RNSA

Rannsóknarnefnd samgönguslysa

Final report on aircraft serious incident

Case no.: **23-016F005**

Date: **13. February 2023**

Location: **North of the Langjökull glacier, Iceland**

Description: **Uncontrolled descent**

ÍSLENSK SAMANTEKT

Flug TK0018 lenti í alvarlegri ókyrrð á flugi í fluglagi 350 norðan Langjökuls, Íslandi. Rannsóknin leiddi í ljós að þegar flugvélin lenti í ókyrrðinni, vegna háloftafjallabylgna, þá fór hún í óeðlilega flugstöðu. Viðbrögð flugáhafnarinnar við ókyrrðinni juku á óeðlilega flugstöðu flugvélarinnar. Flugvélin svaraði öllum aðgerðum flugáhafnarinnar.

Gervitunglamyndir og önnur veðurgögn leiddu í ljós að háloftafjallabylgjur höfðu verið til staðar yfir Íslandi í margar klukkustundir áður en flugvélin lenti í atvikinu. Ekkert SIGMET[1] hafði verið gefið út, sem varaði við miklum háloftafjallabylgjum yfir Íslandi fyrir flugatvikið. Fjórum mínútum eftir að TK0018 lenti fyrst í ókyrrðinni, var SIGMET M01 gefið út, sem varaði við miklum háloftafjallabylgjum yfir Íslandi, en þó ekki á því svæði þar sem atvikið varð. Um 40 mínútum eftir atvikið, gaf Veðurstofa Íslands út SIGMET M02, þar sem fjallabylgjusvæðið var stækkað og upplýsti um sterkar fjallabylgjur á svæðinu.

Sem viðbrögð við atvikinu, sem varði í um 80 sekúndur, þá voru í nokkur skipti hröð, en greinileg, inngrip á stýri, ásamt miklum breytingum á knýj, á meðan flogið var í ókyrrðinni og ofrisviðvörun með titringi stýris virkjaðist í fjögur skipti. Átti flugáhöfnin í vandræðum með að hafa stjórn á flugvélinni. Sjálfstýringin og sjálfvirka eldsneytisgjöfin voru báðar á fyrir ókyrrðina, en stórt inngrip á stýri varð til þess að sjálfstýringin fór af. Flugmennirnir tókust óafvitandi á um stjórn flugvélarinnar, þar sem aðstoðarflugmaðurinn ýtti stýri sínu fram á meðan flugstjórinn togaði stýri sitt að sér. Andstæð inngrip aðstoðarflugmannsins og flugstjórans urðu til þess að stýri þeirra aftengdust. Flugáhöfnin tók á breytilegum aðstæðum án þess að taka af sjálfvirku eldsneytisgjöfina. Varð þetta til þess að báðir flugmennirnir og sjálfvirka eldsneytisgjöfin tókust á um stjórn flugvélarinnar. Flugvélin missti um 8000 feta hæð á um einni mínútu, þar sem hæsti fallhraði hennar var allt að 17.100 fet á mínútu. Sjö einstaklingar slösuðust í atvikinu.

Orsök atviksins var rakin til skorts á ástandsvitund og samvinnu flugáhafnar í viðbrögðum við upphaflegu ókyrrðinni sem flugvélin varð fyrir.

[1] Significant Meteorological Information.

SUMMARY

Flight TK0018 encountered severe turbulence when flying at FL350 north of the glacier Langjökull in Iceland. The investigation revealed an upset to the flight, when the aircraft encountered the turbulence, due to high-altitude mountain waves. The flight crew's response to the momentary turbulence encounter exacerbated the upset condition. The aircraft responded to all inputs by the flight crew.

Satellite images and other weather data revealed that high-altitude mountain waves had existed over Iceland for many hours prior to the incident. There were no SIGMETs in effect, warning of high-altitude severe mountain waves over Iceland prior to the incident. Four minutes after flight TK0018 encountered the upset condition, SIGMET M01 was issued. SIGMET M01 warned of high-altitude severe mountain waves over Iceland, but it did not incorporate the area where the incident occurred. About 40 minutes after the severe turbulence encounter, the Icelandic MET Office (IMO) issued SIGMET M02 where the mountain wave area was enlarged and to notify that severe mountain waves had been observed within the area.

As a reaction to the flight upset, which lasted for about 80 seconds, there were several moments of rapid, sharp, control column inputs, and large thrust changes during the period of turbulent flight and four stick shaker situations occurred. The flight crew struggled to control the lateral and vertical path simultaneously. The autopilot and the autothrottle were engaged leading up to the turbulence encounter, but large control column inputs led to the autopilot disconnecting. A force-fight between the flight crew ensued, with the First Officer (Pilot Flying) pushing on the control column and the Captain (Pilot Monitoring) pulling on the control column. The opposite control column inputs by the First Officer (PF) and the Captain (PM), caused the two control columns to breakout from each other. The flight crew reacted to changing conditions, without deactivating the Autothrottle (A/T). This resulted in the pilots and the autothrottle fighting each other over control of the aircraft. The aircraft lost close to 8000 ft of altitude in approximately one minute, with the highest rate of descent being 17,100 feet per minute. Seven people were injured during the upset condition of the flight.

The cause of the incident was due to a loss of Situational Awareness and a breakdown in Crew Resource Management in response to an initial turbulence encounter.

Table of Contents

1. FACTUAL INFORMATION

Location and time	
Location:	North of the Langjökull glacier between FL350 and FL270 starting at 64° 56' 27.744'' N and 20° 23' 10.788'' W
Date:	13. February 2023
Time[2]:	08:09

Aircraft	
Type:	Boeing 777-300ER
Register:	TC-JJJ
Year of manufacture:	2011
Serial number:	40710
CoA:	Valid
Engines:	Two GE90-115B1L

Other information	
Type of flight:	Commercial flight
Persons on board:	280
Injury:	Two passengers and five crew members
Damage:	Minor damage to aircraft interior parts
Short description:	The flight incurred severe turbulence resulting in an upset condition of the flight

[2] All times in the report are Icelandic local times (UTC+0), unless otherwise stated.

1.1. History of the flight

On 13th of February 2023, a Boeing 777-300ER aircraft, registered as TC-JJJ, was flying enroute from Toronto (CYYZ) to Istanbul (LTFM) under the flight number TK0018.

At 08:09 UTC, when at FL350 north of the glacier Langjökull in Iceland, the aircraft encountered severe turbulence.

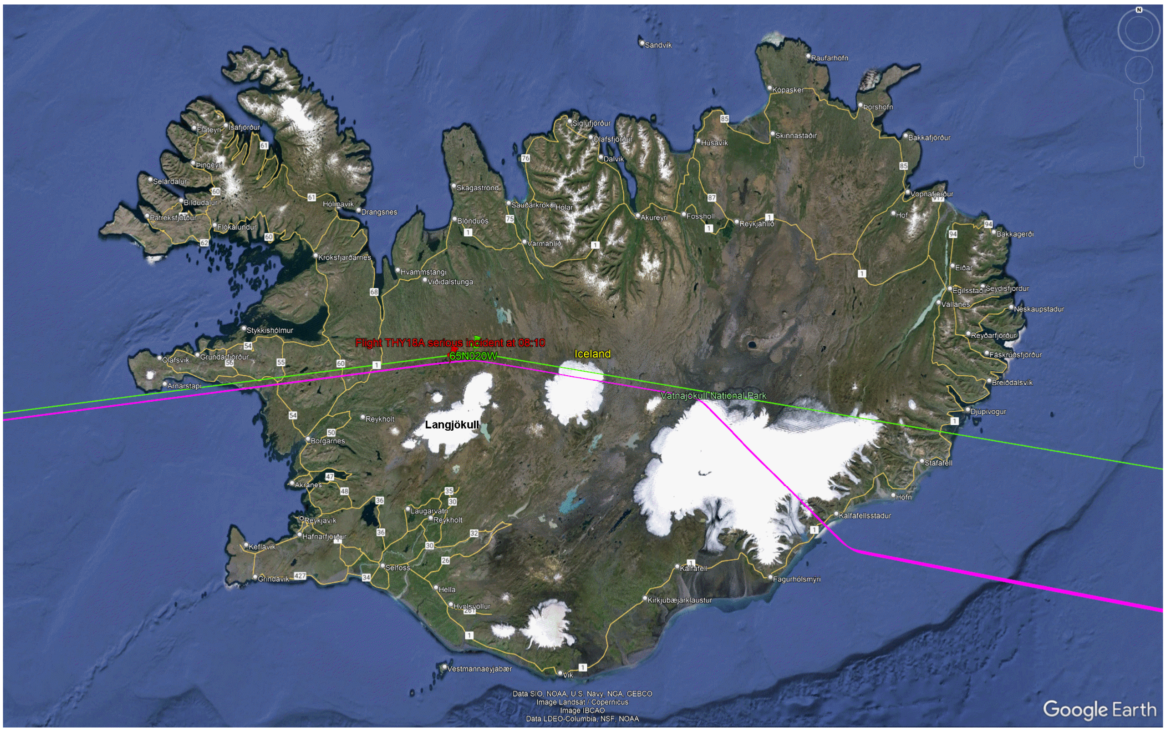

Figure 1: Serious incident occurred when at FL350 north of the glacier Langjökull (green line is the planned route and the magenta line is the actual flight track).

There were three pilots on the flight crew, two Captains and a First Officer, because the length of the flight required a relief pilot (augmented flight crew). One of the Captains, who was also the Commander of the flight, was resting and not on the flight deck when the aircraft encountered the turbulence. The Captain, occupying the left seat, was the Pilot Monitoring (PM) and the First Officer was the Pilot Flying (PF).

According to the flight crew, they were flying along their planned route in Reykjavik CTA[3] when the airplane encountered severe turbulence. The flight crew had expected light turbulence in this area and had therefore turned the seatbelt sign ON, about 10 min before encountering the severe turbulence.

The turbulence encounter resulted in an aircraft upset condition, with an extremely low pitch angle and high rate of descent. The flight crew struggled to control the lateral and vertical path simultaneously and the aircraft lost close to 8000 ft of altitude in approximately one minute, with the highest rate of descent of 17,100 feet per minute. The airspeed increased beyond the airspeed limit. This occurred regardless of the flight crew‘s effort to keep the airspeed within its limit. During the upset, multiple stick shaker activations occurred. The aircraft’s lowest altitude was FL273.

The flight crew regained control of the aircraft and then maintained FL280, still in light turbulence, for a short time and then started climbing. They scanned the instruments for any anomalies within the aircraft systems.

At 08:13, the aircraft re-encountered turbulence.

When the turbulence conditions had improved and conditions permitted, the Commander of the flight re-entered the flight deck. The Commander sat down in the observer’s seat and at 08:15 communicated with ATC, where the following PAN-PAN message was transmitted:

> “Reykjavik Turkish 18Alpha – PAN-PAN, PAN-PAN, PAN-PAN, severe turbulence, we cannot maintain level, descending 290 now passing 300.”

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[3] Control Area.

The Commander then replaced the Captain in the left seat and took over as the Pilot Flying.

After that the flight crew talked to the cabin chief to inquire about any damage and injuries in the cabin. No one was seriously injured, although a few passengers and cabin crew members had incurred minor injuries and were under the supervision of a medical doctor, travelling as a passenger on the flight. After discussing the possibility of diverting the flight to either Glasgow Airport (EGPF) or Copenhagen Airport (EKCH) as well as consulting with IOCC[4], the decision was made to continue the flight to Istanbul Airport (LTFM), where a request for ambulances for the injured was made to ATC.

1.2. Injuries to persons

Two passengers and five cabin crew members were injured and sent to hospital, after landing in Istanbul.

1.3. Damage to aircraft

Two passenger oxygen units became unserviceable, an armrest broke, forward and aft galley lights became unserviceable, and some wall panels were found damaged.

No structural damage was found to the aircraft.

[4] Integrated Operation Control Center of the flight operator.

1.4. Personnel information

Commander / Captain	
Certificate:	ATPL (A)
Ratings:	B777/787 IR TRI, TRE
Medical Certificate:	Class 1, valid
Experience:	

Total flight hours:	20,174
Total flight hours on type:	7253
Commander on B777:	5743
Last 90 days on type:	168:58
Last 24 hours on type:	9:51

Pilot Monitoring / Captain	
Certificate:	ATPL (A)
Ratings:	B777/787 IR
Medical Certificate:	Class 1, valid
Experience:	

Total flight hours:	10,986
Total flight hours on type:	2154
Commander on B777:	2112
Last 90 days on type:	213:00
Last 24 hours on type:	9:51

Pilot Flying / First Officer	
Certificate:	CPL (A) [with ATPL theory credit]
Ratings:	B777/787 IR, P6 Line Flying Under Supervision
Medical Certificate:	Class 1, valid
Experience:	

Total flight hours:	1128
Total flight hours on type:	38
Last 90 days on type:	37:51
Last 24 hours on type:	9:51

1.5. Meteorological information

The following SIGMET U01, applicable to BIRD – Reykjavik FIR, was available in the flight documents:

Mon Feb 13 00:10:07 2023
TZA018 130010
FF BIRDZQZZ BIRKZTZZ
130010 BIRKYMYX
WSIL31 BICC 130000
BIRD SIGMET U01 VALID 130030/130430 BIRK-
BIRD REYKJAVIK CTA SEV TURB FCST WI N6400 W01400 - N6230 W02135 -
N6540 W02640 - N6730 W02050 - N6400 W01400 SFC/FL100 STNR NC=

The following weather charts were available in the flight documents:

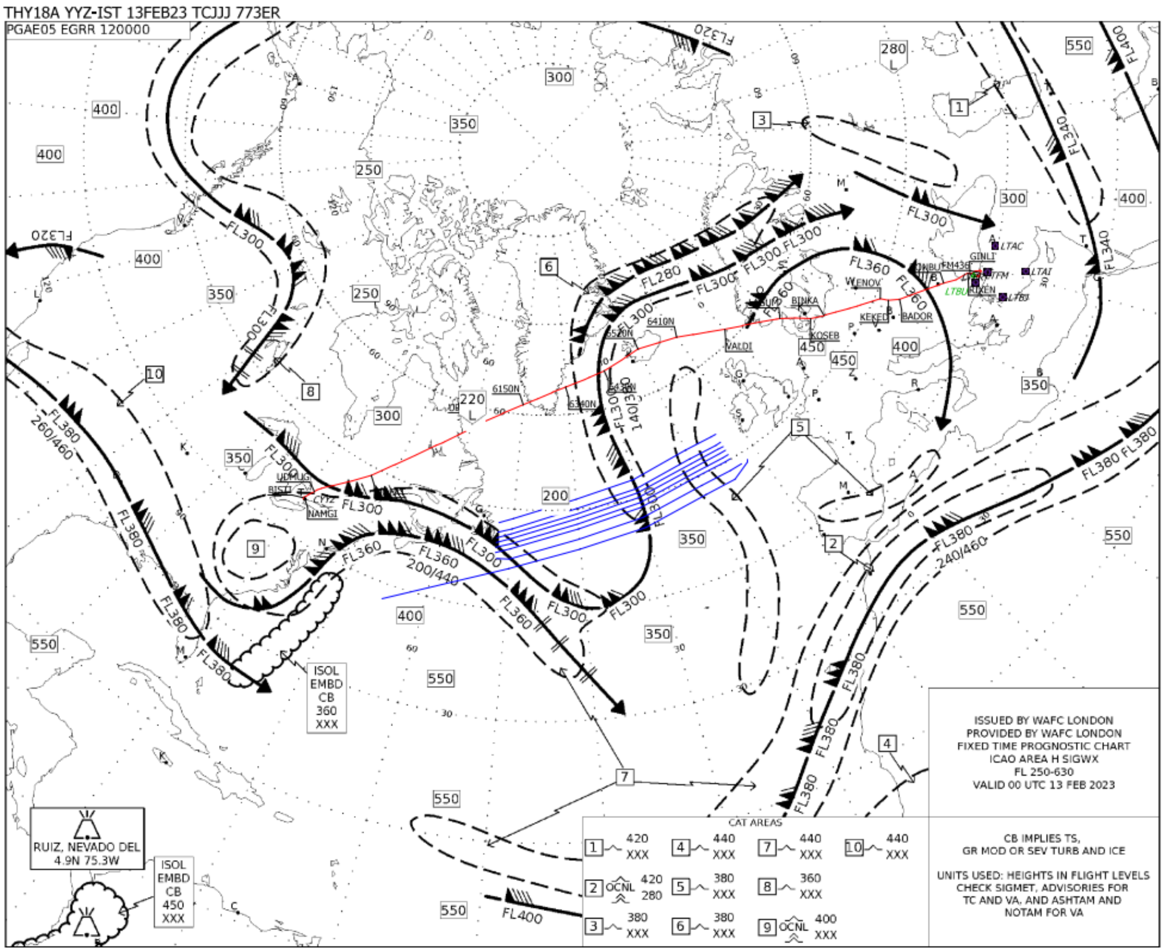


Figure 2: Prognostic chart SIGWX FL250-630 valid at 00 UTC 13. February 2023.

