly. The evolution of the symbol system will allow this phenomenon to be more comprehensible. However, the representation of a significant wind gradient remains difficult. The SIGMET is an additional means of warning of a particular meteorological phenomenon. Clear air turbulence is often caused by a wind gradient.

By flight crews
Available wind charts only give values spaced out in the vertical plane. The significant intervals between these values do not make it possible to forecast a wind gradient that occurs over a reduced altitude section. A strong wind gradient may lead to rapid variations in the indicated speed. Autoflight laws attempt to correct these variations while limiting the amplitude of the corrections, which can lead to speed excursions.

► Crew's reaction
The Captain did not expect a wind gradient of such amplitude. He was surprised by the increase in speed. As a first analysis, he attributed it to a lack of reactivity of the autopilot, which he then overrode. As this action did not have the desired effect, the crew thought there was an airspeed indicator problem. Taking into account the suddenness of the phenomenon and its amplitude, they were not able to re-analyse it. Stress-generating circumstances and time pressure generate a focus on a few parameters and can reduce the attention span. While the Captain was checking the results of his pitch up action on the airspeed indicator, he didn't notice that the pitch, vertical speed and altitude indications were becoming incompatible with stabilisation at the authorised flight level. The flight parameters show that the vertical accelerations suffered by the airplane were mainly the consequence of the manual inputs on the control column.

The level bust by another crew a few minutes earlier, possibly linked to the same phenomenon, may have led the Captain to accentuate his pitch down input to limit passing FL200.

► Information to flight crews
A radio announcement on meeting significant meteorological phenomena can lead the ATC services to relay it and to crews in the same area to anticipating them.

[3] In cruise, the N1 recommended is accessible on the FMS CRZ page.

Turbulence at the top of cumulonimbus

History of flight

An A320 was performing a Paris-Geneva leg at the end of the morning. During the first rotation, the pilots had encountered storms around Geneva but not on the rest of the route. They didn't expect to encounter any on this flight during cruise. The airplane was flying at FL270 at a high Mach level (managed speed of 340 kt) in order to make up for lateness. The pilots had just finished their meal and were preparing the arrival. The co-pilot, PF, entered the information corresponding to a change of QFU in the FMGS for the landing. The cabin crew was finishing the trolley service. The airplane was flying on the edge of a cloud layer when the Captain noticed

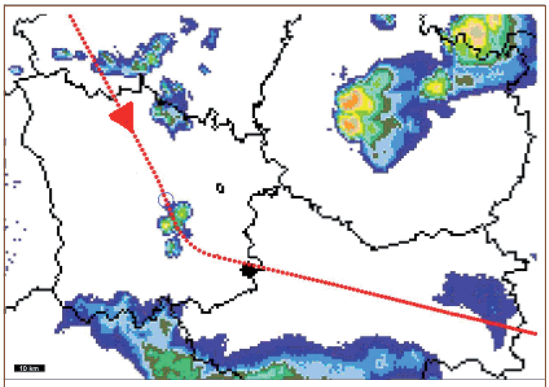
a cumulonimbus straight ahead, whose top was several thousand feet above. He disengaged autopilot and turned left in order to avoid it. He made the cabin announcement “This is the cockpit, turbulence, cabin crew seated, belts fastened”. Seeing that he wasn’t going to avoid the cloud, he selected Mach 0.77 and set the wings horizontal. The airplane entered an area of heavy precipitation (hail) and turbulence. For about twenty seconds, it was subject to vertical accelerations varying from –0.7 g à +3 g. A momentary loss of the N1 generator led to the left side screens shutting down[4].

The airplane rose 750 ft above its former level. The unsecured documentation and the meal trays were thrown about. The “Fasten seatbelts” signs were off at time of the turbulence. A passenger who was not attached was injured. Despite the announcement made by the Captain, the cabin crew did not have time to strap themselves in. At the aft, two flight attendants took the service trolleys into the galleys, without having time to stow them securely nor the time to strap themselves in. They were lifted above their seats, and then fell down, one of them being slightly injured. Forward, a flight attendant was taking the service trolley back towards the galley, preceded by the chief flight attendant. Both were lifted off their feet several times with the service trolley before hitting the ceiling and falling back down, injuring themselves slightly.

