A close look at a severe mesoscale convective system surrounding the Air France 447 crash

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Abstract. To investigate the degree of severity of cloud–top features of the severe Mesoscale Convective System (MCS) might be associated with the Air France (AF) Flight 447 crashed in the tropical Atlantic Ocean on 01 June 2009 from 02:00 to 02:15 UTC, we have used the multispectral data of Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) onboard Meteosat-9 based on detection of overshooting tops. Two SEVIRI water vapor (WV) band images (6.2µm and 7.3µm) and the SEVRI thermal infrared (IR) band images (10.8 µm) provided information about structure and microphysics of MCS cloudiness. Overall, the results obtained suggest that existence of a severe Cloud cluster (MSC) on its route. A striking feature is that this Cloud cluster resulted from the merging of four smaller clusters and its extension from west to east over around 400 km – one which could be potential responsible for the extremeness of the event by itself. Such clusters produced the coldest cloud tops (~minus 81 ºC or colder) above MCS and organized into tight curved areas around the center (i.e., a doughnut or a cold-ring shaped form). As deep convection continued to developed, the disturbance gradually moved westward and began to break away from the MCS. Another conclusion is that the coldest pixels of convection (195K) exhibited brightness temperature difference (WV6.2-WV7.3) values as high +6. Thus, strong overshooting tops are often related to severe weather or strong updraft.

Key words: Meteosat-9, Cloud clusters, overshooting tops, severe weather.

1. Introduction

On the early morning hours on 1 June 2009, Air France (AF) Flight # 447 descended in to the tropical Atlantic Ocean at the approximate location of 2°59′N 30°35′W, while en route from Rio de Janeiro, Brazil to Paris, France. It is still a mystery why the aircraft fell out of the sky, because its black box was not found. Since that there has been much speculation, but no evidence, that weather hazards (e.g., icing, lightning, turbulence) have played a role in the occurrence. Aumann *et al.* (2009) suggest that a Mesoescale Convective System (MCS) embedded in the Atlantic Intertropical Convergence Zone (ITCZ) producing overshooting tops might be associated with the accident of AF 447.

When AF 447 departed Rio de Janeiro late on 31 May 2009 it encountered adverse atmospheric conditions (e.g., MCS, jet streams, stratification) over the southern part of the tropical Atlantic Ocean. Based on a detailed meteorological analysis on the internet, Vasquez (2009) showed that that lightning, icing, hail and warm sink have not been ruled out as contributing to or being the dominant elements of this accident. These factors do not act independently and are also related with energy transfer in the atmosphere (Dutcher, 2003), which is downscale from the hemispheric scale analysis should begin there, gradually working downscale (e.g., synoptic scale) and inward towards the smallest scale (e.g., mesoscale).

The observing, forecasting and briefing facilities are available to the pilots by radio from any flight service station. There is a two-fold problem for the pilots. First, they have little weather information as they fly over the oceans, which are where some of the worst turbulence encounters occur. Typically, onboard radars are often the only source of information over these remote regions. They do not directly measure turbulence. Second, with thunderstorms comes the presents of wind shear associated with downbursts (e.g., microburst) as well as turbulence. The latter is often associated with gravity waves (Trier and Sharman, 2009). In addition, thunderstorms can also cause erroneous readings from altimeter indicator. Thus, something along these lines might help explain what flight 447 encountered, but this is pure speculation.

To investigate the degree of severity of cloud–top features of the severe MCS might be associated with the Air France Flight # 447 crashed in the tropical Atlantic Ocean on 01 June 2009 from 02:00 to 02:15 UTC, we have used the multispectral data of Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) onboard Meteosat-9 based on detection of overshooting tops. Two SEVIRI water vapor (WV) band images (6.2μm and 7.3μm) and the SEVIRI thermal infrared (IR) band images (10.8 μm) provided information about features of MCS cloudiness.

