2 What is in the air?

2.1 Aerosols

Aerosol is the term used to describe suspensions of solid and liquid particles in a gas. Total atmospheric particle concentrations are normally in the range of 100-300 particles per cm^3 (Fitzgerald, 1991). The size distribution is defined by diameter (Ø) and can be separated into the four modes shown in Table 1.

Nucleation mode	Ø < 10 nm
Aitken mode	10 nm < Ø < 50 nm
Accumulation mode	50 nm < Ø < 1 µm
Course particle mode	Ø > 1 µm

Table 1, size distribution modes (Fitzgerald, 1991); (AQEG, 2005); (Vaattovaara, et al., 2006).

2.1.1 Nucleation mode

Nucleation plays a fundamental role where condensation, precipitation, crystallisation, sublimation, boiling, or freezing occur (Seinfield & Spyros, 2006, p. 489). The nucleation mode is smallest group of particles, lower than 10 nm. Such particles have been newly formed by nucleation processes.

2.1.2 Aitken mode

Particles within the nucleation category soon become part of the Aitken category by condensational growth. Condensational growth is where the particles are affected by the condensation of water vapour in saturated airflow (Yang, 1999). This mode can be represented within the red box on Figure 1.

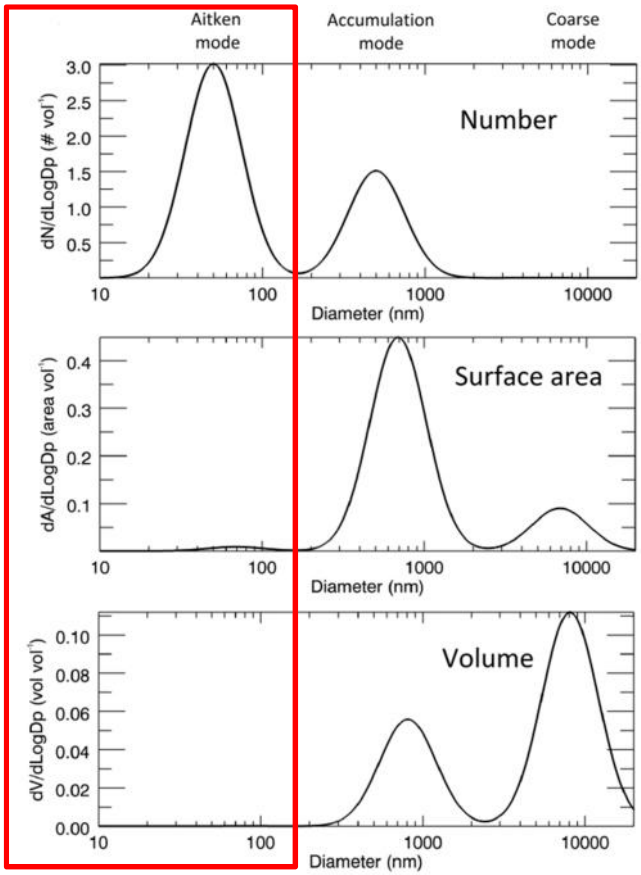

Figure 1, Aitken mode synthetic aerosol distribution in number area and volume space (Niall, 2012)

Particles within the nucleation and Aitken mode have a relatively short existence (minutes and hours) in the atmosphere since they readily transform into larger particles and also deposit quite efficiently to surfaces because of their highly diffusive nature, which results from their low individual mass (AQEG, 2005).

2.1.3 Accumulation mode

The growth of Aitken mode particles, primarily by vapour condensation, leads to formation of the accumulation mode of particles between 50 nm and 1 µm in size and can be represented within the red box on Figure 2.