[4] *Certification specifies a flight envelope between – 1 g and + 2.5 g. The generator shutdown was attributed to the turbulence associated with a low oil level.*

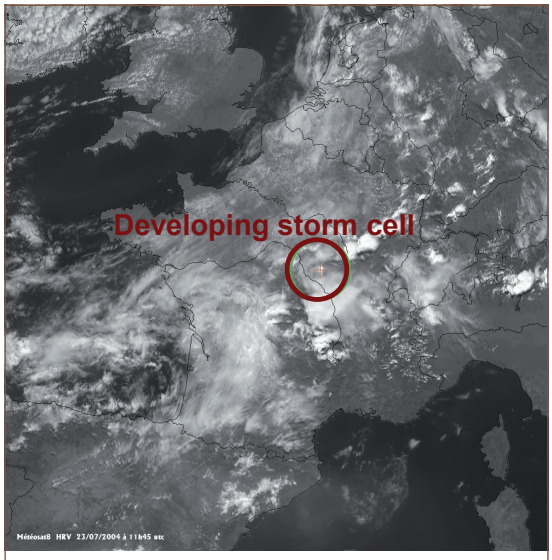
Additional information

► Meteorology



Radar image of the precipitation

Information available to the crew
The crew had a meteorological dossier made up of the TEMSI EUROC chart valid 6 hours before the event, forecasting cumulonimbus in the midst of cloud mass on the route up to FL340, all of the TAF’s and METAR’s and a SIGMET for the Marseille FIR, whose validity had expired, that related to the development of storms in the cloud layer over the north of



Satellite image

the Massif Central: EMBD TS OBS ON LFMM FIR, NORTH MASSIF CENTRAL, TOP CB FL 320/340 MOVE SLW NE, INTSF.

The crew received via ACARS the latest Geneva ATIS announcing a change in QFU nine minutes before passing through the turbulence.

Situation encountered
The cumulonimbus they passed through had begun to be detected by the Bourges radar fifteen minutes before the event. A weak precipitation nucleus indicated that the cloud was not very developed at that time. The sky was full of more or less thick cirrus, from the cumulonimbus generated two hours previously to the southwest. The visibility was thus mediocre at altitude. The radar and satellite images show that the development of the cumulonimbus was very rapid.

The precipitation became significant four minutes before the airplane passed.

► Use of the onboard weather radar
The top of the cumulonimbus being mainly made up of ice crystals, their detection by the onboard weather radar required an active search with changes to the gain, tilt and range, to be able to detect humid zones. This must be done in sufficient time to allow avoidance. In addition, the rapid formation of these clouds requires frequent repetition of the search.

During this flight, the radar[5] was in WX mode, gain on AUTO, the tilt set at -2° and the distance selected on the ND at 160 NM on the Captain’s side and 80 NM on the co-pilot’s side. The Captain expected to encounter storm activity on arrival at Geneva, but not in cruise. The co-pilot focused his attention on programming the FMGS for the arrival. The crew did not carry out any particular search for storms with the aid of the radar.

[5] *The radar detects rain, wet hail and dry ice particles if their diameter is above 3 mm.*

► Operational considerations
The crew's meal can be taken during the flight, even if it is a short leg[6]. The operation manual describes the procedure to follow in case of entry into a zone of severe turbulence:

• SEAT BELT ON
• CC ALERTED
• AP ON
• IAS/MACH SELECTED
(cf. recommended speed)
• A/THR OFF
• N1 AJUSTED
(cf. N1 required)

The recommended speed in a turbulent atmosphere depends on the level and is listed in a QRH table. At FL270, it is 275 kt. The N1 required to maintain the recommended speed is on the same table.

► Arrangement of the cockpit and the cabin
The flight bag, which had been secured before the flight behind the co-pilot's seat, did not move during the turbulence. However, the meal trays placed on the bag as well as the manuals placed in metal boxes flew around during the turbulence. The co-pilot's headset, hanging on its hook, was broken by falling objects.

Lessons learned

► Forecast
The TEMSI EUROC chart in the flight dossier mentioned cumulonimbus on the route, but these were not present on the first round trip. The crew stayed with this assumption without considering the sometimes rapid considering evolutions in storm phenomena.
► Vigilance during the flight
The crew's attention was not drawn to the possible presence of cumulonimbus in cruise. Priority was given to making up the lost time by the choice of a high Mach speed[7]. Bearing in mind the short duration of the flight, the crew was busy with activities (meal, reprogramming the FMGS) which did not encourage surveillance of meteorological phenomena on the radar or outside.

► Cabin safety
The failure to secure a part of the documentation in the cockpit created a risk for people and equipment in case of severe turbulence. The cabin crew, during the meal service, did not have time to secure the equipment and sit down. Since then, the operator has added a procedure in case of severe unpredicted turbulence that allows cabin crew to block the equipment on the spot, sit down on the nearest seat and fasten seatbelts.

[6] The total planned flight time at 340 kt was 48 minutes, of which twenty in cruise

[7] The operator's instructions for making up lost time require accelerating without suggesting any restrictions linked to environmental conditions.

