DEPARTMENT OF PHYSICS

ATMOSPHERIC, OCEANIC AND PLANETARY PHYSICS

Quantifying the Climate Impact of Global and European Transport Systems (QUANTIFY): A Review of the Study of Ship Tracks

G. B. L. Ewen and R. G. Grainger
Atmospheric, Oceanic and Planetary Physics, University of Oxford

AOPP Memorandum 2006.1

February, 2006

University of Oxford

Abstract

This document is a review of the current state of knowledge regarding the study of ship tracks.

Atmospheric aerosol particles are known to have a significant impact on Earth's climate. Of all anthropogenic sources, ship-stack effluents provide the clearest demonstration of the indirect aerosol effect on cloud albedo. Ships are believed to modify cloud microphysics by adding cloud condensation nuclei (CCN) to a developing or existing cloud. These create lines of larger reflectance in cloud fields that are observed in satellite imagery. Ship tracks are most frequently seen off the west coast of California, and the Atlantic coast of both west Africa and south-western Europe.

The most comprehensive study of the ship track phenomenon to date, was the Monterey Area Ship Track (MAST) experiment conducted off the coast of California in June 1994. The MAST experiment concluded that if the ambient or background cloud was of continental influence (and thus contained a higher typical CCN concentration than for clean maritime) the cloud was found to be relatively insensitive to further aerosol emissions, with only a weak microphysics signature in the ship tracks. However, if the background clouds were pristine maritime stratiform then changes in droplet concentration of a factor of 2, and changes in droplet size of up to 50 % were measured.

Ship track measurements have yielded strong hints, but not clear evidence, that precipitation is affected by exhaust from ships. For example during MAST aircraft measurements showed reductions in drizzle flux and concentrations of drops > 50 μm radius in ship tracks when drizzle was more uniformly present in the ambient cloud.

The formation of ship tracks is dependent on a combination of ship-produced CCN and environmental conditions such as droplet concentration and optical thickness of pre-existing clouds, as well as wind speed, updraft velocity and turbulence structure in the marine boundary layer. The factors involved have a complex interaction, and ship track formation is an ongoing area of research in which a unified theory has not yet been reached.

Ship tracks represent a microcosm for what is slowly occurring in the atmosphere. There are many advantages to studying ship tracks as a particular manifestation of the more general problem of the influence of anthropogenic pollution on cloud albedo.

Contents

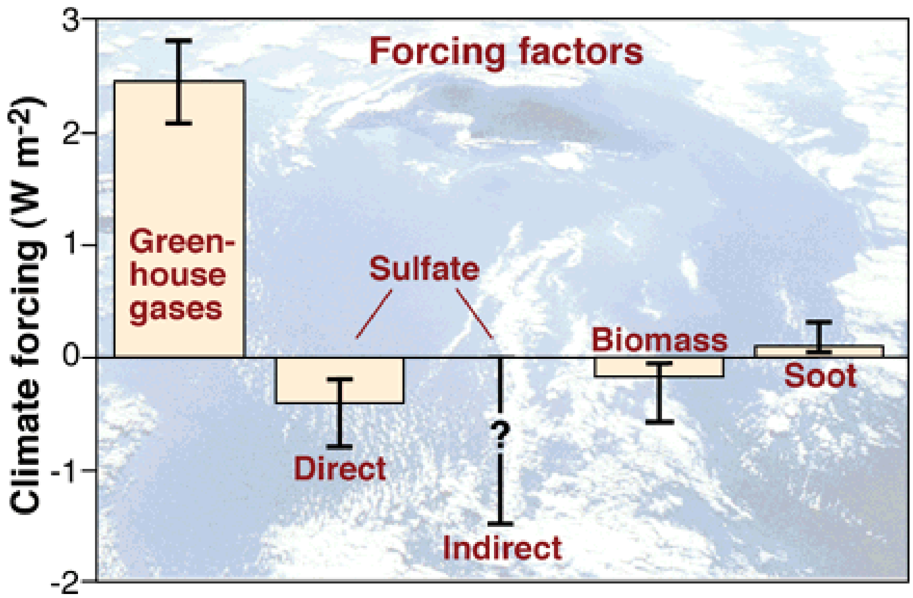

Figure 1: Climate forcing from 1850 to present (Kiehl, 1999). Positive forcing corresponds to warming and negative forcing to cooling of the atmosphere.

1 Introduction

Atmospheric aerosol particles are known to have a significant impact on Earth's climate (Hansen et al., 1997; Ramanathan et al., 2001). However, whereas the effect of greenhouse gases on Earth's radiation budget is well understood, the effect of aerosols is far more complex (Penner et al., 2001) and the uncertainties relating to estimates of the radiative forcings remain large (Ramaswamy et al., 2001).

Aerosols have a direct radiative forcing because they scatter and absorb both solar and infrared radiation in the atmosphere. The net direct effect is thought to be a cooling as an increased presence of aerosol will lead to a net increase in Earth's albedo. Aerosols also influence climate indirectly through their important role in cloud condensation and as ice nuclei (Twomey, 1974; Kaufman and Fraser, 1997). Increases in aerosol causes an increase in the number of droplets in clouds. The increase in droplet concentration tends to decrease the mean cloud particle size which leads to an increase in the cloud albedo, leading to a climate cooling (Twomey, 1977). This process is often referred as the "Twomey effect" or the "first indirect" aerosol forcing.

The large uncertainties in the estimates of aerosol forcing are illustrated in figure 1. In contrast to greenhouse gases, which remain in the atmosphere for a long time and are near uniform in distribution, aerosols tend to be concentrated near their sources and are highly variable in space and time (Toon, 2000). In addition, aerosol effects have a lower order dependence on a range of highly variable properties, such as concentration, composition, optical properties, solubility, and activity as condensation and ice nuclei. Uncertainties in the direct effect are dominated by the uncertainty in the amount and distribution of aerosols as well as the optical properties of the aerosols which determines the effectiveness at reflecting sunlight back to space. Interactions between different types of aerosols may also affect the magnitude of direct forcing. The indirect aerosol effect is even more

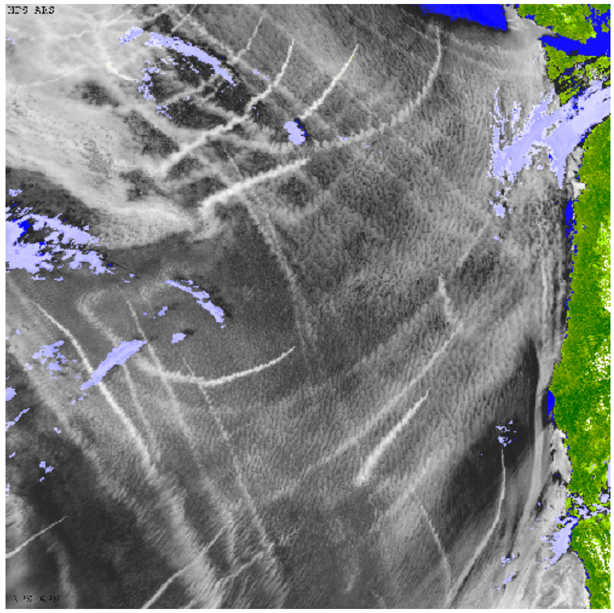

Figure 2: An example of ship tracks off the west coast of Washington, United States (Ferek et al., 1998).

elusive to full characterisation. Remote sensing and in situ observations have indicated that an increase in aerosols below a cloud leads to an increase in droplet concentration within the cloud (e.g. Ramanathan et al., 2001; Heymsfield and McFarquhar, 2001).

Aerosols can occur naturally, originating from volcanoes, biomass burning, dust storms and sea spray. Human activities, in particular the burning of fossil fuel, can generate both sulphate and carbonaceous aerosols[1]. Anthropogenic sources account for about 10 percent of the total amount of aerosols in our atmosphere.

Of all anthropogenic sources, ship-stack effluents provide the clearest demonstration of the indirect aerosol effect on cloud albedo. Lines of larger reflectance in cloud fields are frequently observed in satellite imagery and identified as tracks of ship exhaust (e.g. Coakley et al., 1987). Such perturbations of the marine stratiform cloud field, known as “ship tracks”, are characterised as long-lived, narrow, curvilinear regions of enhanced cloud reflectivity which occur downwind of ships. An example of ship tracks appearing as bright features in AVHRR (Advanced Very High Resolution Radiometer) near-infrared imagery is given in figure 1.

In order to better understand the ways in which aerosols affect climate, an integrated approach of global monitoring of aerosol distribution with validation via the use of chemical transport models (CTMs) and impact studies via the use of general circulation models (GCMs) is required (see Kiehl, 1999). Satellite observations can provide near-global monitoring of aerosol distribution, but they cannot separate natural aerosols from those associated with human activity. However, in order to investigate the effects of anthropogenic aerosol specifically, ship tracks are an invaluable special case for study due to the direct causal nature of their formation. By considering ship tracks as an analogue to anthropogenic pollution in general, the problem is simplified by investigating controlled cases where a specific, isolated source in the marine boundary layer causes a specific, observed change

[1]Black carbon aerosol is often loosely referred to as “soot”.

in cloud albedo. Thus allowing the underlying indirect radiative effect of aerosols on clouds to be characterised.