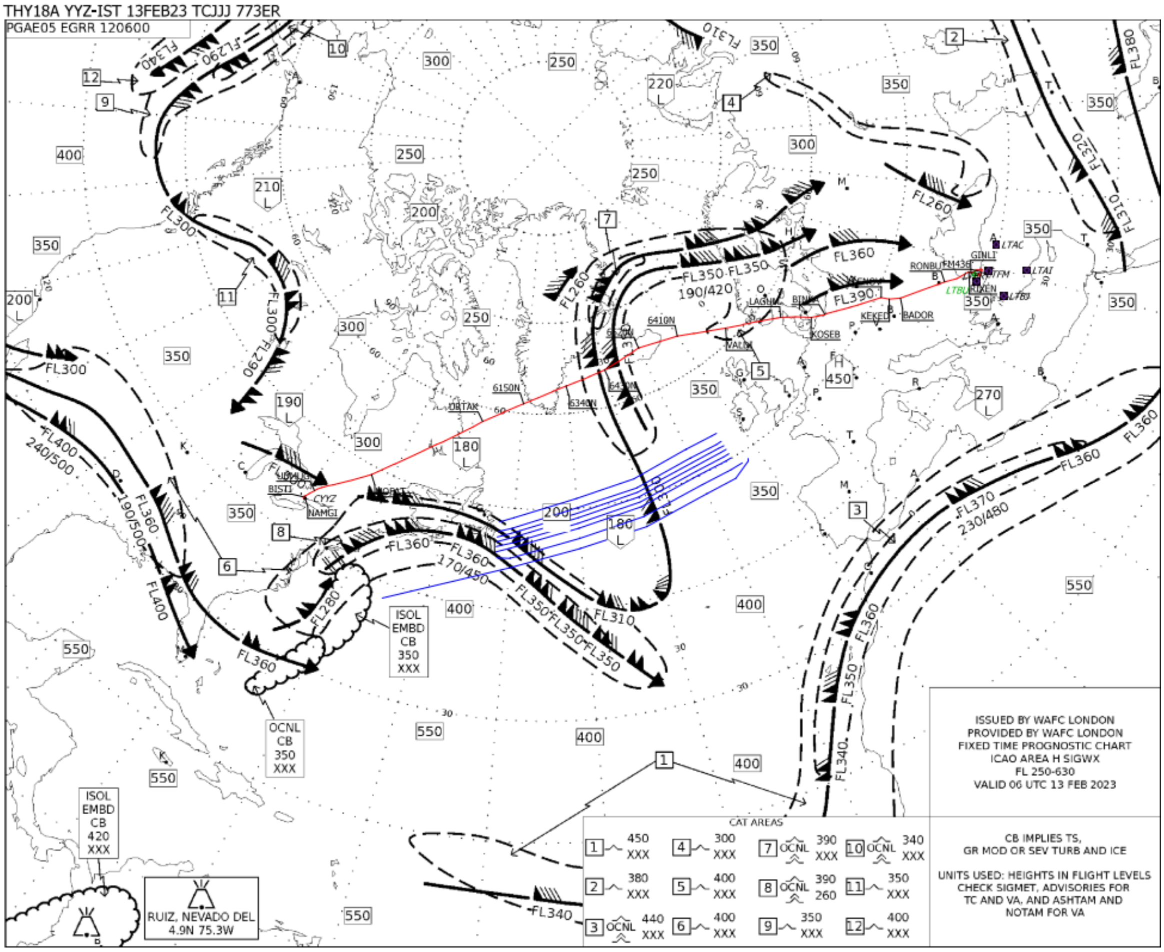


Figure 3 Prognostic chart SIGWX FL250-630 valid at 06 UTC 13. February 2023.

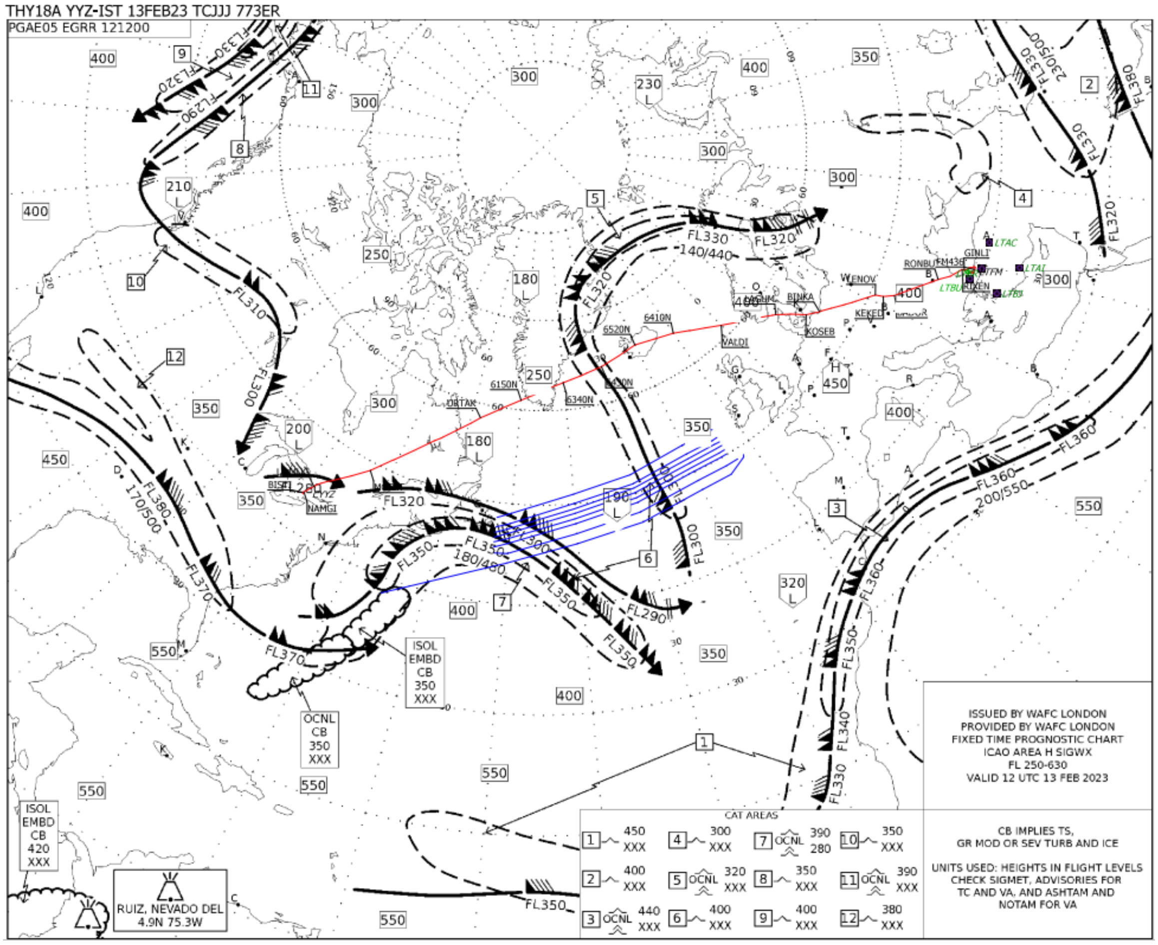


Figure 4: Prognostic chart SIGWX FL250-630 valid at 12 UTC 13. February 2023.

1.6. Flight recorders

The Cockpit Voice Recorder (CVR) recording of the event was not preserved, as the flight was continued to Istanbul and the 120-minute recorder storage capability was exceeded. The Flight Data Recorder (FDR) recordings of the event were available after the flight, and they were used to analyze the serious incident.

2. ANALYSIS

2.1. Weather

The significant weather chart provided in the flight documents and valid at 06 UTC on 13. February 2023 in the North-Atlantic (see Figure 3 and Figure 5), indicated a forecasted moderate and occasionally severe turbulent region in the area north and northwest of Iceland between FL280 and FL390, about two hours before the serious incident occurred.

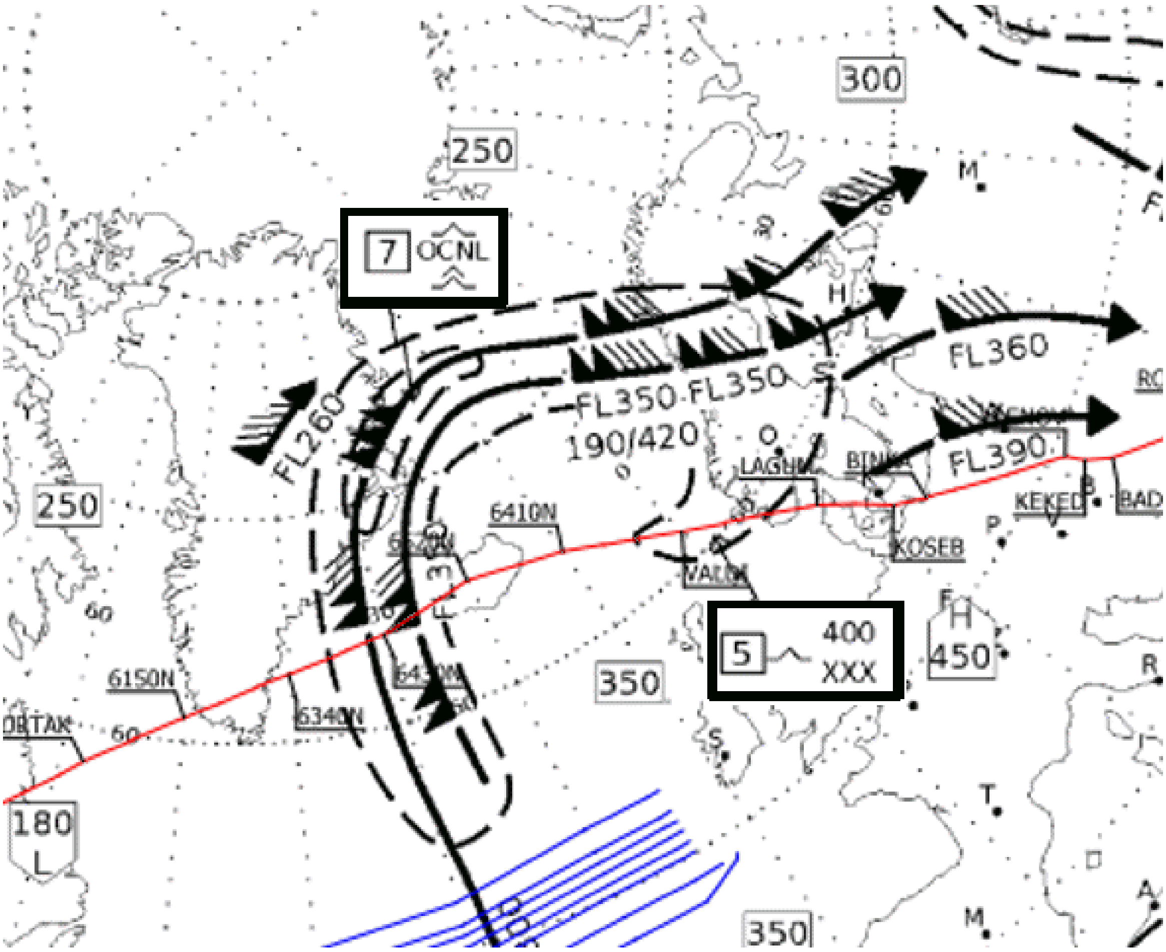


Figure 5: Forecasted weather in the North-Atlantic at 06 UTC 13 February 2023. Flagnote 5 indicates moderate turbulence and flagnote 7 indicates moderate and occasional severe turbulence.

Interviews that were conducted with the flight crew suggest that, during cruise briefings, the flight crew did not review or discuss this weather chart before or while entering the NAT area.

According to the following operator's documents for B777/787, during cruise briefings weather information (WX info) should have been reviewed.

CRUISE BRIEFING
➢ ALTIMETERS & RVSM LEVEL CHECK
➢ ENGINE & SYSTEM PARAMETERS
➢ ENGINE FAILURE & DRIFT DOWN PARAMETERS
➢ ETA & FUEL CALCULATIONS AND FUEL REQUIRMENT
➢ WX INFO, ENROUTE ALTERNATES
➢ CONTINGENCY & OPERATIONAL PROCEDURES IN FIRS

SIGMET U01, which was provided in the flight documents and previously shown in chapter 1.5, was a low level SIGMET, valid from the surface and up to FL100, for the region shown in Figure 6.

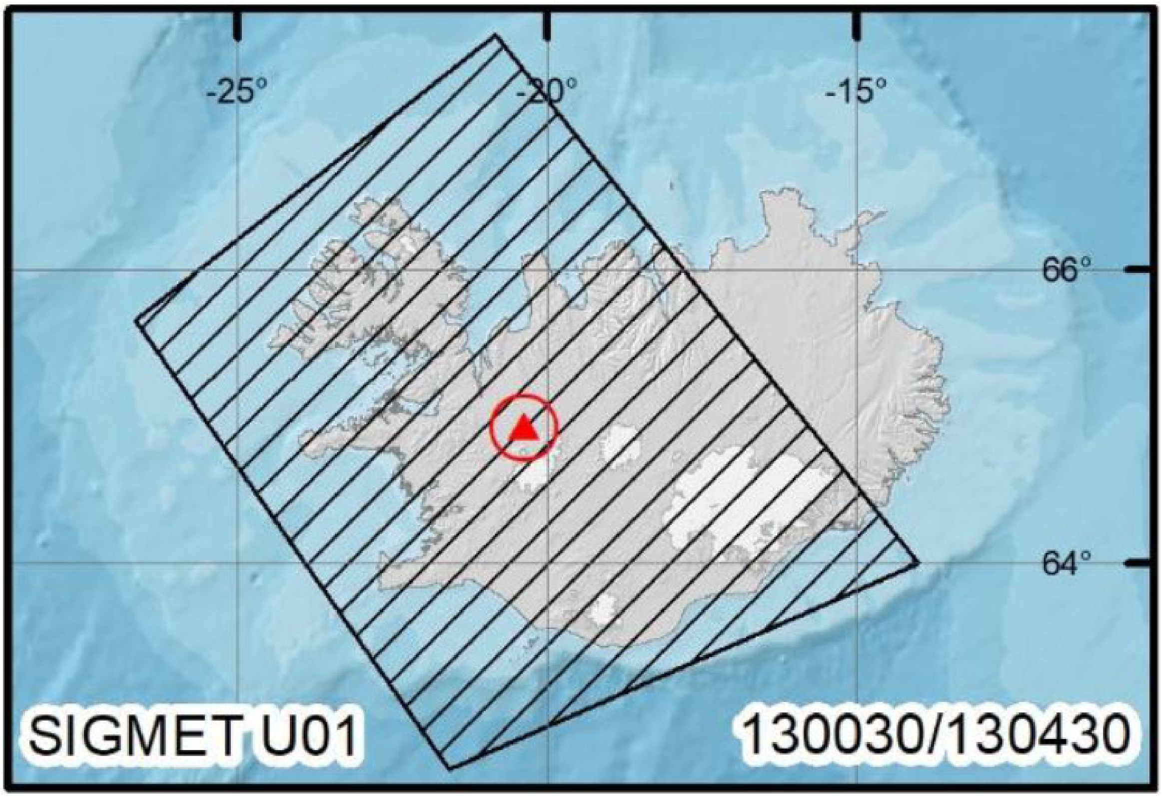


Figure 6: SIGMET U01 valid from ground up to FL100, where severe turbulence was forecasted. Red triangle marks the location of the serious incident. (Source: IMO technical report).

Subsequently during the flight at 04:04, 3 hours and 38 minutes prior to the aircraft encountering the severe turbulence, SIGMET U02 was issued, which indicated that a severe turbulence was forecasted up to FL100 in the area shown in Figure 7.