Severe turbulence at the edge of cumulonimbus

History of flight

► Preparation
A Beech 1900D was performing a flight between Lyon and Angoulême at the end of the day, during July. The crew had a flight dossier including:

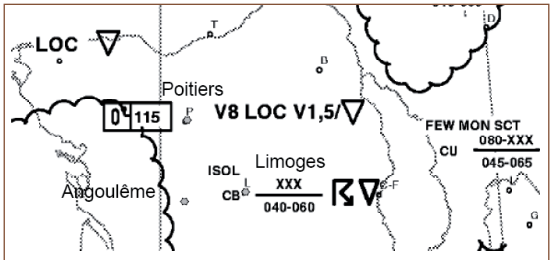
- the TEMSI EUROC chart, valid two hours before the incident, that forecast for the whole route and on arrival, cloud cover with isolated cumulonimbus (base 4,000 to 8,000 ft, tops FL300 to FL360) ;

- the charts of forecast winds that were from the southern sector, below 30 kt up to FL180 and about 50 kt above. The meteorological conditions forecast on arrival were good with, temporarily, the possibility of storms associated with isolated cumulonimbus in the midst of the cloud layer. There was enough fuel on board for forty minutes holding and a diversion to Poitiers.

► Cruise and approach
The co-pilot was PF. The weather radar was on and some course alterations were made in cruise at FL200 to avoid isolated storm cells. The meteorological conditions transmitted by the AFIS agent twenty minutes before arrival were:
wind from 300° / 12 to 15 kt and visibility over 10 km, with presence of cumulonimbus at 5,000 ft, with no precipitation. While the airplane was beginning final approach to runway 28, a very active storm cell coming from the southwest reached the aerodrome. The wind turned rapidly to 220° and strengthened with gusts. The AFIS agent informed them of a lightning strike on the aerodrome. At 4 NM on final, the wind broadcast was 220° / 30 to 45 kt. The crew anticipated the procedure in case of wind shear.

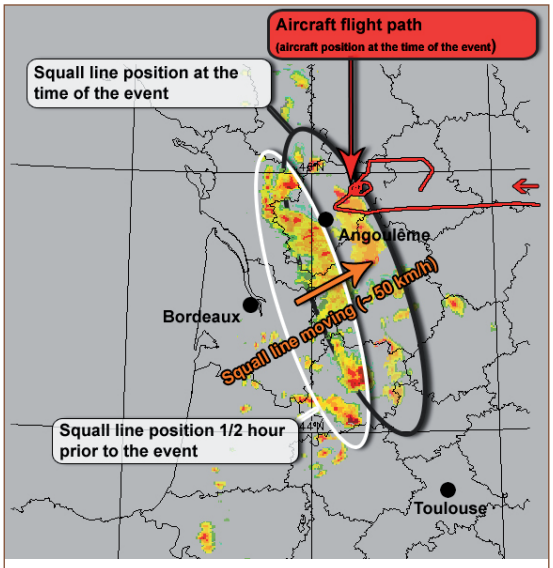
► Go around and hold
Taking into account the turbulence and the cross wind that exceeded the airplane's landing limitation (22 kt) the Captain took over the

controls and performed a go around at about 400 ft. When the AFIS agent announced gusts up to 55 kt, he followed a different route than that of the published go-around, in the opposite



Extract from the TEMSI chart

direction from the storm cell and climbed towards 5,000 ft so as to increase the safety margin in relation to the high ground (8). The crew flew to the northeast of the aerodrome



Overlay of two radar meteorological images taken at a 30 minute interval and the radar track of the airplane.

to review the meteorological situation and by manoeuvring to stay out of the clouds. These manoeuvres were performed with the AP in hold configuration at 150 kt, in a calm atmosphere. The crew took the decision to divert towards Limoges, located fifteen minutes flying to the east, and then retracted the flaps. In a turn to the right, the airplane then entered an area of severe turbulence that lasted 2 min 30 s.

The PF disengaged the autopilot. The altitude increased up to 6,200 ft before dropping towards 4,000 ft in one minute then increased up to 5,500 ft; the indicated speed varied between 160 kt and 250 kt (VMO); vertical acceleration moved between -0.3 g and +1.9 g (9). Bank angle twice reached 42° to the right with pitch values of 10° nose down.

Additional information

► Meteorology

Forecasts
The forecasts mentioned the risk of storms. The phenomenon developed rapidly, leaving no time to amend the meteorological information. A SIGMET indicating Cb in the midst of the cloud mass had been issued but crew did not get it. This information appeared, in addition, on the TEMSI chart[10]. The development of the squall line was not in contradiction with the information supplied.

