

THE METEOROLOGICAL ENVIRONMENT SURROUNDING THE AIR FRANCE #447 DISASTER

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1. ABSTRACT

Air France Flight #447 (AF447) descended into the North Atlantic Ocean early on 1 June 2009, killing all on board. Contact with the Airbus A330 was lost when the flight was several hundred kilometers northeast of the South American coast at an altitude of ~12 km while the aircraft was in proximity to widespread deep convection, which was estimated via satellite to exceed 17 km. There has been much speculation but very little proof that weather played an important role in the incident as a result of icing, lightning, turbulence or some combination of these hazards. Based upon the final ACARS transmission as well as South American radiosonde, satellite, and GFS analysis/simulation data it is possible to reconstruct the horizontal and vertical atmospheric structure at the meso- α/β scale in proximity to the incident. These data lend one to speculate that a favorable environment for aviation turbulence may have existed at this time surrounding the deep convection, and we will describe some of these features in this preprint. Implicit in our analysis is related research by Vollmer (2008) and Kaplan et al. (2005) that serves as a theoretical/synoptic framework for the analyses presented here.

The larger scale environment during the 0000 – 0300 UTC 1 June 2009 period contained the following key synoptic features near the location of the incident (approximately 30°W, 4°N) as determined from the 0000 UTC Fernando de Noronha, Brazil sounding, GFS simulations, GFS analyses, and satellite-derived cloud track wind fields as well as infra-red and water vapor imagery: 1) an anticyclonically curved 100-150 mb subtropical jet streak oriented northwest-southeast in which the left exit region was approaching the incident location, 2) an anticyclonically-curved 70-100 mb tropical jet streak oriented southwest-northeast in which the left exit region was approaching the incident location, 3) a well-defined region of velocity convergence just to the northwest of the moist convection, which was occurring in proximity to and under velocity divergence over the convection and bracketing the incident location in the vertical, 4) substantial cross-jet frontogenesis due to 70 mb

warming over and just downstream from the incident location, 5) increasing vertical wind directional shear in the layers including 150 – 100 mb and 100 – 70 mb primarily from northwest to north to southwest and 6) a dry adiabatic layer between 150 and 100 mb undercutting a strengthening inversion in time in between 100 and 70 mb. The inversion above 100 mb was also in proximity to the top of the moist convection within the anvil region.

2. INTRODUCTION

These predominantly meso- α scale features are similar in many ways to the environment surrounding two mountain wave turbulence events analyzed by Vollmer (2008) and a much larger number of convective turbulence events analyzed by Kaplan et al. (2005). They are consistent with the superposition of two distinct tropopause boundaries, with an unstable layer above the lower tropopause capped by a stable layer above and within the upper tropopause. The wind direction and stratification accompanying the two jet streaks varied substantially through these layers thus establishing a low Richardson number zone under a more stable layer with the tropopause structures. Such an environment could favor shear-induced wave breaking phenomena in between the two tropopause layers, as Kelvin-Helmoltz instability would have been possible along the interface between the stably stratified layer and the unstable layer near 100 mb. Additionally, strong buoyancy-driven vertical motions associated with local deep convection could have lead to parcels being lifted into the stable region, producing a scenario where negatively buoyant downdrafts became favorable for the downward transport of southwesterly momentum aloft into a more northerly flow regime below. The result could be the focusing of rotors and significant turbulence kinetic energy near the incident location.

When AF447 departed Rio De Janeiro late on 31 May 2009 it encountered a complex atmospheric environment over the southern part of the North Atlantic Ocean. This included complex mesoscale convective systems (MCS), jet streaks and stratification all of which paint a mosaic of a **possible** turbulence-producing scenario or paradigm.

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In the remainder of this extended abstract we will attempt to construct a possible paradigm for the development of convective-induced turbulence along the flight path and at the time of the AF447 disaster. It should be reiterated that lightning, icing, hail and instrument malfunction have not been ruled out as contributing to or being the dominant elements of this disaster. We will only focus on a possible turbulence paradigm in this manuscript. The work of Vollmer (2008) described a sequence of meteorological events that led to two important terrain-induced turbulence episodes. In this extended abstract we will apply aspects of that paradigm to the atmospheric environment surrounding the flight track of AF447.