With the recent commencement of the European Union framework project known as Quantify, which aims to quantify the climatic impacts of global and European transport systems and with the International Maritime Organisation (IMO) continuing its effort to address air pollution from ships (see IMO, 2002), a review of the current state of knowledge regarding the study of ship tracks proves a timely and highly useful objective for this report.

2 Formation

Ship tracks can be separated into two classes. The first, and most common form of ship tracks are bands of enhanced cloud thickness embedded in background marine stratus. This common type of ship track is evident only at near-infrared wavelengths in satellite imagery. The second type of ship track is observed at visible wavelengths and appears in regions where the surrounding cloud reflectivity is relatively low. This second type of ship track forms in conditions which would otherwise be cloud-free without the addition of exhaust particles emitted by ships.

The characteristic enhanced reflectance of ship tracks is due to smaller droplets in the clouds and higher droplet concentrations. Ships are believed to modify cloud microphysics by adding cloud condensation nuclei to a developing or existing cloud (Conover, 1966; Twomey et al., 1966). There is considerable evidence supporting this hypothesis, for example, Hindman et al. (1994), Ferek et al. (1998) and Hudson et al. (2000).

Cloud droplets form in the atmosphere through heterogeneous nucleation. Aerosol particles of micron and submicron size act as centres for condensation, and are thus known as cloud condensation nuclei (CCN). The rate of droplet formation is determined by the number of nuclei present, and not by collision statistics. Twomey (1959) showed that the droplet concentration depends on the updraft velocity, the concentration of aerosol nuclei and the cloud forming propensity, or efficiency, of the nuclei (often referred to as the aerosol's *activity spectrum*) as a function of the supersaturation of the atmosphere.

The stratus embedded ship track type results simply from increased concentrations of smaller cloud droplets, which in turn is due to an increase in the concentration of CCN from ship emissions. However, the second type of ship track forms in near-saturated environments due to the interaction between droplet concentrations and vertical mixing in the marine atmosphere (Hindman et al., 1994; Ackerman et al., 1995). At very low droplet concentrations a cloud layer can collapse to a shallow fog. This happens when the cloud layer cannot maintain the vertical mixing (due to infrared cooling at cloud top) that supplies its moisture from the ocean surface. The addition of aerosols from ship exhaust into such a fog can lead to the formation of a visible cloud line downwind of a ship.

The formation of ship tracks is dependent on a combination of ship-produced CCN and environmental conditions such as droplet concentration and optical thickness of preexisting clouds, as well as wind speed, updraft velocity and turbulence structure in the marine boundary layer. The factors involved have a complex interaction, and ship track formation is an ongoing area of research in which a unified theory has not yet been reached. Section 6 gives further discussion of previous case studies.

To understand ship track formation and its subsequent impacts on a global scale, quantifying ship emissions and characterising the composition (e.g. the sulfur content) and its relation to fuel type is imperative. Figure 2 shows the results of a study by Corbett and Fischbeck (1997) showing annual

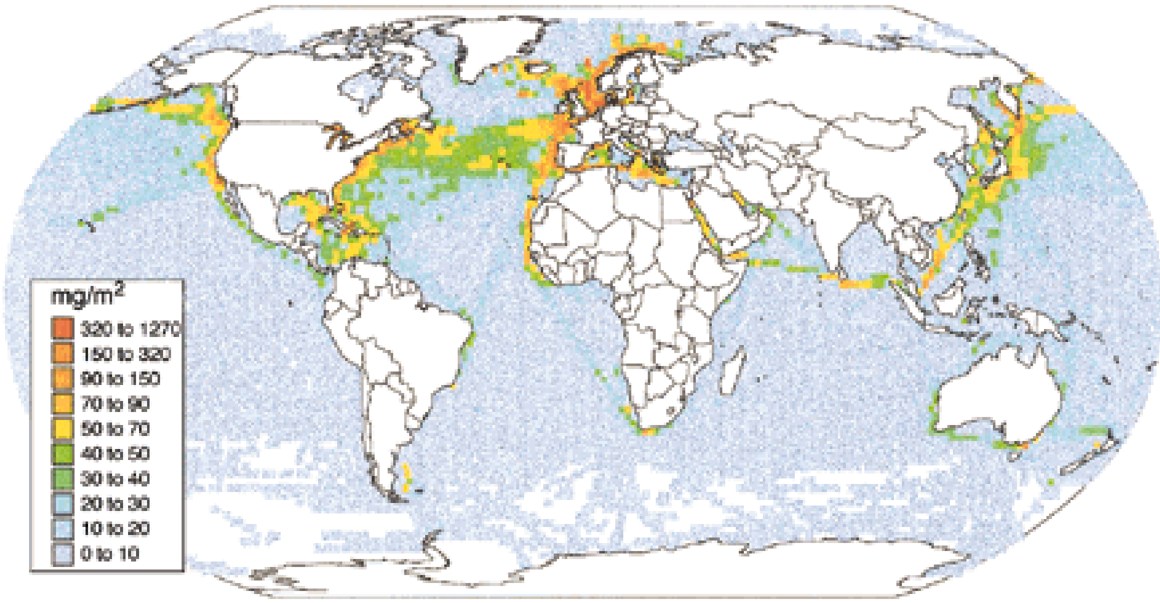

Figure 3: Geographic distribution of annual ship sulfur emissions (Corbett and Fischbeck, 1997).

global ship emissions in terms of the mass of sulfur. From such data it is possible to estimate the geographic regions in which ship tracks are most likely to occur. However, though ship tracks are common, they are absent more often than not even in regions with a constant presence of ship traffic. Cloud dynamics and environmental conditions must be considered along with the microphysics when studying the nucleation of ship-produced CCN. Favourable environmental conditions for ship track production are very common in the marine boundary layer over the subtropical highs. Over these large, quasi-stationary highs, the boundary-layer air is divergent, making it unlikely to draw in CCN-rich continental air. Ship tracks are most frequently observed off the west coast of California, and the Atlantic coast of both west Africa and south-western Europe.

Ship engines are among the world's highest polluting combustion sources per ton of fuel consumed, but an important question is how does the variability of the effluent emitted by ships affect the ability of the resulting aerosol particle sizes to serve as CCN?

The Monterey Area Ship Track Experiment (MAST; Durkee, Noone and Bluth, 2000) attempted to address this question as part of its remit (MAST is discussed further in section 6). Airborne measurements were used by Hobbs et al. (2000) to derive emission factors of SO_2 and NO from diesel-powered and steam turbine-powered ships, burning low-grade marine fuel oil (MFO); they were $\sim 15 - 89$ and $\sim 2 - 25$ g kg^{-1} of fuel burned, respectively. By contrast a steam turbine-powered ship burning high-grade navy distillate fuel had an SO_2 emission factor of ~ 6 g kg^{-1}. Ships burning both MFO and navy distillate fuel emitted from $\sim 4 \times 10^{15}$ to 2×10^{16} total particles per kilogram of fuel burned, with the emission rates from burning MFO fuel approximately an order of magnitude bigger than from burning higher-grade fuel. Hobbs et al. (2000) found that ships burning MFO (both diesel-powered and steam turbine-powered) emitted particles with a larger mode radius ($\sim 0.03 - 0.05$ μm) and larger maximum sizes than those powered by steam turbines burning navy distillate fuel (mode radius ~ 0.02 μm). The larger particle sizes can serve as CCN at lower supersaturations and are thus more likely to produce ship tracks. Consequently, Hudson et al. (2000) showed that the type of fuel burned by a ship is more important than the type of ship engine in determining whether or not a ship will produce a ship track.

Furthermore, Frick and Hoppel (2000) showed that the formation of ship tracks is intricately dependent on both the Marine Boundary Layer dynamics and the background aerosol loading. Ship tracks are less likely to occur when the ship-produced particles are too small relative to the background aerosol.

The particles emitted from ships are primarily organics (e.g. polycylic aromatic hydrocarbons, Russell et al., 2000), often combined with sulfuric acid. Further measurements by Hobbs et al. (2000), of ship-produced particles in ship tracks, show that only about 12 % of particles serve as CCN. However, the fluxes of heat and water vapour from ships do not produce perturbations which are significant enough to play a role in the formation of ship plumes, evidenced by the absence of ship tracks in the wake of nuclear-powered ships.

3 Impact on Cloud Microphysics

It has long been established (e.g. Twomey, 1959) that increases in CCN concentration leads to an increase in droplet concentration. Thus, the primary influence of an injection of CCN to marine stratus from ship emissions is to increase the concentration of cloud water particles. The increase in droplet concentration tends to lead to a decrease in droplet size (Squires, 1958; Albrecht, 1989). However, the temperature and the atmospheric motions driving cloud formation, rather than the number of droplets, control the mass of water condensing in the cloud. This trend has been well documented for pollution and biomass burning smoke aerosols serving as CCN (Rosenfeld, 2000; Kaufman and Fraser, 1997; Kaufman et al., 2002). *In situ* measurements show that in polluted air a sixfold increase in the concentration of sub-micron and micron sized aerosols can produce a three- to fivefold increase in the droplet concentration (Heymsfield and McFarquhar, 2001). Satellite data shows that such a change in aerosol concentration (with liquid water content remaining constant) corresponds to 10-25 % smaller cloud droplets (Bréon et al., 2002), because the condensed water is divided into more numerous droplets. In the case of ship tracks, the ambient marine stratiform clouds are known to be particularly sensitive to the addition of CCN due to their typically low droplet concentrations (Twomey, 1991). Observations of increased droplet concentration and reduced droplet size in ship tracks have been made both remotely and *in situ*.