Mon Feb 13 04:04:56 2023
TZA235 130404
FF BIRDZQZZ BIRKZTZZ
130404 BIRKYMYX
WSIL31 BICC 130403
BIRD SIGMET U02 VALID 130430/130830 BIRK-
BIRD REYKJAVIK CTA SEV TURB FCST WI N6400 W01400 - N6230 W02135 -
N6540 W02640 - N6730 W02050 - N6400 W01400 SFC/FL100 STNR NC=

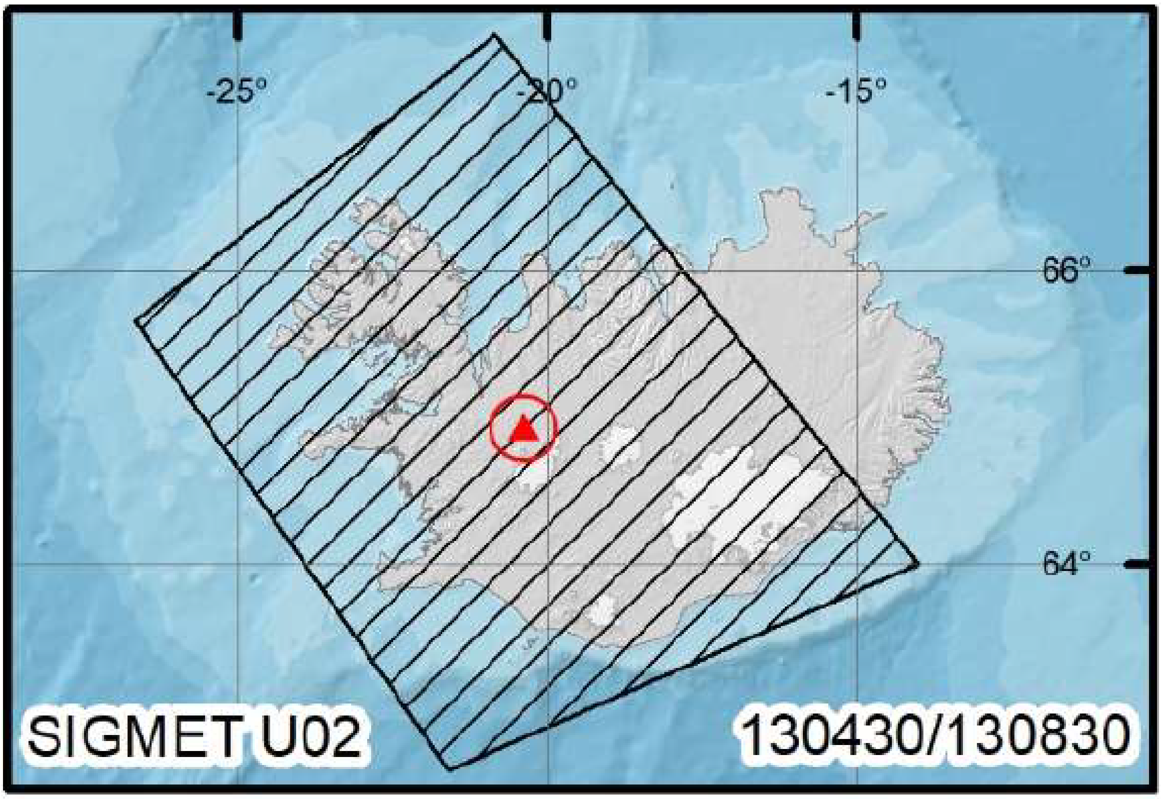


Figure 7: **SIGMET U02 valid from ground up to FL100, where severe turbulence was forecasted. Red triangle marks the location of the serious incident. (Source: IMO technical report).**

At 08:04, 5 minutes prior to the aircraft encountering the severe turbulence, another SIGMET U03 was issued, which indicated that a severe turbulence was forecasted up to FL120 in the area shown in Figure 8.

Mon Feb 13 08:04:32 2023
TZA613 130804
FF BIRDZQZZ BIRKZTZZ
130804 BIRKYMYX
WSIL31 BICC 130746
BIRD SIGMET U03 VALID 130830/131230 BIRK-
BIRD REYKJAVIK CTA SEV TURB FCST WI N6300 W02355 - N6630 W02520 -
N6640 W01255 - N6320 W01300 - N6300 W02355 SFC/FL120 STNR NC=

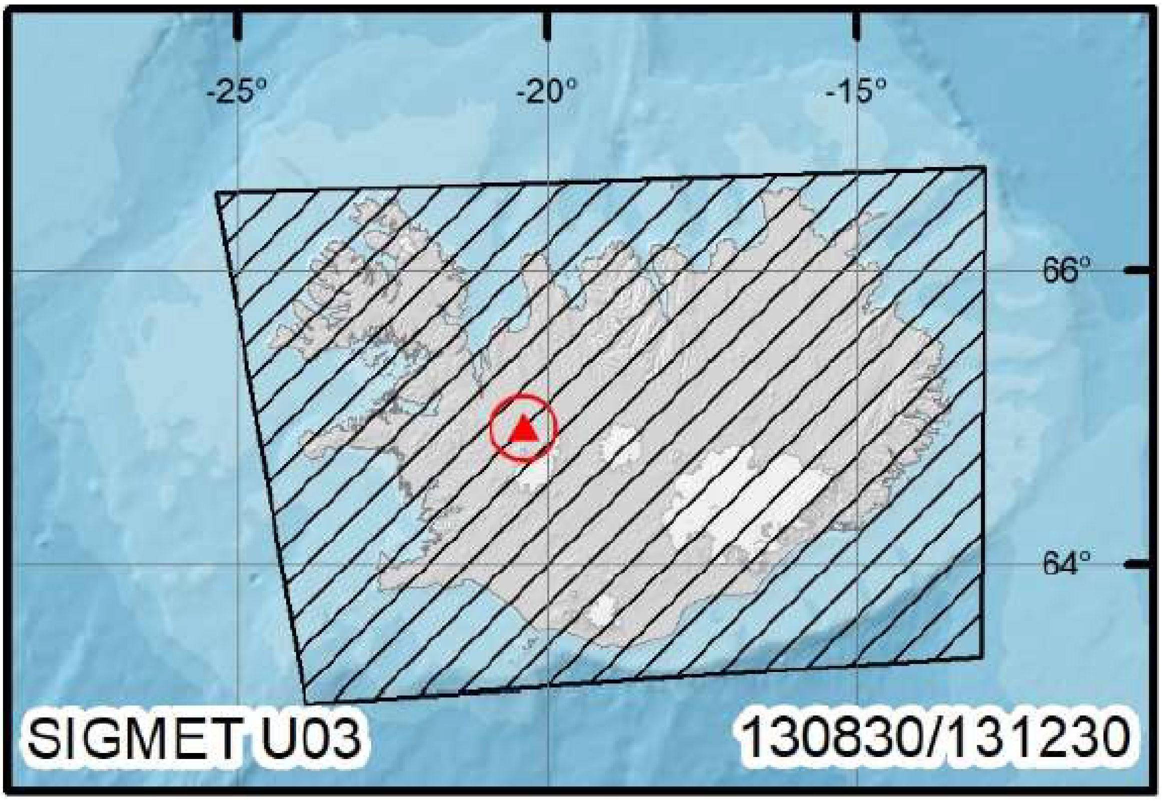


Figure 8: SIGMET U03 valid from ground up to FL120, where severe turbulence was forecasted. Red triangle marks the location of the serious incident. (Source: IMO technical report).

These two SIGMETs were not relayed to the flight crew via the Aircraft Communications Addressing and Reporting System (ACARS) during the flight, as they were not valid for the cruising altitude that flight TK0018 was flying at (FL350), while enroute over Iceland.

When the on-duty forecaster at the Icelandic MET Office had issued SIGMET U03 at 08:04, he then prepared and issued SIGMET M01 at 08:13, regarding severe mountain waves over Iceland. This was 4 minutes after flight TK0018 first encountered the severe turbulence.

SIGMET M01 took effect immediately and was valid for 4 hours, which is the maximum time period for a SIGMET to remain valid. SIGMET M01 was valid for FL300 to FL440, over a large area north of the Vatnajökull glacier.

Mon Feb 13 08:13:09 2023
TZA630 130813
FF BIRDZQZZ BIRKZTZZ
130813 BIRKYMYX
WSIL31 BICC 130804
BIRD SIGMET M01 VALID 130813/131213 BIRK-
BIRD REYKJAVIK CTA SEV MTW FCST WI N6440 W01920 - N6620 W01930 -
N6600 W01315 - N6420 W01440 - N6440 W01920 FL300/440 STNR NC=

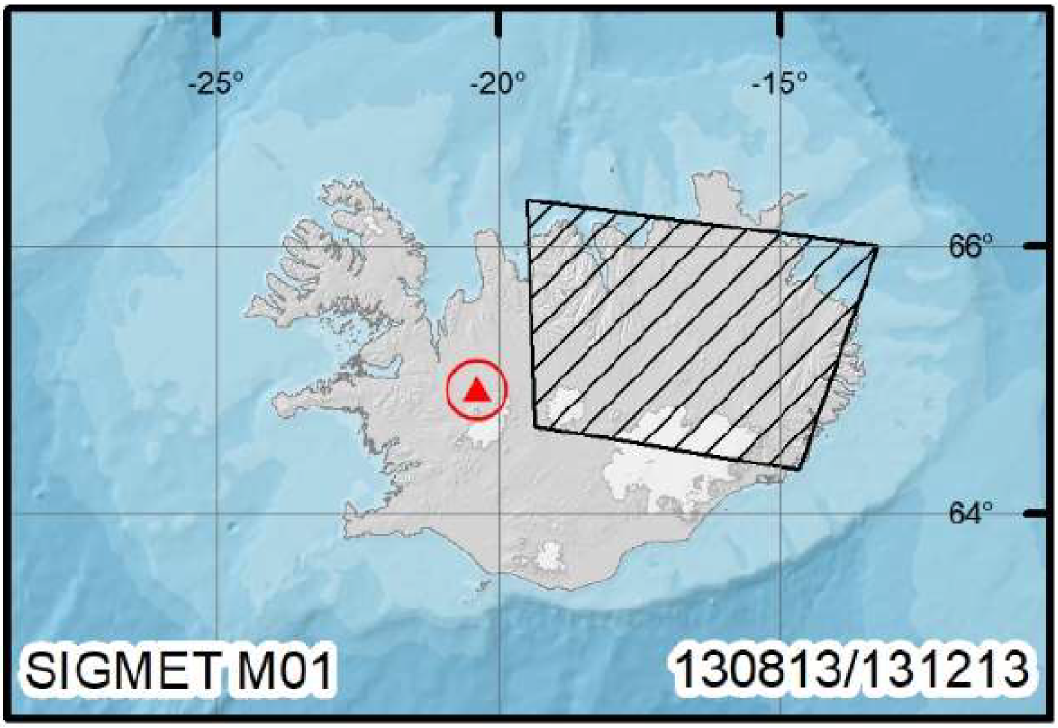


Figure 9: SIGMET M01 valid between FL300 and FL440, forecasting mountain waves. Red triangle marks the location of the serious incident. (Source: IMO technical report).

The flight track of flight TK0018 was north of the glacier Langjökull, or more precisely 18.5 km north of the glacier Eiríksjökull. The serious incident occurred at 08:09 at 64°56’27.744’’N and 20°23’10.788’’W, while the aircraft was flying at FL350 (see Figure 10).

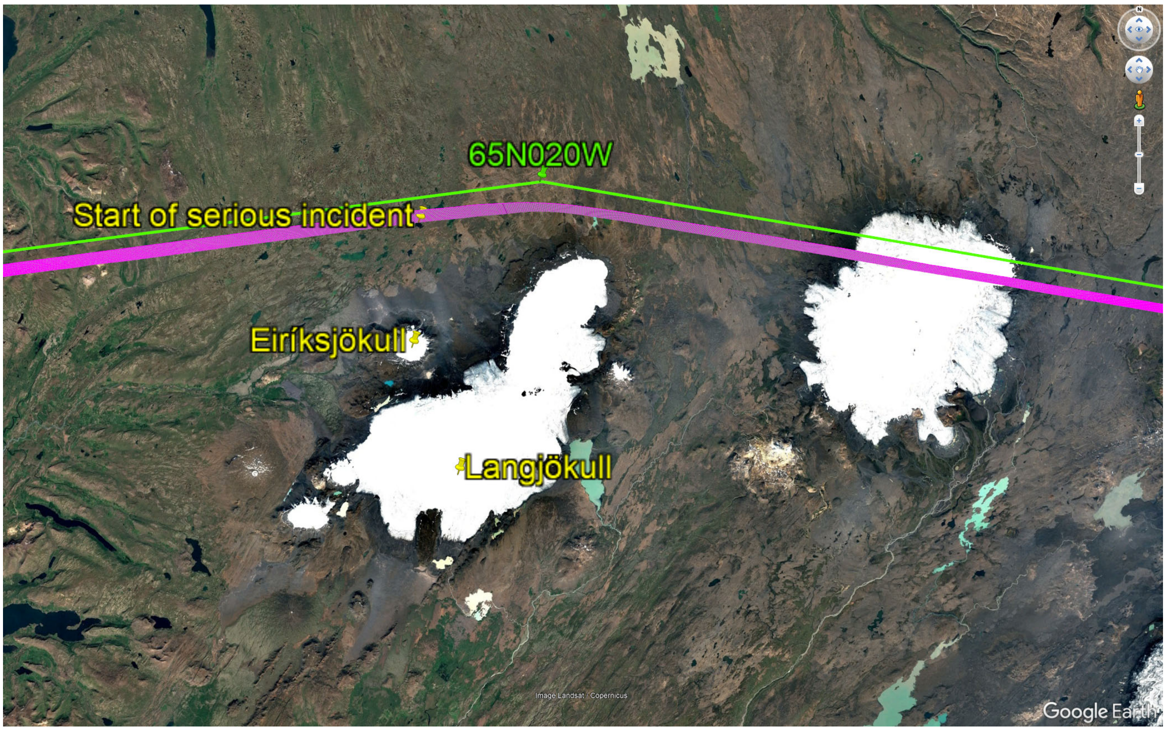


Figure 10: The flight plan (green line), the flight track (magenta color line) and the serious incident location, north of the glacier Langjökull.

At 08:18, during communication with the flight crew of flight TK0018, ATC advised that they had just received a SIGMET (SIGMET M01) for the area in which the flight was located (see Figure 9).

ATC then informed the flight crew, that if they would like to get out of the SIGMET area, ATC could vector them out of it. The flight crew accepted the vectoring and at 08:19 ATC vectored flight TK0018 to the right, out of the SIGMET area (see Figure 11).

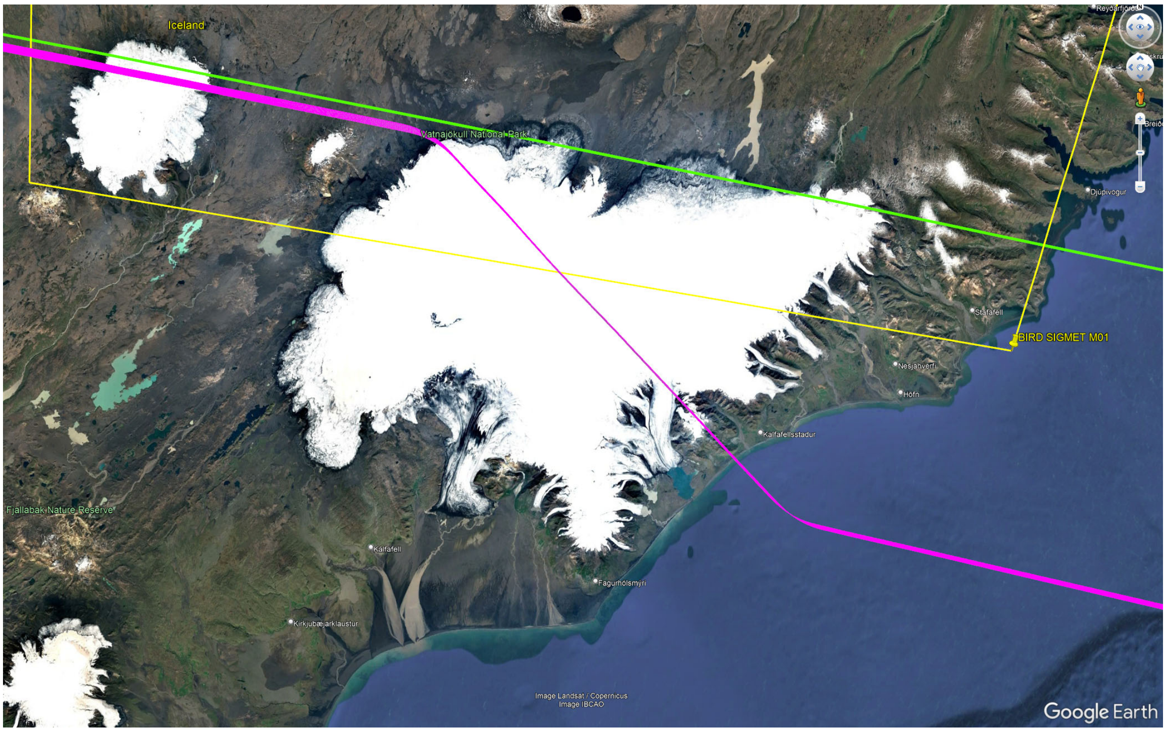


Figure 11: ATC vectors the flight out of the SIGMET M01 area, heading 150°, over the Vatnajökull glacier (magenta color line).

At 08:34 Isavia ANS called the on-duty forecaster at the Icelandic MET Office to inform him that an aircraft had encountered severe turbulence north of the Langjökull glacier (flight TK0018).

As the location of the severe turbulence encounter was not within the SIGMET M01 area, the meteorologist issued new SIGMET M02 at 08:49, where the mountain wave area was enlarged and a notification of observed severe mountain waves within the area was added (see Figure 12).