3. OBSERVATIONS

3.1 Convective Evolution

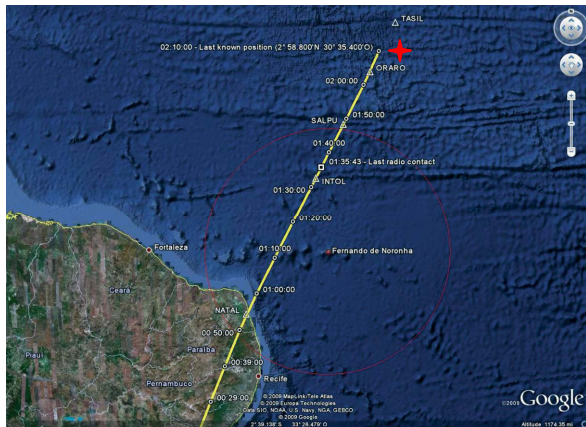
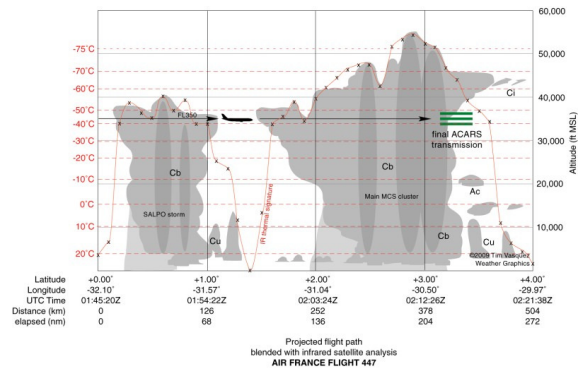
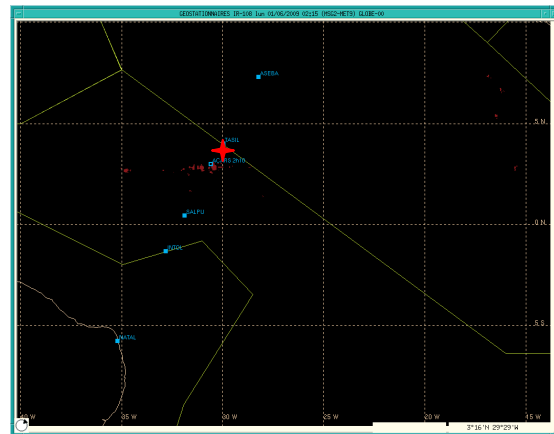


Figure 1: Flight track of AF447 (BEA 2009).

Figure 1 depicts the track of AF447 2 hours and 20 minutes into the flight. The end location being ~1 hour to the northeast of the island of Fernando de Noronha northeast of the Brazilian coast (BEA 2009). This location is ~4°N latitude and 30°W longitude. The key structures in the convective complex systems in the environment at ~0200 UTC can be inferred from Figure 2. The aircraft flies through two MCS during the period from 0145 UTC to ~0220 UTC as can be seen in Figure 2a. While the aircraft was at flight level 350 at this time it can be seen that infra-red satellite imagery depicts two prominent cloud clusters. The second cluster extends to nearly 52,000 feet (~85 mb) and is located along the flight path between ~0203 and 0210 UTC based on ACARS and satellite data (Vasquez 2009). When temperatures below -75C are masked as it can be determined from Figure 2b, i.e., just before the final ACARS contact, AF447 was departing the second MCS prior to its demise. Figure 2c indicates that this second large MCS was in a state of warming with the area of cold cloud tops diminishing and the gradual warming of the coldest cloud tops to ~-80C. These data indicate that AF447 was just downstream of the large cluster of MCS and its accompanying anvil which was in a state of collapse/weakening at the approximate time of the accident.