2. Material and Methods

2.1 Meteosat data, processing, visualization and analysis tools at the laboratory for analyzing and processing Satellite images (LAPIS)

In May 2007, the LAPIS had installed the EUMETCast system – a new C-band satellite reception facility to collect data from SEVIRI, an electro-optical sensor onboard the Meteosat Second Generation (MSG) satellite. The SEVIRI Direct Broadcasting (DB) system produces real-time wide-spectrum geolocated and calibrated (level 1.5 HRIT) products for short-term applications, nowcasting use in Brazil. All the data are archived in the archiving system with satellite image database service through http://www.lapismet.com (Fig. 1).

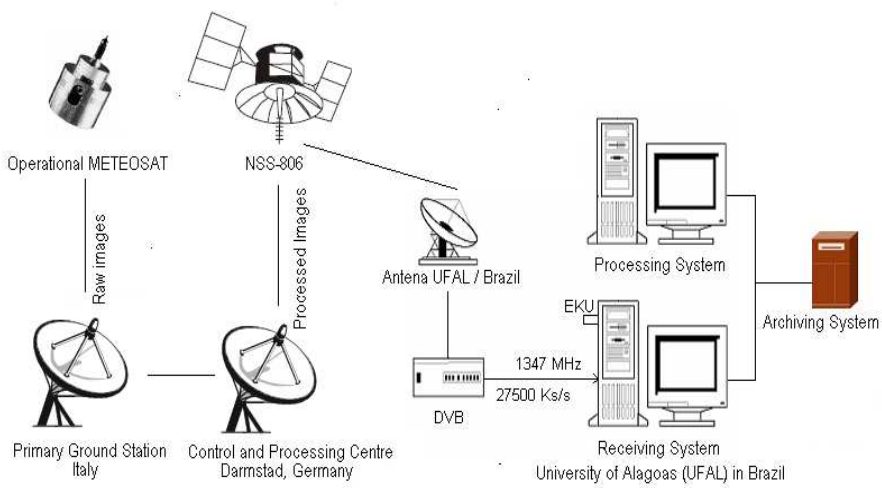

Figure 1. Overview of the broadcasting ground reception and processing system at the University of Alagoas (UFAL) in Brazil.

The LAPIS tool visualization application provides a way to process, visualize and analyze 1.5 HRIT data. This tool is based on open source codes, focused on analyzing convective storms. The available products are: red-green-blue (RGB) day microphysical", "convective storms and "air mass" color compositions to qualitatively identify the cloud-top microphysical characteristics on the basis of the combinations of radiances measured in different bands.

2.2 MSG infrared imagery – Brightness Temperature (BT)

Storms research has focused on understanding cloud features of individual events to identify their intensities in what is termed a "nowcasting" approach. Multispectral satellite analysis has demonstrated its ability to depict cloud-top features, especially in places where conventional data are either sparse or unavailable. Heymsfield and Blackmer (1987) made a comprehensive study to understand the mechanisms responsible for the formation of the so called *enhanced-V feature* (recently referred to as *cold-U/V feature*), found at tops of some of the deep convective storms, discussing nine convective cases with different features from 1979 to 1982 to describe the phenomenon. The cold-U/V shape occurred for all the storms, except one. The severity criteria of the U.S. National Weather Service for a convective storm can be classified as severe if it presents on the following characteristics: a) tornado, b) wind gusts ≥ 50 knots (~ 25 m s^{-1}) and c) hailstones with diameter ≥ ¾ inch (~ 2 cm) (http://www.weather.gov/glossary/index.php?letter=t) (Fig. 2).

It is also well documented (Schmetz et al., 2002; Barbosa and Ertürk 2009; Ertürk and Barbosa 2009) that cloud top BT directly related to the cloud top level environment temperature – valid only for opaque clouds (i.e., *cumulonimbus* clouds) and state of thermal equilibrium between the cloud and its environment. In particular, critical to the success of any attempt to spot the satellite-based storm cell is the BT isotherm of~ 240 – 230 K. The atmosphere must already be conditionally unstable and the large-scale dynamics must be supportive of vertical cloud development. Schmetz et al. (2002) showed that the positive brightness temperature differences (BTD) between WV and IR window bands, hereafter referred to as BTD (WV-IR), using the first generation Meteosat satellite data, while Setvak et al (2008) presented evolution of this phenomenon using the MSG SEVIRI data. These positive differences may result from two possible mechanisms: either local lower stratospheric moisture (LSM) generation by the storms themselves, or from advection from remote sources. Regardless of the LSM source, the positive BTD (WV-IR) values can be used as a proxy for very deep convective clouds (with overshooting tops).