Ground observations
The satellite images, the precipitation radars and recording of the lightning strikes underline the intensity of the phenomena.

Use of onboard radar
During the approach, the crew saw the position of the storm cells on the onboard weather radar. It was thanks to this information that the holding area was selected. However, during the manoeuvres to stay out of the clouds and in the dark, use of the radar was problematic because it did not make it possible to see the areas not in front of the airplane and its image was unusable during turns due to the tilt of the antenna.

Lessons learned

The environmental parameters for an approach performed in stormy conditions can deteriorate very rapidly. The approach was aborted due to these phenomena. The initially appropriate choice of the holding area was not updated. After some minutes, the very active storm cell that had led to the go around at Angoulême reached this area. The turbulence suffered by the airplane was directly linked to this cell. The smooth configuration of the airplane at time of the turbulence made it possible for it to remain within the flight envelope, which is greater than that with flaps extended.

(8) The MSA in the sector is 2,800 ft.

(9) The airplane is certified between -2.0 g and +3.0 g in smooth configuration

(10) The ISOL notation associated with the presence of Cb signifies that up to 50% of the area can be affected.

Severe clear air turbulence

History of flight

In February, an A340 took off from Paris Charles de Gaulle bound for the United States. Over Greenland, the crew of a US Air force airplane, in cruise at FL350, reported severe clear air turbulence on the HF frequency[11]. Six minutes later the A340, in cruise at FL320 in the same area, around 45 W, encountered severe turbulence. The Captain put on the « Fasten seatbelts » sign and made the turbulence announcement for the cabin crew. The severe turbulence lasted about five minutes, during which a passenger injured his arm, and then diminished progressively. A doctor who was present on board gave first aid assisted the cabin crew. Considering the general condition of the passenger and the doctor's advice, the Captain decided not to divert. At the end of flight, the Captain mad an oral report to the technical staff without mentioning the turbulence in the log. A mechanic made a detailed visual examination of the airplane. No reference to the AMM was put in the log.

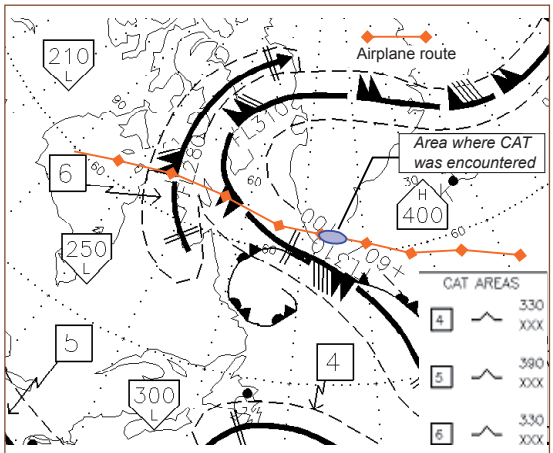
Additional information

► Meteorological situation

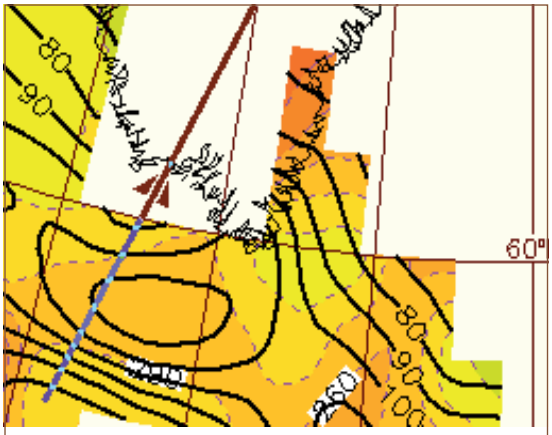
On the route, the situation was as follows:

- the north Atlantic had two depressions, one centred over Hudson Bay extending with a trough to the north of Newfoundland turning towards the Azores and the second centred over the Gulf of Gascony.
- between these two depressions, a narrow but powerful wedge[12] forced warm air beyond the polar circle from Greenland to Norway.
- this situation, quite unusual at this time of the year and at this latitude, generated a 120 kt jet stream oriented SSE/NNW to the south of Greenland.

