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Prediction and Warning of Transported Convective Turbulence in Long-Haul Aircraft Operations

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Introduction

The occurrence of unexpected severe turbulence, whose origin is believed to be convective systems well upstream from commercial jet aircraft, has been reported in a number of instances, resulting in injuries to flight crews or passengers. One incident involving a Hawaiian Airlines (HA) A330 jet near Vanuatu in the South Pacific on 26 March 2012 initiated a research effort by WxOps, Inc. to determine if such events can be anticipated, and the flight crews warned of impending turbulence during long duration flights, so that preventative measures can be taken. In the Vanuatu case, only patchy cirrus clouds were present, but a convective storm had formed six hours earlier and dissipated shortly thereafter. It was observed that by tracking the motion of the storm remnants using the NOAA Air Resources Laboratory (ARL) Hybrid Single Particle Trajectory (HYSPLIT) model with upper level winds from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), the leading edge of the passive cloud outline intersected the route of the HA 452 flight near the location of the turbulence event (Figure 1). Based on this analysis, it was felt that the turbulence could have been predicted and the flight crew warned as early as 3 hours prior to the event. Due to the long period of time and considerable distance between formation of the convective cloud and the turbulence encounter, we refer to this as "transported turbulence" (TT).

Frequency of Transported Turbulence

An analysis of the National Transportation Safety Board (NTSB) database of inflight accidents over a 20-year period (1995-2014) was conducted to estimate how frequently such transported turbulence events may have occurred during that period. Only incidents involving large, commercial jets (Part 121 class) were considered. Out of 219 total cases, 180 were weather-related accidents/incidents. Most of these cases involved injuries to crew and/or passengers. Analysis of likely turbulence causes for the NTSB cases was determined from a combination of Geostationary Operational Environmental Satellite (GOES) infrared (IR) imagery, ground-based radar (when available), flight crew narratives, and the NTSB conclusions.

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A graph of the frequency of all causes is shown in the bar graph in Figure 2. Of the weather related events, 92 (51%) were due to convection, 76 (42%) were due to Clear Air Turbulence (CAT) (which includes mountain waves), 8 (4%) were caused by icing, and 2 (1%) each were a result of crosswinds and wake turbulence.

A breakdown of the convective-related events is shown in Figure 3. The predominant cause was Inadvertent Flight Into Convection (IFIC) which accounted for 55 (60%), followed by Near-Cloud Turbulence (NCT) with 32 (35%). It was sometimes difficult to classify some cases into these two categories due to uncertainty in aircraft location and lack of details in the accident narratives. The remaining 5% did not fit into either category and are identified as Transported Turbulence. These results are consistent with a larger study of inflight NCT based on Eddy Dissipation Rate (EDR) data from commercial aircraft (Lane et al. 2012) that determined a probability of 4% for turbulence beyond a distance of 20 km from a convective storm.

An example of a TT encounter is shown in Figure 4. A B777 aircraft was in route to Sao Paulo, Brazil from Miami when it encountered severe turbulence at Flight Leve (FL) 370 at 0515 UTC on 25 July 2004 south of the easternmost portion of Cuba, over the Caribbean Sea. The GOES-12 infrared (IR) image about 5 1/2 hours earlier (2345 UTC, 24 July 2004) (Figure 4) showed a strong cluster of storms over eastern Cuba. A 5-hr HYSPLIT forward trajectory (red) for FL390 has its end point close to the location of the turbulence. The 0430 UTC GOES IR image (Figure 5) indicated that the convection had dissipated, leaving only cirrus plumes in the area.

Characteristics of Transported Turbulence

A summary of the characteristics of Transported Turbulence based on cases observed so far is as follows:

1. Occurs in cloud-free or partly cloudy conditions at flight level
2. Location is downwind from distant convection as indicated by visual observations or radar
3. There is rapid onset to the turbulence with no prior warning
4. Moderate-severe intensity, often described as "jolts"
5. Short duration (<1 min often 5 sec or less)
6. Flight level winds <30 kt
7. Not reported by other aircraft