Mon Feb 13 08:49:07 2023
TZA695 130849
FF BIRDZQZZ BIRKZTZZ
130849 BIRKYMYX
WSIL31 BICC 130834
BIRD SIGMET M02 VALID 130848/131248 BIRK-
BIRD REYKJAVIK CTA SEV MTW OBS AT 0817Z WI N6330 W01920 - N6450 W02155 - N6640 W02205 - N6630 W01225 - N6450 W01330 - N6330 W01920 FL290/440 STNR NC=

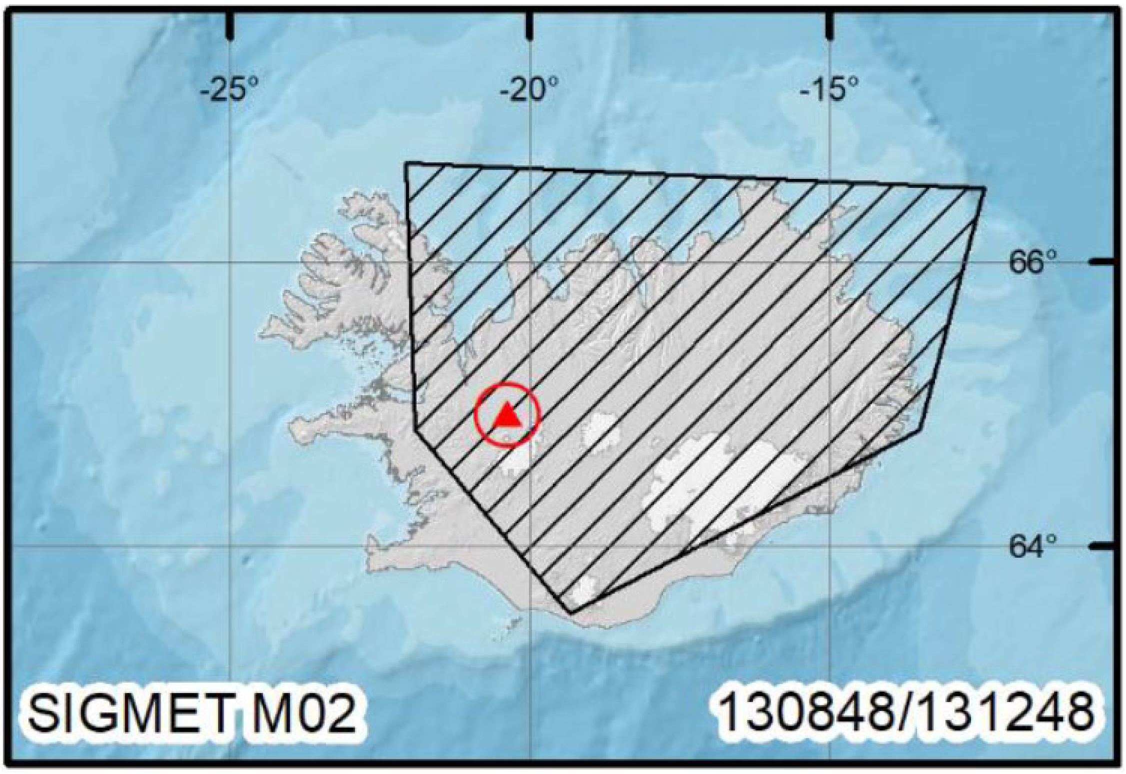
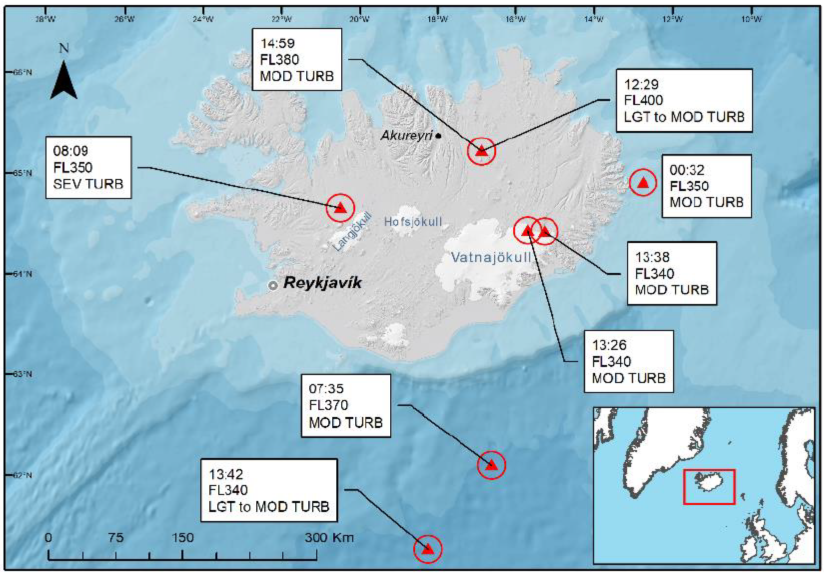


Figure 12: SIGMET M02 valid between FL290 and FL440, severe mountain waves observed. Red triangle marks the location of the serious incident. (Source: IMO technical report).



A few Pilot Reports (PIREPs) were received during the day of the serious incident, regarding turbulence in the Reykjavik FIR (BIRD) (see Figure 13).

Figure 13: Pilot's Reports (PIREPs) of turbulence in the Reykjavik FIR around the event (Source: IMO technical report).

The Icelandic MET Office issued an IMO technical report[5] to SIA-Iceland upon request of the Icelandic Safety Authority (SIA-Iceland)[6] analyzing the serious incident with regards to the weather on 13. February 2023.

Satellite images revealed that mountain waves had existed over Iceland since the day before the serious incident. The mountain waves were forming around 18:00 the day before, becoming more defined later during that evening, north of the glaciers in Iceland.

The highest peak of Eiríksjökull glacier is 5495 feet, while in the case of Langjökull glacier the highest peak is 4456 feet. At the time of the serious incident the wind was blowing from the south over these two glaciers before it reached the area where the serious incident occurred (see Figure 10). The sequence of the events, the data from the Flight Data Recorder (FDR) and the weather data from the time of the serious incident indicate that flight TK0018 (aircraft TC-JJJ) experienced severe turbulence due to a high-altitude mountain waves north of the Langjökull glacier.

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[5] No. BLK/ofl/2024-01

[6] Rannsóknarnefnd samgönguslysa (RNSA).

The intensity of the analyzed vertical wind speed[7] was only a fraction of the sink rate of the aircraft during the serious incident. It should be noted that updrafts and downdrafts do not automatically alter an aircraft's vertical speed, and other factors may contribute to the aircraft sink rate.

This indicated that there was something else, in addition to a turbulent encounter with mountain waves, that was needed to explain the intensity of the sink rate of the aircraft during the serious incident.

During the work on the IMO technical report to SIA-Iceland requested by SIA-Iceland, the Icelandic MET Office found no pilot report (PIREPs) of the turbulence from flight TK0018 in the Icelandic MET Office database. This was unusual, as the SIA-Iceland investigation had revealed that at 08:15 the Commander of flight TK0018 had informed ATC of severe turbulence when he declared PAN-PAN. The investigation revealed that in the PIR[8] message[9] that Isavia ANS had sent to the Icelandic MET Office after flight TK0018 encountered the severe turbulence, there were no weather-related words used. The computer system at the Icelandic MET Office filters for reports containing weather related words and only provides those reports to the on-duty forecasters. Therefore, the PIR message from Isavia ANS was not provided to the on-duty forecaster, until at 08:34 when it was provided via telephone communication.

Additional details regarding weather can be found in Appendix I.

[7] As analyzed by the Icelandic MET Office
[8] Pilot Report
[9] ARP PIR TK0018 6450N01830W/0816 F292, EMR DES FROM F350 TO 280 PANPANPAN NEYDARLAEKKUN B77W.

2.2. Flight operation

Analysis of the FDR data indicated that severe turbulence was encountered while in cruise at FL350. There were several rapid, sharp, control column inputs, and large thrust changes during this period of turbulent flight.

The autopilot and the autothrottle were engaged leading up to the turbulence encounter, but large manual control column inputs led to the autopilot disconnecting. These control column pushes, very likely commanded in response to the stick shaker activation, resulted in a nose down airplane pitch attitude and the airplane began to descend. A force-fight between the flight crew ensued, with the First Officer (PF) pushing on the control column and the Captain (PM) pulling on the control column, leading to control column breakout.

The aircraft encountered overspeed condition, which the flight crew tried to correct by applying the speedbrakes. The flight crew did however not retract the speedbrakes afterwards.

The aircraft attitude reached its lowest pitch of 18 degrees nose down, with the elevator deflection alternating between trailing edge up and down which resulted in high g-loading of the airplane. The two control columns eventually came back together after the descent, with the nearly equal opposing forces allowing the control column deflection to remain close to 0 degrees. The pitch attitude had started to increase, but at this point, the airspeed and Mach had exceeded VMO/MMO, and the airplane experienced an Overspeed Warning. High g-loading re-occurred, a result of the control column inputs commanded to arrest the descent.

The throttles were momentarily retarded by the flight crew to stop the increase in airspeed but were subsequently advanced by the autothrottle. With the pitch attitude becoming positive and the airplane climbing, the airspeed returned to the FMC target speed.

The crew continued the flight with no further anomalies.

Additional details regarding the flight operation can be found in Appendix II.

2.3. Aircraft flight control systems

The Boeing 777 uses Fly-By-Wire (FBW) Primary Flight Control System (PFCS). The system provides both stability augmentation and protection function. These features however do not limit the action of the pilot.

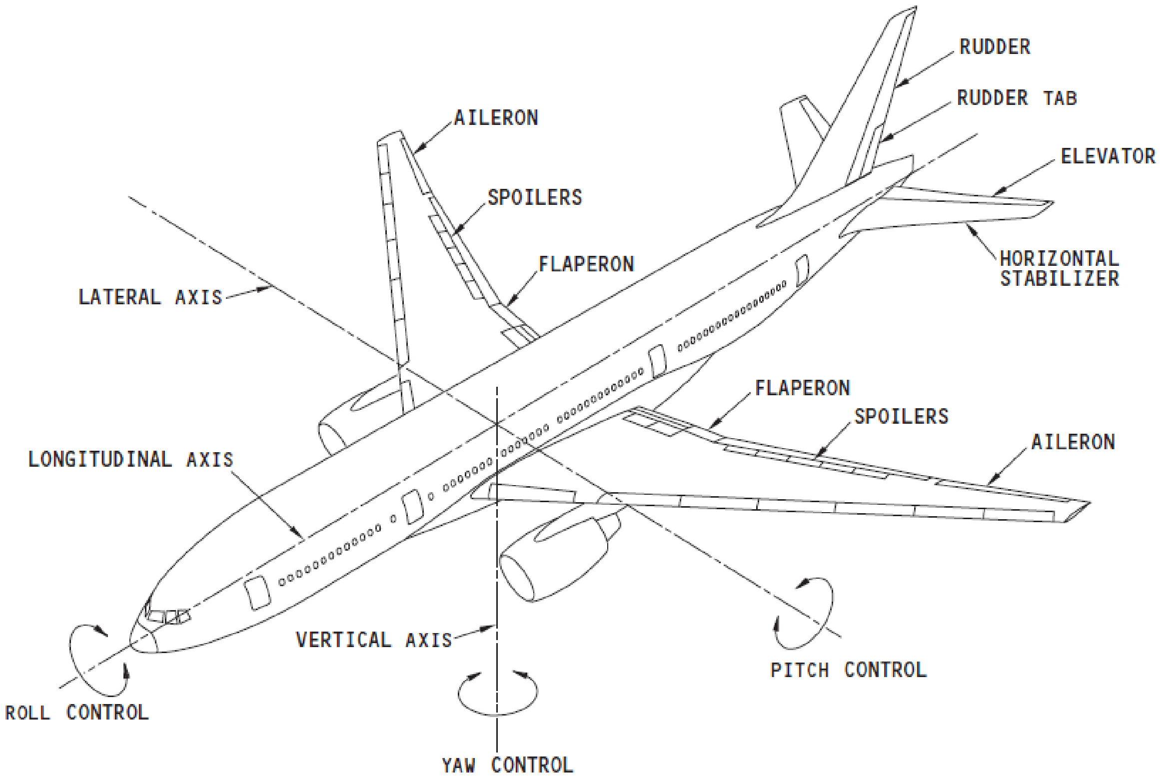

Figure 14: B777 Primary Flight Control System (PFCS)

The Boeing 777 design utilizes envelope protection, which deters pilot inputs from exceeding certain predefined limits but does not prohibit it. As an example, the Boeing 777 bank angle protection feature significantly increases the steering force a pilot encounters when attempting to roll the airplane past a predefined bank angle. The pilot will override the protection by exerting a greater force on the yoke than is being exerted by the back drive actuator. The intent is to inform the pilot that the command being given would put the airplane outside of its normal operating envelope, but the ability to do so is not precluded. This concept is central to the design philosophy of the Boeing 777 Primary Flight Control System.

Stability Augmentation

There is a stability augmentation function for the pitch and yaw control. Stability augmentation controls the airplane attitude to simulate the natural reaction of the airplane that the pilots expect.

The control laws calculate yaw damping and turn coordination commands. A gust suppression function makes the ride quality better and reduces the pilots' workload. In pitch stability augmentation, the Primary Flight Computer (PFCs) use the control laws to calculate the elevator control commands for speed stability and flare compensation.

Protection Functions

The control laws contain several different limits to supply flight envelope protection in the three axes of control. The PFCs calculate protection functions for:

- Bank angle
- Overspeed
- Stall
- Thrust asymmetry compensation
- Overyaw
- Tail Strike

The bank angle protection supplies a roll command opposite to the bank. The overspeed protection supplies a pitch up command when the speed is more than the maximum. The stall protection supplies a pitch down command. The thrust asymmetry compensation

(TAC) automatically controls the rudder movement to make allowance for asymmetrical thrust from the engines. The overyaw protection operates through the wheel-rudder cross-tie function to decrease the yaw command.

The bank angle and the stall protections supply more resistive force to the controls. The pilots can override the protection functions when they move the controls more than the limit. There is no increased force on the controls for the other protection functions.

Pitch control

In the case of pitch attitude control using the control columns, the Boeing 777 primary flight control system (PFCS) takes the average of the left and right pilot control column inputs for the elevator input command. During normal operation, the left and right controls are rigidly linked until opposing forces exceed the breakout threshold for the jam override mechanism within the control system. Therefore, large counter inputs by the pilots to the aircraft pitch attitude, using the control columns, can effectively or partially cancel out the two opposite inputs. This may cause the pilots to implement an even larger input to the pitch control, as they do not feel the aircraft responding.

This is the reason why it is imperative that only one pilot provides control column inputs, while the other monitors the flight. This also highlights the importance of proper CRM.

2.4. Crew qualification

The two Captains were fully qualified to fly the Boeing 777-300ER aircraft registered as TC-JJJ on flight TK0018. The First Officer (PF) was undergoing his line training when the serious incident occurred.

The Commander had the most experience flying this aircraft type, or 7253 flight hours. He had 5743 flight hours as a Commander on the B777 and was both a Type Rating Instructor (TRI) and Type Rated Examiner (TRE). He was, however, resting and not on the flight deck when the aircraft encountered the turbulence.

The Captain (PM) had accumulated 2154 flight hours on the B777 of which he had 2112 flight hours as a Commander on the B777. The Captain (PM) did not have instructor rating at the time of the serious incident.

SIA-Iceland noted that the First Officer (PF) had 38 flight hours on this type of aircraft, of which about 25% were from the serious incident flight. The Pilot Flying was therefore new to this type of aircraft. Prior to the serious incident the First Officer (PF) had finished his ground and simulator training, including the flight operator's Airplane Upset Prevention and Recovery Training. The First Officer (PF) was P6, or co-pilot undergoing Line Flying Under Supervision (LIFUS). To complete the line training, the flight operator requires 10-20 flights/sectors.

The Commander was the Line Training Instructor of the First Officer (PF). The Commander was not on the flight deck when the aircraft incurred the serious incident. According to Turkish DGCA[10] Approved Operations Manual Part-A, Chapter 4 Crew Compositions, 4.1.1.8 Flight Crew Classification (B) Note 1, restriction(s) only apply(ies) below 20,000 feet. So, there was no Line Training Instructor rating requirements for the Captain (PM) when the First Officer (PF) was flying the aircraft during cruise at FL350.

[10] Directorate General of Civil Aviation

2.5. Operational procedures

During part of the upset flight, both the First Officer (PF) and the Captain (PM) provided control column inputs, which were opposite at times, causing the two control columns to breakout from each other, therefore both pilots were simultaneously acting as Pilot Flying, while neither pilot was monitoring the flight, suggesting a breakdown of Crew Resource Management (CRM).

According to information gathered by the investigation, the phrase “I have control” (used by the flight operator) was not used by the Captain (PM), when he tried to take over the controls. According to the Captain (PM) this was because the event occurred suddenly. From the sequence of events, it is apparent that the First Officer (PF) was not aware that the Captain (PM) had also started trying to control the aircraft.

It is imperative that only one pilot acts as the Pilot Flying (PF), while the other fulfills the role of Pilot Monitoring (PM) during flight. Exchange of the controls shall be formal (“I have control”) to avoid a breakdown of Crew Resource Management (CRM).

