Master’s Thesis

Covariance between large scale meteorology and cloud properties over the North East Atlantic Ocean

Author: Roxana CREMER
Supervisor: Prof. Johannes QUAAS
Co-Supervisor: Prof. Manfred WENDISCH
Contact Person: Dr. Tom GOREN

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Abstract

Marine stratocumulus clouds (MSC) cover a quarter of the Earth’s ocean and have a large impact on the radiation budget (Quante, 2004; Chen et al., 2000; IPCC, 2013). Studies, for example Goren and Rosenfeld (2015) showed that the coverage of MSC were linked to continental air mass outbreaks which modify the cloud properties and therefore change the radiative forcing of the cloud.

In order to investigate the gradient in MSC over the ocean and their radiative properties the synoptic feature which drives the formation of MSC was analysed. It was found that the second Empirical Orthogonal Function (EOF) of the sea level pressure in the North East Atlantic describes the synoptic pattern which drives a cyclonic circulation due to which aerosols are transported from Europe onto the Atlantic. The covariance of synoptic features and cloud properties analysed were regarding the cloud cover, cloud droplet number concentration, effective radius, cloud liquid water path and cloud optical depth. It could be shown that the cloud cover increases under a high pressure influence and within the cloud cover two different air masses were found. In order to investigate the anthropogenic signature in the clouds, carbon monoxide and sulphur dioxide were related to the EOF analysis.
## Contents

1. **Introduction**  
   1.1. Marine stratocumulus clouds ................................. 4

2. **Data and Methodology**  
   2.1. Satellite observations ....................................... 7  
   2.2. Reanalysis data .............................................. 9  
   2.3. Study region: North East Atlantic ................................ 10  
   2.4. Statistic analysis ........................................... 11

3. **Results**  
   3.1. Synoptic conditions of MSC plumes .......................... 13  
   3.2. EOF analysis .................................................. 15  
   3.3. Correlation between EOF analysis and microphysical cloud properties ... 17  
   3.4. Anthropogenic influence ..................................... 22

4. **Conclusion and Outlook** ........................................ 24

**Appendix** .......................................................... 25

**Bibliography** ...................................................... 28
1. Introduction

Clouds impact the Earth’s radiation budget. Several studies, for example the Intergovernmental Panel on Climate Change (IPCC (2013)), Quante (2004), Chen et al. (2000), etc., have taken place to investigate the cloud radiative forcing on the Earth’s surface due to the cloud type and properties and geographic location. Radiative forcing is defined as the net change in the energy balance of the Earth system due to some imposed perturbation (Myhre et al., 2013). Boucher et al. (2013) found the global net radiative forcing of clouds to be around $-20 \text{ W m}^{-2}$ (see Fig.1.1). Figure 1.1 shows that over the oceans clouds have, except in the Southern Ocean, a negative effect. Especially at the west coasts of the continents plumes of large negative radiative effect, up to $-70 \text{ W m}^{-2}$, are visible. The radiative forcing due to the cloud type is described by Chen et al. (2000). The high level clouds, i.e. cirrus and deep convective clouds have a large impact on the longwave radiation and low level clouds, such as stratocumulus, altostratus and cirrostratus clouds which all have a with moderate optical thickness strongly influence the shortwave radiation at the top of atmosphere (Chen et al., 2000). Notably low-level, stratiform clouds are cooling the surface energy budget (Shupe and Intrieri, 2004; Wood, 2012; Koren et al., 2010) because of their high reflectivity as can be seen in the marine stratocumulus regions.

Figure 1.1.: Net cloud radiative effect of the Earth in W m$^{-2}$ taken from the IPCC, chapter 7 (Boucher et al., 2013).
at the eastern boundaries of the ocean basins (see Fig. 1.1).

Koren et al. (2010) presents two dependencies of the cloud radiative forcing are displayed in Figure A.II. Aforementioned the cloud height, here cloud top height presented on the ordinate and the cloud optical depth (x-axis) determine the radiative forcing of the cloud. It can be seen that a low cloud up to 4.5 km has always a negative forcing. The negative forcing increases along the abscissa, consequently optical thick clouds have a larger negative radiative forcing due to the increase in reflectivity. Lifting a cloud of a set optical depth (for example 1.76) in higher atmospheric layers will decrease the radiative forcing and at a certain height (7.5 km) the radiative forcing will turn positive.

Aerosol particles (further referred to as aerosols) play an important role as well. Aerosols were shown to have a major impact on the Earth radiation budget (Lamb and Verlinde, 2011) and it is distinguished between the direct and indirect effects of aerosols on the climate (Haywood and Boucher, 2000). Depending on the aerosol properties they can absorb short- and longwave radiation or scatter incoming solar radiation back to space. For example black carbon which absorbs incoming radiation and therefore warms the Earth’s surface and sea salt scatters incoming shortwave radiation back to space (Myhre et al., 2013). These are the direct aerosol effects.

In addition, modifications of clouds can be caused by aerosols. Aerosols are a necessary ingredient for a cloud droplet to form as they act as cloud condensation nuclei (CCN). The indirect aerosol effects describe these interactions between clouds and aerosols (Lamb and Verlinde, 2011). Two main indirect aerosol effects exist. Twomey (1974) discovered the first aerosol effect or Twomey effect. For a cloud with a constant cloud liquid water path (LWP) a difference in the cloud albedo was determined for different concentrations of CCNs. In a cloud with a high amount of CCNs, the cloud droplets stay smaller and the cloud is brighter, hence the cloud has a higher albedo compared to a cloud with a lower CCN concentration. Further studies showed that pollution, for example ship tracks, combustion, etc. induces more particles in the air and hence modifies the clouds characteristic (Twomey, 1977; Rosenfeld and Lensky, 1998; Lohmann and Feichter, 2005).

Albrecht (1989) discovered that not only the increased reflectivity is important but also the inhibited growth of the cloud droplets. This is the second indirect aerosol effect. With more cloud droplets, the drops compete for the available water and grow slower than less cloud droplets. This process leads to a longer lifetime of the cloud because more water vapour is necessary to grow the cloud droplets to drizzle size (Gerber, 1996). A polluted environment enhances the development of clouds with more numerous and smaller droplets.