3. Results

3.1 The cloud top features of the 1 June 2009 storms

According to Bureau d'Enquêtes et d'Analyses (BEA) Interim Report states the last communication from the AF 447 was at 02:14 UTC. When the aircraft likely traversed a broad area of disturbed weather embedded within the Atlantic ITCZ, possibly aided by a tropical wave traversing the region during this time. The storm pattern at 02:15 UTC in the IR 10.8 band of the Meteosat-9 image with the aircraft path is shown in Fig.3. Deep convective bursts (MSC) with cloud tops colder than 198K are detected within the region between 2º N to 4º N latitude and 25º W to 35ºW longitude. Deep convection organized into tight curved bands around the center, the disturbance gradually moved from west to east over around 400 km – one which could be potential responsible for the extremeness of the event by itself. However, increasing westerly upper-level shear gradually displaced the convection to the west of the low-level center and by 02:00 UTC, deep convection began to re-energize near well-defined low-level center. A combination of westerly upper-level shear and wet mid-tropospheric air enhanced the development of deep convection to the region (Fig 2). It induces optimal large-scale forcing for local-scale upward movements over the region. Locally, the Fernando De Noronha (SBFN) sounding at 0000 UTC ~one hour earlier the flight time to the AF 447 accident is shown in Figure 3a. This SBFN sounding display its lapse rate between 150 and 100 mb is ~4°C/km.

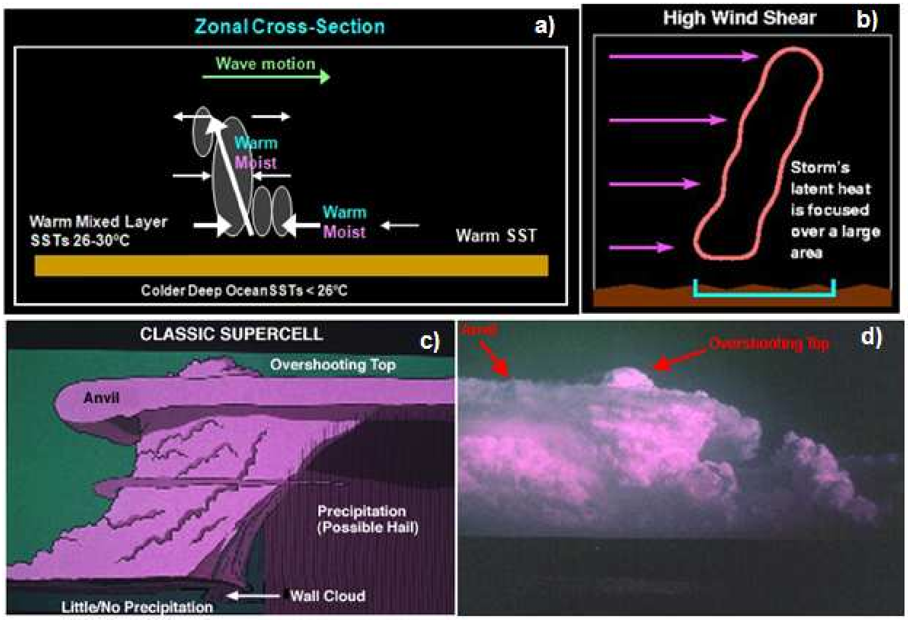

Figure 2. Wet phase is characterized by an "envelope" of deep convection composed of numerous higher frequency "events" (e.g., equatorial waves) that propagate both east and west through the envelope (a). An increase in vertical wind shear can tilt the Cb, spreading the warm core column over a larger area, which increases the minimum surface pressure (b). Severe thunderstorms usually extend all the way to the tropopause (c) and can be seen in photo as storms producing overshooting tops (d).

