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Some considerations related to flight in dusty conditions

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Abstract. Volcanic ash eruptions and mineral dust injection into the atmosphere are of particular importance to the aviation industry. Ash and dust affect almost any aspect of air operations, from airport facilities to cruise flight. This paper is focused on the advantage of using dust forecasting tools and the potential benefit for Air Traffic Management (ATM), flight safety and aircraft performance. It is suggested that state of the art Chemical Weather Prediction (CWP) model coupled with accurate dust cycle module could be a useful operational tool for more efficient Air Traffic Management and aircraft exploitation.

Keywords: Numerical Weather Prediction, dust cycle module, air traffic management, aircraft performance

1. Introduction

Ash from volcanic eruptions and mineral dust from arid regions are two of the main natural sources of particles in the atmosphere of particular interest to aviation. High particle loads due to volcanic eruptions are rare and mostly concern flight at cruise level [3, 4, 21]. Injection of dust particles from desert areas, despite having a clearly localized emission distribution, can affect an extended airspace due to the atmospheric circulation. Volcanic eruptions have an episodic character while dust injection is a more continuous process with seasonal features. The unpredictability of the volcanic activity (explosion) makes it hard to approach by mathematical modeling. Usually, after the initial explosion, mathematical models are used to simulate the advection, diffusion and deposition processes. The production and transport of mineral dust, on the other hand, can be mathematically parameterized at each step of the production, transport and deposition processes.

Areas with major dust production, located in the Northern Hemisphere, create a so-called ‘dust belt’ that extends from Western Africa, Middle East, Arabian Peninsula and Central and South Asia [18]. Large amounts of soil particles are transported from these areas over various distances depending on their size,

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mass and atmospheric circulation [14]. The altitude at which dust clouds may be present usually varies from 6–8 km.

Dust production is triggered when large particles lying on the ground in a desert area are entrained by the wind. These particles have a mean diameter of about 60 μm and because of their size and mass they are transported over short distances before returning to the ground. Once these heavy particles impact and bounce on the ground, they break up creating a splash of smaller and lighter particles. The diameters of these particles are up to 10 μm and they may be transported by wind over much longer distances [23].

Aviation is affected by dust at the airport level and flying levels. Most important effects concern Air Traffic Control (ATC), Air Traffic Management (ATM), traffic from ground to cruise levels, aircraft aerodynamics and engine performance. All these parameters combined, directly affect flight safety. Heavy particles mostly affect ground operations such as taxiing, stand point, takeoff or landing runs. Smaller and lighter particles forming dust clouds affect flight levels, mainly ascending and descending routes. Cruise flight levels can also be affected since, for instance over Mediterranean, spring time dust cloud can reach and persist for days at altitudes of 10000 m [9].

High concentrations of dust particles reduce visibility making all air operations difficult, causing an uncomfortable environment for ATC personnel and aircraft crew, rerouting and/or massive cancellation of scheduled flights. Another important issue for the flight in dusty conditions is the presence of a very dense sand cloud leading to loss of attitude sensation. This loss of attitude sensation, due to the in-flight visibility restriction (brownout), is the cause of many crashes (rollovers), especially helicopters [26]. Often, very high concentrations of dust are associated with stormy weather, making air operations potentially harmful during takeoff and initial climb or approach and landing. During these phases of flight the margins for recovery are tighter due to the proximity to the ground.

An additional concern, related to the presence of high concentrations of airborne particles, is the simultaneous loss of aerodynamic and engine performance experienced by the aircrafts under such conditions. The impact of particles on the aircraft skin causes skin erosion and, consequently, an increase in the total drag. As numerous aerodynamics and flight mechanics textbooks point out (e.g. [6, 23, 26]), in order to maintain the required flight speed when drag increases, higher thrusts settings are needed, subsequently leading to higher fuel consumption. Additionally, endurance and range of the aircraft are consequently decreased.

Airborne particles can cause erroneous flight speed and altitude measurements by affecting the corresponding devices. Dust ingested by the engines causes gradual loss of performance and shortens life span through erosion and corrosion of the components of the engine. In-flight engine flame out may also occur. Dust particles also create a significant total pressure distortion causing a loss of engine performance [2, 7, 8]. The damages caused by the atmospheric dust particles on the aircraft engines highlight the need for more frequent inspections than prescribed by the manufacturer. The forecasting of dusty conditions and accumulation of this information for the fleet would help calculate the exposure and organize inspection, maintenance and repair processes in terms of stock material and human resources.