In situ evidence is somewhat less prevalent than its remotely sensed counterpart. However, the caveat to remotely sensed data is that the reduced droplet size is inferred from the radiometric measurements by an increase in cloud albedo (as shown by Twomey, 1974). This effect was clearly demonstrated by Coakley et al. (1987) using radiance measurements from the Advanced Very High Resolution Radiometer (AVHRR) instruments onboard the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. The reflectivity of the ship tracks at 3.7 μm was shown to be greater than the levels for nearby noncontaminated clouds of similar physical characteristics. In addition, the increase in droplet number also caused the reflectivity at 0.63 μm to be significantly enhanced for the ship tracks with respect to the ambient clouds, despite the likelihood that the exhaust is a source of particles that absorb at visible wavelengths. Platnick and Twomey (1994) also presented measurements of ship tracks from AVHHR instruments, identifying the ship tracks from the regions of enhanced reflectivity in the 3.7 μm channel. Building on the Coakley et al. (1987) study, Platnick

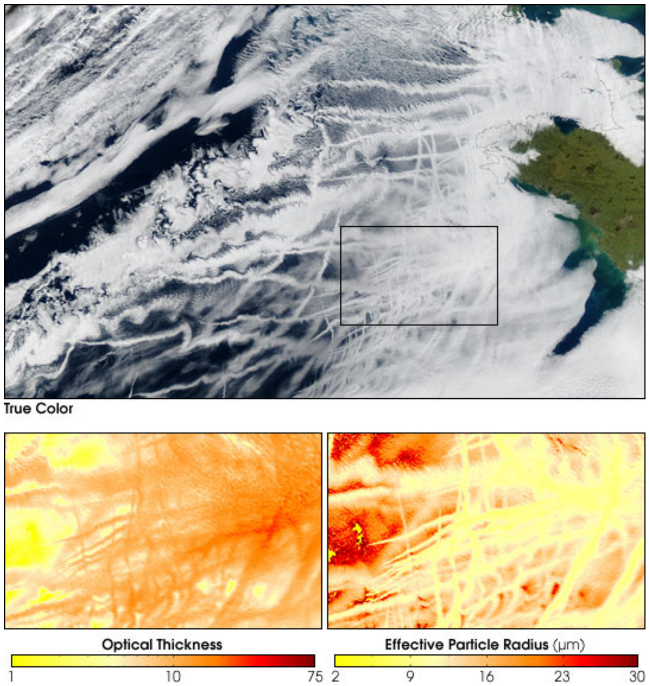

Figure 4: True- and false-colour ship track images off the Atlantic coast of Europe from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite on January 27, 2003 (Kaufman and Herring, 2003).

and Twomey (1994) applied a retrieval algorithm[2] to infer optical thickness and droplet radius from the satellite measurements. For a particular case study of Californian marine stratus and ship tracks, the results showed that in-track radii were between 2 and 10 μm smaller than out-of-track radii. Platnick and Twomey (1994) derived an empirical relation between changes in radius and cloud droplet concentrations, such that typically retrieved changes in radius from $\frac{\triangle r}{r} = -0.15$ to -0.3 give corresponding changes in droplet concentration of about $\frac{\triangle N}{N} = 1$ to 5, respectively, and with no change in liquid water content, corresponding changes of $\frac{\triangle N}{N} = 0.6$ to 1.9, respectively.

More recently, retrieval algorithms similar to that used in Platnick and Twomey (1994) have become more common place (e.g. Matheson et al., 2005) and have been employed to infer optical and microphysical properties of polluted clouds, and in particular ship tracks, on a global basis. Figure 3 shows an image from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA Aqua satellite. Multiple ship tracks off the Atlantic coast of Europe are clearly visible in the false-colour main image and display a complex criss-crossing network. The true-colour images in figure 3 show the retrieved optical thickness and effective radius, available in the standard MODIS cloud product derived using King et al. (1997). The ship tracks display a significant enhancement in optical depth and decrease in particle size with respect to the ambient marine stratus. The effective

[2]The retrieval algorithm is designed to solve the *inverse* problem of inferring optical thickness and droplet radius from the satellite measurements. In this case, the solution was determined from the best fit between the satellite measurements and various entries in a library file. The library contained bidirectional reflectances calculated for the 0.65, 0.85 and 3.7 μm AVHRR channels, and effective cloud and surface emissivities calculated for the 3.7, 10.75 and 12.0 μm channels. The library entries were modelled using the LOWTRAN7 radiation code (see Kneizys et al., 1988).

radius within the ship tracks can be seen to be ~ 10 μm or less in contrast to a typical range of 15 to 25 μm in the ambient cloud.

The most effective *in situ* investigations of microphysical and radiative properties of ship tracks were coupled with remote sensing measurements in order to improve the macro-scale information. Radke et al. (1989) was the first major study of this kind and showed clear increases in aerosol and droplet number concentrations in ship tracks, as well as a shift toward smaller droplet size. King et al. (1993) also found similar microphysical changes in ship tracks off the coast of southern California. The aircraft measurements showed that within the ship track features the droplet concentration showed an increase over the ambient cloud by a factor of 1.5 to 5. The particle radius had a maximum difference of 13 μm less than the ambient cloud, with an approximate average effective radius within the ship tracks between 7 and 8 μm and between 11 and 12 μm in the ambient cloud. Ferek et al. (1998) also used AVHRR measurements in conjunction with aircraft measurements of ship tracks off the Washington coast and concluded that the cloud droplet spectra measured in the ship tracks had an effective radii about one half of those measured in the ambient cloud, with average particle sizes in the ship tracks less than 12 μm. Similar results were obtained from coupled aircraft and satellite measurements during the MAST Experiment by Durkee et al. (2000a) and Ferek et al. (2000). Taylor et al. (2000) summarised the results of 11 aircraft flights during the MAST period. The impact of the aerosol emitted from the ships was found to be very dependent on the background cloud microphysics. If the ambient or background cloud was of continental influence (and thus contained a higher typical CCN concentration than for clean maritime) the cloud was found to be relatively insensitive to further aerosol emissions, with only a weak microphysics signature in the ship tracks. However, if the background clouds were pristine maritime stratiform then changes in droplet concentration of a factor of 2, and changes in droplet size of up to 50 % were measured.

4 Suppression of Precipitation

The previous section has shown that it is well established that ship emissions can modify background stratiform cloud to increase droplet concentration and decrease droplet size. One particularly important repercussion of this microphysical effect is that cloud precipitation will be inhibited.

Clouds precipitate when they survive for long enough to grow water and/or ice particles that are large enough to fall to the Earth. Typically, droplets which grow in clouds from the vapour phase reach sizes of up to about 10 μm in radius. Such particles fall at a rate of a few centimetres per second and will evaporate in dry air after travelling only a few centimetres, which is why we observe clouds suspended in our atmosphere. A raindrop has a typical size of about 200 μm or larger in diameter and falls several meters per second, and can travel many kilometres through dry air before evaporating.

Cloud droplets grow initially from the vapour phase by condensation, but once their *effective radius* (i.e. the ratio of the total volume of all drops in a particular region divided by their total surface area) reaches a value of about 14 μm it is no longer energetically favourable to grow by diffusion and any further growth occurs by the collision and coalescence of droplets (e.g. Rogers and Yau, 1989). About 10^6 cloud droplets must collide and coalesce in order to make a precipitation-sized drop. The rate at which a falling drop sweeps up other drops depends on the fall velocity, cross sectional area, and likelihood that falling particles actually touch and coalesce (Toon, 2000). Each of these processes varies approximately as the square of the radius for cloud drop-sized particles. The precipitation process is therefore highly sensitive to the size of the initial cloud droplets. Those with

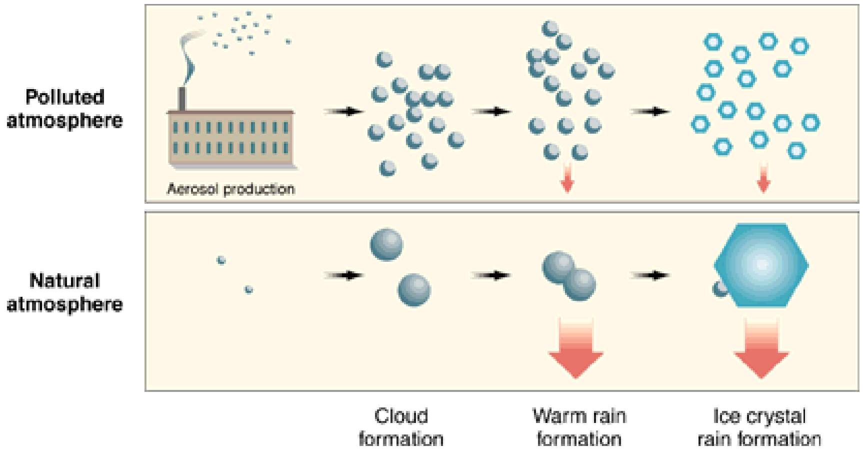

Figure 5: Processes by which aerosols affect clouds. The polluted cloud contains eight times as many droplets of half the size, twice the surface area, twice the optical depth, and higher reflectivity than the natural cloud. (Toon, 2000).

diameters of less than 30 μm have a low probability of growing into raindrops.