IPCC (2013) quantified the radiative forcing due to anthropogenic aerosols. The results are shown in Figure 1.2. The aerosols are classified in short and long living aerosols. For example carbon dioxide is a long living so-called greenhouse gas and as presented in Figure 1.2 its radiative forcing is strongly positive with a very high level of confidence
Figure 1.2.: Global radiative forcing for aerosols and precursors and their uncertainties estimated in 2011 relative to the preindustrial time (1750) in W m⁻². Chart is taken from IPCC (2013).

which indicates the degree of scientific agreement due to expert judgement. Nitrogen oxides (NOx) are categorised as a short living aerosol and has a slightly negative radiative forcing. Despite the medium level of confidence the uncertainties in the radiative forcing are larger than the forcing itself. Partly, the large uncertainty arises from meteorological co-variations and especially for the shallow cumulus regimes (Gryspeerdt et al., 2016). As Kaufman et al. (2005) pointed out, the net aerosol effect on clouds is the largest uncertainty in evaluating climate forcing. In IPCC (2013) the uncertainties within the effect of aerosols were calculated, and it was found that there is a large range in values between negative and positive radiative forcing. The same is valid for the cloud adjustments, as Twomey (Twomey, 1974) and Albrecht (Albrecht, 1989) effect. In the cloud adjustments due to aerosols in Figure 1.2 the positive radiative forcing is neglected but the uncertainty range is huge and the confidence level is low (IPCC, 2013).

The total anthropogenic radiative forcing relative to pre-industrial times increased over the last IPCC reports and was quantified to be 2.29 W m⁻² for the year 2011 as displayed in Figure 1.2.
1.1. Marine stratocumulus clouds

Marine stratocumulus clouds occupy 23% of the air over the oceans in the annual mean (Wood, 2012). MSCs are most prevalent at the east coasts of the Earth’s ocean basins where cold water is up-welling and are characterised by a stratiform shallow cloud cover in the upper few hundred meters of the planetary boundary layer (BL) (Wood, 2012). The BL is marked with a strong temperature inversion above the cloud top with dry and stable air above. MSCs are of climatological importance due to their areal and temporal coverage. In some regions they exceed 60% of the time (Wood, 2012) and therefore have a negative effect on the Earth’s surface radiation budget (see Fig. 1.1). Especially over the ocean, which is an absorber of sunlight due to its low albedo the overlying fields of MSCs create a big contrast. The clouds are bright and therefore have a large reflectivity. Hence they reflect back the incoming solar radiation and cool the surface.

The formation of MSCs can be induced by a variety of mechanisms, for example large-scale cooling. The change in the air temperature gradient increases the buoyancy of the lower BL and therefore the production of turbulence (Wood, 2012; Morrison et al., 2012; Lamb and Verlinde, 2011). Under these conditions water vapour condensates directly to cloud droplets in the inversion layer if a minimum of liquid water is available (Morrison et al., 2012). Additionally, heating of the sea surface can lead to the formation of marine clouds. By heating the sea surface, moisture pockets can start to rise to upper atmosphere layers. Hence the BL is moistened and the water vapour in the pockets condensate (Wood, 2012). Next to the radiative processes dynamics drive cloud formation, too. One mechanism is generating mixing of dry and moist air masses by shear force. Another way is strong downdraught wind which leads to a forced turbulent mixed layer (Morrison et al., 2012).

Figure 1.3.: Annual mean coverage [%] of stratocumulus clouds taken from Wood (2012). Insufficient data caused by no reports about stratocumulus clouds of a lack of observations and stratocumulus clouds are marked in grey.
Marine low clouds are particularly susceptible to perturbations in aerosols because they are spatially extensive (Warren et al. 1988), are relatively optically thin (e.g., Turner et al. 2007; Leahy et al. 2012), and often form in pristine air masses (Platnick and Twomey 1994). Two main regimes can be classified for MSC (Agee et al., 1973), open and closed cells. Closed cells are characterised by a cloud cover of nearly 100 % and a high concentration of particles and cloud droplets (Wood et al., 2015). In these cells the air raises in the middle and sinks at the edges. In the open cells, moisture–free pockets appear, because the air sinks in the middle of the cell. The cloud cover is less than 65 %. These two kind of regimes have different radiative effects and lifetime expectations. Closed cells are more opaque and have a larger albedo. Due to the high cloud droplet number concentration (CDNC) the formation of drizzle takes longer and the clouds do not resolve as fast as open cells (Gerber, 1996). The transition from a closed cell to an open can happen suddenly. Feingold et al. (2010) related the break-up process to oscillation which where triggered by precipitation and therefore asymmetry in the cooling profile and changes in the convective structure of the cloud sheet is induced. Hence the most efficient process for breaking-up low marine clouds is the formation of drizzle (Wood et al., 2011,0; Stevens et al., 2005; Wood et al., 2015). Inside the cloud the droplets grow first from vapour deposition, but when they reach an effective radius of around 15 µm (Gerber, 1996; Rosenfeld et al., 2012) coalescence and collision processes are getting more effective. Consequently the cloud droplets grow to drizzle size. When they fall out of the cloud the atmospheric layer below gets cooled and the remaining cloud droplets increase their radius due to the condensed water. Hence, they overcome the barrier and start to fall out themselves. This break–up mechanism is a cleansing feedback (Stevens et al., 2005; Allen et al., 2011). It happens commonly and can be strengthened as well as weakened by dynamics, as entrainment and updraught (Agee, 1987). Freud and Rosenfeld (2012) determined that the conditions at the cloud base specifically affect the droplet growth inside the cloud. Stronger updraughts at the cloud base induce more CCNs and consequently more cloud droplets.

The CDNC is related closely to the aerosol concentration in the atmosphere (Wood, 2012). Continental air mass is defined by a higher CCN concentration compared to marine air mass. On the continent sources for aerosols are industry, traffic emissions, deserts, biomass burning and cattle. Over the ocean most particles are from natural sources, as sea salt, dimethyl sulfide (DMS) and organic material, which get into the atmosphere due to bubble bursting. An anthropogenic source of aerosol is ship tracks. Goren and Rosenfeld (2012) presented several cases of ship tracks to demonstrate the impact they can have on the development of MSCs. The ships induce aerosols in the air, which nucleate. This leads to an evolution from open to closed MSCs. Rosenfeld et al. (2006) pointed out that maritime air mass is very sensitive to the smallest change in aerosol optical depth (AOD), for instance the ship track demonstrates the role of the dearth of aerosol particles.
Continental effects are another reason for a transition to closed-cells over the ocean. Allen et al. (2011) presented a study in the coastal region over the South East Pacific in which it was pointed out that a small mean effective radius is primarily determined by anthropogenic aerosols, rather than natural ones. Entrainment of polluted air was confirmed to be the main source of CCNs in the cloud sheet.