Soil and volcanic particles can be detected by ground, on board observer or on board C-band Doppler radar (if their size and concentration are large enough). In general, particles are not radar detectable because of their small size and low backscattering constant [10, 11]. Following the Eyjafjalla volcano crisis in April 2010, a threshold concentration optical value for safe conditions was introduced (2 mg m^{-3}) to define non-safe areas in ash affected regions. The recent study by Weinzierl et al. (2012) studied the ability of an onboard observer (pilot) to detect airborne volcanic ash and mineral dust. They concluded that, depending on the viewing angle, the aerosol layer can be visible at lower concentrations (0.25–0.5 mg m^{-3}) if the pilot has a reference view of clear sky conditions. The observer cannot determine if the layer is potentially dangerous (smaller or larger than 2 mg m^{-3}). Therefore, an onboard observer can tell in some conditions the presence of ash layers, but not their intensity. Most of all, he cannot distinguish between ash, mineral dust or other sources of particles (particulate pollutants from industrialized regions, biomass burning etc). Even if real time information about the dust cloud evolution could be available, this would represent a considerable amount of workload for the ATM and ATC units since they would have to continuously change management strategy for the contaminated part of the airspace. These issues highlight the need for reliable tools that can predict affected and safe regions. The early knowledge of dust affected airspace areas can improve airspace management by establishing in advance an air traffic flow channeling so as to avoid the contaminated areas. At the airliner operations room level, the knowledge of the contaminated parts of the airspace will help to design an economically more efficient flight path. This improved flight path will in turn alleviate the work load of the ATM units.

In this work we propose the use of state of the art Chemical Weather Prediction (CWP) systems, in an operational manner, to identify in advance affected geographical and airspace areas. CWP systems are Numerical Weather Systems (NWP) that include natural (and anthropogenic emissions) and chemical processes. Such integrated models provide the user with information on dust concentrations in the atmosphere and its temporal evolution. Additionally, the spatio-temporal characteristics of weather are strongly affected by the presence of dust [12, 20, 24]. As discussed in recent studies (i.e. [1, 16]), biases in the simulated/forecasted meteorological components can be attributed to the impact of dust on thermal stratification, clouds and precipitation.

The main objective of this paper is to discuss the implementation of a CWP model in ATM activities, aiming at improving Air Traffic Operations (ATO) performance and increasing flight safety. The fully coupled RAMS/ICLAMS modeling system has been utilized to study the meteorological and dust conditions during a period of reportedly low visibility due to fog and sandstorms over Tunis, Tunisia on 7 May 2002. On this day, characterized by adverse weather conditions collocated with a dust storm, an air accident occurred during final approach to Tunis airport. It is shown that such an operational model can provide information that can be useful for the ATM unit.

2. Meteorological forecasting

Common forecasting procedures used by Meteorological Services cannot provide detailed quantitative information about dust cloud location and dust particles concentration. Conventional meteorological information is based on observation (METAR, SYNOP, TEMP) as well as Aviation weather maps, while NWP model outputs mainly concern wind shear and heavy rain maps. The advantage of using a state of the art NWP model, with an integrated dust cycle module, lays on the ability of utilizing high resolution outputs for both meteorological and dust parameters (i.e. wind fields, mapping of wind shear, clouds and heavy rain, with peaks of dust concentration and temporal evolution). This approach offers a detailed quantitative assessment that can be vital in cases of severe dust events.

In order to assess the use of NWP tools coupled with dust modules in ATM and analyze the additional information that they can provide, a case study of a severe dust event over Tunis is analyzed. The meteorological information for the following case study is provided by the high resolution CWP model RAMS/ICLAMS that includes an online dust module [6, 15, 20].