Precipitation can also form in clouds through ice processes. Ice has a lower vapour pressure than liquid water, and ice particles therefore grow rapidly to very large sizes by collecting vapour from surrounding liquid droplets.In the upper atmosphere ice crystals can form at temperatures below -35 °C through homogeneous freezing of water droplets. Ice crystals in the lower atmosphere form on ice nuclei, which constitute less than one out of every thousand particles in the ambient atmosphere. The ice particles can grow to precipitation size through the diffusion and deposition processes and then fall to Earth, melting to form rain at temperatures below 0 °C.

The warm cloud simulations of Takahashi (1978) for clouds with depths of approximately 1.5 km show that precipitation decreases significantly for CCN concentrations greater than 150 cm^{-3}. Gerber (1996) investigated the occurrence of precipitation (which takes the form of *drizzle* in the case of shallow clouds) as a function of effective droplet radius for a variety of marine stratus clouds and described a so-called drizzle threshold with an effective radius of about 14 μm. Stratus clouds with effective radii below this threshold generally did not produce significant drizzle.

Ship emissions and pollution can increase the concentration of CCN (usually in the form of smoke or aerosol particles) to over 10 times that of clean air, to about 1000 CCN per cm^3. As the total amount of water in polluted and unpolluted clouds at a particular height is about the same, the water in dirty clouds is distributed over a much larger number of smaller droplets. These smaller water droplets are then less likely to grow into larger drops of precipitation size during the lifetime of the cloud. At colder temperatures, the smaller droplets will freeze more slowly than the larger droplets in clean clouds at sub-zero temperatures. In ascending air currents these supercooled liquid droplets will float around the falling ice particles. The supercooled liquid droplets are thus difficult for the ice particles to capture, and so making it more difficult to grow to precipitation size. Figure 4 shows an example in which the unperturbed cloud sweeps up 64 times the volume of air containing other droplets as the ones in the dirty cloud. Consequently, the polluted cloud with the higher CCN concentration would be much less likely to rain.

There is strong evidence supporting the suppression of rain over polluted regions (Warner and

Twomey, 1967; Warner, 1968; Rosenfeld and Lensky, 1998; Rosenfeld, 1999; Rosenfeld, 2000). In the satellite study by (Rosenfeld, 2000), measurements from the precipitation radar and AVHRR instruments aboard NASA's Tropical Rainfall Measuring Mission were used to demonstrate the precipitation differences inside pollution tracks. The clouds within and outside the pollution tracks had similar dimensions and contained similar amounts of water. The only difference was the reduction in cloud particle effective radius within the pollution tracks to less than 14 μm. Precipitation was only observed outside the pollution tracks. Heymsfield and McFarquhar (2001) also made *in situ* observations of inhibited precipitation in polluted clouds over the Indian Ocean. However, studies by Hobbs et al. (1970) and Hindman et al. (1977) showed results to the contrary. Over large paper mills, which are known to be prolific producers of CCN, clouds affected by such plumes have higher droplet concentrations and broader droplet size spectra and appear to precipitate more readily. This effect is most likely due to the presence of giant soluble particles in the pollution. These large or giant CCN are a complicating factor and could act as seeds for large droplets and initiate the precipitation process, by enhancing the growth rate of raindrops via the collision-coalescence mechanism.

Desert dust also suppresses precipitation from warm clouds (Rosenfeld et al., 2001),but it also has a strong ice-nucleating activity, thus the detrimental impact of dust on rainfall is smaller than that caused by smoke from biomass burning or anthropogenic air pollution.

Ship track measurements have yielded strong hints, but not clear evidence, that precipitation is affected by exhaust from ships. Albrecht (1989) showed that for ship tracks measured off the coast of California on 13 June 1976, the droplet size distributions were narrower and the droplet count was lower, which directly corresponded to a notable reduction in drizzle. During an aircraft campaign off southern California, Radke et al. (1989) and King et al. (1993) observed an increase in cloud liquid water and a decrease in drizzle-size drops in ship tracks. Ferek et al. (1998) also noticed a reduction in drizzle drops in ship tracks off Washington but no associated increase in cloud liquid water. During the MAST Experiment Ferek et al. (2000) used aircraft measurements to report that significant changes in cloud droplet size distribution, as well as reductions in drizzle flux and concentrations of drops $> 50\ \mu$m radius, were observed in ship tracks when drizzle was more uniformly present in the ambient cloud.

The major implication of suppressed precipitation in ship tracks (although perhaps more important for polluted clouds on a global scale), is that the lifetime of the cloud will increase. Ackerman et al. (1995) used numerical simulations to show that ship track lifetimes could be in excess of a day. An increase in cloud lifetime due to the addition of aerosol CCN will enhance the radiative impacts of the clouds and is thought of as the second indirect aerosol effect.

5 Radiative Effects

In order to characterise the impact of ship tracks, or indeed any cloud type, on the climate system a measure of the radiative effect is required. Arking (1991) suggested a *cloud sensitivity* as the most meaningful measure for climate change, defined as the change in energy absorbed by the climate system (i.e. the albedo) to changes in a cloud parameter. In order to determine an indirect aerosol effect it is necessary to determine the relative importance of cloud parameters with respect to cloud sensitivity and then measure the modification of the cloud parameters by aerosols.

Cloud albedo is known to be partially dependent on both droplet size and droplet concentration, which is in turn linked to CCN concentrations during cloud development. As mentioned above, CCN concentrations can be increased by anthropogenic sources, and the overall effect of increasing CCN is to increase cloud albedo. This increase in cloud albedo results in cooling; there is no compensating effect in the infrared. It is useful to define a quantity representing the sensitivity of cloud albedo to changes in CCN concentration. This quantity is referred to as *cloud susceptibility*. However, as CCN concentration is not easily measurable it is more useful to define the figure of merit as a function of the cloud's measurable parameters, i.e. the cloud albedo A and the droplet concentration N. Therefore, the *cloud susceptibility*, defined for the condition of constant liquid water content, is given by (Twomey, 1991; Platnick and Twomey, 1994)

$$\frac{\mathrm{d}A(\tau, \omega_0, g)}{\mathrm{d}N} = \frac{\partial A}{\partial \tau}\frac{\partial \tau}{\partial N} + \frac{\partial A}{\partial \omega_0}\frac{\partial \omega_0}{\partial N} + \frac{\partial A}{\partial g}\frac{\partial g}{\partial N}\,, \tag{1}$$

where τ is the cloud optical thickness, ω_0 is the droplet's single-scattering albedo and g is the asymmetry parameter. The derivative $\mathrm{d}A/\mathrm{d}N$ is approximately equivalent to the change in albedo that would have occurred to an existing cloud if it had developed under identical circumstances but in a slightly "dirtier" air mass such that the final droplet concentration was increased by one droplet per unit volume, i.e. $\triangle N = 1$ (King et al., 1995).

Susceptibilities retrieved with the 3.7 μm channel on the AVHHRR in selected California stratus vary over an order of magnitude (Platnick and Twomey, 1994), from about 0.5×10^{-3} to 10×10^{-3} cm^3. In the case study of ship tracks it was observed that within the tracks susceptibilities were all less than 2.5×10^{-3} cm^3 and generally about 1.0×10^{-3} cm^3, where as outside of the tracks the susceptibilities ranged from 2.5×10^{-3} to about 10×10^{-3} cm^3. A cloud susceptibility of 10×10^{-3} cm^3 means that if the cloud's droplet concentration were to increase by just 1 cm^{-3}, the albedo would increase by 0.01, resulting in a 1 % increase in radiative forcing. The susceptibilities presented by Platnick and Twomey (1994) show that the indirect effect has taken place in the ship tracks and that as a cloud experiences the indirect effect the cloud susceptibility will decrease, giving an indication of the magnitude of the perturbation.

During MAST, Ackerman et al. (2000), Taylor et al. (2000) and Platnick et al. (2000) look at differences between the radiative properties of the indirect of the background clouds and ship tracks. Results similar to Platnick and Twomey (1994) were obtained showing that in general cloud susceptibility is reduced in ship tracks.

Platnick et al. (2000) introduced a modifies cloud susceptibility known as "contrast susceptibility", for assessing the sensitivity of background microphysics on potential track development. It is shown that the relative change in cloud reflectance for ship tracks is expected to be larger in the near-infrared than in the visible and that 3.7 μm channels, widely known to be useful for detecting tracks, has the greatest sensitivity. The 3.7 μm contrast of the tracks was shown to be reasonably correlated to the contrast susceptibility of the background cloud. If the observed correlation were true in general, then estimates of potential ship track formation could be made from the contrast susceptibility without the details of ship effluent, droplet nucleation and dynamic processes.

Taylor et al. (2000) investigated the influence of the ship exhaust effluent on the microphysics and radiative properties of varying types of marine stratocumulus. It was found that in clouds of continental influence, the cloud susceptibility was low, with a corresponding weak microphysics signature in the ship tracks. In clean clouds, the susceptibility was higher and changes in droplet concentration of a factor of 2, and reductions in droplet size up to 50 % were measured. The impact of the ship exhaust on the microphysics of the clean clouds was found to increase the cloud radiative forcing by up to a factor of 4.