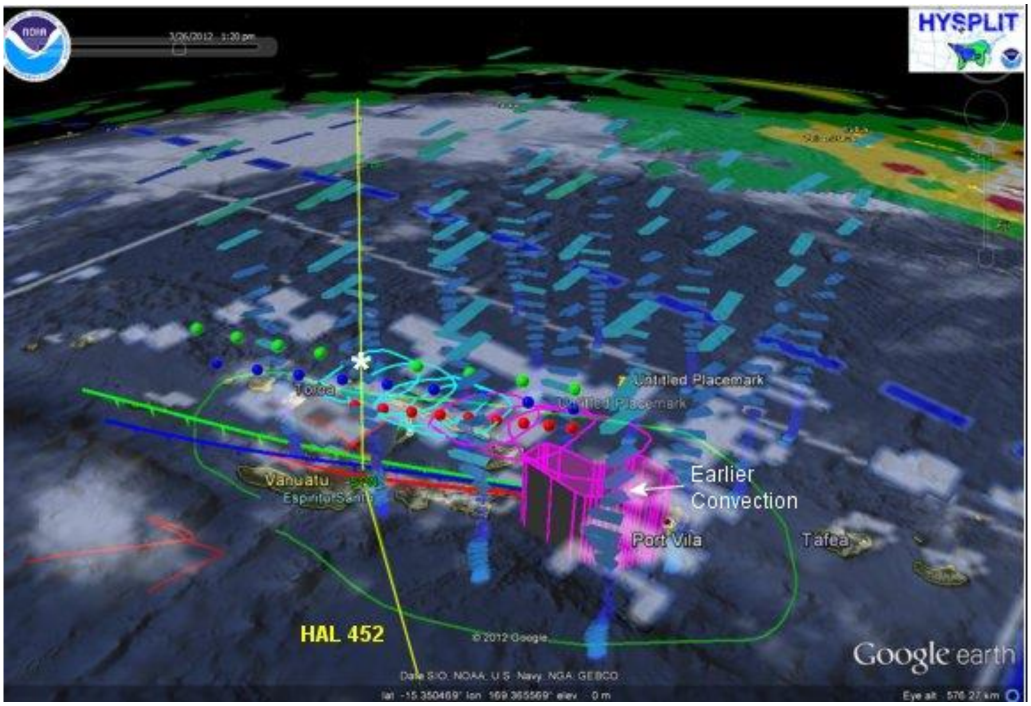

Figure 1. *Potential unpredicted turbulence (cyan contours) associated with advection downwind of a thunderstorms event (magenta). An A330 aircraft encountered severe turbulence (*) just NE of Vanuatu in the South Pacific. Standard predictions for CAT indicated a smooth flight (along yellow flight track). HYSPLIT isentropic trajectories (dots) at flight level ± 2kft suggest how advection can transport CAT or its precursors downwind at high altitudes. The stacked vectors in this 3-dimensional OpsTablet® display show winds aloft from the NOAA NCEP Global Forecast System (GFS). Color shading at top indicates turbulence potential from Jeppesen turbulence product*

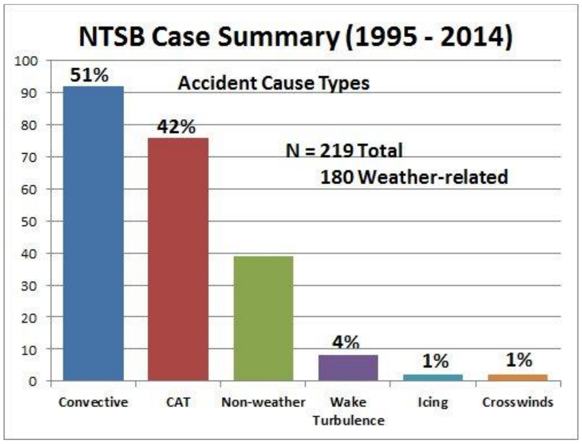

Figure 2. *Summary of accident causes from the National Transportation Safety Board (NTSB) data base for the period 1995-2014. Cause percentages (tops of bars) are relative to total weather related cases (N=180). Results are based on NTSB analyses, satellite, and radar (when available).*

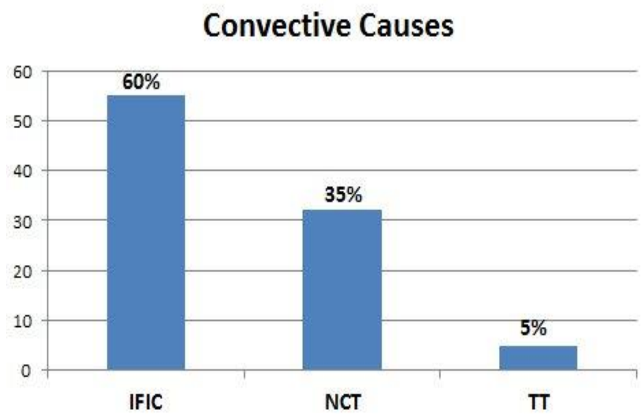

Figure 3. *Percentage of convective type accidents (N=92) as a result of Inadvertent Flight Into Convection (IFIC), Near-Cloud Turbulence (NCT) or Transported Turbulence (TT) for the period 1995-2014.*