In the Turbulent Air Penetration section of the Flight Crew Training Manual (FCTM), the following text describes what actions flight crews should take when severe turbulence is encountered:

> *During manual flight, maintain wings level and smoothly control attitude. Use the attitude indicator as the primary instrument. In extreme updrafts or downdrafts, large altitude changes may occur. Do not use sudden or large control inputs. Allow altitude and airspeed to vary and maintain attitude… Set thrust for penetration speed and avoid large thrust changes… Turbulence at any altitude can momentarily increase the airplane’s angle of attack and activate stick shaker.*

According to the Flight Crew Operational Manual (FCOM SP.16.19), for flight in severe turbulence, it states:

In severe turbulence during cruise, it may be necessary to disconnect the auto throttles to prevent excessive thrust changes. Thrust setting guidance is available on EICAS when VNAV is engaged. Set N1 at or slightly above the magenta VNAV target N1 indication. Change thrust setting only if required to modify an unacceptable speed trend.

If manual flight in severe turbulence becomes necessary, the Manual Flight in Severe Turbulence section of the Flight Crew Operation Manual (FCOM SP.16.19) states the following:

Control the airplane pitch attitude with the elevators using the attitude indicators as the primary instruments. In extreme drafts, large altitude changes may occur. Do not make sudden large control inputs. Corrective actions to regain the desired attitude should be smooth and deliberate. Altitude variations are likely in severe turbulence and should be allowed to occur if terrain clearance is adequate. Control airplane attitude first, then make corrections for airspeed, altitude, and heading.

There were several rapid, sharp control column inputs, and large thrust changes during the period of turbulent flight. The reductions of the Throttle Resolver Angles (TRAs) to idle allowed N1 to decrease, a contributing factor in the loss of airspeed that followed. The control column push, by the First Officer (PF), resulted in a nose-down pitch attitude.

After the autopilot disconnection, large control column inputs were applied which aggravated the situation, combined with extended speedbrakes. These flight crew actions led to a high rate and high-speed descent, degrading the aircraft's controllability further.

This resulted in a nose down pitch upset, due to aggressive and abrupt control inputs, causing a lowest pitch angle of 18.3 degrees nose down as well as a maximum sink rate (V/S) of 17,100fpm.

The flight crew couldn’t resolve the reason for the first and subsequent stick shakers at the time of incident.

Due to extended, and possibly forgotten, speedbrake at high altitude, the aircraft experienced excessive drag. This resulted in a reduced buffet margin and stall warning activation. During excessively high rate of descent, abrupt control column inputs caused increased g-load and subsequent additional stall warnings.

The flight operator’s Approach to Stall or Stall Recovery, in the 777 Flight Crew Operational Manual, requires the actions shown in Figure 15.

TURKISH AIRLINES

777 Flight Crew Operations Manual

Maneuvers **Chapter MAN**

Non Normal Maneuvers **Section 1**

Approach to Stall or Stall Recovery

All recoveries from approach to stall should be done as if an actual stall has occurred.

Immediately do the following at the first indication of stall (buffet or stick shaker):

Note: Do not use flight director commands during the recovery.

Note: If autopilot response is not acceptable, it should be disengaged.

Note: If autothrottle response is not acceptable, it should be disconnected.

Pilot Flying	Pilot Monitoring
• Initiate the recovery: • Smoothly apply nose down elevator to reduce the angle of attack until buffet or stick shaker stops	• Monitor altitude and airspeed • Verify all required actions have been done and call out any omissions • Call out any trend toward terrain contact

• Continue the recovery:
  • Roll in the shortest direction to wings level if needed*
  • Advance thrust levers as needed
  • Retract the speedbrakes
  • Do not change gear or flap configuration, except:
    • During liftoff, if flaps are up, call for flaps 1
	• Monitor altitude and airspeed
	• Verify all required actions have been done and call out any omissions
	• Call out any trend toward terrain contact
	• Set the FLAP lever as directed

• Complete the recovery:
  • Check airspeed and adjust thrust as needed
  • Establish pitch attitude
  • Return to desired flight path
• Re-engage the autopilot and autothrottle, if desired
	• Monitor altitude and airspeed
	• Verify all required actions have been done and call out any omissions
	• Call out any trend toward terrain contact

WARNING: *Excessive use of pitch trim or rudder may aggravate the condition, or may result in the loss of control or in high structural loads.

June 15, 2015 D632W001-THY(THY) MAN.1.1

Figure 15: B777 FCOM Approach to stall or stall recovery, © Boeing reproduced with permission.

The maneuver section recommends disengaging the Autopilot if its response is unacceptable. This is due to envelope protection characteristics in B777.

Related Flight Crew Training Manual (FCTM) “Approach to stall and stall recovery” section includes the following brief information:

> *Envelope protection features within the AFDS[11] and flight control systems reduce the likelihood of inadvertently exceeding the wing stalling angle of attack. However, even though the autopilot and autothrottle are operating correctly, the airplane could fly into a condition where an approach to stall is momentarily experienced. The AFDS is designed to recover the airplane from this condition.*

Unacceptable conditions are defined in Flight Crew Training Manual (FCTM) as below:

> *The following indications are examples of unacceptable performance:*
> - *an approach to a stall is encountered and in the pilot's judgment the AFDS is not responding correctly or rapidly enough*
> - *the airplane enters a fully developed stall*
> - *the airplane enters an upset condition.*

The FCTM Nose low upset recovery recommendation is described in Figure 16.

[11] Autopilot Flight Director System.

Nose Low

Nose Low, Wings Level

If the airplane pitch attitude is unintentionally low, the airspeed can be increasing rapidly. A pilot would likely reduce thrust and extend the speedbrakes. Thrust reduction causes an additional nose-down pitching moment. Speedbrake extension causes a nose-up pitching moment, an increase in drag, and a decrease in lift for the same angle of attack. At airspeeds well above VMO/MMO, the ability to command a nose-up pitch rate with elevator may be reduced because of the extreme aerodynamic loads on the elevator.

Again, it is necessary to maneuver the airplane's flight path back toward the horizon. At moderate pitch attitudes, applying nose-up elevator, reducing thrust, and extending speedbrakes, if necessary, changes the pitch attitude to a desired range. At extremely low pitch attitudes and high airspeeds (well above VMO/MMO), nose-up elevator and nose-up trim may be required to establish a nose-up pitch rate.

Figure 16: FCTM Nose low upset recovery, © Boeing reproduced with permission.

During the high-rate descent, the aircraft got three more stick shaker activations which occurred due to aggressive pitch inputs.

The Flight Crew Training Manual (FCTM 7.14) states:

> *Use care during recovery from a nose low attitude after the buffet and/or stick shaker have stopped. If the pull up is too aggressive, a “secondary” stall or sustained stick shaker can result.*

The flight operator’s Upset recovery, Nose High Recovery and Nose Low Recovery, in the 777 Flight Crew Operational Manual, requires the following actions shown in Figure 17 and Figure 18:

Maneuvers -
Non Normal Maneuvers

TURKISH AIRLINES

777 Flight Crew Operations Manual

Upset Recovery

Historically, an upset was defined as unintentionally exceeding one or more of the following conditions:

- pitch attitude greater than 25 degrees nose up
- pitch attitude greater than 10 degrees nose down
- bank angle greater than 45 degrees
- less than the above parameters but flying at an airspeed inappropriate for the conditions

An upset condition is now considered any time an airplane is diverting from the intended airplane state. An airplane upset can involve pitch or roll angle deviations as well as inappropriate airspeeds for the conditions.

The following actions represent a logical progression for recovering the airplane. The sequence of actions is for guidance only and represents a series of options to be considered and used dependent on the situation. Not all the actions may be needed once recovery is underway. If needed, use minimal pitch trim during initial recovery. Careful use of rudder to aid roll control should be considered only if roll control is ineffective and the airplane is not stalled.

These actions assume that the airplane is not stalled. A stalled condition can exist at any attitude and can be recognized by one or more of the following:

- Stick shaker
- Buffet that can be heavy at times
- Lack of pitch authority
- Lack of roll control
- Inability to stop a descent

If the airplane is stalled, first recover from the stall by applying and maintaining nose down elevator until stall recovery is complete and stick shaker stops.

MAN.1.8 D632W001-THY(THY) December 15, 2022

Figure 17: B777 FCOM Upset recovery, © Boeing reproduced with permission.

TURKISH AIRLINES
777 Flight Crew Operations Manual

Maneuvers -
Non Normal Maneuvers

Nose High Recovery

Pilot Flying	Pilot Monitoring
• Recognize and confirm the developing situation.	

• Disengage autopilot
• Disconnect autothrottle
• Recover
  • Apply nose down elevator. Apply as much elevator as needed to obtain a nose down pitch rate.
  • Apply appropriate nose down stabilizer trim*
  • Reduce thrust
  • Roll (adjust bank angle) to obtain a nose down pitch rate*
• Complete the recovery:
  • When approaching the horizon, roll to wings level
  • Check airspeed and adjust thrust
  • Establish pitch attitude
	• Call out attitude, airspeed and altitude throughout the recovery.
	• Verify all needed actions have been done and call out any continued deviation.

WARNING: * Excessive use of pitch trim or rudder can aggravate an upset, result in loss of control, or result in high structure loads.

Nose Low Recovery

Pilot Flying	Pilot Monitoring
• Recognize and confirm the developing situation.	

• Disengage autopilot
• Disconnect autothrottle
• Recover
  • Recover from stall, if needed
  • Roll in the shortest direction to wings level. If bank angle is more than 90 degrees, unload and roll*
• Complete the recovery:
  • Apply nose up elevator
  • Apply nose up trim, if needed*
  • Adjust thrust and drag, if needed
	• Call out attitude, airspeed, and altitude throughout the recovery.
	• Verify all needed actions have been done and call out any continued deviation.

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December 15, 2022   D632W001-THY(THY)   MAN.1.9

Figure 18: B777 FCOM Nose High and Nose Low recovery, © Boeing reproduced with permission.

All flight crews are trained in high altitude manoeuvres and recovery from upset in simulator trainings. The flight operator's Airplane Upset Prevention and Recovery Training program contains the following sections:

- High altitude characteristics demonstration
- High/low speed buffet demonstration
- Unreliable airspeeds
- Pilot induced upset
- Low altitude upset
- Environmentally induced upset
- Upset recovery

The flight operator's Airplane Upset Prevention and Recovery Training also looks at the following personal competences items:

- Decision Making
- Situational awareness
- Leadership & managerial skills
- Co-operations

Being an Instructor/Examiner, the Commander actively instructs Airplane Upset Prevention and Recovery Training. The Commander's initial Airplane Upset Prevention and Recovery Training was conducted in 2011.

The Captain's (PM) last Airplane Upset Prevention and Recovery Training, prior to the serious incident, was in late February 2020 during Phase 5B – Conversion of his Type Rating period. According to ICAO Annex 6, 9.3.1d) and g), Upset Prevention and Recovery training is to be given on recurrent basis as determined by the State of the Operator. According to Turkish DGCA regulation SHT-FCL, the Airplane Upset Prevention and Recovery Training recurrent requirements is every 3 years.

The First Officer (PF) had completed the flight operator's Airplane Upset Prevention and Recovery Training less than a month prior to the serious incident. His knowledge, handling and competence were deemed per the flight operator's standard. Furthermore, good CRM skills were observed. During this training, the First Officer (PF) was deemed ready for evaluation and ready for the next training.

2.6. Safety actions already accomplished

2.6.1. Flight operator

Being an Instructor/Examiner, the Commander actively instructs Airplane Upset Prevention and Recovery Training.

After the serious incident, the Captain (PM) and the First Officer (PF) completed the flight operator's Airplane Upset Prevention and Recovery Training in June 2023, which they passed.

At the time of the serious incident, updated weather information would have been sent manually to flight crews via the ACARS system. In the case of the serious incident, SIGMETs U02 and U03 were not sent to the aircraft during flight, as they were not valid for the flight's cruising altitude.

After the serious incident, the flight operator determined that internet connection for Electronic Flight Bag or pilot's personal devices (such as Jeppesen app, EWAS[12] app etc.) should be available for flight crew to track recent changes in flight conditions. This would allow for viewing of enroute weather, such as SIGMETs, with a good visualization.

As a result of this the flight operator updated its flight monitoring program with a system to make two-way communications between the Integrated Operation Control Center (IOOC) and flight crews more effective. Variable weather conditions, such as SIGMET

[12] EFB Weather Awareness Solution.

areas, are now reaching the flight crews instantaneously from the EWAS system via ACARS, including the dispatch phase. Areas that are of concern can be sent more effectively to aircraft that are possibly affected by it, where it can be viewed in graphical format. In Figure 19 an example is provided where the flight operator‘s IOOC advises certain flights of an embedded thunderstorm in the updated flight monitoring program.

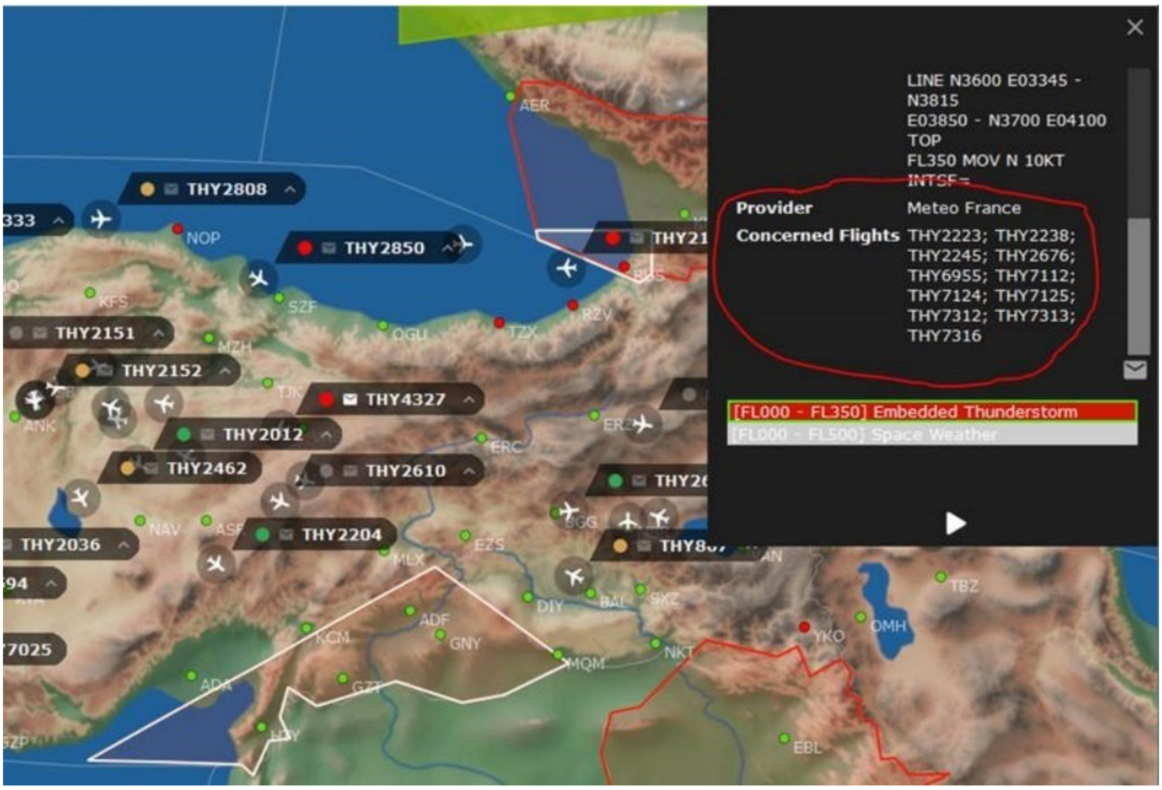

Figure 19: An example of concerned flights being advised of a thunderstorm.

Similarly, in the system, the aircraft location can be monitored with regards to such SIGMET areas, as seen in Figure 20 and this can be viewed by the flight crew in the flight monitoring program in the Electronic Flight Bag providing it with a graphical representation of the SIGMET area with respect to the flight.