The aim of Ackerman et al. (2000) was to evaluate the analytic expression of Twomey (1991) for cloud susceptibility, by comparison to airborne measurements of ship tracks. Twomey's parameterisation was shown to represent the trend of albedo changes with droplet concentrations remarkably well. Together with the albedo changes, the changes in cloud liquid water content and droplet size distributions imply that cloud thickness usually increased in the ship tracks.

The first indirect aerosol effect and the increase in cloud albedo results from the modification of cloud microphysics. In addition, due to the suppression of precipitation, the cloud lifetime increases and there is therefore a longer time scale for the radiative forcing, this is known as the second indirect aerosol effect. The long lifetime of ship tracks was investigate by Durkee et al. (2000a) and is discussed in the following section.

6 Previous Studies

6.1 Studies Prior to MAST

Ship tracks have been observed regularly in satellite imagery since the early TIROS satellites began returning data in the 1960s (see Conover, 1966). The hypothesis put forward by Conover (1966) to explain this phenomena was that aerosol particles produced by the ships under "rather special atmospheric conditions" acted as CCN and led to the formation of streaks of enhanced albedo embedded in stratiform clouds. The special atmospheric conditions included:

1. A convectively unstable layer from the surface to a low-level stable layer.

2. Saturation or slight supersaturation near the top of the convective layer.

3. A convective layer presumably deficient in cloud forming nuclei.

Twomey et al. (1966) commented that the observations presented by Conover (1966) were consistent with the addition of CCN to a cloud layer with drop concentrations of about 1 to 10 cm^{-3}, i.e. a clean maritime boundary layer. Twomey (1974) later presented a link between cloud reflectance, droplet size and concentration, and CCN concentrations which has formed the cornerstone of investigations into the ship track phenomena.

There have been a number of investigations of ship tracks since those early observations. Coakley et al. (1987) and Albrecht (1989) observed the frequent and long-lived occurrence of ship tracks in preexisting stratus and stratocumulus clouds, as evident by the enhanced reflectance of these clouds, especially at 3.7 μm, consistent with a reduced droplet size and increased droplet concentration. Ship tracks have been found to form in very diverse stratiform cloud types and marine atmospheric boundary layer conditions (Evans, 1992; Millman, 1992). Marine boundary layer conditions that have been observed to be susceptible to ship track formation are fog, stratus, and stratocumulus with varying layer depths up to 1400 m but mainly shallow layers. Ship tracks have also been observed at night using 3.7 μm wavelength images (Kauciauski et al., 1993). Ship tracks are visible in the near-infrared because the smaller droplet size distributions in the tracks have a reduced emittance compared to the background cloud, unlike at longer wavelengths where the emittance is uniform.

During the marine stratocumulus intensive field observation (IFO) component of the First ISCCP Regional Experiment (FIRE), conducted off the coast of southern California during July, 1987 (Albrecht et al., 1988), the first *in situ* microphysics and solar radiation measurements of clouds modified by exhaust from ships were obtained. Radke et al. (1989) and King et al. (1993) present selected radiative and microphysics measurements taken from instrumentation onboard the University of Washington C-131A aircraft, as well as AVHRR satellite images. The results showed very clearly that droplet concentration in the ship tracks was enhanced significantly over the ambient cloud and the effective radius was reduced. The up- and downwelling radiation measurements suggest that the single-scatter albedo increased within the ship tracks (King et al., 1993). The measurements also showed significantly enhanced liquid water content and optical depth within the ship tracks, and King et al. (1993) presents a clear illustration of the suppression of drizzle droplets that result from the increased CCN concentrations (as suggested by Radke et al. (1989).

Hindman et al. (1994) presents a well-defined "cloud line" produced by an unidentified steamship detected in satellite imagery and simultaneously photographed from the R/V *EGABRAG*. The *EGABRAG* passed directly through the plume of the ship and onboard instrumentation measured an elevated CCN concentration coincident with the cloud line. It was deduced that the steamship was directly responsible for the production of the cloud line. Further measurements made from the *EGABARG* indicated that the cloud line formed in a shallow boundary layer which was nearly saturated, unstable, drizzling and nearly free of CCN. The *EGABARG* also produced a cloud line was observed in the satellite imagery but it was much less well-defined.

Case studies of California marine status and ship tracks were presented by Platnick and Twomey (1994). Platnick and Twomey (1994) applied a cloud property retrieval algorithm to AVHHR imagery to derive cloud effective radii and optical thickness. Ship tracks were observed in both uniform and thinner, patchier stratus layers. In addition, to clearly demonstrating that ship tracks have smaller effective radii than the ambient stratus and enhanced optical thickness, Platnick and Twomey (1994) also showed strong evidence of horizontal entrainment in ship tracks. However, there appeared to be a limit to the horizontal spreading of tracks, at least over short time periods. Contrary to the trend reported by Radke et al. (1989), some ship tracks were observed to be narrower and have smaller effective radii and higher optical depth near the tip. This trend was not apparent in all tracks and it was suggested that it may be due to the diffusion of CCN before droplet nucleation occurs.

Ferek et al. (1998) obtained in situ measurements in two ship ship tracks observed in satellite imagery off the coast of Washington State. They concluded that the CCN emitted from the ships was responsible for the decrease in the observed cloud drop size in the tracks.

6.2 The Monterey Area Ship Track (MAST) Experiment

The most comprehensive study of the ship track phenomenon to date, was the Monterey Area Ship Track (MAST) experiment conducted off the coast of California in June 1994 (Durkee, Noone and Bluth, 2000). The motivation for the MAST experiment was the importance of the issue of cloud albedo modification by anthropogenic pollution and the lack of knowledge concerning the processes involved in generating ship tracks. MAST was designed using a combination of *in situ* and satellite measurement platforms, such that the possibility of characterising both the ship emission source and the background in a comprehensive manner could be realised. A summary of MAST operations and a description of the platforms and measurement capabilities is given in Durkee, Noone and Bluth (2000). The set of measurements was hoped to be sufficient to test 10 hypotheses concerning the set of conditions necessary for ship tracks to form and the characteristic microphysical and radiative effects induced by the ship emission particles. The hypotheses were grouped into four categories, and within each category, the hypotheses were ranked in order of presumed priority of influence on ship track formation. The set of 11 hypotheses as outlined in Durkee, Noone and Bluth (2000) were:

1. Aerosol-cloud interactions and cloud microphysics

   (a) Submicron aerosol particles from the ship stack are responsible for cloud droplet and radiative features of ship tracks.

   (b) Submicron aerosol particles from the water wake are responsible for cloud droplet and radiative features of ship tracks.

   (c) In a precipitating cloud, aerosol injection and the resulting increase in CCN act to stabilise the drop-size distribution thereby reducing the number of precipitation-sized droplets and increasing the column liquid water content (LWC).

   (d) Gas-to-particle conversion provides a source of CCN for cloud modification down track.

   (e) Ship-enhanced entrainment of aerosol from above the marine boundary layer enhances drop formation, reduces droplet size, and increases reflectance.

2. Boundary layer perturbations by ships

   (a) Heat and moisture injection from ship stack enhances buoyancy and vertical motion affecting (a) cloud formation and (b) the delivery of aerosol to cloud base.

   (b) Mechanical generation of turbulence can enhance and perturb the ambient marine boundary layer structure and help in the formation of cloud features.

3. Cloud dynamics

   (a) Cloud reflectance and LWC changes influence the radiation balance creating circulations that stabilise and confine the ship track region as a radiation-forced dynamic cloud.

   (b) Latent heat of condensation enhances vertical motion within the track and maintains its form.

4. Background environmental conditions

   (a) Ship track formation requires a set of back-ground conditions that involve small boundary layer depth, CCN concentration below a given threshold, and preexisting cloud formation mechanisms.

   (b) A decoupled marine boundary layer inhibits transport of ship effluent to upper cloud.

The MAST experiments were able to conclusively resolve most of the hypothesis listed above, and the bulk of the analysis was presented as a compilation of papers in a special issue of the *Journal of Atmospheric Sciences* (volume 57) in 2000. The hypotheses were tested using a set of dedicated navy ships and using ships of opportunity travelling on the coastal shipping-lanes. The measurement strategy depended on whether or not dedicated ships were being observed. It was possible to operate the dedicated ships in combinations which allowed tests for the importance of particles (direct stack injection, gas-to-particle conversions, and water wake particle production) and the role of heat and momentum release into the boundary layer. A dedicated nuclear ship provided the opportunity to test a ship with no particulate stack emissions, and the various navy vessels allowed the effect of differing fuel types to be investigated. Ships of opportunity were selected on the basis of ease of reach for the research aircraft during the experiment. The ships of opportunity had a wide range of ship sizes, fuel types, and steaming conditions, giving a wide range of conditions under which to test the hypotheses. A detailed analysis of the ship characteristics and fuel emissions is given in Hobbs et al. (2000).