Likewise George et al. (2013) studied CCN concentration variability due to pollution plumes in the south-east Pacific. Due to strong offshore winds continental air mass is transported to the remote ocean. These strong offshore flows happen periodically in the south-east Pacific area and generate a so-called Hook-event. This event is shaped like a hook and formed along the coast extending out into the ocean leading to an enhanced cloud reflectivity. The increased cloud albedo is caused by entrainment of CCNs as described by the Twomey effect (Twomey, 1977) and explains up to 50% of the albedo change in these events. Due to the increase in available CCNs the microphysical properties of the cloud are modified and consequently the cloud radiative.

The variations of microphysical properties in a cloud sheet can be seen especially where maritime and continental air masses are laying next to each other. Goren and Rosenfeld (2015) presented a study with clean and polluted air masses over the North East Atlantic and related it to a continental air mass outbreaks from Europe. As remarked, maritime air mass is cleaner than continental air mass. Less CCNs are present and in marine air the cloud droplets can grow larger because of the leak on competition in between a high CCN concentration and a nearly eternal source of water vapour (Stevens et al., 2005).

The case study by Goren and Rosenfeld (2015) showed that the continental track is linked to a change in the cloud regime over the North East Atlantic Ocean. This fact is caused by the composition of the continental air. It is driers than marine air and normally characterised by a higher amount of aerosol particles. The drying process causes small particles which compete over the available water vapour and grow slower and not as large as cloud droplets in pristine marine air. Therefore the clouds formed from continental air live longer and do not break up easily.

The hypothesis is that the MSCs are connected to the occurrence of continental air masses moving onto the Ocean, so called continental tracks in this region. To address this hypothesis the stratocumulus clouds over the North East Atlantic will be analysed to validate a relation between cloud properties and the most common patterns of large scale meteorology. Additionally in continental air masses the anthropogenic influence can be analysed. With emissions of trace gases clearly originating from human activities, for example carbon monoxide and sulphur dioxide, the human impact can be estimated and is presented here.
2. Data and Methodology

The analysis presented here is based on different data sets. The synoptic parameters were taken from the European Centre for Medium-Range Weather Forecast (ECMWF) reanalysis data Era-Interim, the chemical composition data from the Monitoring Atmospheric Composition and Climate (MACC) and the microphysical properties were retrieved from the moderate resolution imaging spectrometer (MODIS).

The study period is from 2003 until 2012, because all data were available in this time range. The MACC and Era-Interim data were gridded on the same 360x180 grid as the satellite data with a spatial resolution of 1° by 1°.

2.1. Satellite observations

MODIS is on board the A-train satellite Terra since 2002 and collects information about the atmosphere with infrared and visible techniques in the wavelength range of 0.405 µm to 14.385 µm. For this project, ten years of data from the collection 6 Cloud Product were used (Platnick et al., 2017). Daily averaged (level3) variables of multilayer cloud properties on a 1° by 1° resolution global grid are provided.

The parameters used in this thesis are derived by satellite retrievals for clouds described by Platnick et al. (2017) and aerosols by Levy et al. (2013). In this thesis the liquid water cloud fraction (CF) from the Optical Properties Retrieval was used. Furthermore the Liquid Water Cloud Optical Thickness (COD), the Cloud Liquid Water Path (LWP), the Liquid Water Cloud Effective Particle Radius \( r_e \), which are all derived from MODIS Level 2 data were analysed. Following Quaas et al. (2008) these three parameters and the density of liquid water \( \rho_w \) are linearly related:

\[
\text{LWP} = \frac{2}{3} \rho_w r_e \text{COD} \tag{2.1}
\]

The cloud droplet number concentration (CDNC) was calculated following the method of Quaas et al. (2006) with the coefficient \( \gamma = 1.37 \cdot 10^{-5} \text{m}^{-\frac{3}{2}} \) as shown in Equation 2.2. COD (in Eq. 2.2 \( \tau_c \)) and the effective radius \( r_e \) goes into the calculation next to a temperature-dependent condensation rate by Bennartz (2007) (Gryspeerdt et al., 2016).

\[
N_d = \gamma f(T) \tau_c^{\frac{1}{2}} r_e^{-\frac{5}{2}} \tag{2.2}
\]
The aerosol optical depth (AOD) is the *Optical_Depth_Land_and_Ocean_Mean* at 550 nm. The extinction coefficient varies for each aerosol type spectrally, therefore the integral of the coefficients determines the AOD (Levy et al., 2013).

In order to exclude ice and convective clouds from the multilayer data of MODIS, all pixels with a cloud top temperature below $-10^\circ$C and all with a cloud top pressure over 800 hPa were removed. The condition $-10^\circ$C was chosen because there is the possibility in the northern part of the Atlantic, that the top of a stratocumulus cloud is supercooled (Huffman and Norman, 1988), but these ones should be excluded. The pressure condition was taken into account to exclude clouds with a large vertical extent such as in cold air outbreaks. These clouds are also located inside the marine BL, consequently clouds above $\sim 1.6 \text{ km}$ were excluded.

Additionally day microphysical red-green-blue (RGB) composite images of Spinning Enhanced Visible and Infrared Imager (SEVIRI), an instrument on board the Meteosat Second Generation (MSG) geostationary satellite, were used. This data were provided by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Example cases of continental air mass outbreaks from Europe onto the Atlantic were selected with the RGB composite images. With the colours in the composite image the microphysical properties of the clouds can be interpreted. The cloud optical depth is indicated by the red colour. A thick water cloud has a deeper red than an ice cloud, which is optical thin. The values are adjusted by the 0.8 $\mu$m reflectance. The 3.9 $\mu$m reflectance is a measurement for the cloud particle size and is reflected in green. As the droplet size gets smaller, the region in the composite image takes on a deeper green hue. The cloud top

![Figure 2.1: The day micro RGB composite image of January, 27 2010, which is the same day discussed by Goren and Rosenfeld (2015). The broken line shows the interface between maritime (b) and continental (a) air masses.](image-url)
temperatures is modulated by the 10.8 µm cloud tops brightness temperature. A warm cloud top appears more blue in the picture. Taking the colours into account, a convective cloud with a large vertical extent will be more red than a shallow stratocumulus cloud. MSCs appear mostly as a opaque yellow-greenish plume in the RGB composite picture. MSC can also get reddish far over the ocean, because of the larger moisture flux which favours droplet growth and increasing boundary layer height over the ocean.