On 7 May 2002 a low pressure system over NW Africa and Western Mediterranean resulted in cloud development and strong South winds at the area of Tunis international airport in Carthage. High resolution model results show that the wind speed at 850 mb at 12:00 UTC on 7 May 2002 is around 15 m s^{-1} at

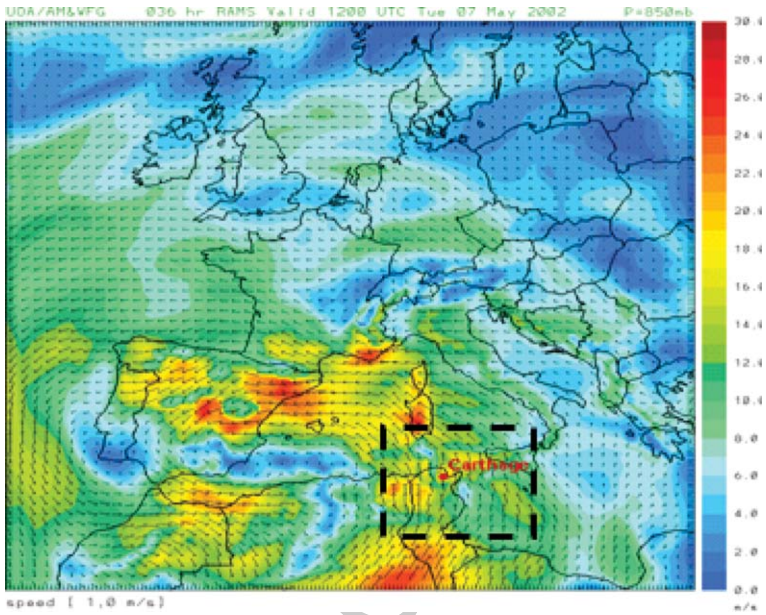

Fig. 1. Model wind speed at 850 mb at 7 May 2002, 12:00 UTC.

the area of Carthage along the north coast of Tunis (Fig. 1). Persisting cloud development is also evident in Fig. 2 throughout the episode. The frontal rain band is accompanied by transportation of Saharan dust as seen with light blue (rain) and grey (dust) colors in the 3D model images of Fig. 3. The most severe weather with high rain rates near the airport is found between 12:00–14:00 UTC which corresponds to the time of the accident as reported by the airport authorities.

More specifically, the dust layer, on May 7th, is found to extend from the surface up to 4 km in the atmosphere (Fig. 4). As seen also in Fig. 4, the convective clouds top at 12 km height and they were continuously precipitating between 12:00–15:00 UTC (May 7th). The West – East horizontal extend of the cloud system is also shown in the (WE) cross-section of Fig. 5. Three distinctive cloud cells are identified at 12:00 and 13:00 UTC (Fig. 5 a, b) merging to one precipitating system at 14:00 UTC. The main dust layer arrived at the same time (14:00 UTC) over the airport. This collocation of the rain maxima and dust cloud created severe meteorological and visibility conditions. At the same time, a secondary dust cloud elevating up to 6 km is also found towards the western part of the modeling domain (Fig. 5 c, d). This type of meteorological information can also be consolidated into the time plots of Fig. 6. These figures depict the time evolution of the vertical profile of the total condensates mixing ratio in the atmosphere over the airport during 7 May 2002. As seen in Fig. 6a, most of the precipitation occurs between 10:00 – 13:00 UTC while deep clouds persist in the area until 20:00 UTC. During the daytime, dust concentrations of more than 100 μg m^{-3} are found aloft mainly between 1–3 km. Due to wash out of dust particles by the heavy rain, dust concentration of more than 250 μg m^{-3} is only found after 20:00 UTC.

Therefore, the implementation of such a high resolution CWP model coupled with a dust module may provide in advance detailed information on weather conditions and the associated dust event at a specified geographical area. The operational use of such a model could enable the ATC units and airliners operations room for efficient flight planning.