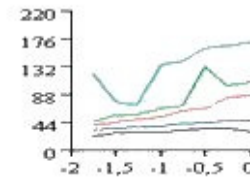
a)



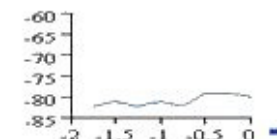
b)

Evolution of the surface (1000 km²)

T <= -60°C T <= -50°C
T <= -40°C T <= -30°C
T <= -64°C



Evolution of the temperature
Temp mini



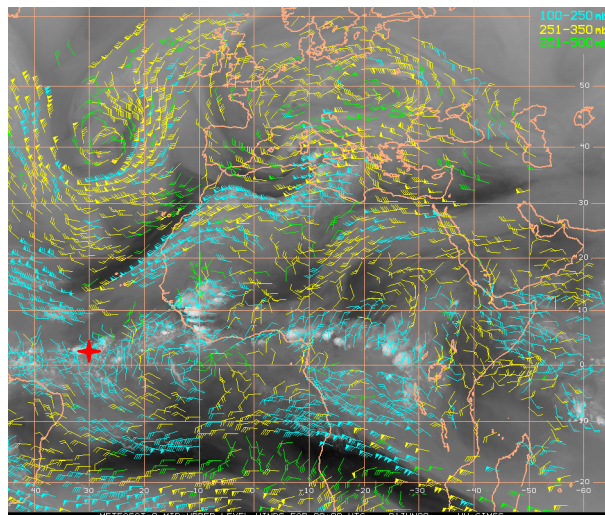
c)

Figure 2: a) Flight track of AF447 from 0145-0221 UTC 1 June 2009 reconstructed from ACARS data and deep MCS cloud locations (shaded) from infra-red imagery (Vasquez 2009). b) Infra-red imagery masked for cloud top temperatures < -75C valid at 0215 UTC 1 June 2009

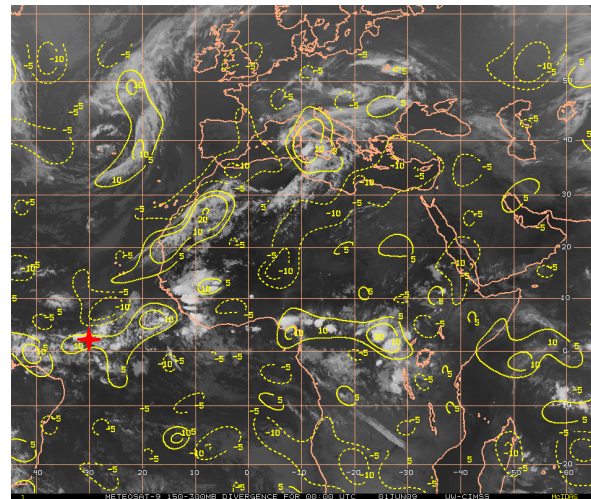
(BEA 2009). c) Cloud top temperature (celsius) categorized versus areal coverage (km²) and time (hr) (top) and minimum cloud top temperature versus time (hr) (bottom) for the period ~2 hours before the accident (BEA 2009).

3.2 Jet and Synoptic Scale Dynamics

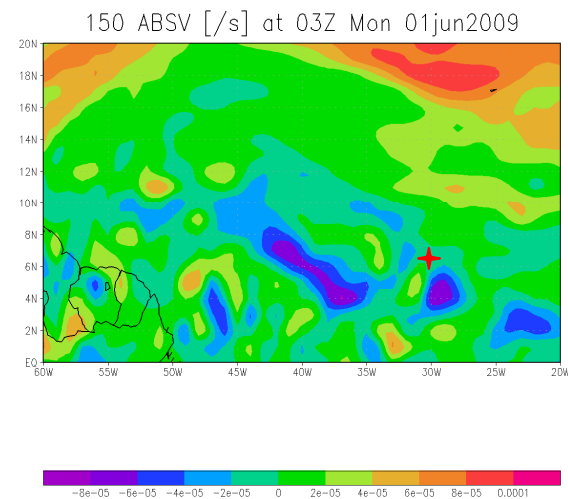
The jet structures between the upper tropical troposphere and lower tropical stratosphere were rather interesting during this time period. Figure 3 depicts the deep tropospheric and lower stratospheric cloud track-derived winds in three layers, i.e., 351-500 mb, 251-350 mb and 100-250 mb at 0000 UTC (CIMMS 2009). The region where AF447 was about to enter just before the accident approximately 2 hours later is just southeast of the subtropical jet streak (STJ) in Figure 3a. Note that AF447 would be located on the north side of the MCS already established at 0000 UTC. The blue arrows depicting the jet structure in the 100-250 mb layer are quite revealing in that the STJ clearly dips down in a cyclonic structure to just north of 6°N latitude. This is remarkably far south for the STJ and the clear slot just to the north of AF447's position at 0200 UTC indicates strong jet-induced subsidence flanking the northern side of the second MCS. Figure 3b's depiction of 150-300 mb mass convergence in this region supports descent and clearing along the southeastern flank of the STJ's exit region where it approaches the second MCS. This indicates northwesterly confluent flow with the STJ near the subtropical tropopause. Such descending flow is consistent with the collapsing of the second MCS about the time AF447 flew through it. In Figure 3c one can see that there is a swath of negative absolute vorticity to the right side of the STJ exit region at 150 mb thus also supporting the concept of low inertial stability above the subtropical tropopause near the accident location.



