Satellite retrieved cloud optical thickness sensitive to surface wind speed in the subarctic marine boundary layer

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Received 22 April 2010
Accepted for publication 7 July 2010
Published 29 July 2010
Online at stacks.iop.org/ERL/5/034002

Abstract
The optical and microphysical properties of low level marine clouds, presented over the Norwegian Sea and Barents Sea, have been investigated for the period 2000–2006. The air masses were transported for more or less seven days over the warmer North Atlantic before they arrived at the area investigated. The main focus in this study is on investigating the relationship between cloud optical thickness (COT) and surface wind speed \( (U_{10\,m}) \) using satellite retrievals in combination with operational meteorological data. A relatively strong correlation \( (R^2 = 0.97) \) is obtained for wind speeds up to 12 m s\(^{-1}\), in air masses that were probably to a major degree influenced by wind shears and to a minor degree by buoyancy. The relationship \( (U^{2.5}) \) is also in between those most commonly found in the literature for water vapor \( (\sim U^1) \) and sea salt \( (\sim U^{3.4}) \). The present results highlight the magnitude of marine sea-spray influence on COT and their global climatic importance.

Keywords: sea salt, surface wind speed, cloud optical thickness

Online supplementary data available from stacks.iop.org/ERL/5/034002/mmedia

1. Introduction
Aerosol particles in the atmosphere influence the Earth’s radiation balance directly by scattering or absorbing incoming solar radiation (e.g. Kahn et al 1998, von Hoyningen-Huene et al 2003, 2006) or indirectly by influencing the properties of the clouds that are formed on the particles (see e.g. Twomey 1977, Twomey et al 1984, Charlson et al 1992, Glantz and Noone 2000). It is well established, according to in situ observations, that the generation of sea salt aerosol is strongly dependent on the surface wind speed (see e.g. O’Dowd et al 1997, Nilsson et al 2001, Glantz et al 2004). It has also been suggested that the impact on climate may change the primary marine aerosol production significantly, through changes in either surface water temperature (Mårtensson et al 2003), or wind speed (Latham and Smith 1990). From this perspective, sea salt emissions have been estimated to be 3340 Tg in 2000 and predicted to be 5880 Tg in 2100 (IPCC 2001).

Relationships between ground and satellite retrieved aerosol optical thickness and surface wind speed have been found by Mulcahy et al (2008) for the Northeast Atlantic and by Glantz et al (2009) for the middle North Pacific. In both studies sea salt is a strong candidate for yielding enhanced scattering of radiation. From the references in the latter study several additional relationships obtained over other ocean regions can be found. The emissions of sea salt could actually be the dominant source also of cloud condensation nuclei (CCN) particles, especially in remote areas with moderately and high wind speeds and low water temperatures (Pierce and Adams 2006). Thus, an important negative or positive climate feedback is expected due to changes in the emissions of sea salt. However, while a relationship between simulated CCN and surface wind speed is suggested, observed detection of influences on the cloud properties has not been confirmed—the latter probably because, at least partly, boundary layers and clouds are in many situations also highly thermodynamically...
influenced, which then masks the effects of the surface wind speed. Absorption of short wavelength radiation probably also plays an important role in creating turbulence and mixing of air in the boundary layers (Svensson et al 2000, Glantz et al 2004).

In the present study low level liquid stratocumulus clouds over a cold ocean have been investigated, on the basis of satellite cloud retrievals and reanalyses of meteorological parameters, in order to estimate an empirical relationship between cloud optical thickness (COT) and surface wind speed. Section 2 includes brief descriptions of the method used to estimate this relationship and the platforms producing the data. In section 3 the results of retrieved COT, effective cloud radius \( r_{\text{eff}} \) and liquid water content (LWP) as well as estimated \( N_d \) as a function of wind speed will be presented. Finally, in section 4 a discussion and summary are given.

2. Methodology and data processing

2.1. Cloud retrievals

Satellite cloud product data (level 2), COT, \( r_{\text{eff}} \) and LWP, from the moderate resolution imaging spectrometer (MODIS) sensor onboard the Aqua satellite have been analyzed for the Norwegian Sea and Barents Sea (marked with the white box in figure 1) for the months March–October and years 2000–2006. The microphysical and optical properties of the clouds (with 1 km horizontal resolution) are derived by comparing radiation signals from a visible channel (0.86 \( \mu \text{m} \)) and infrared channel (2.1 \( \mu \text{m} \)) and iteratively lining these up against libraries of pre-calculated values for homogeneous clouds that are plane-parallel (Platnick et al 2003). To estimate cloud top temperature (CTT) the 11 \( \mu \text{m} \) method (used on clouds at pressures above 700 hPa) proposed by Platnick et al (2003) has been applied to the MODIS data (with \( \sim 4 \) km horizontal resolution). The CTT has been combined with the European Centre for Medium-Range Weather Forecasts (ECMWF) sea surface temperature (SST), shown in figure 2, in order to estimate the boundary layer height (BLH\( _{\text{estim}} \)). The latter is used to include only low level clouds (\( < 1 \) km) in the analysis. For this estimate an adiabatic decrease in temperature of 1 K per 100 m is assumed. The higher BLH\( _{\text{estim}} \) compared to the ECMWF model, particularly for the shallowest layers shown in figure 2, is probably explained by underestimated CTT. The latter occurs when the 11 \( \mu \text{m} \) method is used for the situations with inversion presented (http://modis-atmos.gsfc.nasa.gov/MOD06_L2/qa.html). Figure 2 shows also close agreement for temperatures estimated at 2 m above the surface (\( T_{\text{2 m}} \)) and at the surface (ST), obtained by the ECMWF and MODIS, respectively. In addition, to exclude too thin clouds, only pixels with COT > 5 (Kokhanovsky et al 2005) are included here. Finally, pixels flagged as multilayered clouds, containing ice or uncertain cloud phases, were removed as well. For the period investigated the proportions of cloud pixels used are 31 \( \pm 16\% \) and 28 \( \pm 16\% \), corresponding to the clean and continental conditions, respectively, of total amount of pixels in the area investigated (figure 1).