2.2. Reanalysis data

The Era-Interim reanalysis provides information about global atmospheric and surface parameters on 60 vertical levels, from the surface (1000 hPa) up to 0.1 hPa and a spatial resolution of 80 km (Dee et al., 2011). For the vertical column hybrid sigma–pressure coordinates are used, which means that the vertical resolution is best in near–surface layers. In the planetary boundary layer where marine stratocumulus clouds are found the resolution is 25 hPa. The record is produced with the ECMWF integrated forecasting system, which incorporates a forecast model with three fully coupled components for the atmosphere, land surface and ocean waves and covers the time period from the 1st January 1979 to the present day.

The National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) released as well a reanalysis dataset: The NCEP/NCAR Reanalysis. From 1948 to the present global data from measurements, observations, satellite data and numerical weather prediction models are provided. For the current study the sea level pressure anomaly and the climatological mean wind were used (Kalnay et al., 1996). The anomaly is calculated on the base of the climatology of the years 1981 to 2010 (Kalnay et al., 1996). Therefore the long term total mean is subtracted from the daily mean. A look at the anomaly was taken to see the spread from the climatological mean during the presence of large MSC sheets.

To investigate a possible anthropogenic influence MACC data, developed for the years 2003 until 2012 in a spatial resolution of 80 km, were analysed as well. The focus of this reanalysis study is on chemically reactive gases, aerosols and greenhouse gases (Inness et al., 2013). The parameters taken into account are the sulphur dioxide and carbon monoxide concentration near the surface. Both chemicals are for the most part man–made (Myhre et al., 2013; Daniel and Solomon, 1998; Shindell and Faluvegi, 2010). Sulphur dioxide is mostly produced by combustion of fossil fuels, such as oil and coal and therefore described as the main precursor of anthropogenic aerosols by Stevens (2015). The sulphur inside the fuels is set free during the oxidation. A natural source, which is especially important over the ocean is dimethyl sulphide (DMS). DMS forms sulphur dioxide when it is oxidized by the hydroxyl radical (Quinn and Bates, 2011). Carbon monoxide is a product of incomplete combustion. Both can also appear in combustion of natural sources,
such as a forest fire or a volcanic eruption, but sources as anthropogenic combustion, for example car traffic, heating and chimneys are bigger and especially persistent.

2.3. Study region: North East Atlantic

The North East Atlantic is dominated by the low pressure belt. A persistent low pressure system lies over Iceland and in front of the Iberian islands a high pressure determines the synoptic conditions. This pattern is described by the North Atlantic Oscillation (NAO) (Hurrell et al., 2003). The NAO index is calculated over the pressure gradient from the North to South Atlantic and has two phases. For a positive NAO-phase the pressure gradient is enhanced. The situation is signified by strengthened pressure systems over Iceland and the Azores which stabilise the westerlies over the Atlantic which enhances and straightens the jet stream. Hence humid and warm air is transported towards Europe. In the negative NAO-phase the pressure gradient is weak, the low and high pressure systems are both weak and the jet stream is wavy. Due to this situation the wind is weaker and cold, dry air is transported from the Arctic downwards over the European continent towards the ocean. These are the most common synoptic pattern over the Atlantic.

The North East Atlantic was chosen to be the study region because of the presence of stratocumulus clouds as presented in Figure 1.3. The conditions for the formation of MSCs is favoured in this area and following Goren and Rosenfeld (2015) who showed the impact of a continental air mass outbreak on the MSC formation including an anthropogenic influence the North East Atlantic is a good place to study the covariance between large scale meteorology and cloud properties.

Goren and Rosenfeld (2015) presents a case study, which took place in January 2010 and combined observation data to explain the occurrence of a large MSC sheet in combination with continental tracks over the North East Atlantic ocean. During the study period a high pressure system over the British Islands favoured the formation MSC sheets. Due to this high pressure system an anticyclonic circulations dominates the weather and transports continental air from Europe onto the Atlantic. Goren and Rosenfeld (2015) tracked the movement of the cloud and took the sulphate mixing ratio which is a mostly man-made aerosol, from the Goddard Chemistry Aerosol Radiation and Transport into the analysis. In combination with the day and night microphysical RGB image it was pointed out that continental influence and cleaner maritime air are lying next to each other and could be differentiated by their microphysical properties in the RGB images.

Under these circumstances the anthropogenic emissions influence the formation of MSCs. Therefore the North East Atlantic is a good study place to further investigate the covariance between clouds and aerosols under the influence of synoptic features.
2.4. Statistic analysis

To find connections between the microphysical properties of MSCs and large scale meteorology the empirical orthogonal function (EOF) was used. This method finds statistically dominant patterns of variability in time or space. The goal is to decompose the data by using the orthogonal basis determined by the data itself. Therefore the covariance matrix of the data set is calculated, which is also called scattering matrix. It contains the orthonormal eigenvectors which are called EOF of the sample. The eigenvectors need to be orthonormal to satisfy the assumed null hypothesis. For this statistical approach the null hypothesis implies that the set of variables is linearly uncorrelated. The number of possible EOFs depends on the number of variables which will be analysed. In most cases the first few EOFs fully explain the variance in the data. Where the first EOF is the strongest pattern to explain the variance of the sample and contains the largest eigenvalues. As described by von Storch and Zwiers (2002) the second one is orthogonal to the first one, because of the orthogonality of the Hermitian matrix which is a squared matrix equal to its conjugate transpose. With increasing order of EOF it gets more difficult to interpret the statistic pattern with a physical meaningful explanation.