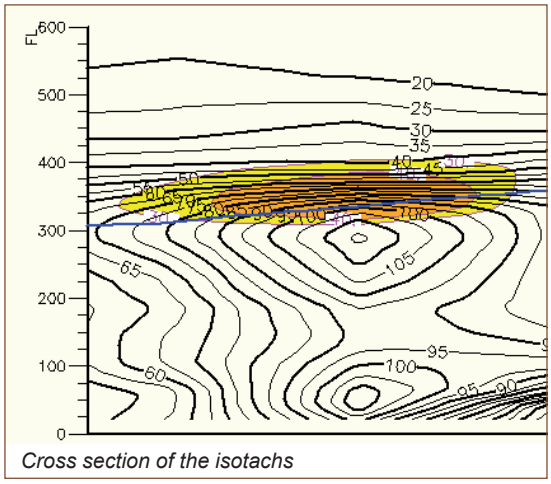
The cross section of the atmosphere, perpendicular to the jet stream shows a tightening of the isotachs towards the top, the hot air forcing the upper cold air. This tightening, located between FL300 and FL400 generated a vast area of clear air turbulence.



Extract from the TEMSI chart available to the crew



Horizontal position of the isotachs (the brown line corresponds to the axis of the cross section below)



Cross section of the isotachs

► Meteorological forecast

The situation described above was forecast ten hours before take-off by the French Arpège forecast model. However, the TEMSI chart supplied by the WAFS world centre in England indicated moderate turbulence in this area. The following was noted in the flight dossier: «area of CAT MOD from 45 W to 78 W then nothing notable on the rest of the route ». Only one air report (AIREP) concerning this turbulence was received by the ATC.

►Flight data

The « Fasten seatbelts » sign was used three times before the area of the event. Eighteen minutes before the event, the wind strength went progressively from 60 kt to 120 kt, and then dropped by 100 kt in two minutes.

Simultaneously the wind direction varied from southeast to southwest. A first acceleration of +1.5 g brought the warning sign on. A series of accelerations varying between +1.96 g +0.26 g was then recorded over five minutes. More moderate turbulence continued for an hour and

[11] *Civil crews do not monitor HF frequencies, so this message towards ATC was not heard by the crew of the A340. The controller asked them twelve minutes later if they had encountered any turbulence and a SIGMET message was issued subsequently.*

[12] *Between 20° W and 30° W with a gradient of 3 °C per 1,000 ft between FL300 and FL340. The tropopause was at FL385 at a temperature of -66 °C.*

twenty minutes. The autopilot and the autothrust (ATHR) remained active throughout this phase of flight. The Mach selected of 0.81 in cruise was reduced, first to 0.784 then to 0.776 until the end of the turbulence. The speed (CAS) varied between 256 kt and 308 kt.

► Procedures in a turbulent atmosphere
The recommended mach or speeds for penetration into turbulence are defined so as to ensure the lift required at the load factors caused by vertical gusts, while limiting the structural constraints as much as possible. In case of moderate turbulence, the procedure specifies maintaining autopilot and reducing speed to a value greater than the recommended speed. When the turbulence is severe, it is recommended to de-activate the ATHR and drop the speed below the recommended value (280 kt at level FL 320). The table in the onboard documentation is given in indicated airspeed up to FL350 and in Mach above that.

Lessons learned

► Choice of the route and updating meteorological information
Crossing a jet stream perpendicularly to the forecast position of the latter on the TEMSI chart could lead to the supposition of a turbulence encounter, even if the centre of the jet stream has a laminar flow. The airplane penetrated the turbulent area downwind. In fact, the forecast on the position of the jet stream was relatively imprecise. The airplane suffered significant acceleration, its speed increasing by 60 kt, immediately lost when penetrating the CAT zone at the top of the jet stream. The wind shear suffered was proportional to the temperature gradient[13]. Information on forecasts for the area and the intensity of the turbulence could not alert the crew with any precision[14]. Only the AIREP message transmitted by the American crew could have done so, but it was not re-transmitted in time. The crew did not however transmit this type of message themselves. Rules of the air define the rules applicable to the transmission of AIREP's. SIGMET's can then be issued on this basis.

► Conduct of flight in turbulent atmosphere
The pilot selected a Mach number, and not a speed, in accordance with the instructions in moderate turbulence, which led to speeds above the recommended speed (308 kt maximum) without, however, approaching VMO[15]. These actions were not sufficient in face of the strength of the turbulence that was in fact encountered.

► Inspection of the airplane
The pilot did not write up the severe turbulence in the log. He was not aware, at that time, of the accelerations that the airplane was subjected to. From its side, the airline's operations control centre did not possess the means to instantly access the technical flight data for this airplane. In the absence of acceleration data, a check of the airplane was only superficial and the procedure in the AMM was not applied.

[13] Variation of 10 °C in about a minute.

[14] According to the message in the flight dossier the CAT zone extended over 900NM on the planned route.

[15] The conditions being such that the tropopause, very high in this area at this time of the year, made it possible to keep a sufficient margin with the maximum speed in operation.

Summary

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