2.2. Meteorological parameters

Operational meteorological data, with a spatial resolution of 0.25° (~17 km), produced by the ECMWF Meteorological Archival and Retrieval System (MARS) were analyzed in this study. Beside the meteorological parameters mentioned in

Figure 1. ECMWF mean SST field, averaged according to 12:00 UTC for days corresponding to the months May and June, and years 2000–2006. The solid light and dark gray lines denote seven-day back trajectories, classified as clean (52 days) and polluted (30 days), respectively, started at 73°N/5°E and 12:00 UTC (at an altitude of 100 m) obtained by the NOAA HYSPLIT model for the months March to October and years 2000–2006. The white box denotes the present area investigated (77°N–70°N and 19°W–22°E).
Figure 2. The solid and dashed black lines denote MODIS mean ST and CTT, respectively, and solid and dashed gray lines denote ECMWF mean $T_{2m}$ and SST, respectively, obtained for the marine cases in figure 1. The error bars denote one standard deviation. Estimated mean boundary layer height (BLH$_{estim}$) and the corresponding one standard deviation are also shown (see section 3.1 for explanation).

section 2.1 also assimilated fields of 10 m wind speed ($U_{10m}$) as well as diagnosed BLH and convective available potential energy (CAPE) are used here. Examples of $U_{10m}$ fields over the area investigated can be found in the supplementary figures available at stacks.iop.org/ERL/5/034002/mmedia. To identify air masses that were originated south of the area investigated, back trajectories were also analyzed. Figure 1 shows seven-day back trajectories, with corresponding air masses classified as marine (52 days) and continental (30 days), respectively, started at $73^\circ N/5^\circ E$ and 12:00 UTC (at an altitude of 100 m) obtained by the NOAA HYSPLIT 4 model for the years 2000–2006. The clean marine cases also correspond to seven-day back trajectories started at $73^\circ N/10^\circ W$ and $73^\circ N/20^\circ E$ (at 12:00 UTC and 100 m), which are also mainly stretched over the North Atlantic (not shown in figure 1). Figure 1 also shows the ECMWF mean SST field, averaged according to 12:00 UTC for days corresponding to the months May and June, and years 2000–2006. Similar SST fields appear when mean values have been calculated for the remaining months of the period investigated, although differences in the absolute values occur between the different seasons (supplementary figures available at stacks.iop.org/ERL/5/034002/mmedia).

3. Results

The statistical distributions of COT, $r_{eff}$ and LWP are skewed for more or less all days analyzed in the present study (not shown). Therefore, median values of these parameters have been calculated for each day and averaged according to all days that are included in the investigation. Finally, due to differences in horizontal resolutions between the satellite parameters (section 2) the three quantities above have been averaged according to a box of 4 km $\times$ 4 km. To investigate surface wind speed sensitivity in the following section, data were sorted into bins of 1 m s$^{-1}$ wide and spaced in 1 m s$^{-1}$ increments.

Figure 3 shows the MODIS mean COT and the corresponding one standard deviation as a function of ECMWF mean $U_{10m}$ for the marine cases in figure 1. The solid black line is a power fit according to the mean values of COT. The dashed gray line is explained in section 3.1.

3.1. Surface wind speed sensitivity

Figure 3 shows the MODIS mean COT and the corresponding one standard deviation as a function of ECMWF mean $U_{10m}$ for the marine cases in figure 1. The solid black line is a power fit according to the mean values of COT. The dashed gray line is explained in section 3.1.
ECMWF (figure 4). In addition, for the cloud thickness \(H\) only a small increase due to higher wind speeds is shown in figure 4. The latter parameter was estimated using an equation from Bennartz (2007), which has been derived using adiabatic cloud theory:

\[
H = (2 \times \text{LWP}/c_w C_T)^{1/2}.
\]

\(c_w\) is the condensation rate at 80% of its adiabatic value and is expressed as

\[
c_w = 0.8 \frac{1}{R_{H_2O} T} \frac{d e_{sat}(T)}{dT} \frac{dT}{dz}
\]

where \(C_T\) is the cloud fraction (here set to 1), \(e_{sat}\) is the water vapor pressure, calculated according to a formula given by Emanuel (1994). In addition, \(T\) represents the CTT. Finally, figure 5 also shows the droplet number concentration \(N_d\) obtained for adiabatic conditions by combining equation (1) with the derived column droplet number concentration (Bennartz 2007):

\[
N_{\text{dcol}} = \frac{5 \tau}{6 \pi k r_{\text{eff}}^2}
\]

where \(k\) (the ratio between the volume radius and the \(r_{\text{eff}}\)) is 0.7.