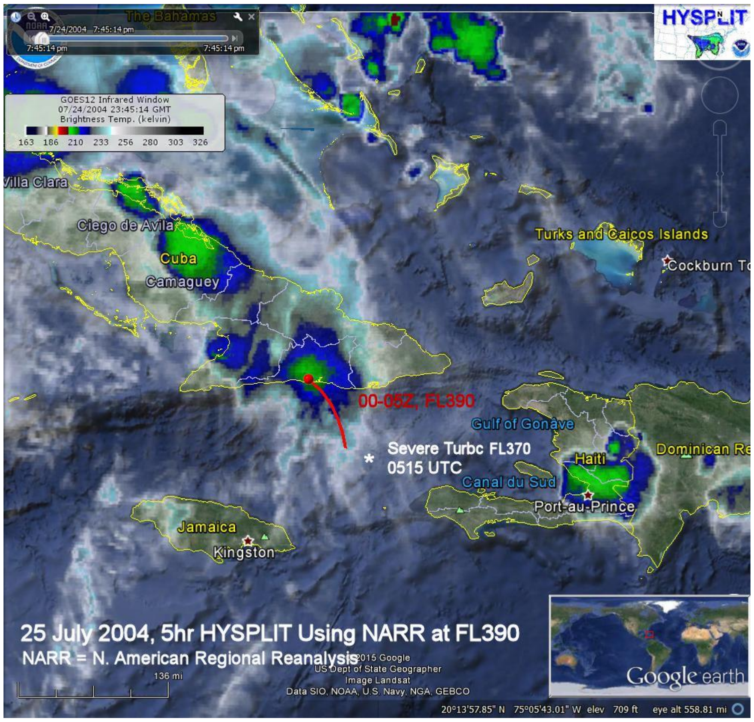

Figure 4. *GOES enhanced infrared at 2345 UTC, 24 July 2004 showing a cluster of convective storms over eastern Cuba. A B777 aircraft encountered moderate-severe turbulence (*) at 0515 UTC, about 5 ½ hours later. A 5-hr HYSPLIT forward trajectory (red) from 00Z – 05Z terminates close to the site of the turbulence. (Image source: NOAA National Climate Data Center (NCDC))*

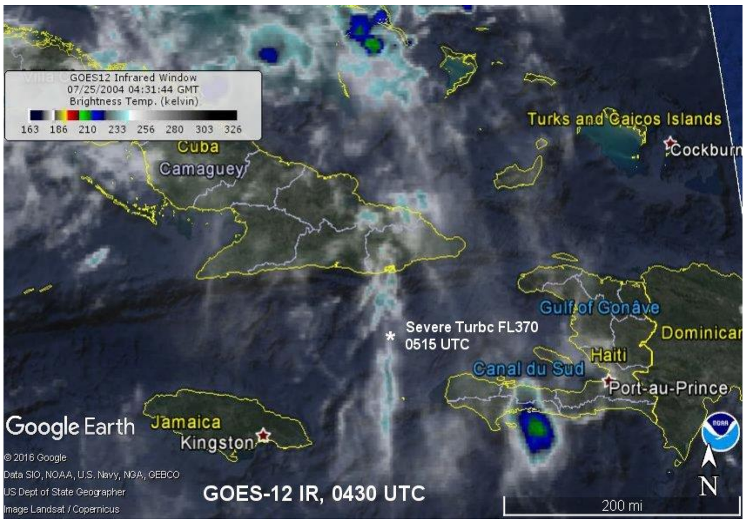

Figure 5. *GOES enhanced IR at 0430 UTC, 25 July 2004, about 45 min prior to the turbulence encounter. By this time, the convection had dissipated. (Image source: NOAA NCDC)*