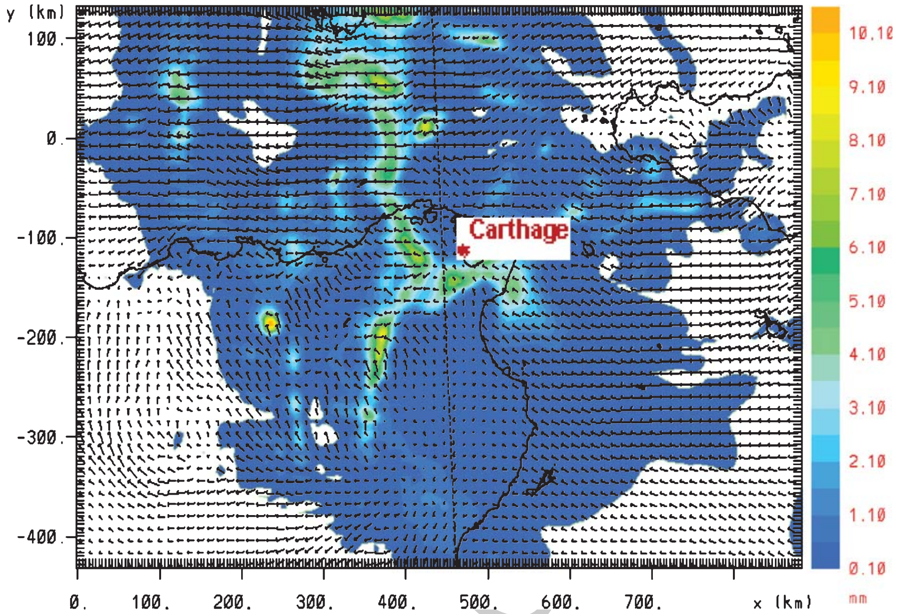

Fig. 2. Vertically integrated cloud condensates at 7 May 2002, 12:00 UTC. The dashed red lines indicate the locations of the vertical cross-sections of Figs. 5 and 6.

3. Impact of dust on aircraft engine performance

Dust can be ingested by the engines either on ground or in flight. Practical experience shows that dust particles can seriously affect any air-breathing engine. Since most of passenger or cargo aircrafts are fitted either with turbofan or turboshaft engines the discussion does not include piston engines.

On the ground, large particles such as sand or gravel and finer particles, up to a diameter of 10 μm, can be ingested. At high thrust settings, during stand point or take – off run, the engines operate at high temperatures and flow rates. An unsteady vortex is formed in front of the air inlets of the engines causing high mass rate ingestion of particles as shown in Fig. 7. This will also happen during landing operations.

Once ingested by the engine, the particles impact and bounce on cold areas causing surface damages leading to gas flow deterioration, gradual loss of performance, increase in specific fuel consumption and decrease in surge margin. At various locations, along the airflow path through the engine, air bleeding is performed for hot surfaces cooling, such as turbine blades or combustor walls. Impacts of dust or volcanic particles will result in a rough surface glass deposit. This deposit will block the cooling holes, leading to thermal corrosion. The glass deposit, due to its rough surface, can significantly disturb the airflow around the turbine blades. This disturbance can cause stall and engine flame out. Lowering the engines setting to idle, thus lowering the working temperature, may be a partial solution to the problem since the engine temperature may be still higher than the particles' melting temperature [3, 4, 19, 27, 28].

The ingested amount of dust is strictly related to the aircraft configuration, the flight speed and the angle of attack, the particles concentration (at the undisturbed area far ahead of the aircraft) and the shape of the particles trajectories tubes. Each trajectories tube connects an engine inlet area to the undisturbed region far upstream of the aircraft, where particles concentration is not affected by the presence of the aircraft. As discussed in previous studies [16] the trajectories depend on the forces acting on the particles, which