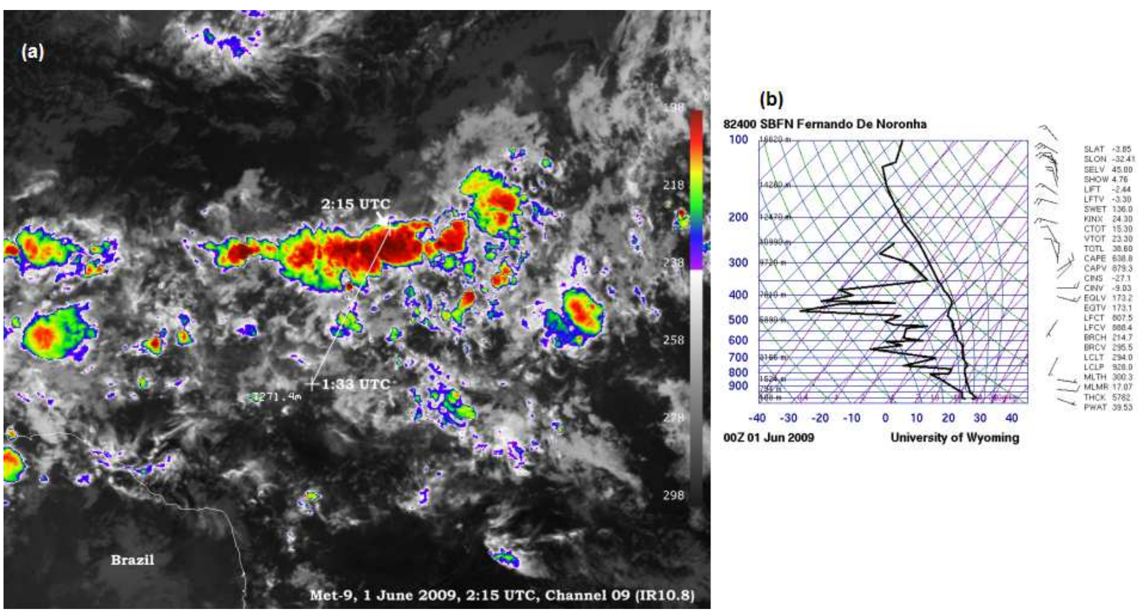

Figure 3. Cloud-top features seen in the enhanced SEVIRI IR10.8 band image in the tropical Atlantic Ocean on 01 June 2009 02:15 UTC (a). 82400 SBFN Fernando de Noronha sounding valid at 0000 UTC on 01 June 2009 (b).

A closer look of the enhanced IR image of cloud cluster provides a more detail in Figure 4 at 2:00 UTC and Figure 5 at 2:15 UTC. There are four active areas of Cloud cluster that developed very rapidly over the period from 02:00 to 02:15 UTC when the minimum cloud top IR brightness temperature is -81º C or colder (light purple color enhancement). Maddox

(1980) defined an MCS is one of the typical Cloud clusters that lasts for six hours or more over of the region (~100,000 square kilometers) where cloud top temperature is –32°C or below.

