Title: A case study of high sea salt aerosol (SSA) concentrations as a hazard to aviation.

Author(s): Tony Tighe¹

¹ Aviation Services Division, Met Éireann, Shannon Airport, Co. Clare, Ireland.

This article is provided by the author(s) and Met Éireann in accordance with publisher policies. Please cite the published version.

NOTICE: This is the author’s version of a work that was accepted for publication in Meteorological Applications. Changes resulting from the publishing process such as editing, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Meteorological Applications, 22(4), pp.806-810.

Citation: Tighe, T., 2015. A case study of high sea salt aerosol (SSA) concentrations as a hazard to aviation. Meteorological Applications, 22(4), pp.806–810. DOI: 10.1002/met.1529

This item is made available to you under the Creative Commons Attribution-Non commercial-No Derivatives 3.0 License.
A case study of high sea salt aerosol (SSA) concentrations as a hazard to aviation

Tony Tighe, Aviation Services Division, Met Eireann, Shannon Airport, Republic of Ireland

Abstract: On the night of 2\textsuperscript{nd} January 2014 an aircraft on approach to Cork airport was required to abort a landing attempt due to sea salt aerosol (SSA) accretion on the windscreen. The salt reduced forward facing visibility to dangerously low levels. This was the first time such an incident was recorded by Irelands Air Accident Investigation Unit. This paper describes the meteorological conditions at the time of the aborted landing approach. Sea salt aerosol formation mechanisms are elaborated as is the relationship between SSA concentration enhancement and meteorological variables. A brief comparison between the meteorological conditions surrounding this and another notable event documented by the US naval service is made. The potential for SSA to be a significant hazard to aviation is considered as are recommendations for further research.

KEY WORDS sea salt aerosol; aviation hazard; visibility; high winds

1. Introduction

Cork airport (51°50’29” N 008° 29’28” W) is situated 15 km from the south coast of Ireland at an elevation of 502 ft above mean sea level (MSL). It is the second busiest airport in Ireland with approximately 2.25 million passengers recorded in 2013.

The local climatology is defined by its geographical situation being highly influenced by north Atlantic weather systems - ranging from dynamic fast moving series of depressions to occasional periods of settled high pressure weather. The airport’s maritime and coastal location leave it vulnerable to inclement weather conditions due to orographic and coastal effects.

On the 2 of January 2014 the visibility of a twin engine turbo-prop aircraft (an ATR 72) on approach to Runway 25 at Cork airport was diminished to the extent that required the landing attempt to be aborted. The phenomenon that caused the reduced visibility was subsequently discovered to be accretion of sea salt onto the aircraft windscreen. This was the first recorded time that such an incident occurred to an aircraft on approach to an Irish airport. Two other aircraft on the same night reported visible sea salt deposits on their windscreen (another ATR 72 and an Airbus 320) that also reduced visibility - but to a lesser degree. Contact between Irelands Air Accident Investigation Unit (AAIU) and colleagues in neighbouring jurisdictions did not uncover any past records of
similar incidents. Also, an extensive trawl of the literature did not uncover any similar incident involving a commercial airliner.

However, the US Navy have recorded one notable case of a research aircraft experiencing power loss and engine failures due to SSA fouling (Reid et al, 2007). The US Navy Research Laboratory issued a comprehensive ‘Mishap Report’ to describe this incident in detail and the meteorological conditions obtaining at the time. They have also documented episodes where high SSA concentration environments adversely impacted on helicopter engine performance up to, and including, engine failure. These incidents all occurred at low flying velocities at low levels within the marine boundary layer (MBL).

2. Synopsis of the incident
Feedback from air accident investigators and the aircrew involved revealed the following sequence of events:

At 2300 UTC, on 2 January 2014 an ATR72 aircraft on approach to Cork Airport was required to abort a landing approach to Runway 25 (RWY25) due to high winds and the associated severe mechanical turbulence encountered. The aircraft was vectored by air traffic control (ATC) on a left hand circuit to the south of Cork airport (EICK) and crossed the coast between Kinsale and Cork Harbour at an altitude of approximately 4000 ft.

The aircraft continued its go-around before coming onto a westerly heading for the second approach to RWY25. At this point the pilot and crew noticed a rapid deterioration in forward facing visibility due to what was later discovered to be the accretion of SSA to the windscreen. The pilot later described the rate and magnitude of the salt accretion as “insidious” due to the dramatic and rapid nature of the phenomena. Even as the aircraft ascended into shallow cloud cells in an attempt to clear the contaminant the salt accretion continued. Before entering cloud the flight path had been through ‘clear air – cloud free conditions’. The aircraft was travelling at a speed of approximately 170 KT. The aircrafts windscreens were heated.
Visibility was reduced to the degree that the airfield lighting at EICK appeared as an ‘amorphous blur’ to the pilot and crew necessitating the second landing attempt to be aborted. Some wash off did occur when the aircraft encountered a very light rain shower causing a slight improvement in visibility allowing a safe landing to be completed on the third attempt.