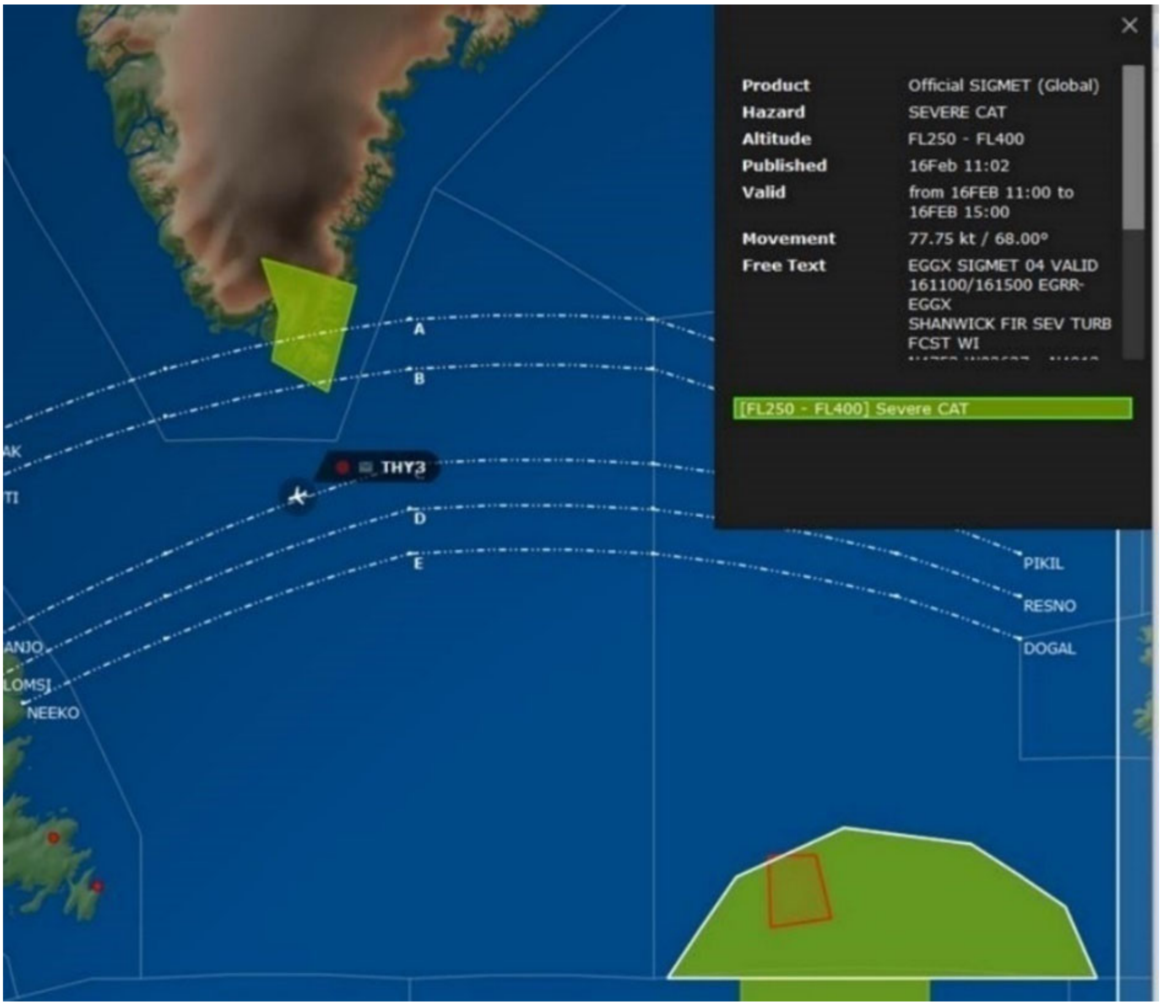

Figure 20: An example of an aircraft location in graphical relation to SIGMET area.

2.6.2. Icelandic Met Office

The Icelandic Safety Investigation Authority requested that the Icelandic MET Office issue a report regarding the serious incident. The conclusion of the report indicated that internal procedures regarding SIGMET issue were lacking, and improvements were needed with regards to presentation of weather forecasts and satellite images. The Icelandic MET Office set forth the following goals for improvement:

1. Improved continuing education of forecasters, especially when it comes to monitoring and analyzing of satellite images with regards to mountain waves.
2. Internal procedure LBE-004 SIGMET revised regarding issuing of SIGMETs, where conditions due to formation of mountain waves were added along with two tables based on ICAO Annex 3 requirements.
3. Color coding in operational weather charts of NWP (Numerical Weather Prediction) products revised to better reflect moderate and severe turbulence according to ICAO Annex 3 requirements.
4. Increased targeted use of satellite images while monitoring dangerous weather phenomena that can affect aviation.
5. Start generating NWP charts that show cross sectional views of wind speeds over Iceland.
6. Improved automation in analyzing weather phenomena (such as turbulence, icing, mountain waves, thunderstorms etc.) in high resolution weather forecasts.
7. Review of joint procedures between the Icelandic MET Office and Isavia regarding registration and distribution of Pireps, as the Icelandic MET Office filters out reports that do not include weather related words.

The Icelandic MET Office had planned to have all the above-mentioned improvements implemented no later than 1. October 2024, but item no. 6 remained open at the time of publication of this report.

3. CONCLUSION

3.1. Weather

The investigation determined that flight TK0018 (aircraft TC-JJJ) experienced severe turbulence and significant downdraft due to a high-altitude mountain wave north of the Langjökull glacier.

Satellite images and other weather data revealed mountain waves had existed over Iceland since the day prior to the serious incident, up to the tropopause. Nevertheless, SIGMET M01 warning of high-altitude mountain waves in the area was not issued until at 08:13 in the morning of the serious incident. This was 4 minutes after flight TK0018 encountered the severe turbulence. In addition, the area of SIGMET M01 did not incorporate the area where the flight encountered severe turbulence.

Following the severe turbulence encounter of flight TK0018, the Icelandic MET Office issued SIGMET M02 where the area from M01 was enlarged with a notification of severe mountain waves observed within the area.

3.2. Flight Operation

The information regarding the magnitude of the turbulence was not available to the flight crew and caught them by surprise, causing difficulties in coping with the situation.

It is imperative that only one pilot acts as the Pilot Flying (PF), while the other fulfills the role of Pilot Monitoring (PM) during flight.

Both the First Officer (PF) and the Captain (PM) provided control column inputs, which were opposite at times, causing the two control columns to breakout from each other, therefore both pilots were simultaneously acting as Pilot Flying, which indicates a breakdown of Crew Resource Management (CRM).

The Boeing 777 primary flight control system (PFCS) takes the average of the left and right pilot pitch control inputs when the column position are split due to breakout of the jam override mechanism. For this reason, it is imperative that only one pilot provides pitch inputs to the control column. This also highlights the importance of proper CRM.

With neither pilot acting as Pilot Monitoring, the thrust lever and speedbrakes or other warnings/cautions were not being monitored during the serious incident. Improper task sharing seems to have led to a monitoring deficiency and the flight crew was unable to scan and follow parameters efficiently. This resulted in a loss of Situational Awareness.

The flight crew applied speedbrakes to correct the overspeed condition, but did not retract the speedbrakes afterwards. Speedbrake deployment lowers the margin to stick shaker and increases sink rate.

The flight crew reacted to changing conditions while always keeping the Autothrottle (A/T) ON. This resulted in control inputs (often with counter inputs) being made during the upset condition, not only by the First Officer (PF), but also by the Captain (Pilot Monitoring) as well as the Autothrottle.

3.3. Causes

SIA-Iceland found the following to be the causes of the serious incident:

- An encounter with severe turbulence.
- Breakdown in Crew Resource Management.
- Loss of Situational Awareness.

3.4. Contributing factors

SIA-Iceland found the following to be contributing factors to the serious incident:

- SIGMET for high-altitude severe mountain waves had not been issued prior to the incident.
- The Captain (PM) did not follow procedure by using the phrase "I have control" (used by the flight operator), when he tried to take over the controls.
- Inappropriate control inputs during the aircraft upset.
- The autothrottle remained engaged and speedbrakes remained deployed during the aircraft upset.

4. SAFETY RECOMMENDATIONS

SIA-Iceland issues the following safety recommendations:

23-016F005-T1:

> SIA-Iceland recommends to the Icelandic MET Office to improve automation in analyzing weather phenomena (such as turbulence, icing, mountain waves, thunderstorms etc.) in high resolution weather forecasts.

23-016F005-T2:

> SIA-Iceland recommends to the Icelandic MET Office to present SIGMET areas in graphical format on maps.

23-016F005-T3:

> SIA-Iceland recommends to Turkish Airlines to re-evaluate their CRM training, to emphasize the importance of each pilot's role in flying the aircraft.

23-016F005-T4:

> SIA-Iceland advises Isavia ANS to ensure that Pilot Reports to the Icelandic MET Office include all weather related information.

Safety Actions:

SIA-Iceland advises flight operators, to consider implementing a graphical flight monitoring program in the Electronic Flight Bags that provide flight crews with updated graphical representation of SIGMET areas with regards to the flight and its planned route.

SIA-Iceland advises local Meteorological Watch Offices (MWOs) on the importance of monitoring and issuing SIGMETs for severe mountain waves.

The following board members approved the report:

- Guðmundur Freyr Úlfarsson
- Geirþrúður Alfreðsdóttir
- Bryndís Lára Torfadóttir
- Gestur Gunnarsson
- Hörður Arilíusson
- Tómas Davíð Þorsteinsson

Reykjavík, 8. May 2025

On behalf of the Safety Investigation Board of Iceland

Ragnar Guðmundsson
Investigator-In-Charge

5. APPENDIX I - WEATHER

On 13th of February 2023 the moisture in the troposphere was sufficient to give indications of vertically propagating mountain waves over Iceland. The first indications of mountain waves over Iceland could be seen on the AVHRR and VIIRS[13] infrared heat images captured in the afternoon of 12th of February. In Figure 21 a), there are already indications of mountain waves, although these indications are small and hard to spot. The mountain waves became clearer later during the evening and then shadow areas could be spotted north of the glaciers, as can be seen in c) and d) of Figure 21. A shadow area is a sign that a powerful downdraft is occurring in the area, which causes the cloud cover to dissipate due to evaporation. Next to the downdraft area there was an area of powerful updraft area, which caused moist air to rise to even higher altitudes. This moist air was captured in the images as whiter and colder cloud tops (mountain wave tops). From the images in Figure 21, it can be interpreted that the mountain waves grew significantly through the night and became more intense. From the timeline in Figure 21, it can be interpreted that the satellite weather data indicated powerful mountain waves over Iceland many hours before the serious incident occurred.

The analysis of the meteorological conditions over Iceland prior to the serious incident therefore revealed that according to the weather forecast and observations there were conditions for the possible formation of mountain waves over Iceland. This was due to stable inversion layer at mountain level, tense wind blowing over the glaciers and the wind direction not changing much with altitude.

Atmospheric sounding measured at Keflavik Airport with a weather balloon and the forecasted atmospheric soundings at Egilsstaðir Airport, in east of Iceland, indicated a fairly strong speed and directional shear around FL350, which was the same flight level as flight TK0018 was flying at when the serious incident occurred.

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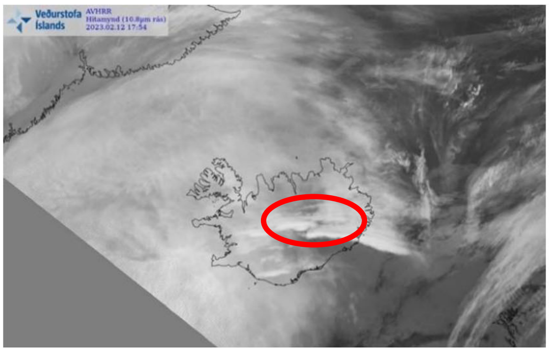
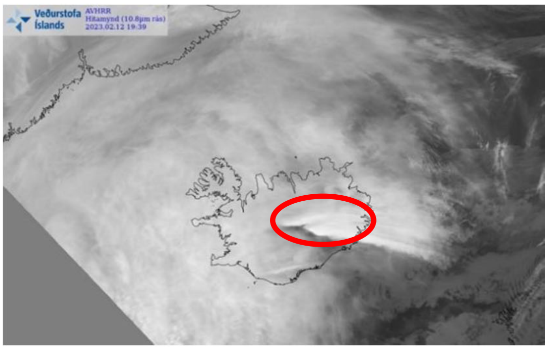
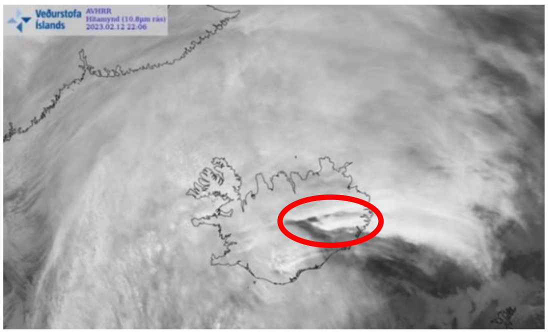
[13] AVHRR and VIIRS are certain instruments in NOAA polar orbiting weather satellites.



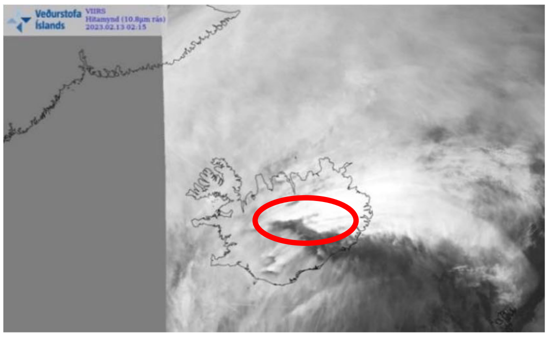
a) AVHRR at 17:54 UTC on 12. February



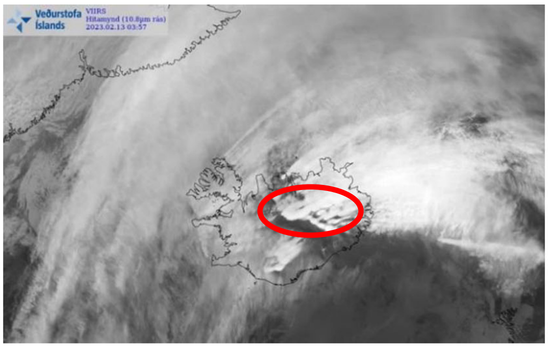
b) AVHRR at 19:30 UTC on 12. February



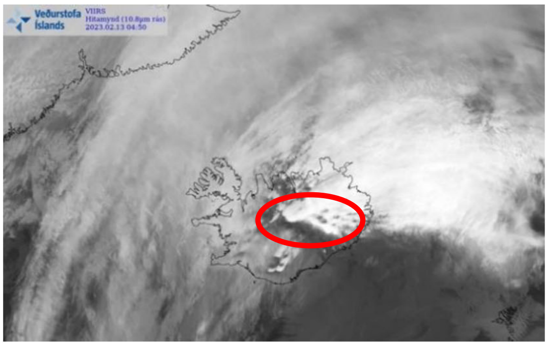
c) AVHRR at 22:06 UTC on 12. February



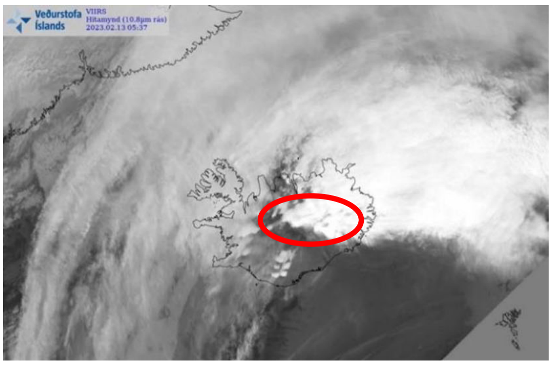
d) VIIRS at 02:15 UTC on 13. February



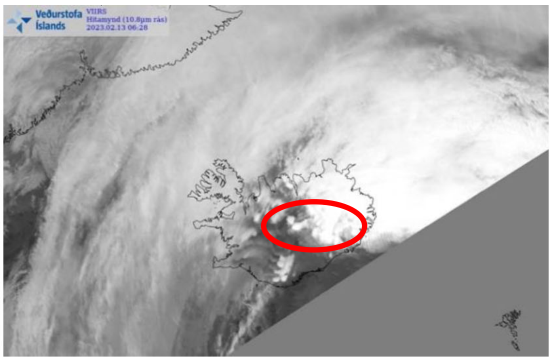
e) VIIRS at 03:57 UTC on 13. February



f) VIIRS at 04:50 UTC on 13. February



g) VIIRS at 05:37 UTC on 13. February



h) VIIRS at 06:28 UTC on 13. February

Figure 21: AVHRR and VIIRS infrared heat images captured in time stamped order a)-h) from 12. February to 13. February 2023.

This was just below the tropopause altitude, which is a region where turbulence often is enhanced. The circumstances were therefore ideal for mountain waves to form and propagate to the tropopause, where they could dissipate.

The procedures at the Icelandic MET Office were clear with regards to the issuing of SIGMET for low altitudes when the surface wind measurements passed 50 knots in several places, and that was done. However, similar procedures were lacking in the case of mountain waves.

The procedures at the Icelandic MET Office could be improved, with regards to issuing SIGMETs due to mountain waves and the forecasted data was not clear with regards to vertical wind speed. In addition, at the time of the serious incident, no cross-section forecasts over areas for vertical wind speed were issued.

The World Area Forecast Centers (WAFC) charts do not forecast mountain waves. It is therefore important that local Meteorological Watch Offices (MWOs) monitor such weather conditions and issue SIGMETs for severe mountain waves.

The calculated vertical wind and headwind data from the FDR aligned with the airspeed deviations leading up to the turbulence encounter. The calculated wind data from the FDR also indicated that at the onset of turbulence, the head-/tailwind component relative to the track gradually transitioned from a tailwind of 25 knots to a varying headwind of 25 knots, and the crosswind component transitioned from a right crosswind of 40 knots to an alternating left and right crosswind.