In the North East Atlantic the NAO was the dominating feature which is traditionally described by the pressure gradient, however, it can be examined with an EOF analysis, too. Figure 2.2 shows the first EOF of the sea level pressure of the years 1979 to 2016. In this time period 19.5% of the variability can be explained with the first EOF. The spatial analysis describes the pattern of the positive NAO phase. An enhanced low pressure

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![Figure 2.2.](image-url)  
**Figure 2.2.:** First EOF of ERA–Interim’s sea level pressure in the North Atlantic region for the years 1979 to 2016. Percentage in the upper right corner shows the explained variance.
system near Iceland, here it is 0.03% lower than the climatological mean low pressure in this region and an enhanced high pressure over the Azores. The spatial pattern of the first EOF and its explained variance change throughout the year and is dependent on the analysed time range (not shown), but the NAO is present in the first EOF.

In this project the first three EOFs of the sea level pressure of Era-Interim were calculated for the time period 2003 to 2012 in time and space (comp. Fig. 3.3). To exclude the seasonality from the data, the dataset were split up into the seasons and than the trend of the yearly seasonality was subtracted. The removal of the season was then correlated with the same day values of the MODIS and MACC parameter for each grid point. All parameters (x) are normalized before the calculation. Therefore each time step (t) was divided by the temporal mean of the grid point:

\[ x_{t, \text{lat,lon}} = \frac{x_t}{\bar{x}} \]  \hspace{1cm} (2.3)

The correlation between the EOFs and the parameter was calculated with equation 2.4.

\[ \frac{\Delta x_i}{\Delta \text{EOF}_{1,2,3}} \]  \hspace{1cm} (2.4)

The significance of the correlation was evaluated with the p-value. For a confidence level of 95% which corresponds to a p-value < 0.05 the data points were marked.
3. Results

3.1. Synoptic conditions of MSC plumes

In order to identify samples of MSC plumes over the Atlantic ocean daily microphysical RGB images from the geostationary MSG were assessed subjectively to find well-defined MSCs over the North East Atlantic. In total three years (2009 to 2011) were analysed from which 45 cases with significant large plumes of MSCs were chosen. A list of the chosen dates can be found in Table A.II.

In the day microphysical RGB image MSCs appear yellow-greenish, which implies that these are warm low level clouds (not much red) characterised by small droplets (green) (see Sec. 2.1). Figure 2.1 shows a selected RGB image of the study region for the January, 27 2010. A plume of MSCs extended South of Iceland over the North East Atlantic. North of the interface (broken line in Fig. 2.1) the pink colour indicates a deeper cloud sheet and with less coverage. South of the interface the cloud sheet appears in a strong yellow hue and covers nearly 100%. Only partly and in small areas the blue colour, which indicates the ocean can be seen through the sheet. Further out over the ocean close to the interface the MSC becomes more pink in the colour which indicates a increasing COD. In this area and south of it the cloud sheet develops a more fluffy structure and the Atlantic can be seen more often in small parts. This development in the cloud cover was describe by Rosenfeld et al. (2006) and Stevens et al. (2005) as a breaking-up from closed cell structure to pockets of open cells. This takes place in open cells when the mean effective radius exceeds $\sim 15 \mu m$ and drizzle starts (Gerber, 1996) (see Fig. ??). The drizzle is a cleansing effect. The clouds gets more pristine and a positive feedback loop begins until the cloud completely dissolved or new CCNs get activated (Reutter et al., 2009; Rosenfeld et al., 2006; Goren and Rosenfeld, 2015).

The colours in the RGB image (see Fig. 2.1) indicate two different air masses lying next to each other with different microphysical properties. The region marked with (a) in Figure 2.1 is characterised by many smaller droplets and a higher coverage and in the region marked with (b) the air mass is characterised by thicker clouds with less droplets. This leads to an air mass with continental origin south of the interface (a) and north of the interface (b) a cleaner maritime air mass can be found.
Figure 3.1.: Sea level pressure anomaly in hPa for days with MSCs fields over the North East Atlantic. The black arrows indicate the wind direction and speed. Data from NCEP/NCAR (Kalnay et al., 1996).

For the selected cases with MSC plumes the composite sea level pressure anomaly is shown in Figure 3.1. It can be clearly seen that a positive pressure anomaly dominates the North East Atlantic. The positive anomaly extends from its center East of Ireland over the North Sea and Atlantic.

A positive sea level pressure anomaly means that the pressure is higher than its climatology mean. Taking a closer look at the wind in Figure 3.1 an anticyclonic circulation can be seen which corresponds to a high pressure system laying over the ocean. Due to this synoptic feature, advection of maritime air towards Iceland and Great Britain can be observed and on the eastern flank of the high pressure offshore winds transport continental air from the European continent onto the Atlantic. Such a circulation favours the formation of MSC and potentially allows the formation of stratocumulus clouds in the advected continental air mass. Especially the continental track plays an important role because within particles from the continent which function as CCNs are transported onto the ocean. Following Wood (2012) the CDNC is primarily determined by the available CCNs, more clouds are expected in the area of continental air mass outbreaks due to the increase in the amount of CCN. An example for a MSC formed in continental air is the MSC plume south of the interface which is shown in Figure 2.1. Aforementioned the yellow-greenish colour in the day microphysics RGB illustrates small cloud droplets which form an opaque closed cell.

Clouds which formed and developed in maritime air masses are marked by larger droplet sizes and are thicker with more water content and therefore have a higher optical depth (Stevens et al., 2005; Rosenfeld et al., 2006). This is visible as well in Figure 2.1 north of the interface line where the open cells of MSCs are more red than the closed cell south of the transition line.
3.2. EOF analysis

For explaining the synoptic features driving the formation and development of MSc plumes the EOF analysis was used. The spatial EOFs of the sea level pressure from Era-Interim for the years 2003 to 2012 were computed. At first, a look on the explained variance of the first EOFs was taken and displayed in Figure 3.2. According to the theory the first EOF explains the largest variance in the data. Here the first EOF (EOF1) explains approximately one fifth (19.5%) of the variance, the second EOF (EOF2) 15.1% and the third EOF (EOF3) 13.8%. Together, nearly 50% of variance in the data is resolved. There is a stronger decrease in the following EOFs which explain each less than 9% of the variance. Therefore this study focuses on the first three EOFs for the analysis, because they explain the most of the variance.

In Figure 3.3 in the upper panel the EOF1 is shown and displays the negative phase of the NAO, as described in Data and Methodology (Section 2.3). Under these condition convective clouds can be observed in the northern part connected to the Iceland low, which is still present but weakened. South in the region of the negative sea level pressure anomaly MSCs can be found but not connected to continental air mass outbreaks as observed in Figure 3.1.