a)



b)



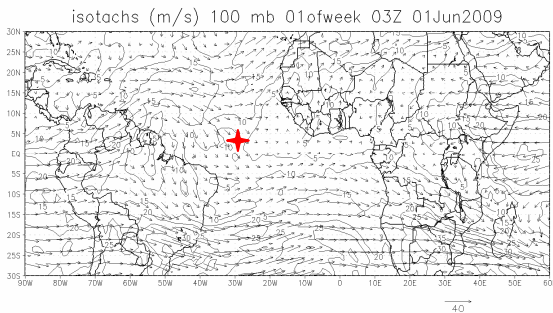
c)

Figure 3: a) Cloud track derived wind barbs from water vapor imagery for 100-250 mb (blue), 251-350 mb (yellow) and 351-500 mb (green) vapor valid at 0000 UTC 1 June 2009 over the southern North Atlantic Ocean and Africa (CIMMS 2009). b) Mass divergence ($s^{-1} \times 10^{-5}$) derived from cloud track derived winds valid at 0000 UTC 1 June 2009 (CIMMS 2009). c) GFS simulated absolute vorticity ($s^{-1} \times 10^{-5}$) valid at 0300 UTC 1 June 2009.

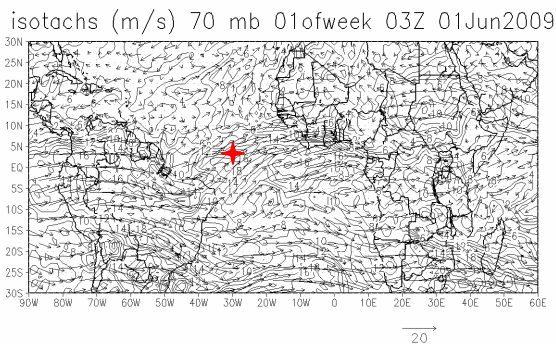
3.3 GFS Simulations

More detailed insight into the fine scale vertically varying atmospheric structure near AF447's final location will now be gleaned from GFS simulated fields from the 0000 UTC 2009 GFS simulation cycle. Figures 4a-b depict the 0300 UTC 1 June 2009 simulated 100 mb and 70 mb isotachs and wind vectors, respectively. Clearly evident in proximity to the accident location (just ~40 minutes earlier) is a pronounced shearing zone in the vertical between the upper part of the STJ and lower part of the tropical jet (TJ) within the tropical stratosphere over the accident location. The rather robust TJ at 70 mb with velocities ~18 m/s from the southwest is overrunning the weaker northwesterly STJ with velocities ~10 m/s at 0300 UTC. This indicates the likelihood of substantial velocity and directional wind velocity shear within the lower tropical stratosphere near the top of the second MCS and in the immediate vicinity of AF447's final position at ~0220 UTC. Thus increased vertical wind shear is in proximity to a weakening expansive and very high MCS accompanying the likely juxtaposition of the STJ and TJ tropopause near the accident location and time. Figure 5 supports the fact that the accident location was also a region of colder air at 100 mb based on the GFS simulated lower stratospheric temperatures. Hence the stratospheric shear zone lies just north of the second MCS in a region of colder air relative to the AF447 location coming off the Brazilian Coast beneath the tropical tropopause and likely above the subtropical tropopause.