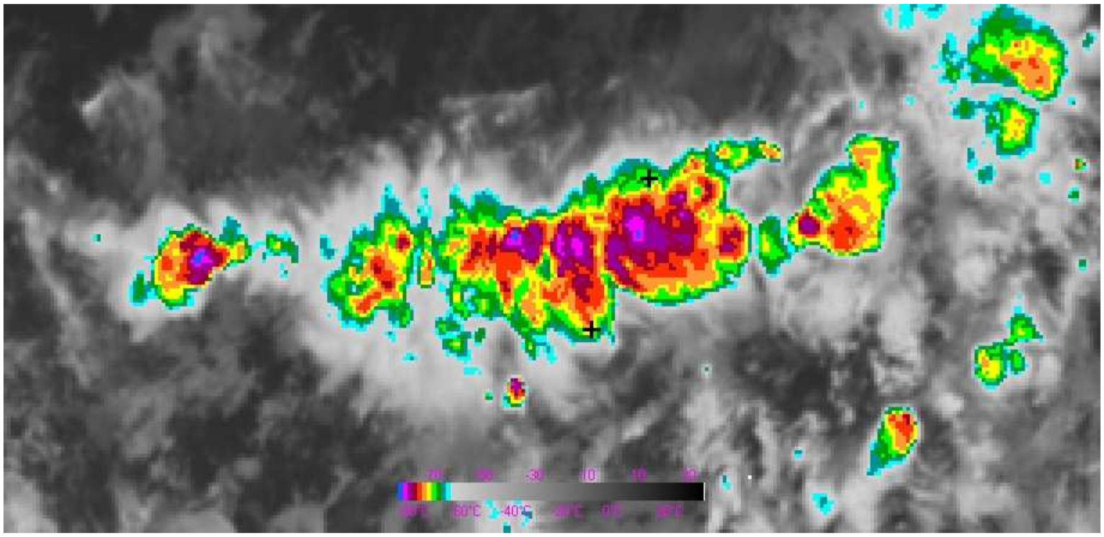

Figure 4. The cloud-top shows "cold ring" is related to severe weather at 02:00 UTC.

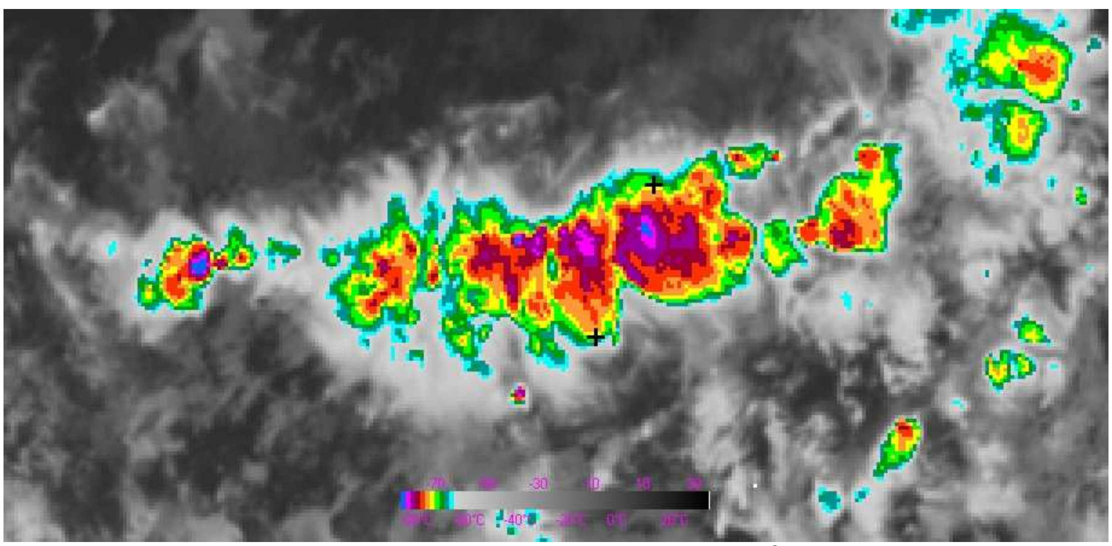

Figure 5. Deep convective bursts with cloud-tops colder than -81^{o} C (blue color) at 2:15 UTC.

A minimum of minus 81°C or colder indicates that the updrafts in these Cloud clusters must have been very strong with significant overshooting of the tops into the stratosphere. Of particular interest is their shape pattern at 02:15 UTC – they appear near 1.75º N latitude and 31.7º West longitude in the form of a doughnut or a cold-ring shaped storm. The cold-ring shaped storm may have been further enhanced by increased local availability of water vapor as it traversed the higher SST values within the ITCZ. The cold-ring shaped storm is maintained but if the vertical shear becomes large or the wind speed increases. In fact, these conditions, in turn, may be viewed as reflecting the integrated impact of strong winds at surface and an updraft of the warm temperatures from warm SST associated with the intensity of convective activity. Figure 6 shows daily OSI-SAF (Ocean and Sea Ice Satellite Application Facility) SST image displayed using the LAPIS tool, on 1 June 2009. The SSTs in adjacent areas of the eastern coast of Northeastern Brazil and the northwestern coast of Africa varies between 28 ºC and 30 ºC. Although in isolated areas over the tropical Atlantic

Ocean are registered higher values than the last one. This SST product has three components namely; GOES-East, MSG, NOAA-HL derived SSTs (Météo-France, 2005a).