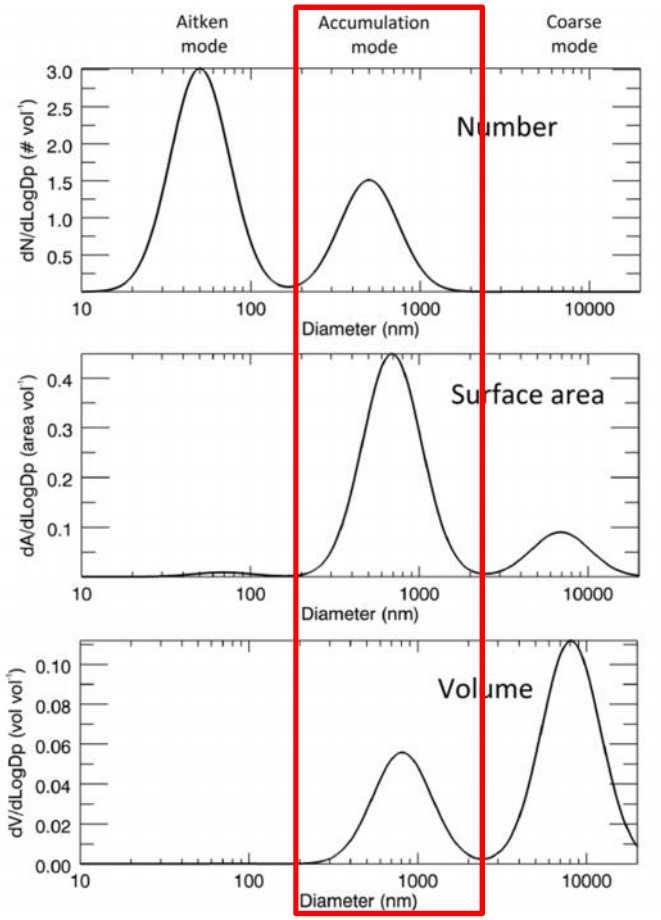

Figure 2, accumulation mode distribution in number area and volume space (Niall, 2012)

These particles are too large to be subject to rapid chemical reactions and are too small to settle from the air rapidly under gravity. Resulting in a long atmospheric lifetime (7–30 days) (AQEG, 2005), although they are still susceptible to incorporation into rain which can significantly shorten atmospheric lifetime.

2.1.4 Course particle mode

The course article mode is greater than ~1 µm in diameter, representing 95% of the total volume and mass, but only 5-10% of the particle number distribution (see Figure 2).

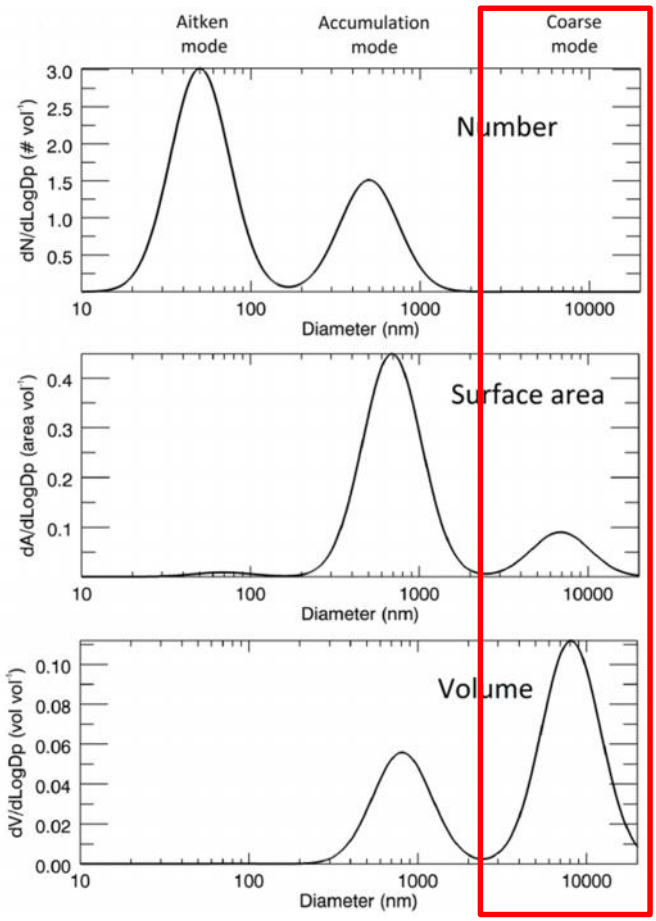

Figure 3, course mode distribution in number area and volume space (Niall, 2012)

These particles are typically generated mechanically and consist of dusts from industrial operations and the evaporation of sea spray. Within this size range, gravitational settling velocities become appreciable and therefore atmospheric lifetimes – although significant – are defined by hours (Brimblecombe, 2003, p. 211)) when comparing to the accumulation mode (AQEG, 2005).