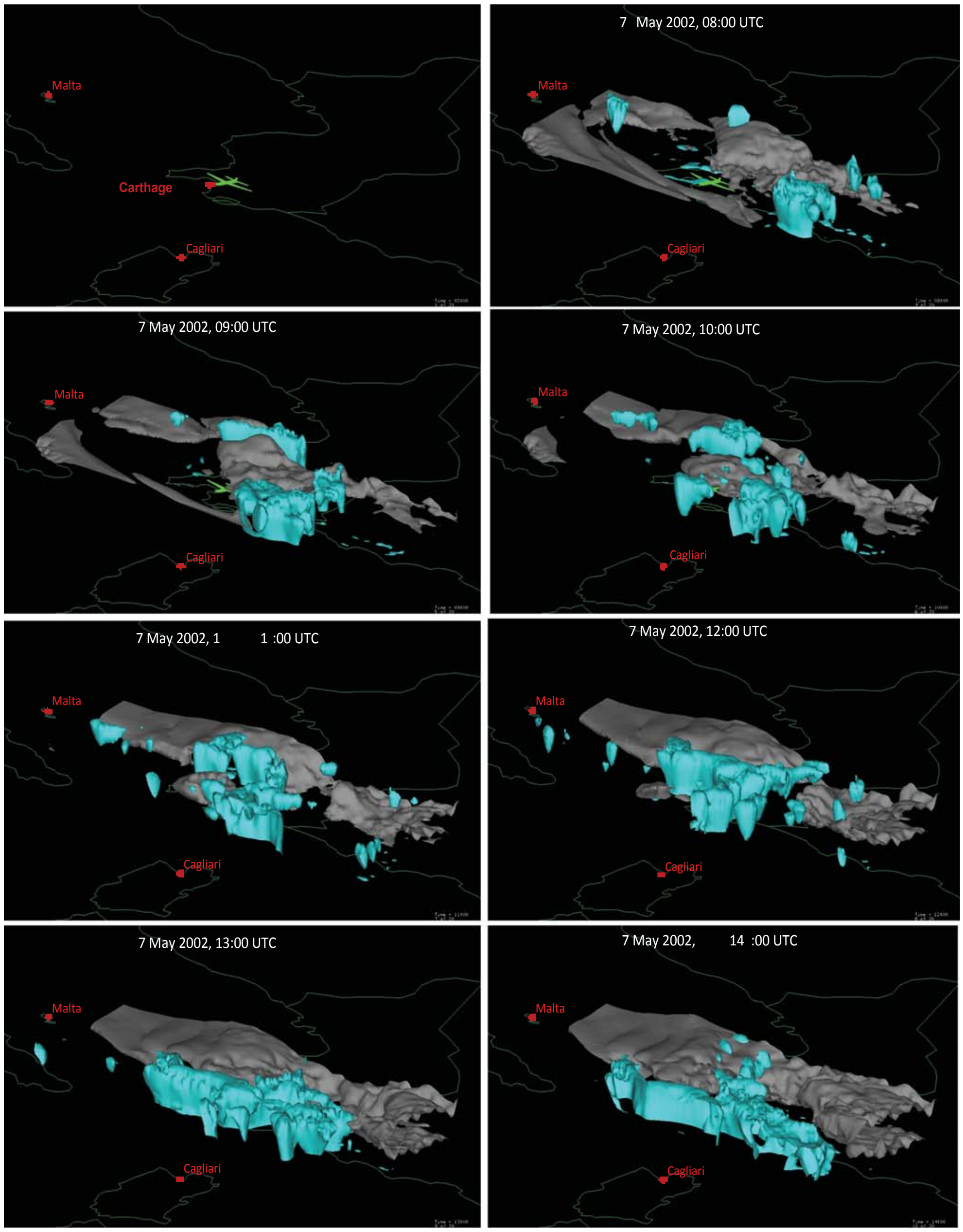

Fig. 3. Rain (light blue) and dust (grey) over Carthage airport on 7 May 2002 from 08:00 till 14:00 UTC. The red compass denotes the orientation of the image.

in turn depend on the airflow around the aircraft and the shape, size and mass of the particles. Therefore the information on the size distribution along with the concentration distribution of the airborne particles may be of crucial significance.

It must be pointed out that the aircraft skin carries an electrostatic charge due to the friction with the air, so it creates an electrostatic field around it. Dust particles also carry an electrostatic charge. It is expected