At the time of the serious incident the on-duty forecaster at the Icelandic MET Office only had access to a single high-resolution model (IGB). When the high-resolution model forecast data was analyzed, there were indications of the formation of mountain waves north of the glacier Langjökull.

6. APPENDIX II – FLIGHT OPERATION

Prior to the upset, the aircraft was flying at FL350 at 0.83 Mach, or an airspeed of 281 knots with a gross weight of about 570,000 pounds.

The Autopilot was engaged with pitch mode set to Vertical Navigation (VNAV) Mode and roll mode set to Lateral Navigation (LNAV) Mode. The Autothrottle was engaged and set to Speed Mode (SPD MODE).

1) At 08:09:12 UTC, the airspeed started to decrease, aligning with a negative vertical wind (downdraft) and increase in tailwind acting on the airplane. This was followed by a Throttle Resolver Angle (TRA) increase and increased engine N1, to regain airspeed.

2) At 08:09:31 UTC (timestamp 17,980 in Figure 25), the aircraft heading started to deviate to the left, indicating increased wind from the left side. The Mode Control Panel (MCP) selected heading had been changed by the flight crew just over two minutes prior and continued to follow the FMC track.

3) At 08:09:40 UTC (timestamp 17,989 in Figure 23 to Figure 25 and Figure 27), oscillations in acceleration and angle of attack, the airspeed began to increase, indicative of a turbulence encounter. An initial increase in vertical acceleration followed by a sharp decrease to near -1 g's occurred at the onset, simultaneous with an updraft followed by a rapid downdraft. The control column force data indicate that the First Officer (PF) started applying control column force at this time. The autopilot remained engaged. Symmetric aileron deflection trailing-edge-up occurred.

4) At 08:09:43 UTC (timestamp 17,992 in Figure 23, Figure 23 and Figure 27), the angle of attack decreased to -1 degree. The flight crew reduced throttles to idle as airspeed approached 300 knots, around 20 knots higher than their cruise speed,

and Mach increased to nearly the Maximum Operating Mach (MMO) of 0.89. With autothrottle still engaged, a TRA rate increase was commanded, likely indicating that the TRA reduction to idle was too low. Periodic TRA reductions to idle were commanded, likely by the flight crew, over the next minute, and each time was countered by a throttle increase command by the autothrottle.

5) At 08:09:46 UTC (timestamp 17,995 in Figure 23, Figure 23 and Figure 27), the **s**peedbrakes were deployed as airspeed reached 300 knots and Mach reached 0.88.

6) At 08:09:59 UTC (timestamp 18,008 in Figure 23, Figure 23 and Figure 27), airspeed and Mach began to decrease. The flight management computer (FMC) targeted airspeed/Mach was reached and maintained for about 8 seconds.

7) At 08:10:06 UTC (timestamp 18,015 in Figure 23, Figure 25, Figure 25 and Figure 27), the aircraft altitude was 34,971ft, the speed was 0.82M, or 279 knots, and the aircraft had started descending with V/S of -272fpm. A further TRA reduction to nearly idle which allowed N1 to decrease, even as A/T subsequently began to increase TRA, in combination with the still deployed speedbrakes and a headwind component change contributed to the airspeed reducing an additional 20 knots over the next 7 seconds. The Master Warning began to intermittently engage for the next 65 seconds, mostly aligned with activations in the Altitude Alert Engine Indication and Crew Alerting System (EICAS) message, Overspeed Warning.

8) At 08:10:08 UTC (timestamp 18,017 in Figure 23 and Figure 27), the stick shaker began to intermittently activate as the airplane experienced brief, sharp increases in angle of attack. The First Officer (PF) responded with a control column push of 50-60 pounds, possibly in response to the first stick shaker engagement, which likely reached the maximum override column force of 60 pounds in cruise required to disconnect the autopilot, and the autopilot was subsequently disconnected.

With the autopilot now disengaged and the PF pushing on the control column, the airplane pitch attitude began to lower (nose-down).

9) At 08:10:12 UTC (timestamp 18,021 in Figure 23, Figure 23, Figure 26 and Figure 27), the stick shaker activated for the second time. The speed was 0.788M, or 268 knots, the vertical acceleration was 0.5g and aircraft started to descend with V/S of -1360fpm.

10) At 08:10:15 UTC (timestamp 18,024 in Figure 23, Figure 23 and Figure 27), the Captain (PM) began to apply opposing control column inputs (based on control column force data) and continued to pull on the control column while the First Officer (PF) was pushing on the control column. The Altitude Alert EICAS message annunciated, as the pressure altitude began to decrease below the MCP selected altitude.

11) At 08:10:18 UTC (timestamp 18,027 in Figure 23, Figure 25, Figure 24 and Figure 27), the lowest airspeed and Mach during the descent was reached, at 256 knots and 0.76M respectively. At this point, a maximum forward thrust was commanded, the pitch attitude continued to decrease, and airspeed began to increase again. The First Officer (PF) continued to push on the control column as the airspeed was increasing and the airplane pitch attitude was approaching 10 degrees nose down. The airplane reached a bank angle of 17 degrees to the right, which the flight crew countered with an opposing control wheel deflection of approximately 35 degrees.

12) At 08:10:25 UTC, the control columns momentarily broke out from each other, due to the simultaneous pull from the Captain (PM) and push from the First Officer (PF) that combined exceeded the required control column breakout force of 50 pounds.
13) At 08:10:27 UTC (timestamp 18,036 in Figure 23 and Figure 27), a second momentary breakout of the control columns occurred.

14) At 08:10:28 UTC (timestamp 18,037 in Figure 23 and Figure 27), a control column pull from the Captain (PM) briefly changed the airplane pitch attitude from 10 degrees nose down to 2.5 degrees nose down, but subsequent control column pushes from the First Officer (PF) after stick shaker activation quickly lowered the nose back down and lower the pitch attitude down again.

15) At 08:10:29 UTC (timestamp 18,038 in Figure 23, Figure 26 and Figure 27), the third stick shaker activation occurred. This was at speed 0.79M, with V/S -9008fpm and 0.559g vertical acceleration.

16) At 08:10:35 UTC (timestamp 18,044 in Figure 23 and Figure 27), the aircraft reached a lowest pitch attitude of 18.3 degrees nose down.

17) At 08:10:35 there was a short burst of transmission, without anything being said, on the Reykjavik CTA south sector frequency.

18) At 08:10:36 UTC (timestamp 18,045 in Figure 23 and Figure 27), the First Officer (PF) control column input momentarily transitioned from a push to a pull, which in combination with the Captain (PM) control column pull, led to a sharp increase in the elevator trailing-edge-up (airplane nose-up). The sharp increase in pitch rate led to a maximum vertical acceleration of 1.25 g's, occurring immediately after a minimum vertical acceleration of -1.7 g's was attained.

19) At 08:10:37 UTC (timestamp 18,046 in Figure 23, Figure 23, Figure 26 and Figure 27), while descending through 32,000ft, the fourth activation of the stick shaker was recorded. The aircraft speed had exceeded 300 knots, its vertical speed (V/S), or descent rate, was -15,920fpm and the vertical acceleration was 1.06g. The Captain (PM) applied a control column pull of nearly 100 pounds while the First Officer (PF) applied a control column push of 100 pounds, causing the two control columns to breakout from each other.

20) At 08:10:42 UTC (timestamp 18,051 in Figure 23, Figure 23, Figure 26 and Figure 27), the aircraft exceeded its maximum operating speed (VMO/MMO) at 30,692ft, with -15,952fpm.

21) At 08:10:45 UTC (timestamp 18,054 in Figure 26 and Figure 27), the Captain (PM) applied a control column pull of 130 pounds, as the aircraft exceeded its maximum operating speed (VMO/MMO), resulting in a pitch attitude increase. A maximum sink rate (V/S) of -17,100fpm was reached.

22) 08:10:46 UTC (timestamp 18,055 in Figure 23 and Figure 23), the Overspeed Warning triggered. The alert was active for 20secs.

23) At 08:10:48 an ATCO working the Reykjavik CTA south sector frequency transmitted:

”18Alpha Reykjavik?”

24) At 08:10:54 UTC (timestamp 18,063 in Figure 23, Figure 23 and Figure 27), the airspeed had reached a maximum of 368 knots (approximately Maximum Operating Velocity [VMO] + 18) and Mach 0.92 (MMO + 0.03) while the pressure altitude was approaching 27,500 feet. Opposing control column forces between the left seat and right seat were still observed, with the control column positions now together at around 0 degrees.

25) At 08:10:58 UTC (timestamp 18,067 in Figure 23 and Figure 27), the airplane pitch attitude reached 0 degrees.

26) At 08:11:00 UTC (timestamp 18,069 in Figure 23, Figure 23 and Figure 27), the lowest pressure altitude observed was 27,295ft.

27) At 08:11:06 UTC (timestamp 18,075 in Figure 23, Figure 23 and Figure 27), the Overspeed Warning ceased after the airspeed/Mach decreased below VMO/MMO. The pressure altitude began to increase and opposing control column forces ceased as the airplane recovered and started climbing again.

28) At 08:11:06 the ATCO transmitted on the Reykjavik CTA south sector frequency:

> ”Turkish 18Alpha Reykjavik?”

29) At 08:11:12 UTC (timestamp 18,081 in Figure 23), the autopilot was engaged again.

30) At 08:11:26 UTC (timestamp 18,095 in Figure 23), the speedbrakes were retracted.

31) At 08:11:45 the south sector ATCO transmitted again:

> ”Turkish 18Alpha Reykjavik, do you read?”

32) At 08:12:02 a pilot of the flight crew of flight TK0018, noticeable while being out of breath, responded:

> “ATC, Turkish 18Alpha, severe turbulence experienced. We are climbing, FL350 now.”

33) At 08:12:12 the ATCO responded:

> “Turkish 18Alpha roger.”

34) At 08:13:46 UTC, the airplane reached FL315, where the airplane experienced another period of prolonged turbulence, evident by additional oscillations in

acceleration and air data. The flight crew disengaged the autopilot and began a descent to FL280.

35) According to the flight operator, when the turbulence conditions improved and conditions permitted, the Commander entered the flight deck and communicated with ATC while sitting in the observer's seat. The Commander then took over as Pilot Flying.

36) At 08:15:17, after entering the flight deck, the Commander of flight TK0018 contacted ATC on the Reykjavik CTA south sector frequency:

> "Reykjavik Turkish 18Alpha – PAN-PAN, PAN-PAN, PAN-PAN, severe turbulence, we cannot maintain level, descending 290 now passing 300."

37) At 08:15:29 the ATCO responded:

> "Turkish 18Alpha, roger, that's copied."

38) At 08:16:29, the flight crew of flight TK0018 contacted ATC again. During this communication the aircraft was cleared FL280 block FL290.

39) At 08:18:24 ATC contacted the flight crew of flight TK0018 and inquired if the ride was better at FL285. The flight crew responded that they were now experiencing light to moderate turbulence. ATC then responded that they had just received a SIGMET area that the flight was in right now (SIGMET M01). ATC then informed the flight crew, that if they would like to get out of the SIGMET area, ATC could vector them out of it. The flight crew accepted the vectoring.

40) At 08:19:07 ATC vectored flight TK0018 to the right, heading 150°.

41) At 08:21:11 UTC, the airplane encountered a third period of turbulence, this time light, causing no anomalies to the flight.

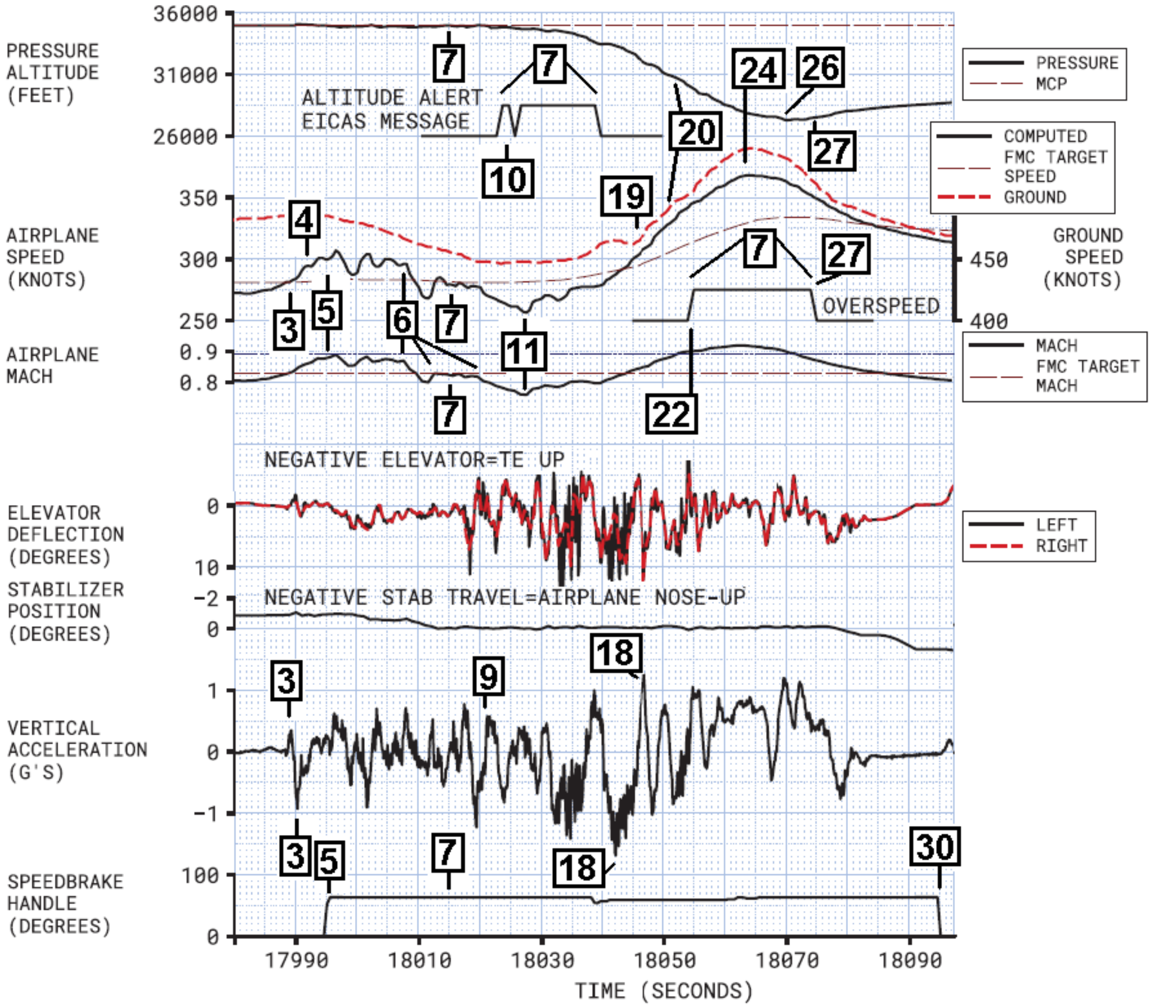


Figure 22: FDR parameters.

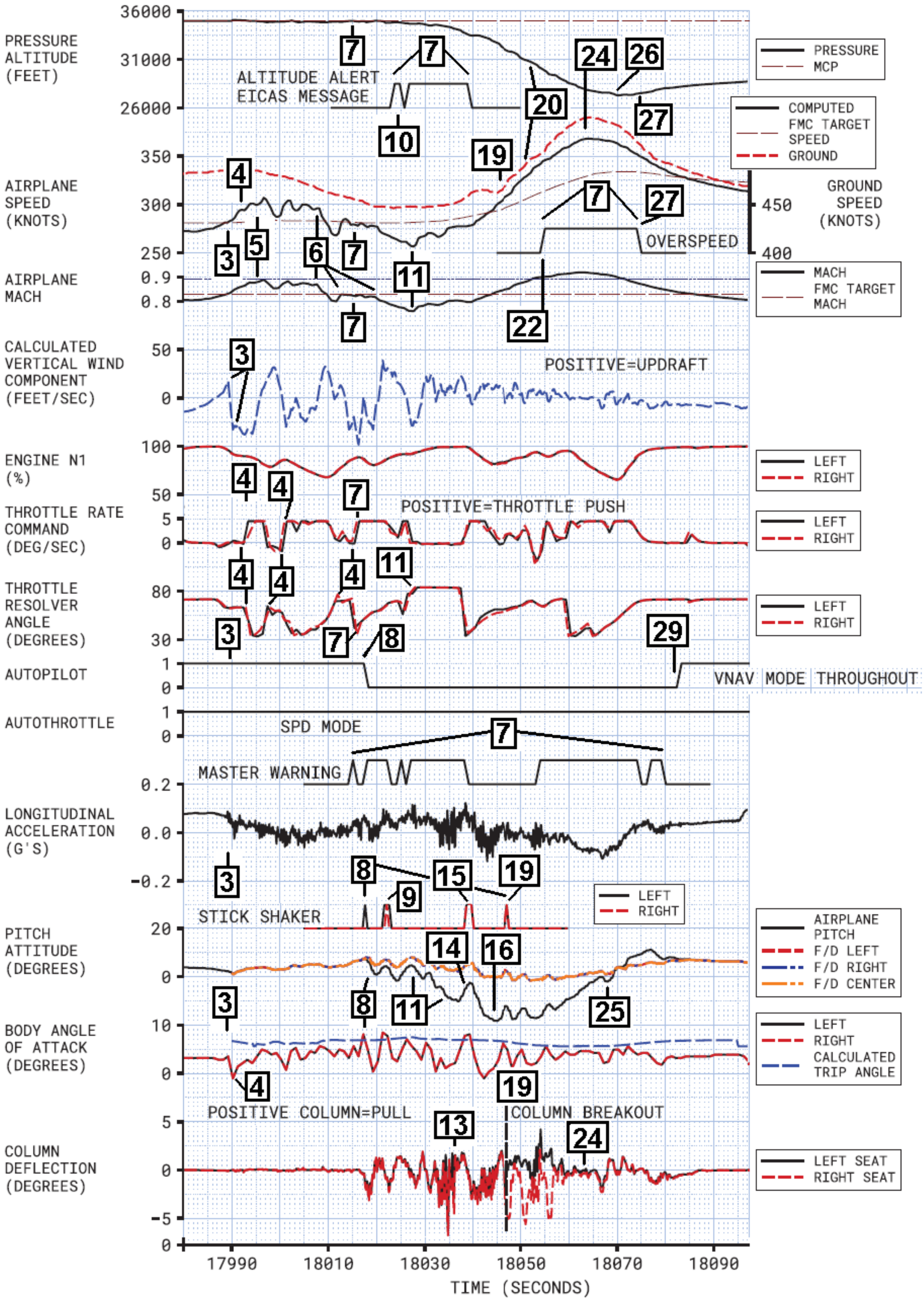


Figure 23: FDR parameters.