3. Sea salt aerosol (SSA) in the boundary layer
At this point it is useful to consider SSA in the boundary layer, its’ formation mechanisms and general characteristics. What follows is a mainly qualitative description of these phenomena as uncovered in commonly cited literature relating to the subject.

3.1 SSA concentrations are highly variable with concentrations recorded over seas much greater than those recorded over land (Tsyro et al, 2011 ; Jennings et al 1998). Estimates suggest that the open ocean produces between $10^9 - 10^{16}$ metric ton of sea salt aerosol annually (Blanchard, 1985). SSA mass peaks in winter when wind speeds are at their highest (Fan and Toon, 2011).

SSA concentration in the maritime boundary layer depends on a number of meteorological and oceanographic conditions. These include: wind speed, removal processes (such as rain ‘wet scavenging’ and dry deposition), relative humidity, air and sea surface temperature (and the difference between them), wave breaking characteristics, water salinity, fetch, wave height, occurrence of organic films and the thermodynamic stability of the lower atmosphere (Wu et al, 1984; Andreas et al, 1995; Monahan et al, 1986; Reid et al, 2007).

SSA’s have a lifetime ranging from 30 minutes for coarse particles ($r=2.5 - 15 \mu m$) up to 60 hours or longer for fine particles ($r = 0.13 - 2.5 \mu m$) (Gong and
Barrie, 1997; Keene et al, 1998; Reid et al, 2007) before returning to sea or land via moisture scavenging, rain wash-out or dry deposition. Giant sized particles return to ground level very quickly due to higher deposition velocities unless there is sufficiently high vertical velocities or mechanical turbulence conditions to keep them airborne (Gong and Barrie, 1997; Keene et al, 1998). SSA concentrations are relatively constant from surface to the top of the boundary layer (Reid et al 2007).

SSA formation is ongoing over the oceans but at wind speeds of 5 ms\(^{-1}\) there is sufficient mixing available to suspend SSA particle sizes of up to 20 µm. Studies show that maritime cloud condensation nuclei (CCN) concentrations peak at wind speeds of 17ms\(^{-1}\) (O’Dowd and Smith, 1993; Jennings et al, 1998). The majority of giant maritime giant CCN are sea salt aerosol. At wind speeds greater than 17 ms\(^{-1}\) the rate of formation of SSA decreases again.

Due to the highly hygroscopic properties of SSA, particle size is also highly dependant on relative humidity (RH) (Lewis and Schwarz, 2004; Zhang et al, 2005; Fan and Toon, 2011). The higher the RH the larger the SSA particle size as it strives for equilibrium with the surrounding atmosphere. However, the RH and SSA particle size relationship is not linear as it is influenced by organic mass fractions of the ocean water and surface as well as secondary organic species generated photochemically in the atmosphere.

Despite the fact that there exists a good qualitative understanding of SSA formation, meta-analysis of the research in this field shows that the exact quantifiable relationships between, for example, wind speed or RH and SSA concentrations and particle size vary widely (Porter and Clarke, 1997; Andreas et al, 1998; Reid et al, 2001, Lewis and Schwarz, 2004).

### 3.2 SSA formation mechanisms

SSA generation is a wind driven process whereby evaporation from sea spray drops leads to the formation of the aerosol. Three types of spray drops are considered with regard to SSA formation named after their production mechanism. Two of these droplet formation mechanisms are considered to be indirect (film and jet droplet formation) and one a direct mechanism (spume droplet formation) (Blanchard, 1983; Wu et al, 1992; Andreas et al, 1995).

#### 3.2.1 Indirect mechanisms for droplet formation (film and jet droplets):

1. Wind blows over the ocean causing waves to break and entrain air into the water. This forms clouds of bubbles beneath the water surface and foam patches on top.

2. The bouyant air bubbles rise through the sea water reaching the surface and floating with a thin film cap.
3. The bubbles then burst by two mechanisms (Blanchard, 1963; MacIntyre, 1972; Spiel, 1995; Andreas, 2002):

a) the film cap shatters generating 10’s to 100’s of small ‘film’ drops – of size 0.1 µm radius up to a max of 50 µm radius (most lie in the 1-2.5 µm range considered to be fine sized particle).

b) the bubble collapses causing a jet of water to be projected upwards from the waters surface under high acceleration from the bubble cavity. The jet quickly becomes unstable and breaks up into several droplets called jet drops. Jet drop radii range 1 to 300 µm with a peak around 10 µm which can be considered as ‘coarse’ sized particles (Andreas 2002).