The meteorological conditions in June 1994 differed significantly from the expected climatological norm. Typically, a persistent subtropical high-pressure system sets up in early June over the eastern North Pacific, initiating alongshore flow and the characteristic stratiform cloud sheet off the California coast. However, in 1994 the subtropical high was repeatedly suppressed by active troughs moving inland, which in turn caused offshore flow and forced the stratus sheet to form over 300 km off the California coast, limiting the amount of cloud within the MAST range of operations. The anomalous meteorological conditions was somewhat disappointing as the conclusions drawn from the hypothesis tests depend on the environmental conditions during the experiment. In addition, the field program was not long enough or large enough to completely investigate all of the environmental conditions in which ship tracks have been observed. However, MAST was successful in providing sufficient data on the primary physical processes involved in ship track formation so that physically based models could be developed to investigate the effects of ship effluent pollutants in meteorological conditions not observed during the experiment. In particular, Noone et al. (2000b) and Noone et al. (2000a) presented case studies of ship track formation in moderately polluted and polluted environments, respectively, which provide detailed information for future modelling studies.

A detailed description of the average or *composite* ship track characteristics for the entire MAST observation period is given in Durkee et al. (2000a). The composite ship track is 296 ± 233 km long, 7.3 ± 6 hours old, and averages 9 ± 5 km wide. The ship is, on the average 16 ± 8 km from the head of the ship track along the relative wind vector and corresponds to a time of 25 ± 15 minutes. The set of ship tracks examined during the MAST experiment formed in marine boundary layers that were between 300 and 750 m deep, and no tracks formed in boundary layers above 800 m. The tracks form in regions of high relative humidity, small air-sea temperature differences, and moderate winds (average of $7.7 \pm 3.1\,\mathrm{m\,s^{-1}}$). The average ambient cloud reflectance in AVHRR 3.7 μm channel observations is $11 \pm 4\,\%$, while the composite ship track value is $14 \pm 5\,\%$. The relative track brightness is $7 \pm 26\,\%$ and $37 \pm 34\,\%$ for the 0.63 and 3.7 μm wavelengths, respectively.

The following sections describe the main conclusions of the MAST experiment considering each group of hypotheses in turn.

6.2.1 Aerosol-Cloud Interactions and Cloud Microphysics

Except from hypothesis 1(iv), the group 1 hypotheses were successfully resolved. Testing the group 1 hypotheses required the chemical and microphysical properties of aerosols to be distinguished between the potential sources: ship stack emissions, ship water wake, aerosol from above the boundary layer, and newly formed particles. Consequently, the complimentary measurements taken during the experiment included:

- CCN concentration and supersaturation spectra
- droplet residual aerosol size distributions and chemistry
- cloud interstitial and out-of-cloud aerosol size distributions
- particle thermal volatility

- filter collections for hydrocarbon analysis
- filter collections for major ion analysis
- cloud droplet concentration, size distributions, and effective radius
- liquid water content.

Hudson et al. (2000), Russell et al. (2000) and Öström et al. (2000) describe the particle characteristics observed in and out of ship tracks. Hudson et al. (2000) confirmed hypothesis 1(i), showing that ship exhausts accounted for the modified microphysical and radiative characteristics of the ship tracks with respect to the background marine stratocumulus. Enhancements in droplet concentrations in clouds affected by four ships were fairly accurately predicted from ship emission factors and plume and background CCN spectra. There was evidence that ships burning fuel types which resulted in a higher emission rate of CCN were responsible for a greater percentage of the observed ship track clouds.

Hypothesis 1(i) was also confirmed by Durkee et al. (2000b), as well as resolving hypothesis 1(ii). It was found that ships powered by diesel propulsion units that emitted high concentrations of aerosols in the accumulation mode produced ship tracks. Ships that produced few particles (such as nuclear ships), or ships that produced high concentrations of particles but at sizes too small to be activated as cloud drops in typical stratocumulus (such as gas turbine and some steam-powered ships), did not produce ship tracks. By combining statistics, case studies and model simulations, it was shown that provided a cloud layer is susceptible to an aerosol perturbation, and the atmospheric stability enables aerosol to be mixed throughout the boundary layer, the direct emissions of cloud condensation nuclei from the stack of a diesel-powered ship is the most likely, if not the only, cause of formation of ship tracks. There was no evidence that salt particles from ship wakes cause ship tracks.

Ferek et al. (2000) Tested hypothesis 1(iii) and presented strong evidence in support of the hypothesis. Significant changes in cloud droplet size distribution, as well as reductions in drizzle flux and concentrations of drops $> 50\ \mu$m radius, were observed in ship tracks when drizzle was fairly uniformly present in the ambient cloud, although drizzle was a relatively infrequent occurrence throughout the MAST measurement period. Radiometric measurements showed that increased droplet concentrations in ship tracks, which resulted in reduced droplet sizes, can significantly alter the liquid water path. However, an increase in the liquid water content in the cloud droplet size range was not always observed in ship tracks, primarily because of the relatively small (or often negligible) amounts of water available in the drizzle mode.

Ferek et al. (2000) also presented two independent modelling simulations which showed that the presence of smaller cloud droplets reduced the efficiency of drop growth by collisions, thus decreasing drizzle in ship tracks. One of the model simulations suggested that increased LWC may not be observable because suppression of drizzle reduces the supply of liquid water due to drizzle falling from higher in the cloud.

Hypothesis 1(v) was confirmed by a number of the MAST studies (e.g. Hobbs et al. (2000), Frick and Hoppel (2000), Ferek et al. (2000), Platnick et al. (2000)) through the diverse range of measurement devices. In situ microphysical measurements generally showed an increase in the number concentration, and a decrease in the size, of cloud droplets in ship tracks, which was also confirmed by aircraft and satellite radiometric measurements. Statistics from radiometric measurements showed a clear enhancement in the reflectance of ship tracks over the ambient cloud. Durkee et al. (2000a) found there was a strong relationship between ship type and ship track characteristics. Ship tracks from diesel ships were found to be 18 % longer, 32 % older, and 16 % wider than ship tracks from steam turbine ships. There was rarely a significant contrast between the ambient and track visible wavelength reflectance for either ship type, but diesel-ship tracks were 27 % brighter than the ambient cloud in the near-infrared compared to a contrast of only 7 % for steamship tracks. These observations are consistent with diesel ships producing greater numbers of CCN that are able to perturb cloud droplet size (Hobbs et al., 2000).

6.2.2 Boundary Layer Perturbations by Ships

For ship tracks to form in the cloud-topped marine boundary layer, whatever quantity it is that causes them (ship-generated aerosols, additional heat and moisture from the stack, mechanically generated turbulence) must be transported from the near-ship environment up to cloud level before it dissipates to background levels. The group 2 hypotheses concern the effects of heat and mechanically generated turbulence on ship track formation.

To test the atmospheric response expected from these hypotheses, the critical atmospheric parameters to measure during MAST were:

- CCN supersaturation spectra (from ship and aircraft)
- high-resolution temperature, humidity, and vertical velocity values (from ships and aircraft)
- cloud droplet concentrations and size distributions
- environmental conditions (within and above the marine boundary layer).

It is very difficult to obtain the above atmospheric parameters to sufficient precision to resolve the group 2 hypotheses, thus the numerical modelling study by Liu et al. (2000) was critical to the conclusions drawn from MAST.

Liu et al. (2000) investigated the group 2 hypotheses using a large scale eddy simulation. In a series of experiments, hypothesis 2(i) was tested by studying the effects of additional buoyancy caused by the heat from the ship engine exhaust, the strength of the subcloud transitional layer, and the subcloud layer saturation conditions. It was concluded that additional heat from ship engine and the resultant increase in ship plume buoyancy may indeed increase the amount of ship effluent penetrating into the cloud layer. However, the result depends on the strength and temperature of the stable subcloud transitional layer.

In addition to the measurements listed above, Hooper and James (2000) present in situ and remote lidar measurements of ship plumes made on the R/V *Glorita*. The lidar data was used to investigate hypothesis 2(ii). There was no evidence in the lidar measurements (of a spray plume created by a nuclear ship) that ship-generated turbulence influences either the vertical movement of the spray particles or the final shape of the spray plume.

6.2.3 Cloud Dynamics

The group 3 hypotheses address the persistence and lack of dispersion of the ship tracks. Durkee et al. (2000a) found that the average age of the ship tracks during MAST was 7.3 ± 6 hours and although the composite ship track length was found to be 296 ± 233 km but the average ship track width was only 9 ± 5 km, showing the small dispersion over large spatial and temporal scales.

In order to test the group 3 set of hypotheses, similar measurements to those required to test the group 2 hypotheses are required. The dispersion properties of marine boundary layers were analysed from studies of ship tracks in Durkee et al. (2000a). It was found that the dispersion processes were highly variable with probable dependence on wind speed, stability, boundary layer depth, and the orientation of the ship's course relative to the wind. Liu et al. (2000) also explored the role of dispersion in the cloud-topped marine boundary layer.

While the group 3 hypothesis were not as conclusively tested as the other groups, the conclusion from the MAST Experiment was that such dynamical influences are not a necessary prerequisite for formation and maintenance of ship tracks.

6.2.4 Background Environmental Conditions

As stated above, the conclusions drawn from any field experiment depend on the conditions encountered, thus it was not possible for MAST to properly test the group 4 hypothesis as the campaign was restricted to a specific location and only operated for a limited time. However, MAST was successful in describing the boundary conditions in which ship tracks form in a comprehensive fashion.