The EOF2 is the next most common pattern in the sea level pressure variance. An extended high pressure system with its centre over Iceland is found. The synoptic pattern that is displayed in the middle panel of Figure 3.3 by this EOF allows advection of continental air onto the ocean. Compared to the sea level pressure anomaly in Figure 3.1 the same pattern occurs hence it can be concluded that a high pressure anomaly is necessary in the North East Atlantic over the British Islands to observe continental tracks.
Figure 3.3.: First (upper panel), second (middle panel) and third (lower panel) EOF of sea level pressure anomaly in hPa in the North Atlantic region of the years 2003 to 2012 from ERA–Interim were taken into account. Percentage in the upper right corner shows the variance explained by the EOF.
from the mainland. Under these circumstances the north-east wind transports continental air onto the ocean.

The spatial EOF3 explains 14.6% of the sea level pressure variance. It describes a synoptic pattern of a high pressure anomaly dominating the Atlantic and a low pressure anomaly the mainland. This results in a south-east transport of continental air towards the south-west Atlantic Ocean which explains MSC plumes along the Northwest coast of Africa. Nevertheless, the second spatial EOF provides the synoptic situation necessary for the investigation of continental tracks from which anthropogenic influences can be concluded.

3.3. Correlation between EOF analysis and microphysical cloud properties

In this section a linear correlation analysis between the first three EOFs of the sea level pressure over the North East Atlantic and the microphysical parameters from Terra was made. Therefore each grid point at each time step of the microphysical variables was correlated to the daily EOF value.

At first the liquid cloud fraction was correlated to the EOFs as seen in Figure 3.4. In panel (a) of Figure 3.4 a positive correlation can be seen over the northern Ocean and in the Southern area a negative one. The occurring feature is alike the bimodal pattern which appears in the first spatial sea level pressure EOF in Figure 3.3. However, over the European continent a negative pressure anomaly corresponds to less clouds. For most parts for a positive pressure anomaly more clouds can be found and the same is valid for a negative pressure anomaly.

Figure 3.4b shows the correlation with EOF2. Over the ocean close to the shore lines a strong significant positive correlation is displayed, especially at the west coast of Ireland. Further away onto the ocean the correlation strength decreases. Here the positive sea level pressure anomaly correlates with a higher liquid cloud fraction. Again an exception is Portugal where a strong negative correlation can be found and at the east coast of Iceland.

Figure 3.4.: The correlation of the daily EOF index and the liquid CF for the first three temporal EOFs. a: dCF/dEOF1 b: dCF/dEOF2 c: dCF/dEOF3. The black points indicate the significant p–value (0.05).
Therefore it can be concluded, that next to the sea level pressure another meteorological parameter influences the cloud cover. In the Portuguese area when MSCs are transported over land the moisture fluxes from the ocean is missing hence the MSCs dissolve. At the coast of Iceland the orography could be the driving factor. As the island lies within the west wind region and is relatively high, clouds could be dissolved precipitation due to forced elevation at orography.

The correlation with EOF2 is akin to the case study presented in Section 3.1. Clouds are found closer to the shores this results in a high and significant correlation. Although further onto the ocean clear sky or nearly clear sky conditions are found therefore the correlation is equal to zero or slightly negative which indicates that the clouds dissolved. Thence a positive sea level pressure anomaly is present over Great Britain in the EOF2 (see Fig. 3.3 middle panel) and the correlation with the cloud fraction shows a strong correlation over the area of Iceland it can be assumed that the circulation is anticyclonic. This results in a continental air mass transported into the Atlantic ocean. Consequently the general conditions for the formation of MSCs are fulfilled and additionally they can form in a continental track as shown by Goren and Rosenfeld (2015).

The comparison with EOF3 shows a significant strong relation over the ocean (see Fig. 3.4c). In the sea level pressure a strong positive anomaly is located over the Atlantic. In this situation over the continent a low pressure system dominates the synoptic situation, hence the circulations is from the north-west towards south-east. However, over the Atlantic the formation of MSCs is favoured as in the second comparison due to the high pressure anomaly.

The correlation with the CDNC is presented in Figure 3.5. For the comparison with EOF1 no clear pattern is portrayed. Close to the continent, especially the UK, a positive correlation is shown in the areas with a negative pressure anomaly. Further out over the ocean, still with a negative pressure anomaly, the correlation is negative and in the region from 50° to 40°W and 30° to 35°N the maximum in the positive correlation can be found.

Figure 3.5.: The correlation of the daily EOF index and the CDNC for the first three temporal EOFs. a: $d\text{CDNC}/d\text{EOF1}$ b: $d\text{CDNC}/d\text{EOF2}$ c: $d\text{CDNC}/d\text{EOF3}$. The black points indicate the significant p-value (0.05). The broken line in panel (b) shows the interface between the maritime and continental air mass.
The region from $50^\circ$ to $40^\circ W$ and $30^\circ$ to $35^\circ N$ in Figure 3.5a is significant because the area of maximal positive correlation can be found there surrounded by negative correlation. The low pressure anomaly determines the region and less CDNC are found there. In combination with the correlation of the cloud cover in Figure 3.4a it can be concluded that the clouds developed and the droplets grew.

In Figure 3.5b a strong positive correlation is shown over Europe and close to the European coast. With the decreasing pressure anomaly to the south west the correlation changes its sign and loses its strength. In the northern part of the Atlantic the correlation is significantly weaker. In the area of a positive pressure anomaly a slightly negative correlation can be seen which indicates less CDNC. The shown feature resembles the case study in Section 3.1, where maritime and continental air lies next to each other. Here the maritime air mass lies in a region with the slight but significant negative correlation in the northern part north of the interface line, characterised by few but larger cloud droplets. The continental air mass is south of the interface line (see Fig. 3.5) and as suggested before with Figure 3.4b, is transported in a plume onto the ocean due to the circulation.

The right panel of Figure 3.5 shows the correlation of EOF3 with CDNC. Again a positive pressure anomaly is related to an increasing number of cloud droplets close to the shores. The region from $50^\circ$ to $40^\circ W$ and $30^\circ$ to $35^\circ N$ is noteworthy because of its maximum in the negative correlation which indicates a pristine air mass coming from the southern Atlantic ocean. This is line with the negative correlation in Figure 3.4, where clouds are not present any more.