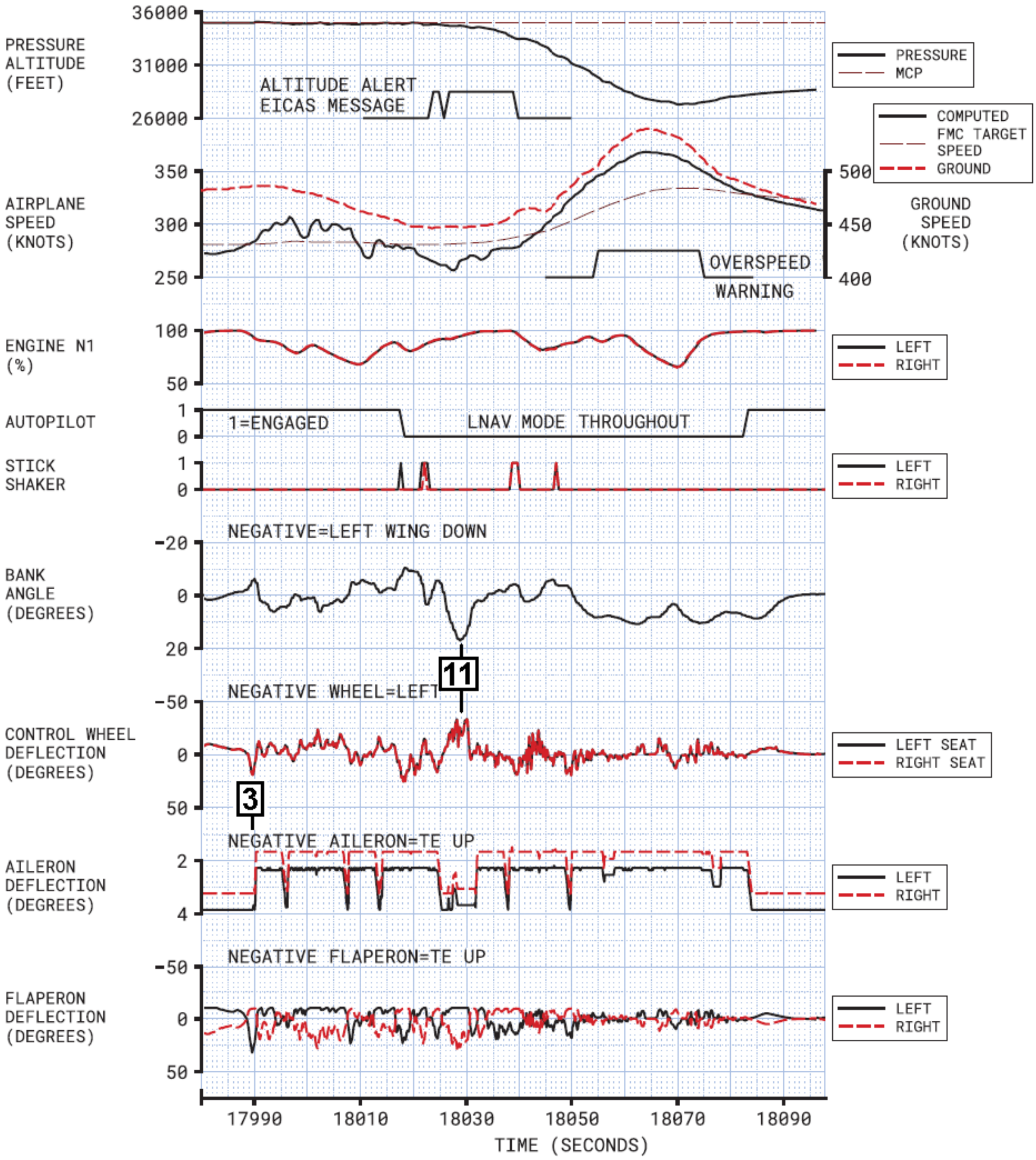


Figure 24: FDR parameters.

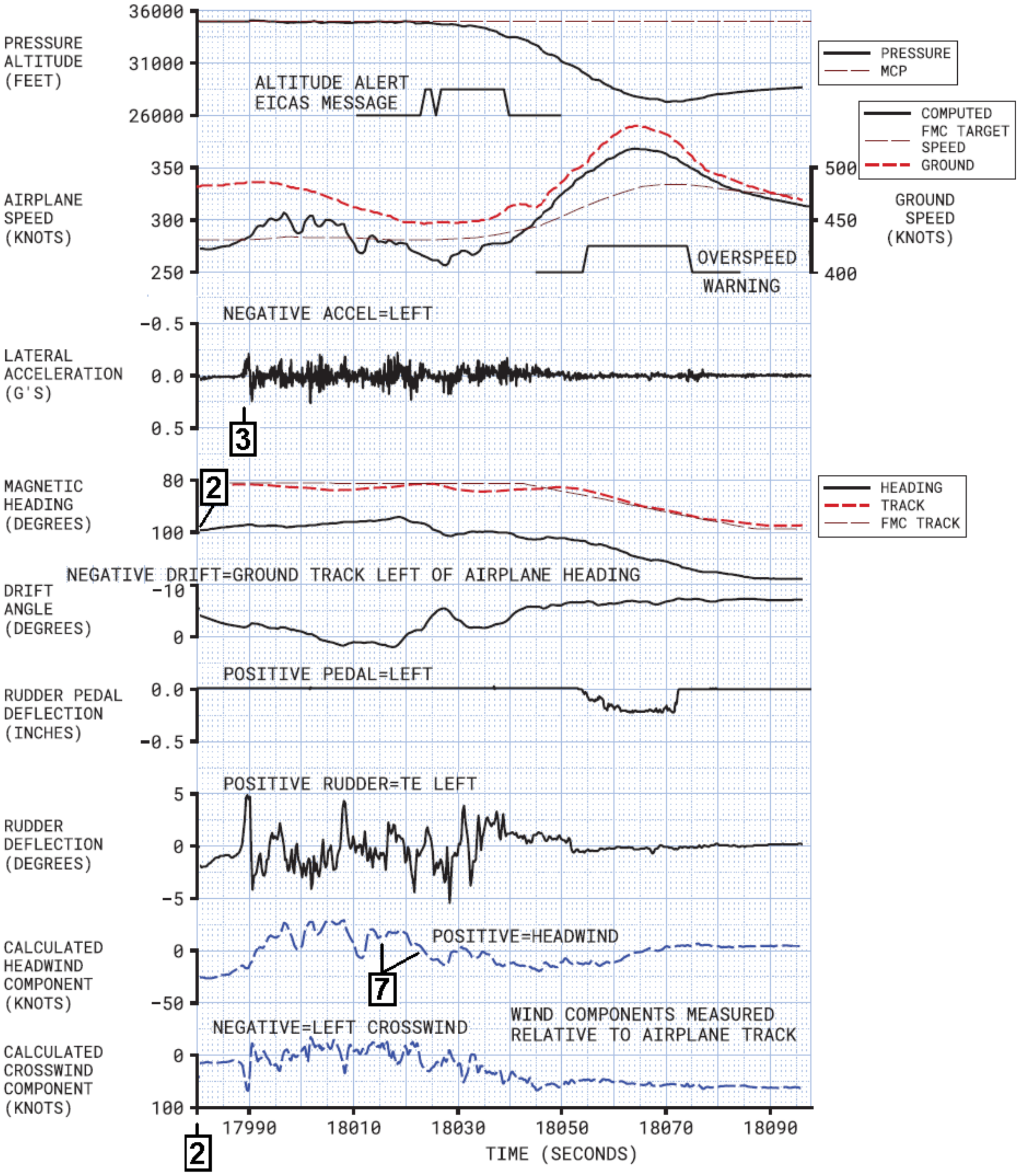


Figure 25: FDR parameters.

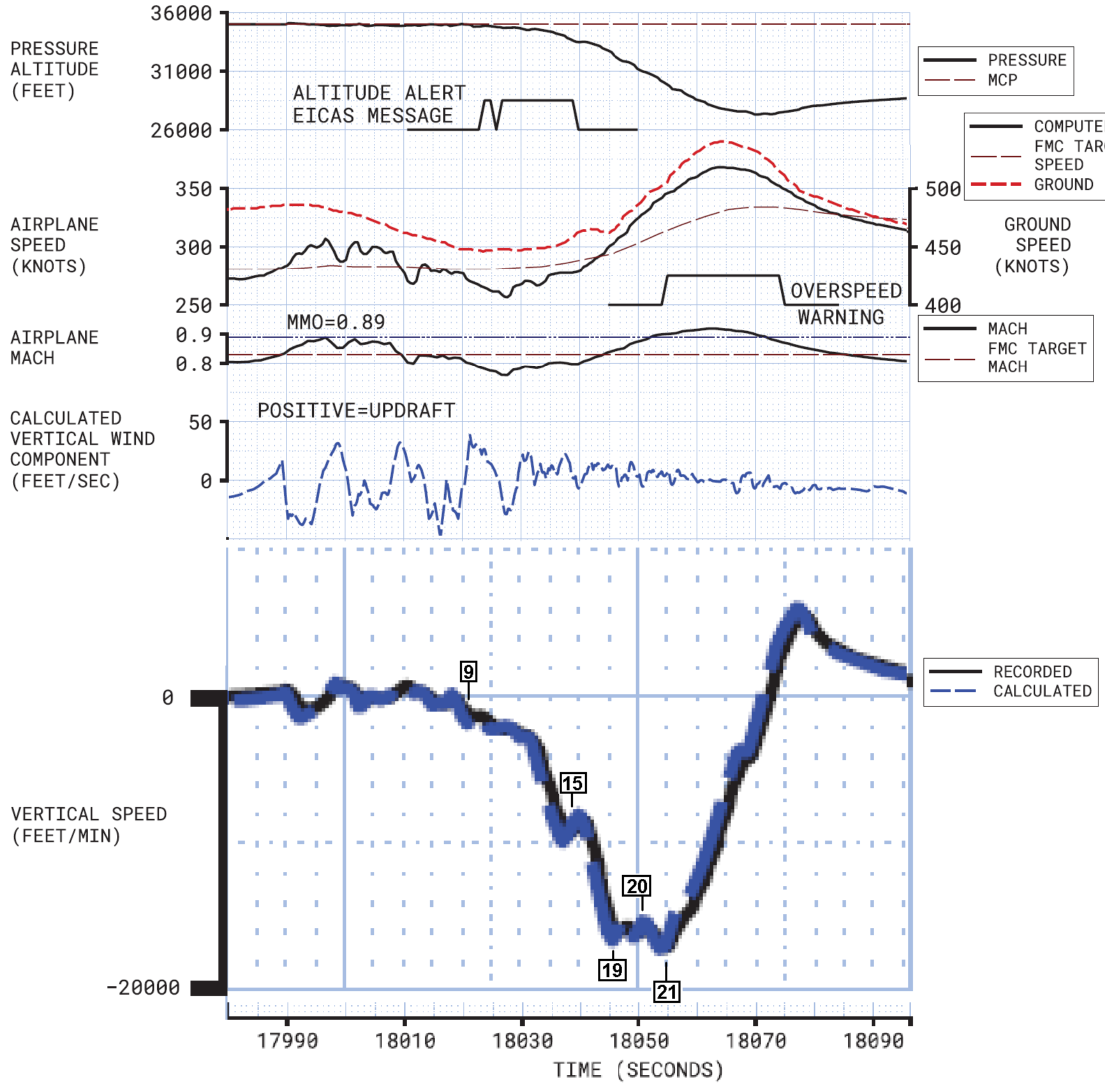


Figure 26: FDR parameters

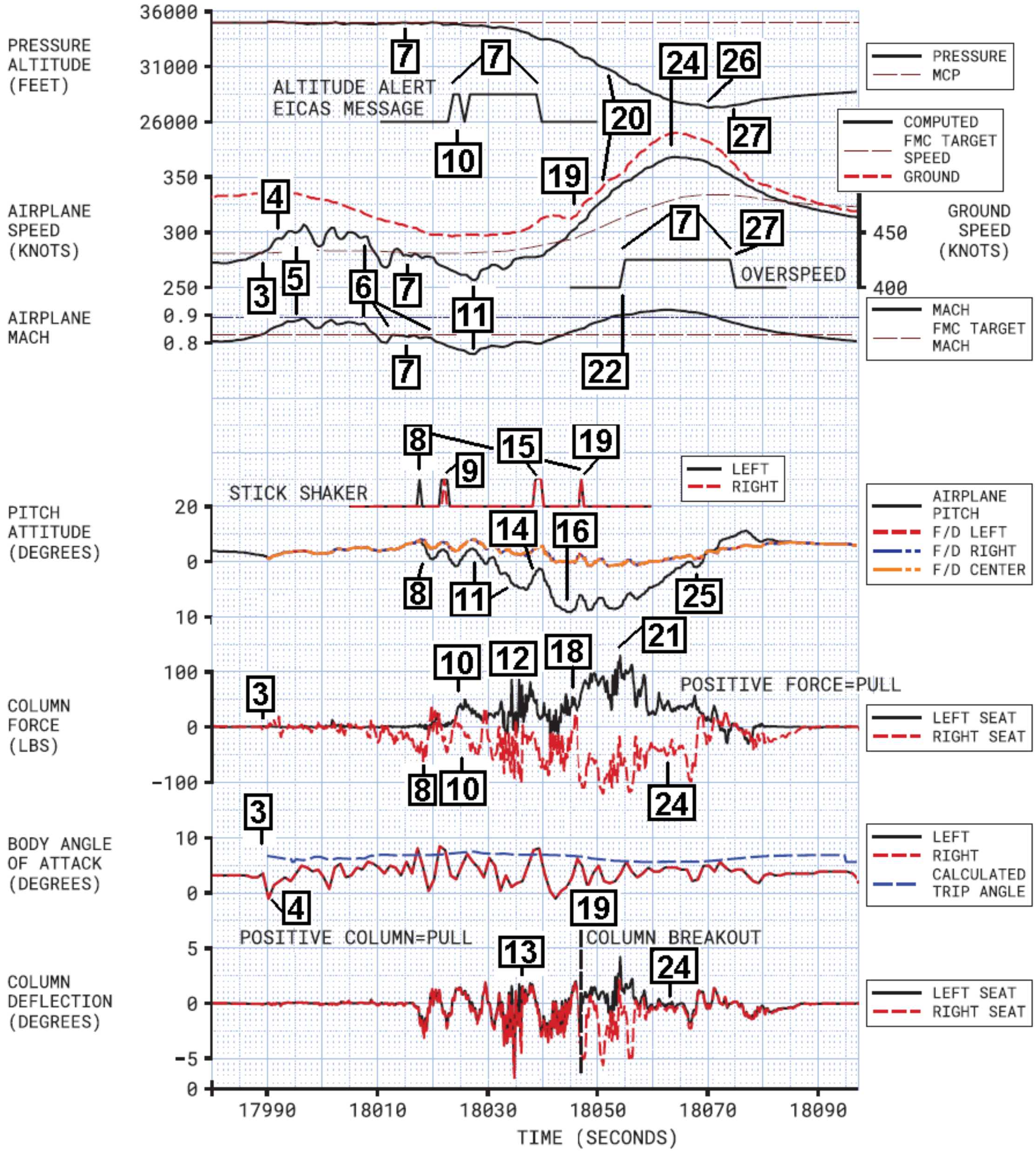


Figure 27: **FDR parameters**