4. The smaller the drop size the longer it spends in the air before falling back to sea allowing a lengthier period for evaporation to take place and for aerosols to form (Reid et al, 2007; Fan and Toon, 2011).

5. Water evaporation from the drop results in a sea salt aerosol becoming an atmospheric constituent.

3.2.2 Direct mechanism for sea spray drop formation

Droplets known as spume drops are generated in circumstances of high winds tearing the tops from wave crests. These drops are suspended in the atmosphere for a time allowing water evaporation and SSA formation to take place. The majority of ‘giant’ sized particles are formed by this method (those with $r > 15$ µm).

4. Synoptic and mesoscale weather situation

Synoptic and mesoscale weather conditions were examined in order to understand the atmospheric circumstances present at the time the incident occurred.

Met Eireann operates a number of surface observation sites at and in the vicinity of Cork Airport (EICK). These include an observation site at EICK with a human observer and, also, automatic weather sensors at the coastal site at Sherkin Island and Bouy M3 (positioned off the coast to the south of Cork city). Wind and wave height data was available from the Marathon Gas platform situated in the Kinsale gas field over which the aircraft travelled along its’ flight path. RADAR imagery was available from the Shannon airport Doppler weather RADAR. MSG satellite imagery to help position fronts, troughs, low pressure centres and to locate regions of moist and dry air.
A deep depression of 947 hPa was centred to the west of Ireland and was tracking quickly northeastwards. An associated strong and gusty southwesterly airflow lay across the southwest of the country. EICK METAR reports at the time of the event show surface winds of 22027G45KT over land with offshore winds reported as 24045G56KT. Gradient (925 hPa) wind speeds are estimated to have reached 60 KT. The atmosphere was thermodynamically unstable with the environment curve of the midnight Valentia ascent cooling significantly with height with a lapse rate of circa 10 °C km⁻¹ in the MBL. The first notable inversion in the environment curve was measured at approximately 600hPa. CAPE values measured from the Valentia tephigram (co-ordinates N51°56'23" W10°14'40") were positive reinforcing the scope for vertical mixing via thermal updraughts.

The unstable airmass coupled with the tight pressure gradient and associated strong winds allowed a deep mixing layer to exist under conditions of strong mechanical turbulence.

The airmass was relatively dry with a dewpoint depression of circa 5 °C at the surface and a calculated surface relative humidity (RH) of 71%. The dry air environment continued throughout the maritime boundary layer (MBL) to a height of 870 hPa with an estimated RH of 64% at 4000ft - the flight level at which the salt accretion began.

Figure 2: 030000 sounding from Valentia observatory (one hour after the event)

Figure 3: Surface analysis chart for 030000
Figure 4: Satellite image (Meteosat Second Generation infra red) for 2300 UTC on the 2 January 2014 with the incident area circled

5. Relating the meteorological conditions observed to the high concentration of SSA and comparisons with other recorded events

5.1 The establishment of high SSA concentrations was facilitated by the high wind environment with mean speeds close to optimal for SSA development (suggested to be 17 ms$^{-1}$). The relatively dry airmass ensured rapid evaporation
of water from sea spray, spume and other sea water droplets. Mechanical
turbulence eddies and thermal instability facilitated the transport of SSA's aloft
allowing for elevated concentrations of SSA to altitudes of at least 4000 ft in a
relatively deep maritime boundary layer. High concentrations of SSA were
maintained by the absence of precipitation and low relative humidity that limited
water scavenging or wash out. The low RH also suggests that the SSA particle
sizes were at the smaller end of the spectrum. These smaller particles have a
naturally longer lifespan in the MBL and can be more freely transported aloft.

5.2 An incident described in Mishap Investigation Report (01-07) published by
the United States Naval Research Laboratory identified a set of meteorological
circumstances for an incident that occurred on 9 February 2007 to a navy
research aircraft (Lockheed Martin WP-3D turboprop) that caused visibility
obscuration and engine failure due to SSA ingestion. The aircraft was flying in a
hurricane strength wind environment in a precipitation free zone in the dry slot
behind a back-bent warm type occluded front in the immediate aftermath of a
North Atlantic explosive cyclogenesis event. The wind speed at flight level was
45ms\(^{-1}\) (95 KT). The environmental temperature lapse rate of 10 °C km\(^{-1}\) in a
deep maritime boundary (MBL) layer of depth estimated to be 1500 to 1800 m.
The research aircraft began accumulating SSA with 35ms\(^{-1}\) surface winds to the
extent that visibility became obscured. There were also high seas with estimated
wave height of 10 to 15 m.