In order to analyse the size of the cloud droplets the effective radius was correlated. In the first mode (see Figure 3.6a) a negative correlation occurs over the northern ocean in the region around Iceland and Great Britain. From France to the tip of Greenland a interface between positive (south) and negative (north) correlation can be observed. In this case again the region from $50^\circ$ to $40^\circ W$ and $30^\circ$ to $35^\circ N$ is notable because the correlations turns negative. In the northern part with the negative correlation more clouds can be found and they are probably characterised by smaller droplets as indicated by the

![Figure 3.6.](image-url)

**Figure 3.6.** The correlation of the v and the effective radius for the first three temporal EOFs. a: $dr_e/d$EOF1 b: $dr_e/d$EOF2 c: $dr_e/d$EOF3. The black points indicate the significant p-value (0.05).
correlation of the effective radius. Therefore it can be concluded that in this region a low amount of CDNC can be found and therefore the cloud droplets grow bigger and have a larger effective radius. A possible reason for the changing sign of the correlation of the effective radius is the cleansing feedback (Rosenfeld et al., 2006).

In the second comparison (see Fig. 3.6b) over and next to Europe the effective radius is decreasing while the sea level pressure is rising (see Fig. 3.3 EOF2). And further onto the ocean the correlation sign switches and with a positive sea level pressure anomaly the effective radius increases. In conclusion closer to the continent the effective radius is small due to the increase in CDNC which was observed in Figure 3.5b. However, during the travel over the ocean in cleaner air masses the effective radius increases, hence the cloud droplets grow and at one point they can reach drizzle size and fall out (Gerber, 1996).

Although in Figure 3.6b the interface between maritime and continental air mass cannot be seen as clearly as in the correlation with the CDNC in Figure 3.5b.

Figure 3.6c shows the correlation with EOF3. In the centre of the ocean the effective radius correlates negatively with the sea level pressure anomaly. This means in the area with more clouds, as shown in 3.4c, and a large amount of CDNC (see Fig. 3.5c) the effective radius is small. Further onto the ocean the correlation is positive in the regions with less clouds and a lower CDNC, consequently the effective radius increases. The strongest correlation can be found over the North Sea with 1.3 which could be explained by the dominating circulation that transports continental air from the east onto the North Sea and if its blocked by the high pressure circulation over the Atlantic. Figure 3.7 displays the relationship of the cloud LWP and the daily EOF. In the first correlation the LWP is decreasing for an increasing cloud cover over the ocean south of Iceland and in the Southern region of the Atlantic increasing for a decreasing cloud cover. A similar picture is drawn in the comparison with the EOF2 in 3.7b. In the region with a positive sea level pressure anomaly over the British Islands the cloud LWP is decreasing. This is caused be the cloud type. MSCs are shallow, warm, low clouds and have a a smaller liquid water path than vertical extended cloud like convective ones. The same is valid for the third correlation shown in Figure 3.7c, for a positive pressure anomaly the LWP is decreasing.

Figure 3.7.: The correlation of the daily EOF index and the LWP for the first three temporal EOFs. a: dLWP/dEOF1 b: dLWP/dEOF2 c: dLWP/dEOF3. The black points indicate the significant p-value (0.05).
Due to the fact that the LWP correlations is constant under the influence of the positive sea level pressure anomaly in Figure 3.7b it can be concluded that the same type of cloud is observed. Otherwise, for example when the air would become drier, the correlation would change significantly in this region.

The correlation of the cloud optical depth shown in Figure 3.8. For the correlations arise a very similar distribution as in the LWP correlation in Figure 3.7. In positive pressure anomalies the cloud optical thickness decreases and the opposite. This could be caused by the linear dependency between COD, LWP and effective radius (see Eq. 2.1).

Following Twomey (1974) in the clouds with many smaller droplets and a constant liquid water path the clouds appear more reflective. However, in all three correlations the clouds appear less opaque for more clouds with smaller droplets. Especially in the second correlation in Figure 3.8b where a continental air mass is indicated the clouds should be opaque as observed in Figure 2.1. Accordingly, the small changes which can be observed in the correlation with the effective radius in Figure 3.6b with a constant LWP (see Fig. 3.7b) have no impact on the COD. Possibly the cloud fraction effect and cloud LWP effect, quantified by Goren and Rosenfeld (2015) to be larger than the Twomey effect leads to a correlation which is the inverse of the expected correlation of COD.

Figure 3.8.: The correlation of the daily EOF index and the COD for the first three temporal EOFs. a: dCOD/dEOF1 b: dCOD/dEOF2 c: dCOD/dEOF3. The black points indicate the significant p-value (0.05).
3.4. Anthropogenic influence

In order to identify the effect of anthropogenic aerosols on the MSC occurrence and development a correlation with AOD was made as shown Figure A.III but not further discussed because the AOD is not trustworthy. Large uncertainties exists within the retrieval (Levy et al., 2013) and the data can be only trusted in clear-sky scenarios (Gryspeerdt et al., 2016). However, in this study the focus lies on the cloud-aerosol-interaction, therefore carbon monoxide (CO) and sulphur dioxide (SO2) concentrations at the surface from the MACC reanalysis were chosen. Both chemicals can function as a tracer of human activity (Myhre et al., 2013; Daniel and Solomon, 1998; Shindell and Faluvegi, 2010).

Figure 3.9 displays the correlation of CO concentration with the EOF index. The correlation with EOF1 shows a positive correlation over Great Britain and the Atlantic Ocean close to the shores (see Fig. 3.9a). This indicates a stronger anthropogenic influence over the ocean close to the shore. In EOF2 in Figure 3.9b a clear transition line over the North Atlantic can be seen, similar to the once observed in the CDNC correlation (see Fig. 3.5). The transition line indicates that maritime and continental air masses are lying next to each other. A higher correlation is found over Europe in Figure 3.9b, which is expected due to the human production of CO.

Compared to EOF2 in Figure 3.3 it is suggested that the high pressure over Great Britain transports anthropogenic emissions from the mainland of Europe southwards onto the North East Atlantic. It can be seen, that the maritime air is transported from the Southwest Atlantic northwards. Therefore no correlation can be found South of Iceland because it is pristine air.

These results are in accordance with Goren and Rosenfeld (2015), who showed the transport of a polluted air mass from western Europe onto the North East Atlantic and interfacing with a maritime air mass.