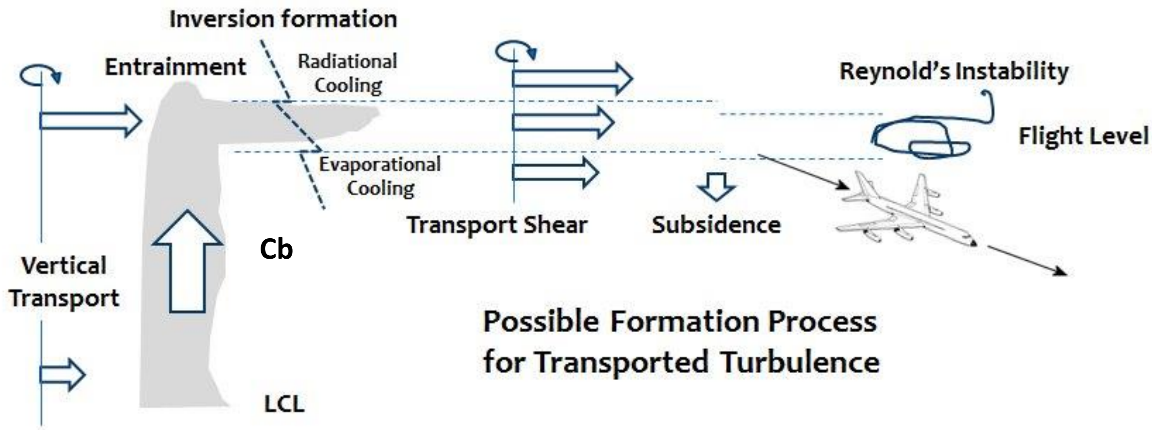

Figure 6. *Schematic showing possible processes downwind from thunderstorms that account for development of "transported turbulence."*

Possible Causes of TT

While it was previously mentioned that NCT can occur at rather long distances from the storm system, we do not believe that TT is produced in the same way. Figure 5 shows schematically how the TT might be generated. The convective cloud anvil spreads laterally, transporting vertical and horizontal shear as it does. Any turbulence at this point is fairly benign. Other processes involved as the cloud remnants drift downstream include sub-cloud evaporational cooling of the ice-water cloud due to an encounter with dry air aloft, and differential radiational cooling of the cloud layer. The result can be Reynolds instabilities which may create surprise turbulence for aircraft in the vicinity. There are few visible clues since most of the cloud has disappeared. This phenomenon may perhaps best be identified as "Far-Cloud Turbulence" due to the distance and time elapsed.

A Prototype Forecast Product for TT

The development of a prototype Transported Turbulence Product (TTP) by WxOps for use by air crews was based on the assumption that remnants of the cirrus anvil generated by strong convective systems could produce moderate to severe turbulence hours later, after being advected (transported) downstream, even if there was no visible cloud. Turbulence source regions were identified by locating convective cloud systems where satellite IR temperatures indicated cloud top heights had reached jet cruising altitudes and especially if they were accompanied by in-cloud lightning observed by ground-based time-of-arrival systems. The potential turbulence regions were then advected at hourly time steps with the NOAA Air Resources Laboratory's (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein, et al., 2015), using upper wind data from the Global Forecast System (GFS) model. The advantage of HYSPLIT is that once the original source area is identified, it can be tracked for long periods as a passive tracer, even if the clouds are not identifiable. A PC version of HYSPLIT was used which allows unlimited trajectories to be run. Segments of flight tracks intersected by the trajectories were identified as TTP and displayed in a format which allows immediate import into Common Operating Environment (COE) and Geographic Information Systems (GIS) now common in Electronic Flight Bag (EFB) equipment available on many commercial jets.

Inflight Testing: December 8-10, 2015

Several real-time examples were produced during 8-10 December 2015 for Hawaiian Airlines flights over the South Pacific enroute to and from Hawaii, Australia, and New Zealand. The analyses were run on the patented OpsTablet® system, which merges weather, navigation and geospatial information in a single workstation. The OpsTablet® currently uses Google Earth as a COE but will eventually transition to the open source World Wind Earth software.

One example of a TTP is shown in Figure 6 for December 8-9, 2015 for HA flight 451 from Honolulu, HI to Sydney, Australia. Several areas of strong convection were identified in the large region of deep convection south of the Equator. The source regions for TT (shown as polygons) were advected using HYSPLIT toward the flight track of HA 451. The two red circled portions of the route indicate flight segments where possible turbulence could be expected. Pilot reports indicated that light turbulence did occur during those segments where smooth flight was expected. Considering the long oceanic trajectory, perhaps light turbulence would have been a more likely outcome than moderate-severe. This test case was considered a partial success. Further tests will be conducted as the OpsTablet® systems are fielded.

