Study of a possible wake vortex encounter of an aircraft over the Arabian Sea

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Abstract. A Jet airways aircraft encountered severe turbulence over the Arabian sea. We have performed high-resolution numerical simulations of the weather conditions at the time of the incident to ascertain the possible cause of the incident: atmospheric clear-air turbulence or a wake vortex encounter. Our analysis of the turbulence indices and parameters related to vortex propagation/decay at the flight altitude, suggests that wake-vortex encounter was the more likely cause of the incident.

1. Introduction
Atmospheric turbulence is one of the factors which can affect passenger comfort and flight safety. Other than pilot reports, clear-air turbulence (CAT) indices estimated from synoptic weather charts have been the traditional method of warning pilots. The evolution of high-resolution numerical weather models coupled with extensive observation networks has led to improvements in the prediction skill of these models. This has led to the feasibility of using high-resolution forecasts for not only turbulence forecasts but also optimization of air routes (See for example, study by Sharman et al [1]). Another possibility is of distinguishing the source or nature of the encounter. It is well known that CAT is not a single phenomena, but can be caused by different mechanisms, like Kelvin-Helmholtz instability, mountain waves, inertia-gravity waves etc. At times, even other phenomena like wake-vortex encounters at cruise level are reported as CAT in the absence of accurate first-hand information. We examine a case of a flight over the Arabian sea which was initially reported as a turbulence event by external sources, but diagnosed by its pilots [2] to be an encounter with the wake vortices of another aircraft. By performing an analysis of the results of an NWP model, we assess the possibility of which of the explanations is more likely.

2. Turbulence encounter: a case study
It was reported that a Boeing 737-800W flight of Jet Airways (9W565) from Dammam to Thiruvananthapuram encountered turbulence along its route on 4th October 2014. According to available information in the public domain [3], the estimate of the incident time was 01 UTC and location, was close to the Indian coast. The possibility of turbulence at this location was estimated using numerical models and some of the initial findings were reported in [4]. Later, we learnt of the exact location and time through a private communication with the captain of the aircraft [2].
The encounter happened at 23:11 UTC when it was cruising at an altitude of 37000 feet. The exact incident location was at 63.99E and 17.56N. Prior to the incident, the pilots noticed an Airbus A380 passing in the opposite direction, 1000 feet above. The aircraft underwent a “strong rolling downward motion towards the left” and lost altitude of around 500 feet. There were further “violent excursions to the left and right” [2]. The loss of control and reduction in airspeed which followed was typical of an encounter with a strong wake vortex.

Wake vortex encounters during takeoff and landing have been well studied and there are operational procedures to avoid/minimize such hazards. In recent times, there have been a few reports by the commercial airliners in which wake-upset during cruise was suggested as a possible cause [6]. This could possibly be due to the increase in large aircraft such as Airbus A380. It is therefore important to study reported cases so that such encounters can be avoided/minimized in the future.

The typical flight path, with a mark of incident location, is shown in Figure 1. The infrared images [7] from Kalpana satellite are shown Figure 2. From Figure 2, we can observe that there is not much of convective activity in the flight route except near Cochin and Thiruvananthapuram. Also, at the location of the incident, the skies were clear.

3. Numerical simulations of atmospheric conditions
The atmospheric conditions during the turbulence incident were simulated using two numerical weather prediction models in a coupled way. The first is a hydrostatic, global model, Varsha GCM, which solves the governing equations using spectral techniques [8]. This model was integrated at a coarser resolution (about 80km) and the simulated fields were fed to a limited area model (LAM) as lateral boundary conditions. The second model used was the public domain, high resolution, non-hydrostatic model [9, 10], WRF, developed by National Center for Atmospheric Research (NCAR). This LAM is highly scalable and has multiple options to solve various sub-grid scale physical processes. Figure 3 shows the schematic of the coupling method, where the GCM is initiated using global analysis and then the output is used to initiate the
LAM.

We conducted two simulation experiments with different horizontal and vertical resolutions for the LAM, the first one is with a single computational domain having horizontal resolution of 20km and 28 levels in vertical and the second one is with four nested domains of resolutions 27, 9, 3 and 1km in horizontal and 50 levels in vertical. In both the cases, we have used the analysis data from NCEP-FNL [11] as the input condition. The results presented in this paper are based on the first simulation experiment.

Figure 3. Schematic diagram showing coupling of the Varsha GCM and the WRF limited area model

The large scale upper level (at 250hPa) wind fields, from the model simulations, at 22UTC and 23UTC are shown in Figure 4. One can see that at the cruise altitude, winds were around 5 m/s and mainly from west to east. Also, there was a region of horizontal wind shear close to the location of the incident.

From the WRF simulations, we analyze the possibilities of CAT due to atmospheric conditions and suitability of conditions for a wake vortex encounter. It is clear that given the resolution of
the WRF model, CAT which occurs at the aircraft scale cannot be directly resolved. However, since the energy associated with turbulence on this scale cascades down from the larger scales of atmospheric motion, the attempt is to infer the presence of CAT from the large-scale fields which are resolved in the computation.