Figure 4: a) GFS simulated 100 mb wind isotachs (m/s) and vectors valid at 0300 UTC 1 June 2009. b) GFS simulated 70 mb wind isotachs (m/s) and vectors valid at 0300 UTC 1 June 2009 (NOMADS 2009).



a)



b)

3.4 Adjusted SBFN Sounding Structure

The implications of these features for the vertical atmospheric structure just downstream from the second MCS at ~0200 UTC can only be estimated inferentially. However there is proof for the vertically intersecting STJ and TJ as well as relatively cold air sandwiched in between near 4°N and 30°W at the time of the AF447 accident. To try and build/estimate a sounding at this time and location of the accident we will employ the Fernando De Noronha (SBFN) sounding at 0000 UTC ~1 hour's flight time to the south-southwest of the AF447 accident and subsequently adjust it for the colder air at 100 mb relative to the 0000 UTC SBFN sounding simulated by the GFS near the accident location at 0300 UTC. This original SBFN sounding and its adjustment for the colder air at 100 mb simulated 3 hours later to the north-northeast can be seen depicted in Figure 6a. Note that the 0000 UTC SBFN lapse rate between 150 and 100 mb is ~4C/km where one could anticipate the STJ tropopause. A very shallow inversion in this layer

near ~125 mb signals the STJ tropopause. Above this is a much more stable layer with a second inversion in between 100 and 70 mb probably reflecting the tropical tropopause with little temperature decrease over the deeper 30 mb layer. When this sounding is adjusted for the estimated ~2C cooling at 100 mb north-northeast of SBFN it acts to decrease the static stability by ~1C/km over the accident location between 150 and 100 mb and increase the static stability by the same amount in the layer in between 150 and 100 mb. As can be seen in Figure 6b, the accident location was already a region straddling a huge decrease in bulk Richardson number at 0000 UTC from ~89 << 10 over the southern North Atlantic with values <1 just north of the accident location. It is clear that AF447 would be entering a zone of Richardson number decrease that could be even greater by 0300 UTC if the simulated GFS temperatures are correct near the accident location. This there is supporting evidence for a zone of low if not near critical Richardson number values just below the anvils over

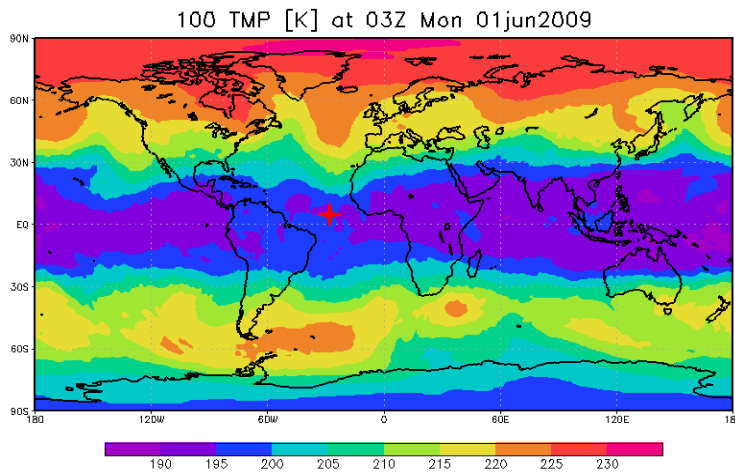
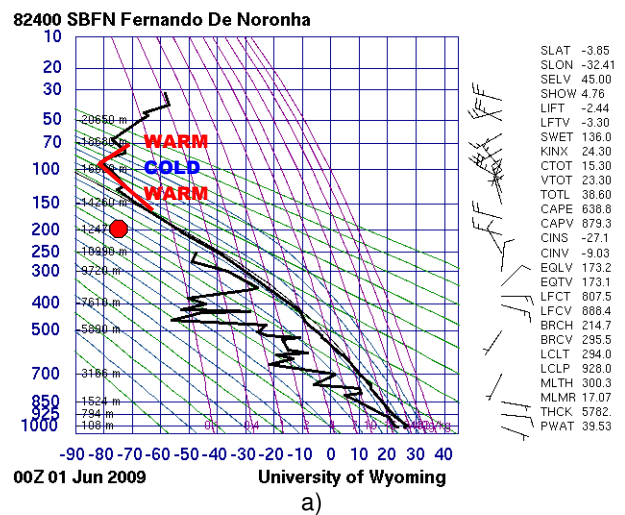