#### 3.2. Comparisons between clean and polluted air masses

Table 1 shows MODIS cloud parameter results, retrieved for clean and polluted conditions (52 and 29 days, respectively). The cases have been classified according to the air mass transport illustrated in figure 1. The mean values and the corresponding one standard deviation shown in the table, averaged according to daily median values, have also been weighted according to the proportion of cloud pixels used in the area investigated. For the \(r_{\text{eff}}\) and COT parameters the clean and polluted mean values deviate significantly from each other, both with confidence interval greater than 99%. Table 1 shows also relatively high LWP values, probably due to the transport of the air masses over the ocean one or two days before the interactions with the clouds occurred over the area investigated.

### 4. Discussion and summary

Low level marine clouds presented over the Norwegian Sea and Barents Sea have been investigated for the years 2000–2006. The more or less northward transport of the air masses, before they arrived at the area investigated, suggest stable stratification in the marine boundary layers and thus minor influence of buoyancy. The latter is supported by the estimated mean SST field (section 2.2) and the low CAPE values shown in figure 4. Thus, the shallow marine boundary layers investigated were probably instead to a larger extent affected by wind shears. This means that the observed changes in the cloud properties were probably mainly caused by emission processes at the sea surface and shear-generated turbulence. Consequently, beside higher emissions of sea salt (e.g. O’Dowd et al 1997, Nilsson et al 2001, Glantz et al 2004) and water vapor (Glantz et al 2009) higher wind speeds also lead to higher updraft and supersaturation, and thus, more efficient vertical mixing and activation of hygroscopic aerosols in the marine boundary layer. The relationship between daily mean COT and surface wind speed \(U^{2.5}\) shown in figure 3 is also in between those most commonly found in the literature for water vapor \(\sim U^{1}\) and sea salt \(\sim U^{1.4}\).

The result of a correlation between COT and wind speed is very promising in the sense that the latter quantity is probably associated with relatively small uncertainties, at least outside the tropics, in climate model estimations. Thus, the relationship allows a very simple but powerful way to incorporate climate forcing in model predictions. The present results highlight the magnitude of marine sea-spray influence on COT and the global climatic importance.

The differences in cloud microphysical and optical properties between polluted and clean air masses, shown in table 1, give some support for the satellite retrievals. Even so, on the basis of theoretical arguments and explicit 3D computations, Marshak et al (2006) find on the other hand substantially overestimations in the retrievals of \(r_{\text{eff}}\). In addition, the mean COT estimated here is associated with large error bars, particularly for the lowest and highest wind speeds (figure 3). This seems be due, at least to some extent, to the low amount of data available for these wind speed ranges. In addition, large one standard deviations corresponding to the estimated mean \(N_d\) are shown in figure 5, although these values are in any case in the range of droplet numbers observed from aircraft over the warmer northeast Atlantic in clean air masses (Glantz et al 2003).

| Classification | \(r_{\text{eff}}\) (\(\mu m\)) | LWP (gm\(^{-2}\)) | COT |
|----------------|-----------------|---------|-----|
| Clean          | 13.42 ± 1.54    | 111 ± 31| 12 ± 3|
| Polluted       | 9.74 ± 0.94     | 115 ± 44| 17 ± 6|
Since the space-borne sensors mainly detect the upper part of the clouds, due to the plane-parallel model, uncertainties are probably induced in the present results. The analyzed cloud parameters are thus only rough estimates of the real clouds, but still serve as good indicators of the cloud conditions (Kokhanovsky et al. 2005). Uncertainties may also be induced in the analysis due to the more long-lived accumulation-mode sea salt aerosols, although the local wind seems to be in any case a good enough proxy for the Lagrangian wind on the timescales considered for the accumulation and coarse-mode aerosol particles (Nilsson et al. 2001). In addition, the difference in spatial resolution of the MODIS and ECMWF data could also explain some of the variability that occurs in the present results.

The present results of the microphysical and optical properties of the low level clouds as well as the estimated $N_d$ could be evaluated on the basis of model simulations. From this perspective, a process model should be used, able to accurately handle both predictions of vertical mixing of water vapor and clouds as well as sea salt particles, for example according to a turbulent dynamical closure scheme (Glantz et al. 2004), and descriptions of gas-phase chemistry and aerosol cloud interactions (Mårtensson et al. 2010).

Acknowledgments

The author gratefully acknowledges Moa Sporre (Division of Nuclear Physics, Lund University), for contributing with technical guidance, and the availability of the MODIS and ECMWF data sets. The work was financed through research grants from the Swedish Research Council for the Environment, Agricultural Sciences and Spatial Planning (FORMAS) and the Swedish Research Council—financier of basic research (VR).

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