2.2 The aqueous phase

The aqueous phase is the term used to describe the liquid water entrained within the atmosphere. Water can be present in the atmosphere as precipitation (rain, snow, sleet), clouds, fogs, mists and dew.

2.2.1 Precipitation

Precipitation is a wet deposition process where a chemical species is removed from the atmosphere. This process is commonly described as rain, snow and sleet.

Particle size distributions generated from precipitation are within the course particle mode with mean sizes ranging between 1 to 3 mm depending on concentration (Brimblecombe, 2003, p. 212).

2.2.2 Clouds, fogs and mists

Table 2 summarise the differentiations between the clouds fogs and mists. Clouds can be differentiated from fogs and mists by their altitude.

	Range LWC	Common LWC	Range droplet size	Common droplet size
Stratus and stratocumulus clouds	0.05 - 3 g (water) m^{-3}	0.1 - 0.3 g (water) m^{-3}	0.5 - 50 µm	10 - 20 µm
Fogs	0.02 - 5 g (water) m^{-3}	0.1 - 0.3 g (water) m^{-3}	0.5 - 50 µm	10 - 20 µm
Mists	0.02 - 5 g (water) m^{-3}	0.1 - 0.3 g (water) m^{-3}	0.5 - 50 µm	0.5 - 10 µm

Table 2, aqueous phase LWC and droplet sizes (Seinfield & Spyros, 2006, p. 286), (Mason, 1975, pp. 40-59, 94-124)

The table above shows range and modal in liquid water content (LWC), or in other words water density of the aqueous phase and droplet size.

2.2.2.1 Clouds

Clouds cover approximately 60% of the Earth's Surface (Heymsfield, 1993, p. 97) and base height altitudes range between 0 – 18km (Warren, et al., 1988).

The cloud types that are of particular interest are stratus and stratocumulus the elevated cousin of fog, which is a stable cloud deck which tends to form when a cool, stable air mass is trapped underneath a warm air mass. These cloud base height altitudes range, between 0 – 3 km and are most commonly observed over oceans (Seinfield & Spyros, 2006, p. 286).

2.2.2.2 Fogs

Fogs have similar microphysical structures to clouds and can be classified by their water density or liquid water content (LWC), altitudes and visibility. Fog differs from cloud only in that the base of fog is at the earth's surface while clouds are above the surface. Fog forms when the difference between air temperature and dew point is generally greater than 85% relative humidity (RH). Visibility reduction in fog depends on concentration of cloud condensation nuclei and the resulting distribution of droplet sizes (American Meteorological Society, 2013).

2.2.2.3 Mists

Mists (not to be confused with precipitation term "drizzle") can be differentiated from fog by visibility. Generally fog is measured by observing the reduction in horizontal visibility less than 1 km and mist is defined with the visibility observation less than 6 km (Chung, et al., 1999). Mist may be considered an intermediate between fog and haze:

- Mist is applied to liquid particles with air saturation greater than 70% RH and particles are smaller (a few µm maximum) in size
- Haze is often used for solid aerosols with air saturation less than 70% RH and does not contain aerosol larger than the critical size according to Köhler theory.

Mist is commonly observed in marine and coastal areas when the air temperature of fog is increases and condensation competes with evaporation.

2.3 Sea salt aerosol (SSA)

SSA is the term used to describe aerosol in the accumulation and course particle mode (greater than 50 nm) that has been mechanically produced by bursting bubbles or wind-induced wave breaking (Blanchard & Woodcock, 1957); (Monahan, et al., 1983).