Neither the case being reported in this study nor the US NRL reported incident
have the advantage of having measured SSA concentrations, at any atmospheric
levels, available. Therefore, comparisons must be restricted to the
meteorological conditions for which data is available as illustrated in table 1.

table 1: Comparison of meteorological conditions for the two incidents

<table>
<thead>
<tr>
<th>Incident</th>
<th>Incident under consideration</th>
<th>Comparison US NRL incident of 9th February 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface wind</td>
<td>40-45 KT gust 50-60KT</td>
<td>68 KT (estimated)</td>
</tr>
<tr>
<td>Flight level wind</td>
<td>60 – 70KT</td>
<td>85 – 95 KT</td>
</tr>
<tr>
<td>Surface Temperature/ Dewpoint</td>
<td>8/3 °C</td>
<td>n/a</td>
</tr>
<tr>
<td>Sea Temperature</td>
<td>11 °C</td>
<td>14 °C</td>
</tr>
<tr>
<td>Surface RH</td>
<td>71% (estimated)</td>
<td>n/a</td>
</tr>
<tr>
<td>Flight level RH</td>
<td>64% (estimated)</td>
<td>fluctuating between</td>
</tr>
<tr>
<td>Environmental Lapse Rate in MBL</td>
<td>9 or 10 °C km(^{-1})</td>
<td>10 °C km(^{-1})</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Nil</td>
<td>Nil</td>
</tr>
<tr>
<td>Wave height</td>
<td>10 m</td>
<td>10 - 15 m</td>
</tr>
<tr>
<td>CAPE</td>
<td>Positive</td>
<td>Positive</td>
</tr>
<tr>
<td>Aircraft speed</td>
<td>170 KT</td>
<td>200 KT</td>
</tr>
<tr>
<td>Measured SSA concentrations</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

There are some differences in parameter values in the table 1 for the two
incidents. However, it should be noted that the ATR 72 involved in the incident
on approach to EICK did not report engine stalls, failures or any loss of power. It was a visibility obscuration scenario only.

There is currently a paucity of literature relating high SSA concentration environments to visibility obscuration of aircraft. The data garnered from these two incidents can be considered a first step in classifying weather conditions that are conducive to the development of high SSA concentrations, in maritime environments, that are a potential hazard to aircraft visibility (see table 2). The author recommends that further research is conducted in this area to refine this classification.

**table 2: Proposed criteria for high SSA concentrations significant as visibility hazard for aircraft**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface wind</td>
<td>&gt; 35 KT</td>
</tr>
<tr>
<td>Gradient wind</td>
<td>&gt; 60 KT</td>
</tr>
<tr>
<td>Thermodynamic profile</td>
<td>Environment lapse rate &gt; 9 °C km⁻¹ in boundary layer</td>
</tr>
<tr>
<td>Wave height</td>
<td>&gt; 8 m</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Nil</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>&lt; 80%</td>
</tr>
</tbody>
</table>

5. **Computer modelling to forecast potential high sea salt aerosol concentrations**

Modelling sea salt aerosol concentrations is a challenging task due to the number of formation mechanisms of the aerosol and the documented differences in skill between models. However, some models are found to realistically reproduce observed distribution of sea salt concentrations, in certain environments. It is noted that the modelled concentrations are not as accurate for sites where sea spray is of greater influence (Tsyro *et al.*, 2011) - such as in Irish and Finnish coastal waters.

There are also widely used high resolution numerical weather prediction models with known skill in forecasting meteorological parameters in the boundary layer – including those listed in the tables earlier.

6. **Recommendation for future research**

A recommendation for further research is for the establishment of a collaborative project between experts in these fields with the intention of producing a guidance product for aviation meteorologists. Such guidance would have the potential to mitigate risk in the particular high SSA concentration environments. Also, the aircraft manufacturers may take note of the contents of this paper and modify aircraft as necessary to combat the risk through use of effective windscreen washing systems.
7. Conclusions

- Visibility reduction in commercial aircraft due to sea salt accretion to windscreens is a rare, or rarely reported, event.
- However, high concentrations of sea salt aerosols are a hazard to aviation and can result in both visibility obscuration and engine fouling.
- Certain identifiable, and forecastable, meteorological conditions act to increase sea salt concentrations to hazardous levels in the boundary layer in maritime regions. These include high wind speeds (with significant concentration enhancements under very high wind conditions i.e. \( U > 18 \text{ms}^{-1} \) – Jennings), low RH and a thermally unstable environment.
- Modelling sea salt aerosol concentrations is possible with a reasonable level of accuracy and could be used to develop warnings protocols for the aviation sector.
- Global warming has the potential to exacerbate the hazard potential of sea salt aerosol to aviation through the increased likelihood of more frequent and more intense north Atlantic depressions impacting on Northwest Europe.
- SSA is a sufficient threat to aviation to warrant further laboratory controlled research. The intent would be to inform aviation stakeholders of risk level and risk mitigation solutions for this phenomena.

References


