Knowledge gained about marine stratocumulus and the aerosol indirect effect from studies of ship tracks

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Over the past two decades, cloud properties retrieved from multispectral satellite imagery in studies of ship tracks have demonstrated that Twomey was essentially correct. Clouds in hazy environments have larger droplet number concentrations but the droplets are smaller than in clouds in similar environments that are relatively clean. Parameterizations of the aerosol indirect effect in most climate models suggest that the smaller droplets in polluted clouds suppress precipitation, giving rise to clouds with more liquid water and enhancing the cloud albedo increase originally described by Twomey. Studies of ship tracks, on the other hand, have shown that when an extensive region is overcast by marine stratus, the polluted clouds lose liquid water when compared with nearby unpolluted clouds. The loss occurs because clouds with smaller droplets experience enhanced entrainment rates which lead to greater rates of droplet evaporation. When the clouds are broken, however, polluted clouds retain liquid water while the surrounding unpolluted clouds dissipate, presumably losing liquid water through drizzle. MODIS imagery combined with CALIPSO lidar data and meteorological analyses show that strong temperature inversions and dry free tropospheres favor extensive overcast by marine stratus while weak inversions and moist free tropospheres promote broken clouds. With weak inversions and moist free tropospheres, the increased entrainment rate for the polluted ship tracks allows them to grow into the subsiding free troposphere while the nearby unpolluted clouds not only dissipate but remain at lower altitudes. With strong inversions and dry free tropospheres, the polluted clouds associated with ship tracks have the same altitudes as the nearby unpolluted clouds. Here, the response of already polluted clouds to additional particle pollution is studied using intersections where two ship tracks cross. Aircraft observations linking droplet concentrations in low-level clouds to subcloud particle concentrations suggest that the increase in droplet concentrations decreases as the particle concentration in the subcloud layer increases. In the case of ship track crossings, the effect of the additional pollution is determined from the cloud properties retrieved for the area occupied by the crossing and those predicted from the gradients at the crossing in the properties along the two ship tracks. Compared with the response of the clouds to pollution by either of the ships, the changes that occur at the crossing confirm that the additional response for already polluted clouds is much smaller than that for the unpolluted clouds. The increase in the column droplet number concentration caused by a ship decreases as the droplet number concentration of the pre-existing cloud increases. Owing to the variety of environmental conditions and polluting ships included in this study, the observations exhibit considerable scatter. Nonetheless, the changes in the column droplet number concentrations caused by ships trends with the droplet concentrations in the unpolluted clouds in the same way as the trend derived from aircraft observations.