SSA contains dissolved salt molecules suspended in water which makes it hygroscopic, meaning it readily exchanges moisture with the surrounding atmosphere, fluctuating its

equilibrium water content and radii which is dependent almost entirely by ambient relative humidity (RH) (Lewis & Schwartz, 2004, p. 10).

This means that the mass of the solute (salt) contained in each aerosol particle will remain constant. However, the actual amount of water contained can vary as a function of ambient relative humidity, i.e.:

- as the humidity decreases, some of the water in the aerosol will evaporate, and;
- as the humidity increases, the salt in the aerosol will condense water from the air.

As this process of evaporation and condensation occurs, the diameter of the aerosol will vary. It is important to note that while the water content of the aerosol may fluctuate with humidity, the salt content remains unchanged (Carleton & Shelton, 1985).

The Marine Boundary Layer (MBL) is defined from 0 m to heights typically between 700 – 3000 m above sea level (Lewis & Schwartz, 2004, p. 45). Typical SSA concentrations in the MBL are around 5-30 particles per cm^3 (Blanchard & Cipriano, 1984); (O'Dowd & Smith, 1993). Also SSA concentration shows a strong dependence on wind speed and ranges from about 2 $\mu g\ m^{-3}$ to as much as 50 $\mu g\ m^{-3}$ or more at wind speeds in excess of 15 $m\ s^{-1}$ (Fitzgerald, 1991).

The smallest SSA particles that can activate to form cloud droplet ranges from approximately 0.04 µm to near 0.1 µm, this means that nearly all of the SSA mass concentration (more than 99.995%), can function as cloud condensation nuclei and activate to form cloud drops (Lewis & Schwartz, 2004, pp. 20-22).

3 NGTE salt-in-air marine atmosphere standard

Table 3 data was produced in 1971, when the British National Gas Turbine Establishment – Naval Marine Wing (NTGE-NMW) defined its salt-in-air marine atmosphere standards in the NGTE Marine Aerosol Distribution Standards. Since this standard was established, additional testing, sampling trails, and modelling have been carried out, resulting in a changing in the understanding of the marine aerosol. Nevertheless, the standard is still in place and serves as a very stringent development standard for marine air intake separators protecting gas turbines (Fewel & Pierzkowski, 1995).

Wind velocity	20 knots (10.29m/s)		30 knots (15.43m/s)		40 knots (20.58m/s)	
Particle size	%	ppm	%	ppm	%	ppm
<2	1.4	0.0038	0.1	0.0038	0.007	0.0038
2 – 4	4.6	0.0122	0.6	0.0212	0.070	0.0377
4 – 6	10.9	0.0286	3.9	0.1401	1.1	0.5585
6 – 8	13.8	0.0364	8.5	0.3060	3.8	1.9
8 – 10	13.8	0.0364	12.0	0.4320	7.0	3.5
10 – 13	15.8	0.0416	18.0	0.6480	16	8
>13	39.3	0.1040	56.9	2.0486	72	36
TOTAL	100	0.2630	100	3.6000	100	50

Table 3, test data recorded by the National Gas Turbine Establishment (Pack & LCDR, 1973)

It should be noted that on NGTE's admission, the ambient aerosol loadings in Table 3 are assumptions based on limited statistical data compiled from nine surveys by various ships (approximately 0 m above sea level) and countries in an area limited primarily to the North Sea and English Channel. Additionally the NGTE loadings were considered to be a "pessimistic interpretation of the available results" (Randels, et al., 1972).

Subsequent U.S. Navy investigation of the NGTE data indicates the assumed NGTE standard to be in most cases as much as 100 times higher than supporting survey data (Carleton & Shelton, 1985).

4 Fitzgerald aerosol research

Fitzgerald (1991) performed a review of the physical and chemical properties for marine aerosol showing a keen interest in the finer particulate modes (Aitken and accumulation). In his research he compares the particle size and volume distributions from publications ranging from 1974 to 1989 which are summarised in Table 4 to provide further insight on the development in the understanding of marine aerosol.