Figure 5: GFS simulated 100 mb temperatures (K) valid at 0300 UTC 1 June 2009 (NOMADS 2009).

the region and time of the AF447 accident. As can be inferred from Figure 6b such a region could be favorable for shearing instability if the convective cells perturbed the tropical tropopause resulting in Kelvin-Helmholtz wave genesis. Furthermore the wave breaking could be occurring in a region in-between the two tropopause where the wind vector shears dramatically from northwest to southwest thus establishing an environment for descending winds arriving from a different direction possibly triggering vortex structures accompanying vertically varying vertical vorticity as hypothesized by Vollmer (2008) and Clark et al. (2000).



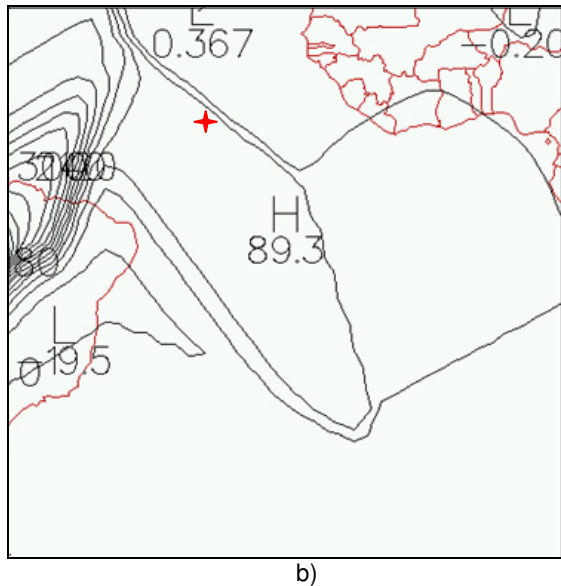


Figure 6: a) Fernando De Noronha sounding valid at 0000 UTC 1 June 2009. Note adjustments (red line) for 0300 UTC temperatures in the 70 – 150 mb layer over the accident location at 0300 UTC and altitude of aircraft (red circle). b) Bulk Richardson number in the layer from 100-150 mb (red triangle is accident location) (Plymouth State 2009).

4. Hypothesis for Possible Descending Turbulent Vortices

Based upon the work of Vollmer (2008) and Clark et al. (2000) one could employ the analyses described early inferentially to create a possible paradigm for significant turbulence that may have contributed to the AF447 accident:

- 1) A double tropopause forms in which a cold unstable layer is “sandwiched” in between relatively warm stable layers
- 2) Convective forcing results in Kelvin-Helmholtz waves forming in the unstable shear layer where warm air transitions to colder air and the inertial stability is low
- 3) Parcels influenced by the waves in the cold shear layer are lifted into the upper warm layer, become statically neutral and decelerate
- 4) Parcels entrain new momentum as they are stretched vertically and a spinning microvortex forms in the upper stable tropopause layer
- 5) The coldest parcels descend and accelerate as they become negatively buoyant through the lower tropopause
- 6) They descend, warm and stabilize as they transport the upper-level microvortex and cold air from aloft

into a different wind shear zone

- 7) Result is a rogue vortex which interacts with different wind field and becomes a local source of eddy dissipation/turbulence and an aircraft hazard upon impact.

5. CONCLUSION

Juxtaposed jets and massive convective systems existed just prior and during the AF447 accident. A possible contributing factor to the accident may have been aviation turbulence. We have developed a paradigm in this extended abstract describing how the unique environment in the lower stratosphere at the time of this accident may have contributed to extreme aviation turbulence.

The paradigm requires that deep convection impulsively forced the organization of Kelvin-Helmholtz waves in between two juxtaposed tropopause where low Richardson numbers and low inertial stability exist. The assumption includes lifting by the waves until negatively buoyancy is attained and parcels acquire/entrain momentum from the differing flow aloft thus creating high amounts of horizontal and vertical vorticity. As these parcels are dragged downwards by negative buoyancy they become turbulent in the layer where the aircraft was located thus producing a potential hazard to flight control.

6. ACKNOWLEDGEMENTS

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