3.1. Turbulence indices

There are many theories in literature explaining the phenomenon of clear air turbulence (CAT) and some of them have been successful in predicting various classes of turbulence (i.e., light, moderate and severe). But, the forecasting skill of severe CAT has only improved recently [12]. There are many turbulence forecast indices, which are estimated from NWP model outputs, reported in literature [13, 14, 15]. Most of them were developed to predict the CAT from the large scale atmospheric fields. Algorithmic details of such indices are summarized in [16]. The formula used for the two such indices are given below.

**Brown’s index**

\[
\Phi = \sqrt{0.3\zeta_a^2 + D_{SH}^2 + D_{ST}^2}
\]

where, \(\zeta_a\) is the absolute vorticity, \(D_{SH} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\) is the shearing deformation and \(D_{ST} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\) is the stretching deformation.

**Ellrod index**

\[
E_1 = S_v * \sqrt{\left( D_{ST}^2 + D_{SH}^2 \right)}
\]

where \(S_v = \left| \frac{\partial V}{\partial z} \right| = \sqrt{\left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2}\) is the vertical wind shear.

As the first step, we estimated these indices, from the model simulations, to examine the possibility of CAT near the incident location. The estimated values of Brown’s and Ellrod indices are shown in Figure 5 as an example. It can be seen that the indices does not show any indication of CAT in that region. There are regions where the indices are high, but these are far away from the region where the incident took place.
3.2. Wake vortex encounter
Next we examine the quantities which govern the strength, propagation and decay of wake vortices at the location and altitude of interest. Basic aircraft parameters, are shown in Table 1.

| Type of Aircraft | Boeing 737-800 | Airbus A380 |
|------------------|----------------|-------------|
| Maximum Takeoff Weight (kg) | 79015 | 575000 |
| Wing span $b_L$ (m) | 35.79 | 79.8 |
| Cruise Speed $V_{m,c}$ (m s$^{-1}$) | 231.40 | 242.98 |

Transportation of aircraft trailing vortices is complex phenomena. Environmental condition plays a substantial role in the transportation of vortices. Contours of crosswind and vertical velocity in a plane perpendicular to the flight path at the location and time of the incident are shown in Figure 6. One can see that there is considerable cross-wind at the flight altitudes (corresponding to both the aircraft). The vertical velocities are however small.

From the basic aircraft parameters, the estimate of vortex strength ($\Gamma_0$) for the A380 is $977.5 m^2/s$, initial vortex Spacing, $b' = b_L \pi /4$ is $62.67m$, descent velocity based on vortex induction $w_0$ is $2.48m/s$, Brunt Vaisala Frequency is $0.01182s^{-1}$, and a time scale for decay is $t' = b'/w_0$ is $25.2s$.

Since the atmospheric vertical velocities are small (fig 6), an estimate for the descent time to the altitude of the 737 aircraft is $t_1 = 300/w_0 \sim 120$ seconds. Non-dimensionalizing with $t'$, we get $t_1^* = 4.8$.

Since there is decay of vortex strength with time and lateral spread of the vortices, the relevant questions are i) is the vortex of sufficient strength at this time to affect the second aircraft? ii) is one of the vortices within the span of the second aircraft?

Proctor et al [17], have studied the problem of vortex decay away from ground in stratified and
turbulent environments. Using their results, we estimate the non-dimensional vortex strength \( (\Gamma/\Gamma_0) \) at \( t^*_1 \) is 0.22. This implies a vortex strength of 215 \( m^2/s \) which is sufficiently strong.

Proctor and Ahmad [18] studied the cross wind effects on aircraft trailing vortices. They concluded that if the gradient of the crosswind shear is negative \( (\partial^2 U_c/\partial z^2 < 0) \) then, clockwise rotating vortex will descend at a rate faster than counter-clockwise rotating vortex. Also, if the vertical gradient of crosswind is positive \( (\partial U_c/\partial z > 0) \) then, the lateral separation between the vortices increases. This increase in lateral and vertical separation between the vortices increases their linking time and decay rate. Thus one of the vortices will have comparatively more life span than the other.

From our numerical simulation, we estimated that \( \partial^2 U_c/\partial z^2 = -4.36 \times 10^{-8} \) which is negative and \( \partial U_c/\partial z = 1.08 \times 10^{-4} \) which is positive. The estimated values from our simulation was found in accordance with the criteria given by the Proctor and Ahmad. This shows that one of the vortices can have comparatively more life span than the other.

\( (a) \quad (b) \)

Figure 6. Velocity field in a plane perpendicular to the aircraft path at 23UTC: (a) cross wind velocity; (b) vertical velocity.

Also, the magnitude of the cross-wind (around 6 m/s) is sufficient for one of the vortices to be blown back in to the path of the second aircraft.

4. Summary
We have performed high-resolution numerical simulations of the atmospheric conditions corresponding to the time and region where an aircraft encountered severe turbulence. From our estimates of both CAT indices and parameters related to vortex descent and decay, we find that the encounter was more likely to be due to the wake vortex from an A380 which passed overhead and less likely due to atmospheric conditions alone. While more analysis may be required to confirm these findings, we have demonstrated the utility of using such numerical simulations to understand aviation weather phenomena and also use for purpose of advance warnings.

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