Authors	Location	Sampling height (m)	Instrumentation and particle size (µm)
Mészáros & Vissy (1974)	South Atlantic and Indian Oceans (40° - 65°S)	Ship level	Optical and electron microscope analysis of filter samples (0.03<r<60 µm)
Gras and Ayers (1983)	Cape Grim, Tasmania (40°S, 144°E)	95	Diffusion battery with Pollak CNC (0.002<r<0.1 µm), CLIMET OPC (0.15<r<5.0 µm)
Haaf & Jaenicke (1980)	North Atlantic during JASIN (59°N, 10°W)	14	Electric mobility analyser (0.003<r<0.4 µm)
De Leeuw (1986)	North Atlantic (57°N, 20°W)	11	Rotorod inertial impactor (5.5<r<42.5 µm)
Exton et al. (1986)	Coastal site on Outer Hebrides (57°N, 7.5°W)	10	PMS ASAS and CSAS probes (0.08<r<16 µm)
Hoppel et al. (1989)	Subtropical, Atlantic (20-30°N, 15-70°W)	Ship level	Differential mobility analyser (0.006<r<0.5 µm), replication impactor (0.5<r<15 µm)

Table 4, summary of the sampling location, sampling height and method of measurement for the particle size and volume distribution shown (Fitzgerald, 1991).

Figure 4 is a plot of the aerosol particle size and distributions in clean marine air. The plot implies that the highest size distribution of particles is within the Accumulation mode. This means that the majority of the particles are between 50 nm and 1 µm.

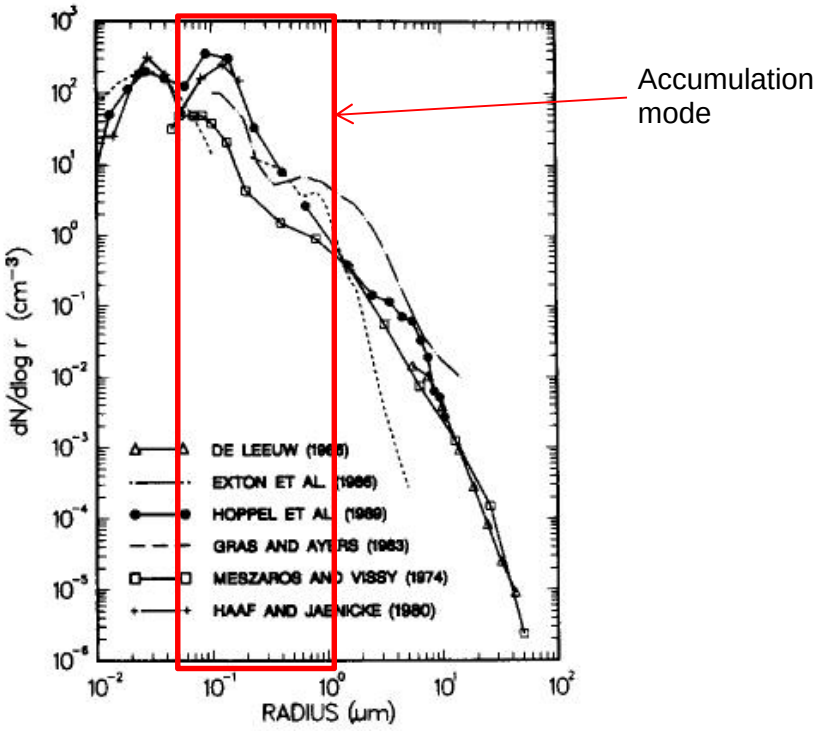

Figure 4, published measurements of the size distribution of aerosol particles in clean marine air (Fitzgerald, 1991).

Figure 5 shows the particle volume distributions calculated from the size distributions in Figure 4. This plot shows that volume distributions are within the course particle mode. This means that the majority volume in contained within particles are greater than 1 µm.