The large scale aspects of ship track formation were examined by Coakley et al. (2000). Satellite imagery from the AVHRR instruments aboard *NOAA-11* and *NOAA-12* was used to determine the altitudes, visible optical depths, and cloud droplet effective radii for low-level clouds. In order to deduce the conditions that are conducive to ship track presence, comparisons of cloud properties are made between clouds within 50 km of ship tracks and those further than 200 km from the tracks. It was found that ship tracks rarely appeared in in low-level clouds having altitudes greater than 1 km. However, the appearance of ship tracks showed no correlation to the effective radii or the visible optical depth of the ambient clouds in which the ship tracks were embedded. The results indicate that if the occurrence of ship tracks in satellite imagery data depends on the coupling of clouds to the underlying marine boundary layer, then cloud-top altitude and the area of complete cloud cover by low-level clouds may be useful indices for this coupling.

Liu et al. (2000) and Durkee et al. (2000a) investigate the relationship between boundary layer conditions and ship track formation. Liu et al. (2000) particularly explored hypothesis 4(ii), and showed that in simulations of a decoupled boundary layer the transport of ship effluents may be suppressed by the subcloud transitional layer. Durkee et al. (2000a) showed that the ship tracks observed during MAST formed in boundary layers between 300 and 750 m, with a sharp decrease in track occurrence around 700 m, and no ship tracks occurring above 800 m. This drop-off of track occurrence with increasing boundary layer depth is consistent with lower concentrations of the ship-generated aerosol, and therefore CCN, in deeper boundary layers. A ship would need to produce twice the CCN concentration in a 700 m deep boundary than in a 350 m deep boundary layer to cause the same increase in CCN at the base of the cloud.

6.3 Post MAST

Due to the comprehensive nature of the MAST Experiment, the study of ship tracks has made slower progress following its conclusion.

Coakley and Walsh (2002) investigate AVHRR observations of the effects of ships on low-level clouds off the west coast of the United States in order to derive limits for the degree to which clouds might be altered by increases in anthropogenic aerosol. Expectedly, where ship plumes are observed, the droplet concentrations were increased, leading to decreases in droplet size. A semiautomated algorithm was used to separate polluted portions of clouds from unpolluted areas using the 3.7 μm channel. Analysis of several hundred 30 km segments of ship tracks revealed that changes in visible optical depth were about half the values expected, given the changes observed for the derived droplet radii and assuming cloud liquid water amount remained constant. Radiative transfer calculations were used to demonstrate that the shortfall in the optical depth change is unlikely to be due solely to the absorption by the polluting particles. Coakley and Walsh (2002) concluded that is was likely that polluted clouds lose liquid water, with an approximate equivalent loss of 15 to 20 % of the initial liquid water.

The modifications of existing clouds by the exhaust of ships are well-known and the resultant microphysical effects have been studied at great length, particularly during MAST. However, the complete characterisation still needs improvement and to that end Schreier et al. (2006) presents a case study study of the impacts of ship emissions on the microphysical, optical and radiative properties of marine stratus. Satellite-data from MODIS on Terra are were used to examine a scene from 10 February 2003 where ship tracks were detected close to the west coast of North America. Ship track pixels were distinguished from the unperturbed pixels and a semi-analytical retrieval technique was used to derived cloud optical and microphysical properties. Within the ship tracks significant changes in droplet concentration, the effective radius and the optical thickness were found compared to the unperturbed case. On average, the optical thickness was increased from 20.7 to 34.6 and the effective radius was decreased from 13.2 μm to 10.1 μm. The calculated droplet concentration increased from 79 to 210 cm^{-3}. There was no significant evidence for a change in liquid water path. The results were in agreement with theory and the MAST experiment (e.g. Hobbs et al., 2000). The resulting cloud properties were then used to calculate changes in the radiative energy budget below and above the cloud. The resultant radiative forcing due to ship tracks for a selected satellite scene was estimated to be a cooling of $-1.57\ \mathrm{W\,m^{-2}}$ of the atmosphere-Earth system.

The ship track phenomena is reasonably well understood, and its importance as a contributor to climate and precipitation pattern change is established. However, the temporal behaviour of ship tracks, the influence of the thermal radiation, and the effect of drizzle suppression on the budget of latent heat, require further investigation. In addition to studies of the climate impacts of ship tracks, novel studies such as Rao et al. (2005) have made use of satellite imagery (MODIS and the Ocean Colour Monitor (OCM) in particular) of ship tracks to estimate the velocities of ships, which is useful from a commercial and military perspective. Further recent studies have focussed on the general effects of ship tracks and modelling their effects, rather than the characterisation of the tracks themselves. For example, Beirle et al. (2004) has estimated nitrogen oxide emissions in shipping lanes derived from satellite data and found to be in good agreement with emission inventories, and Devasthale et al. (2006) have used AVHRR imagery to study the average impacts of ship emissions on cloud properties over coastal areas over a 5 year period, finding a pronounced effect on cloud top temperature and cloud albedo in regions of high ship traffic density.

7 Conclusions

Ship tracks may represent a microcosm for what is slowly occurring in the atmosphere. There are many advantages to studying ship tracks as a particular manifestation of the more general problem of the influence of anthropogenic pollution on cloud albedo. From a thorough understanding of modifications to cloud microphysics and radiative effects when the pollution is an isolated source, i.e. a ship, and when the background can be characterised, this should improve the understanding of the indirect aerosol effect and it may lead to a generalisation for global aerosol distributions.

The first step is to develop a climatology of ship track cloud properties in order to assess the radiative impact of ship tracks as a pollution source. This can then be used for thorough comparisons to modelling studies, inclusive of accurate ship fuel and emission indices, in order to investigate the important mechanisms of the radiative effects and the aerosol feedbacks. In situ measurements alone are not enough to capture the variability of ship track cloud formations as they cover such large spatial scales, and the only viable means is to develop such a climatology from satellite remote sensing data. Systematically assessing the global impact of ship tracks (over long time scales) will be a major step toward improving knowledge of shipping impacts on climate change and also the impact of anthropogenic pollution in general.

Acknowledgements

This work was partially funded by the EC within the QUANTIFY Integrated Project under contract no. 003893 (GOCE).

References

Ackerman, A. S. et al. (2000). Effects of aerosols on cloud albedo: Evaluation of twomey’s parameterization of cloud susceptibility using measurements of ship tracks, *J. Atmos. Sci.* **57**: 2684–2695.

Ackerman, A. S., Toon, O. B. and Hobbs, P. V. (1995). Numerical modeling of ship tracks produced by injections of cloud condensation nuclei into marine stratiform clouds, *J. Geophys. Res.* **100**(D4): 7121–7133.

Albrecht, B. A. (1989). Aerosols, cloud microphysics and fractional cloudiness, *Science* **245**: 1227–1230.

Albrecht, B. A. et al. (2004). Evidence for natural variability in marine stratocumulus cloud properties due to cloud-aerosol interactions, *Proceedings of the 14th International Conference on Clouds and Precipitation*, Bologna, Italy.

Albrecht, B. A., Randall, D. A. and Nicholls, S. (1988). Observations of marine stratocumulus clouds during FIRE, *Bulletin of the Am. Meteor. Soc.* **69**: 618–626.

Arking, A. (1991). The radiative effects of clouds and their impact on climate, *Bulletin of the Am. Meteor. Soc.* **71**: 795–813.

Beirle, S. et al. (2004). Estimate of nitrogen oxide emissions from shipping by satellite remote sensing, *Geophys. Res. Lett.* **31**: L18102.

Bréon, F. M., Tanré, D. and Generoso, S. (2002). Aerosol effect on cloud droplet size monitored from satellite, *Science* **295**: 834–838.

Coakley, J. A. and Walsh, C. D. (2002). Limits to the aerosol indirect radiative effect derived from observations of ship tracks, *J. Atmos. Sci.* **59**: 668–680.

Coakley, J. A., Bernstein, R. L. and Durkee, P. A. (1987). Effect of ship-stack effluents on cloud reflectivity, *Science* **237**: 1020–1022.

Coakley, J. A. et al. (2000). The appearance and disappearance of ship tracks on large spatial scales, *J. Atmos. Sci.* **57**: 2765–2778.

Conover, J. H. (1966). Anomalous cloud lines, *J. Atmos. Sci.* pp. 778–785.

Corbett, J. J. and Fischbeck, P. (1997). Emissions from ships, *Science* **278**: 823–824.

Devasthale, A., Kruger, O. and Grassi, H. (2006). Impact of ship emissions on cloud properties over coastal areas, *Geophys. Res. Lett.* **33**: L02811.

Durkee, P. A. et al. (2000a). Composite ship track characteristics, *J. Atmos. Sci.* **57**: 2542–2553.

Durkee, P. A. et al. (2000b). The impact of ship-produced aerosols on the microstructure and albedo of warm marine stratocumulus clouds: A test of MAST hpyothesis 1i and 1ii, *J. Atmos. Sci.* **57**: 2554–2569.

Durkee, P. A., Noone, K. J. and Bluth, R. T. (2000). The monterey area ship track experiment, *J. Atmos. Sci.* **57**: 2523–2541.

Evans, M. E. (1992). *Analysis of ship tracks in cloudiness transition regions*, Master's thesis, Department of Meteorology, Naval Postgraduate School.

Ferek, R. J. et al. (1998). Measurements of ship-induced tracks in clouds off the washington coast, *J. Geophys. Res.* **206**: 23199–23206.