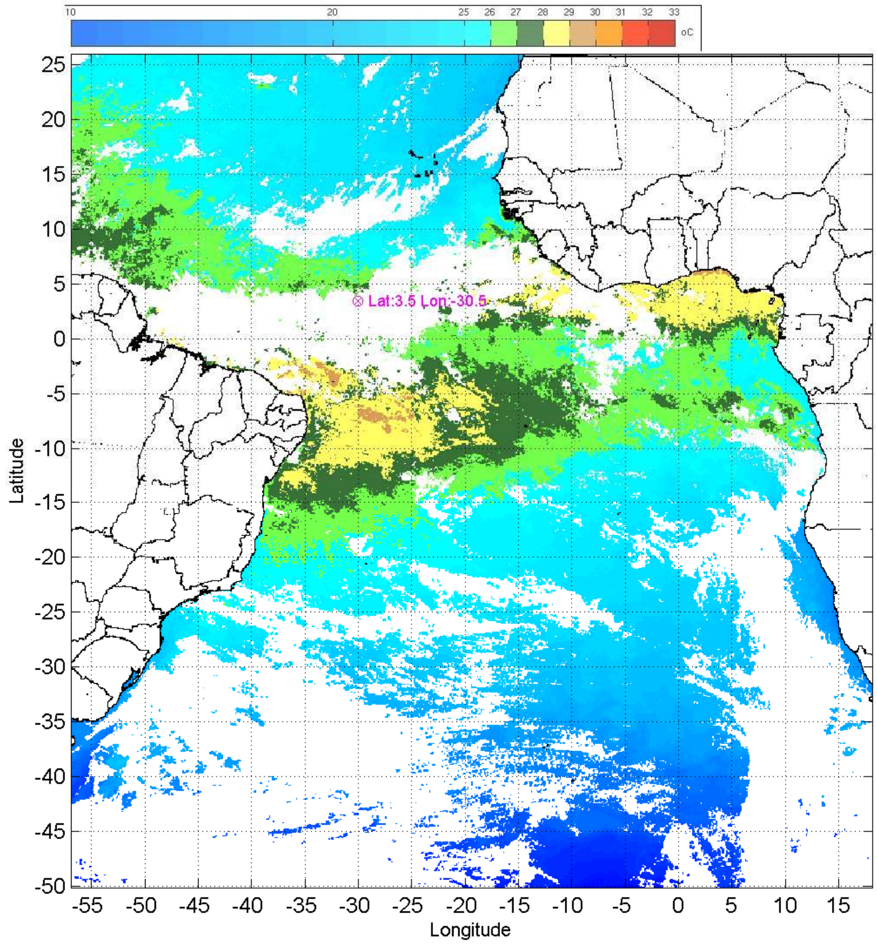

Figure 6. Sea Surface Temperature (SST) image displayed on 1 June 2009 at 00:00 UTC and the position of the AF 447 (3.5º S; 30.5ºW).