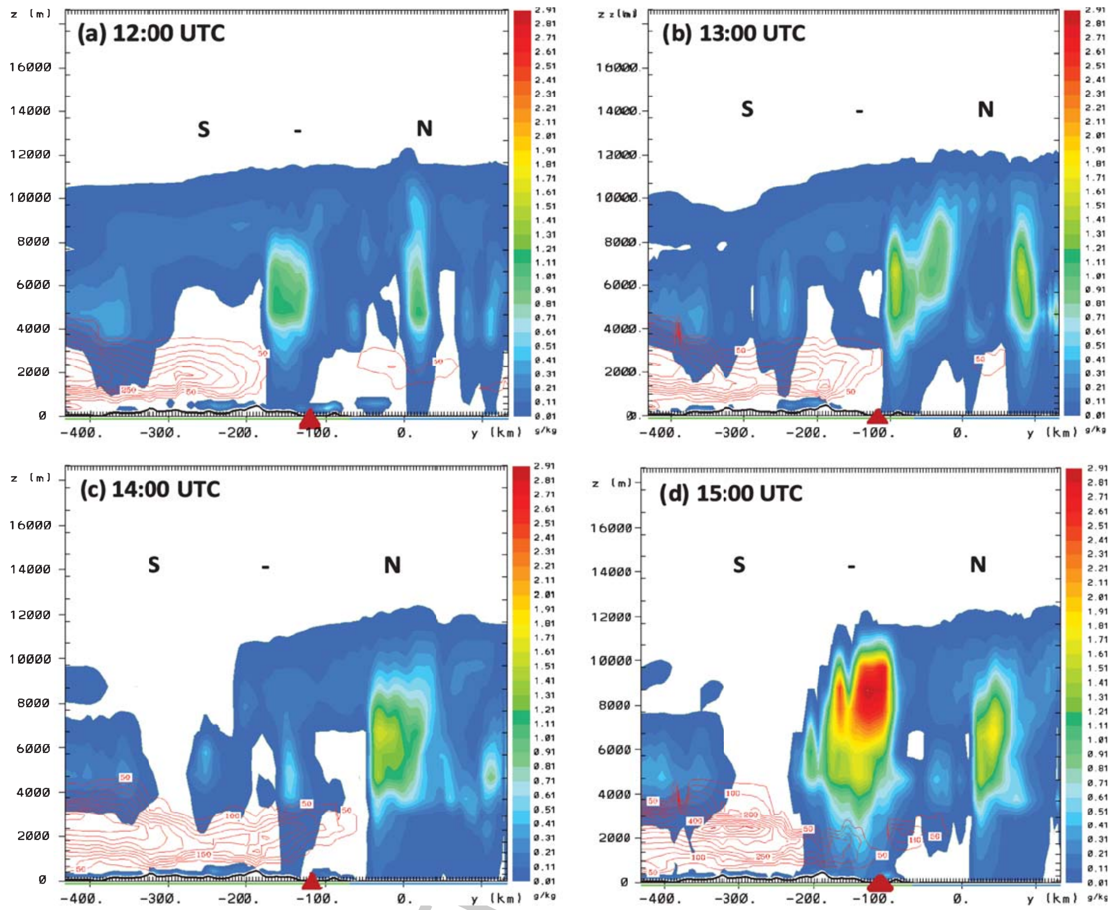

Fig. 4. South – North vertical cross section over Carthage Airport. Total condensates mixing ratio (color scale in g kg^{-1}) and dust concentration (red contour lines every 50 μg m^{-3}). The location of the airport is indicated with a red triangle on the horizontal axis.

that electrostatic forces (Coulomb forces) would also be exerted on the dust particles, thus influencing their trajectories by modifying the resultant force exerted on them. These electrostatic forces are due to their mutual electrostatic interaction and to the electrostatic field created by the aircraft. However this is not confirmed, at least by our numerical simulations, even for small size light particles, which means that the order of magnitude of the electrostatic forces are negligible as compared to the aerodynamic forces exerted on the particles.

In the case of a helicopter, during near ground operations the air mass passing through the main rotor has a large vertical downward velocity component, whose effects are easily seen when landing in dusty or sandy ground. The air flow pattern makes causes particles passing through the exhaust gases, which contain negatively charged particles, to become electrically charged. In this way an electrostatic field is created around the helicopter, disturbing the radio links and posing a potential hazard for ground personnel or flammable materials [17]. The total loss of orientation due to the so called brownout should also be taken into consideration as a possible outcome of such conditions.