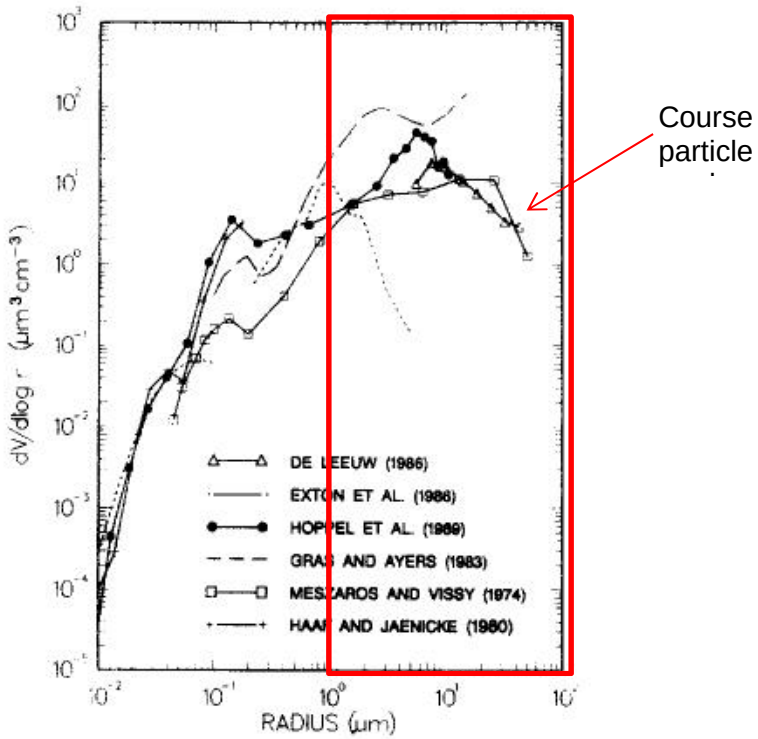

Figure 5, particle volume distributions corresponding to the size distributions in Figure 4 (Fitzgerald, 1991).

When comparing the Figure 4 and Figure 5 all 6 tests have the same correlation despite the different altitudes:

- The coarse mode constitutes about 90-95% of the total mass but only 5-10% of the total number of particles.
- The finer modes (accumulation and Aitken) constitutes to only 5-10% of the total mass but 90-95% of the total number of particles.

When comparing this conclusion with Table 2, the most common droplets within clouds, fogs and mists are approximately 10 µm which is within the course mode and would constitute to the majority of the overall droplet water volume.

5 Comparing NGTE and Fitzpatrick research papers

When comparing the number of particles from NTGE research to Fitzgerald's 6 comparisons the following statements can be made:

- The NGTE particle size distributions show a positive correlation where particles over 1 µm contribute to 100% of the total number of particles.
- Fitzpatrick particle size distributions show a negative correlation where particles over 1 µm contribute to 5-10% of the total number of particles.

There this means there is no similarity between the two papers, not only the particle sizes distribution, but also the correlation is completely different. It could be argued that NGTE testing was implemented at a different altitude or location, so when comparing locations and altitude:

- The NGTE only implemented their surveys around the North Sea and English Channel at ship level which would approximately range between 0 - 5 m above sea level.
- Fitzpatrick reviews 6 different research papers, survey locations and altitudes are varied around the globe and between 0 – 95 m above sea level.

Mészáros & Vissy (1974) and Hoppel et al. (1989) papers both carried out research and ship level and when compared have similar correlations with the 4 other research papers included in the Fitzpatrick's (1991) research at high altitudes. The Mészáros & Vissy (1974) and Hoppel et al. (1989) papers are also at the same attitude as the NGTE standard and when compared do not show any similarity.

The NTGE particle size concentrations are not an accurate representation of SSA observe internationally and the U.S Navy statement regarding the NTGE "in most cases as much as 100 times higher than supporting survey data" rings true.

5.1 Conclusion

Further investigation should be implemented on weather conditions (clear and cloudy) to determine the relation between the above aerosol and the data publicised in Table 2, where cloud and fog droplets are also observed greater than 1 µm and commonly found within the 10 – 20 µm range, and for mist droplets within the 0.5 – 10 µm range.