The physical mechanisms associated to overshooting tops are well documented. These were studied on the pioneering work of Fritz and Laszlo (1993) and from few authors since. The BTD (WV6.2-WV7.3) approach described above can be applied for detection of the overshooting tops. Figure 6 shows scatterplot, over the 2º N to 4º N latitude and 25º W to 35º W longitude, of BT (IR10.8) against BTD (WV6.2-WV7.3) at 02:00 UTC. Before discussing the results, it is important to understand how to interpret the figure. Results corresponding to pixels characterized by BTD (WV6.2-WV7.3) >0, which are warmer moisture layer adds additional radiance in the WV bands over the thermal emission originating from the cold storm top, indicate that the WV band is warmer (BT higher) as compared to the IR window bands. These pixels are therefore identified as the overshooting tops. It is important to note that we define the "overshooting tops" as the pixels in which an air parcel absorbed significant amounts of moisture above most of the storm. Consequently, these positive pixels are identified as a possible severity of the storm. In general, Figure 7 shows that the distribution of coldest pixels of convection (minus 81°C) exhibited BTD (WV6.2-WV7.3) values as high +6 from 02:00 to 02:15 UTC, suggesting strong updraft (red dots).

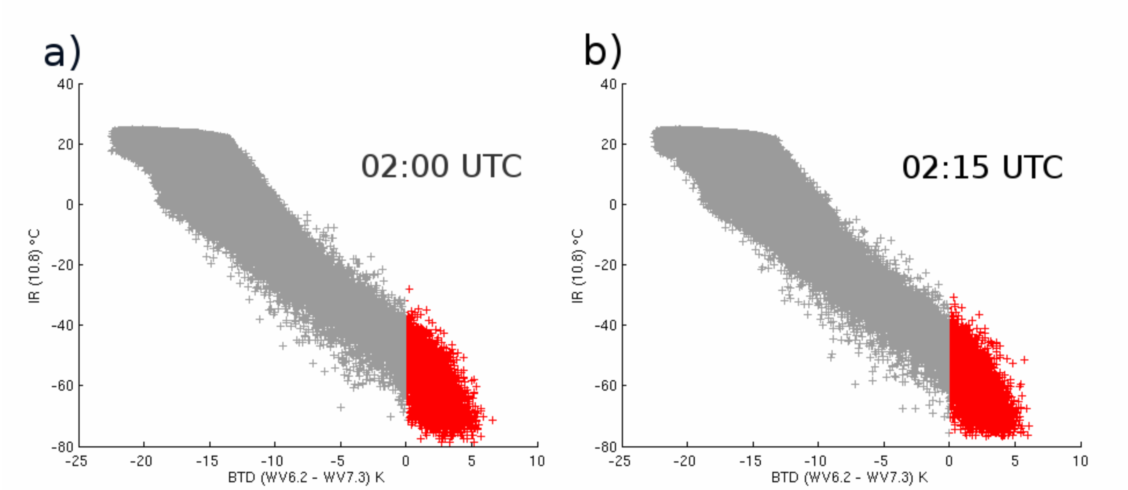

Figure 7. The distribution of the BT (IR10.8 pixels) against BTD (WV6.2-WV7.3 pixels) scatterplots over the 2º N to 4º N latitude and 25º W to 35º W longitude (based on Fig.4 and Fig. 5 image pixels) from 02:00 to 02:15 UTC. The red dots delimited by the positive values of BTD (WV6.2-WV7.3 pixels).

4. Conclusions

In this research, we have thus used the SEVIRI data onboard Meteosat-9 available at the LAPIS to assess the degree of severity of cloud–top features of the MSC might be associated with the AF 447 crashed in the tropical Atlantic Ocean on 01 June 2009, lasting approximately from 02:00 to 02:15 UTC. Overall, the results obtained suggest that existence of a severe Cloud cluster (MSC) on its route. A striking feature is that this Cloud cluster resulted from the merging of four smaller clusters and its extension from west to east over around 400 km – one which could be potential responsible for the extremeness of the event by itself. Such clusters produced the coldest cloud tops (~minus 81 ºC or colder) above MSC and organized into tight curved areas around the center (i.e., a doughnut or a cold-ring shaped form). As deep convection continued to developed, the disturbance gradually moved westward and began to break away from the MCS. Another conclusion is that the coldest pixels of convection (195K) exhibited BTD (WV6.2-WV7.3) values as high +6. These results are in line with other research (Aumann, 2009), which have stressed Tropause Penetrating Convection (TPC) might be associated with the AF 447 crash. However, as mentioned above, such Cloud clusters were severe to justify the event by themselves.

Acknowledgments

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