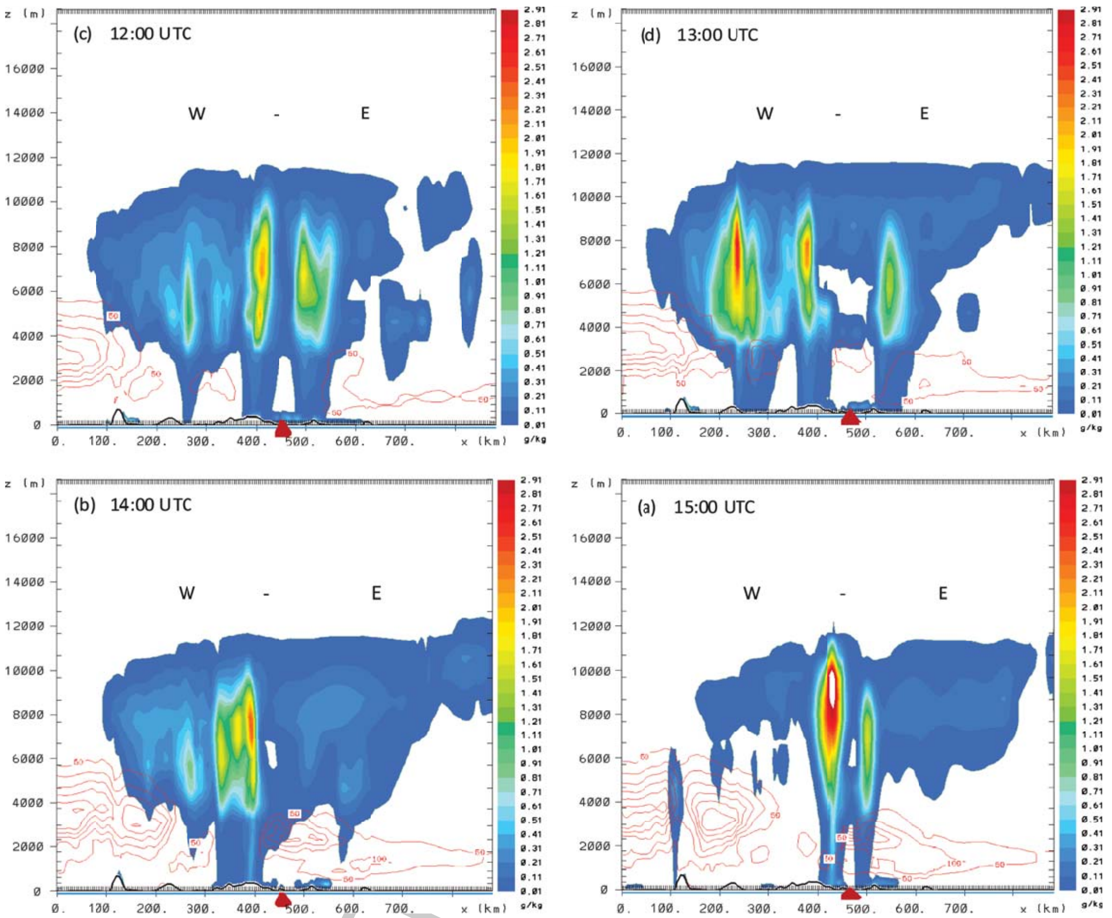

Fig. 5. West – East vertical cross section over Carthage Airport. Total condensates mixing ratio (color scale in g kg^{-1}) and dust concentration (red contour lines every 50 μg m^{-3}). The location of the airport is indicated with a red triangle on the horizontal axis.

4. Operational use and benefits

As it was pointed out in Section 2, a state of the art CWP model may provide a detailed mapping of the horizontal and vertical extent of wind field, rain, cloud and dust concentration and size distribution, together with the time evolution of the phenomena. A computer cluster could run a CWP model for numerous adjacent geographic regions to provide a detailed insight of the meteorological conditions over an extended area (the entire Mediterranean area for instance). Nested configurations covering specific areas (airports) of interest is also feasible provided the modelling system has two-way interaction nesting capabilities, as the one mentioned in this study.

Based on this tool, an ATM unit web performance could be significantly supported by a-priori information, having a clear picture of a possible dust or weather event approaching the area/airport of interest well before it actually happens, including detailed information on the location, extend and time evolution of the hazardous area. Rerouting flights or delaying scheduled take off and landings could be planned ahead. Such information can also be useful in flight planning and scheduling in airlines operations rooms, especially for charter flights.