Ferek, R. J. et al. (2000). Drizzle suppression in ship tracks, *J. Atmos. Sci.* **57**: 2707–2728.

Frick, G. M. and Hoppel, W. A. (2000). Airship measurements of ship's exhaust plumes and their effect on marine boundary stratocumulus, *J. Atmos. Sci.* **57**: 2625–2648.

Gerber, H. (1996). Microphysics of marine stratocumulus clouds with two drizzle modes, *J. Atmos. Sci.* **53**: 1649–1662.

Hansen, J. E., Sato, M. and Ruedy, R. (1997). Forcings and chaos in interannual to decadal climate change, *J. Geophys. Res.* **102**: 25679–25720.

Heymsfield, A. J. and McFarquhar, G. M. (2001). Microphysics of INDOEX clean and polluted trade cumulus clouds, *J. Geophys. Res.* **106**: 28653–28674.

Hindman, E. E., Hobbs, P. V. and Radke, L. F. (1977). Cloud condensation from a paper mill. part II: Calculated effects on rainfall, *J. Appl. Meteor.* **16**: 753–755.

Hindman, E. E., Porch, W. M., Hudson, J. G. and Durkee, P. A. (1994). Ship-produced cloud lines of 13 july 1991, *Atmos. Environ.* **28**: 3393–3403.

Hobbs, P. V. et al. (2000). Emissions from ships with respect to their effects on clouds, *J. Atmos. Sci.* **57**: 2570–2590.

Hobbs, P. V., Radke, L. F. and Shumway, S. E. (1970). Cloud condensation nuclei from industrial sources and their apparent influence on precipitation in Washington State, *J. Atmos. Sci.* **27**: 81–89.

Hooper, W. P. and James, J. E. (2000). Lidar observations of ship spray plumes, *J. Atmos. Sci.* **57**: 2649–2655.

Hudson, J. G. et al. (2000). Cloud condensation nuclei and ship tracks, *J. Atmos. Sci.* **57**: 2696–2706.

IMO (2002). *MARPOL 73/78, Consolidated edition of the International Convention for the Prevention of Air Pollution from Ships*, International Maritime Organization (IMO), London.

Kauciauski, A., Durkee, P. A., Skupniewiez, C. and Nielsen, K. E. (1993). Radiative characteristics of ship tracks at night, *Proc. Cloud Impacts on DOD Operations and Systems (CIDOS-93)*.

Kaufman, Y. and Herring, D. (2003). Ship tracks over the atlantic [online], *Available from*: http://earthobservatory.nasa.gov/Newsroom/ [Accessed 2 December 2005]. NASA Earth Observatory News: New Images.

Kaufman, Y. J. and Fraser, R. S. (1997). The effect of smoke particles on clouds and climate forcing, *Science* **277**: 1636–1639.

Kaufman, Y. J., Tanré, D. and Boucher, O. (2002). A satellite view of aerosols in the climate system, *Nature* **419**: 215–223.

Kiehl, J. T. (1999). Solving the aerosol puzzle, *Science* **283**: 1273–1275.

King, M. D., Radke, L. F., Lyons, J. H., Ferek, R. J., Coffman, D. J. and Casadevall, T. J. (1993). Optical properties of marine stratocumulus clouds modified by ships, *J. Geophys. Res.* **98**: 2729–2739.

King, M. D., Tsay, S. C. and Platnick, S. (1995). *In Situ* observations of the indirect effects of aerosols on clouds, *in* R. J. Charlson and J. Heintzenberg (eds), *Aerosol Forcing of Climate*, John Wiley and Sons Ltd., pp. 227–248.

King, M. D., Tsay, S. C., Platnick, S., Wang, M. and Liou, K. N. (1997). Cloud retrieval algorithms for MODIS: Optical thickness, effective particle radius, and thermodynamic phase, *Technical Report MODIS Algorithm Theoretical Basis Document No. ATBD-MOD-05*, NASA Goddard Space Flight Centre, Greenbelt, Maryland, USA.

Kneizys, F. X. et al. (1988). User's guide to LOWTRAN7, *Technical Report AFGL-TR-88-0177*, Air Force Geophysics Laboratory, Hanscom Air Force Base, MA, USA.

Liu, G. et al. (2000). Modeling of ship efficient transport and its sensitivity to boundary layer structure, *J. Atmos. Sci.* **57**: 2779–2791.

Matheson, M. A., Coakley, J. A. and Tahnk, W. R. (2005). Aerosol and cloud property relationships for summertime stratiform clouds in the northeastern atlantic from advanced very high resolution radiometer observations, *J. Geophys. Res.*

Millman, T. (1992). *A temporal analysis of east pacific and east atlantic ship tracks*, Master's thesis, Department of Meteorology, Naval Postgraduate School.

Noone, K. J. et al. (2000a). A case study of ship track formation in a polluted marine boundary layer, *J. Atmos. Sci.* **57**: 2748–2764.

Noone, K. J. et al. (2000b). A case study of ships forming and not forming tracks in moderately polluted clouds, *J. Atmos. Sci.* **57**: 2729–2747.

Öström, E., Noone, K. J. and Pockalny, R. A. (2000). Cloud droplet residual particle microphysics in marine stratocumulus clouds observed during the monterey area ship track, *J. Atmos. Sci.* **57**: 2671–2683.

Penner, J. E. et al. (2001). Aerosols, their direct and indirect effects, *in* J. T. Houghton, L. M. Filho, B. A. Callander, A. K. N. Harris and K. Maskell (eds), *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Inc., New York, pp. 289–348.

Platnick, S. and Twomey, S. (1994). Determining the susceptibility of cloud albedo to changes in droplet concentration with the advanced very high resolution radiometer, *J. Appl. Meteor.* **33**: 334–347.

Platnick, S. et al. (2000). The role of background cloud microphysics in the radiative formation of ship tracks, *J. Atmos. Sci.* **57**: 2607–2624.

Radke, L. F., Coakley, J. A. and King, M. D. (1989). Direct and remote sensing observations of the effects of ships on clouds, *Science* **246**: 1146–1149.

Ramanathan, V., Crutzen, P. J., Kiehl, J. T. and Rosenfeld, D. (2001). Aerosols, climate, and the hydrological cycle, *Science* **294**: 2119–2124.

Ramaswamy, V. et al. (2001). Radiative forcing of climate change, *in* J. T. Houghton, L. M. Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds), *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Inc., New York, pp. 289–348.

Rao, N. S. et al. (2005). Estimation of ship velocitices from MODIS and OCM, *IEEE Trans. Geosci. and Remote Sensing Letters* **2**: 437–439.

Rogers, R. R. and Yau, M. K. (1989). *A Short Course in Cloud Physics*, third edn, Pergamon Press, Oxford, UK.

Rosenfeld, D. (1999). TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall, *Geophys. Res. Lett.* **26**: 3105–3108.

Rosenfeld, D. (2000). Suppression of rain and snow by urban and industrial air pollution, *Science* **287**: 1793–1796.

Rosenfeld, D. and Lensky, I. (1998). Space borne based insights into precipitation formation processes in continental and maritime convective clouds, *Bulletin of the Am. Meteor. Soc.* **74**: 2457–2476.

Rosenfeld, D., Rudich, Y. and Lahav, R. (2001). Desert dust suppressing precipitation: A possible desertification feedback loop, *Proc. Natl. Acad. Sci. U.S.A.* **98**: 5975–5980.

Russell, L. M. et al. (2000). Combustion organic aerosol as cloud condensation nuclei in ship tracks, *J. Atmos. Sci.* **57**: 2591–2606.

Schreier, M. et al. (2006). Impact of ship emissions on the microphysical, optical and radiative properties of marine stratus: a case study, *Atmos. Chem. Phys. Discuss* **6**: 1023–1071.

Squires, P. (1958). The microstructure and colloidal stability of warm clouds, *Tellus* **10**: 256–271.

Takahashi, T. (1978). Precipitation mechanisms in a shallow convective cloud model, *J. Atmos. Sci.* **35**: 277–283.

Taylor, J. P. et al. (2000). Effects of aerosols on the radiative properties of clouds, *J. Atmos. Sci.* **57**: 2656–2670.

Toon, O. B. (2000). How pollution suppresses rain, *Science* **287**: 1763–1765.

Twomey, S. (1959). The nuclei of natural cloud formation: the supersaturation in natural clouds and the variation of cloud droplet concentration, *Geofis. Pura et Appl.* **43**: 243–249.

Twomey, S. (1974). Pollution and the planetary albedo, *Atmos. Environ.* **8**: 1251–1256.

Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds, *J. Atmos. Sci.* **34**: 1149–1152.

Twomey, S. (1991). Aerosols, clouds and radiation, *Atmos. Environ.* **25A**: 2435–2442.

Twomey, S., Jacobowitz, H. and Howell, H. B. (1966). Comments on ”anomalous cloud lines”, *J. Atmos. Sci.* **23**: 101–108.

Warner, J. (1968). A reduction in rainfall associated with smoke from sugarcane fires - an inadvertent weather modification?, *J. Appl. Meteor.* **7**: 247–251.

Warner, J. and Twomey, S. (1967). The production of cloud nuclei by cane fires and their effect on cloud droplet concentration, *J. Atmos. Sci.* **24**: 704–706.