Figure 3.9c which shows EOF3, has no significant correlation over the ocean, but only a very light correlation can be found over the Atlantic. This indicates that the co-variability between the meteorology and aerosols is important. In Figure 3.9c the interaction between

![Figure 3.9.](image-url)

Figure 3.9.: The correlation of the daily EOF index and the carbon monoxide for the first three temporal EOFs. a: dCO/dEOF1 b: dCO/dEOF2 c: dCO/dEOF3. The black points indicate the significant p-value (0.05).
the high pressure system over the Atlantic and the low pressure system over the European continent determines the circulation, which transports air south-eastwards. The high pressure systems over the Ocean favours the formation of MSCs but in cleaner air conditions. However, the CO is transported with the circulation south-eastwards and not onto the Atlantic, as it is shown clearly in Figure 3.9c and therefore an anthropogenic influence on MSCs can be excluded.

The correlation of the SO2 concentration with the temporal EOFs is displayed in Figure 3.10. In Figure 3.10a a slightly positive correlation can be observed over the Bay of Biscay extending towards Iceland and the coast of Greenland. At the north-west coast of Africa and further into the Atlantic the correlation is rather weak and negative. EOF2 (see Fig. 3.10b) shows a positive correlation nearly all over the Atlantic, only in the south-west the correlation changes its sign. The EOF3 is mostly negative, only in front of the Portuguese coast and in the north-western part a positive correlation can be found (see Fig. 3.10c). Hence no clear connection between SO2 and an anthropogenic influence cannot be seen in the correlation. The connection between SO2 and cloud formation as described by Quinn and Bates (2011) cannot be observed either. In the second correlation (see Fig. 3.10b) SO2 reaches its maximum over the Ocean south of Iceland this could be probably the new formation of SO2 from DMS as shown by Quinn and Bates (2011).

Despite the fact that SO2 is produced by human activities it was not the best choice to investigate the anthropogenic influence because the production of SO2 by DMS oxidation is dominating over the Atlantic.
4. Conclusion and Outlook

In this study the influence of continental tracks on the formation and microphysical properties of MSCs over the North East Atlantic was investigated. Additionally, the impact of anthropogenic aerosols was analysed. In order to do so the first three EOFs of the sea level pressure over the Atlantic were calculated as a proxy for the dominating synoptic feature. The daily indices of the EOFs were correlated with microphysical parameters, i.e. liquid cloud cover, CDNC, LWP, effective radius and COD, from the satellite MODIS and the MACC reanalysis.

With the results it was shown that a high pressure anomaly over the British Islands and extending onto the Atlantic favours the occurrence of MSCs under the influence of continental air mass outbreaks from Europe. George et al. (2013) and Goren and Rosenfeld (2015) showed these continental air mass outbreaks and related them to the dominating circulation. The synoptic feature appearing in the second EOF of the sea level pressure is the determining factor for the circulation which transports aerosols from Europe onto the Atlantic Ocean.

The correlations with the microphysical properties draw a coherent picture. In the CDNC analysis it was presented that two different air masses are lying next to each other characterised by different amounts of cloud droplets. The maritime air mass lies north of the interface and is characterised by a smaller amount of CDNC, whereas south of the interface continental air mass can be found. The constant correlation of the LWP approves that in these two air masses the same type of cloud namely MSCs occur. The correlation of COD is inconsistent with the studies by Twomey (1974) and Wood (2007). In this study the COD decreases with increasing CDNC, but it is expected that the COD increases because of the Twomey effect for a constant LWP which is valid here (see Eq. 2.1). Wood (2007) pointed out that this increase in COD can happen on a short-time scale but it always responds positively. However, Goren and Rosenfeld (2015) quantify that the cloud cover effect and cloud LWP effect larger than the Twomey effect. Therefore, in this study no clear explanation without further analysis for the role of the COD can be given. In general the results shown in this study agree with the studies of Goren and Rosenfeld (2015) and George et al. (2013).

When studying the anthropogenic signature in the clouds the surface concentrations of CO and SO2 are analysed. The analysis of CO shows the expected result with a strong positive correlation in the continental air mass and no correlation in the maritime air
mass. This finding confirms that the continental track carries anthropogenic aerosols and has impact on the formation of MSCs over the North East Atlantic.

Stevens (2015) describes SO2 as the main precursor of anthropogenic aerosols, but here no correlation could be found in the analysis. This leads to the conclusion that SO2 is a good proxy for anthropogenic influence over the continents and for global studies, but in this regional analysis over the North East Atlantic SO2 did not show any anthropogenic signal. In further analysis NOx could be used. NOx is man-made but it is difficult to estimate the radiative forcing because it can have a warming and cooling effect in different chemical reactions (Myhre et al., 2013).

Furthermore, the relations of the microphysical properties to each other can be studied by correlating the made analysis. With these correlations dependencies and uncertain pictures in the microphysical influence can be estimated. Additionally, the reflectivity of the cloud could be used for estimating the radiative properties of the cloud. Besides, the anthropogenic influence needs to be discussed more. Therefore a comparison between pre-industrial and present-day General Circulation Model simulations can be used for studying anthropogenic signals and quantifying the radiative forcing.

Further investigations to define the relationship between large-scale meteorology and microphysical cloud properties are necessary to find microphysical influences of MSC development. A statistical analysis to discover these drivers and their importance is the principal component analysis. Along a climatological trajectory the influence of varying parameters can be examined and evaluated. Hence, a change in the driver and the importance can be examined.
Appendix

A.I. Change of radiative forcing with cloud optical depth and cloud top height

Figure A.II.: Cloud radiative effect at the top of atmosphere depending on the cloud optical depth and the cloud top height in km. The daily averaged radiative forcing in W m\(^{-2}\) is shown in colour for an averaged effective radius in the range 20\(\mu\)m to 40\(\mu\)m. Figure taken from Koren et al. (2010).
A.II. Example Days

Table A.I.: Days with clear MSC field over the North Atlantic.

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<td>2011-03-02</td>
<td>2011-06-05</td>
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</table>

A.III. Correlation between EOF analysis and AOD

Figure A.III.: The correlation of the dailys EOF value and the AOD for the first three temporal EOFs. a: dAOD/dEOF1 b: dAOD/dEOF2 c: dAOD/dEOF3. The black points indicate the significant p–value (0.05).
References


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Statement of authorship

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Roxana Cremer, Leipzig, 27th September, 2017