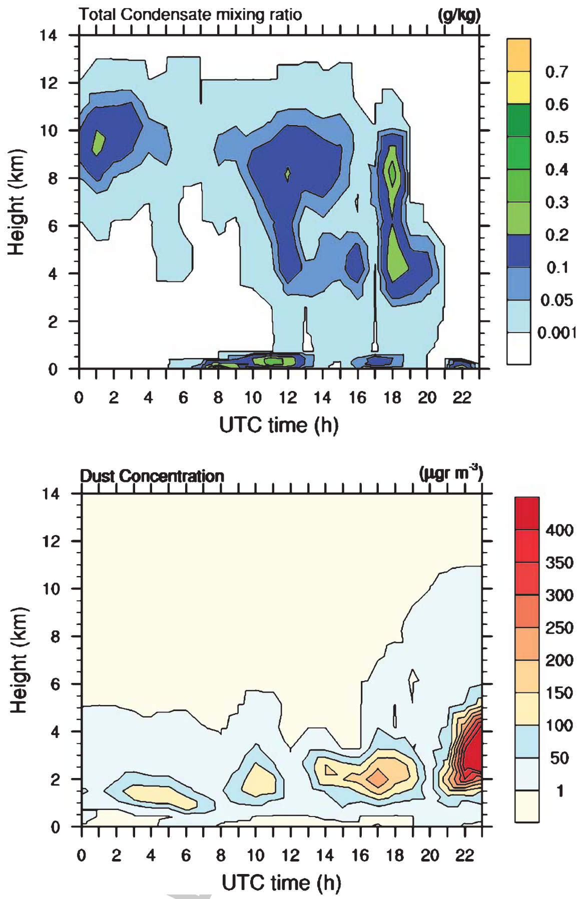

Fig. 6. Time evolution (00:00 – 23:00 UTC) of: (a) total condensates mixing ratio vertical profile and (b) dust concentration vertical profile during 07 May 2002 over Carthage Airport.

Fig. 7. Sand ingestion at high power settings.

The detailed picture provided to the ATM by this kind of high resolution CWP models might enhance flight safety. Aircrafts may be prevented from entering a hazardous area, even a non-radar detectable one. Since dust clouds are formed by fine particles non-radar detectable, ATM will timely efficiently assist air crew by warning it and proposing alternate flight paths. The same approach can be also used in the case of any kind of cloud or heavy rain and wind shear areas.

The avoidance of dust affected areas can prevent aircrafts from erosion and corrosion damage and performance deterioration. It can also extend engine life span, minimize grounding time for repairs and extend intervals between successive engines inspections. Efficient ATM and flight scheduling can alleviate clean air space congestion, due to rerouting, thus minimizing midair collisions probability and reducing delays. Air space congestion alleviation can also enhance fuel savings, since holding time for air space passing through or waiting for takeoff or landing will be reduced. Fuel savings would also be obtained by minimizing aircrafts performance deterioration leading to environmental and economic benefits.

These state of the art CWP models could also be coupled to a specialized optimizer in order to choose the least fuel and time consuming allowed alternate flight path. This optimizer could also choose the closest and most suitable airport for an emergency landing according to local meteorological conditions, aircraft landing requirements and airport capabilities.

The routinely use of state of the art CWP may be a useful technique for ATM units. However, onboard, the assessment of the deterioration of aircraft performance through an objective criterion easily applied by the crew, since it is the final recipient of any flight information, is also crucial. This criterion may concern easily measurable parameters, such as the climb rate decrease or the increase in power setting in order to maintain a required flight speed. Some levels of severity of the phenomenon can be established based on the percentage of the required power setting increase and of the climb rate decrease. These severity levels and the corresponding percentages can be established by aircraft and engine manufacturers. Given a severity level specific reactions from the crew could be triggered. Such a criterion can also be used in icing (Jeck, FAA Technical Paper) and heavy rain conditions for completeness of the ATM warning system.

5. Conclusions

Air operations are seriously affected by dusty conditions influencing ATM and flight safety issues, as well as both short and long term aircraft performance. This paper proposes the use of state of the art Chemical Prediction Models, which include dust modules, for forecasting spatial and temporal evolution of meteorological and dust features. This way, a dust event and the corresponding contaminated part of the airspace can be known well in advance. This early knowledge would permit an earlier scheduling of air traffic channeling. Airspaces adjacent to the contaminated one may be prevented from being congested from rerouting, thus helping towards a more efficient ATM, increasing air traffic safety and minimizing environmental and financial drawbacks.

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