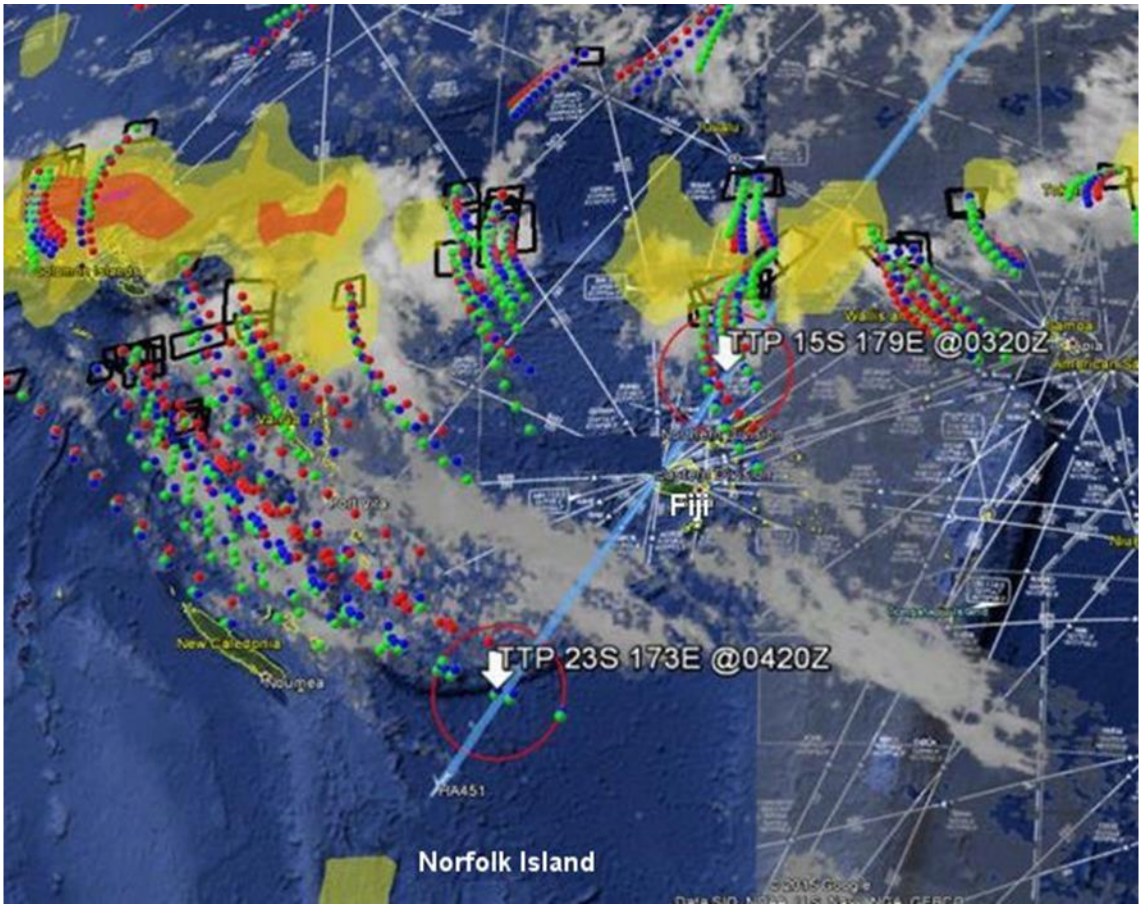

Figure 7. *Enlarged portion of OpsTablet® display used to generate TTP on 8-9 December 2015 for Hawaiian Flight 451 from Honolulu to Sydney, Australia. Possible turbulence source areas (black polygons) are advected by HYSPLIT model at three levels (colored balls). Potential inflight turbulence was located where trajectories cross flight track segments at appropriate times, and are indicated by two red circles.*

The potential for inflight use of the TTP has been recently enhanced by implementation of a faster satellite communications uplink (Inmarsat Swift Broadband (SBB)) to allow weather products to be rapidly displayed in the cockpit. Inflight tests of OpsTablet® using the new SBB in November 2016 on several Hawaiian B767 aircraft were successful, and the OpsTablet® is expected to become operational by mid-2017.

Summary and Future Work

Severe turbulence that occurs a considerable distance downwind from convective storms is a rare but significant hazard since it is unexpected and could lead to injuries to passengers and crew of jet aircraft. The prototype Transported Turbulence Product (TTP) developed by WxOps, Inc. has the potential to provide warnings to aircrews, especially on long-haul flights over oceanic routes. Proposed future work will involve assigning probability of moderate or greater turbulence, probability of detection and false alarm rates, and TTP automation, possibly in collaboration with future commercial partners.

Acknowledgments

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References

Lane, T. P., R. D. Sharman, S. B. Trier, R. G. Fovell, and J. K. Williams, 2012: Recent Advances in the Understanding of Near-Cloud Turbulence. *Bull. Amer. Meteor. Soc.,* **93**, 499-515.

Shipley, S.T., M.D. Spence, and G.P. Ellrod (2017) Prediction and warning of transported turbulence in long-haul aircraft operations, ***US Patent No. 9,564,055***, Filing date June 15, 2016.

Stein, A. F., R. R. Draxler, G. D. Rolph, B. J. B. Stunder, M. D. Cohen, and F. Ngan, 2015: NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System. *Bull. Amer. Meteor. Soc.,* **96**, 2059-2077.