Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Case study on the effect of aircraft induced cloudiness on the short wave solar irradiance at the land surface

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WAGENINGEN UNIVERSITY
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Internship Report

June 2012

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Internship Earth System Science (ESS-70433)

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1. INTRODUCTION

Aviation contributes to anthropogenic climate forcing in various ways. Aircraft engines emit greenhouse gases, their precursors and aerosols [*IPCC*, 2007]. Moreover, jet aircraft change upper-troposphere cloudiness by artificially triggering ice cloud formation and potentially changing natural cirrus occurrence and properties [*Schumann*, 2005]. Aviation induced cloudiness (*AIC*) is in fact presently believed to be the most significant climate effect from aviation [*Burkhardt et al.*, 2010]. Flying through sufficiently cold and humid air the engine exhaust mixing with ambient air produces line-shaped condensation trails (contrails). These man-made ice clouds can persist as long as the environment is ice-supersaturated and can evolve to cirrus clouds (contrail-cirrus) [*Schumann*, 2005]. Nowadays, a sky full of contrails is a pretty familiar sight in parts of the world where air traffic is heavy.

The radiative effect of contrails and cirrus is twofold. Solar down-welling radiation is reflected (cooling effect) and upwelling thermal radiation is trapped (warming effect). The average effect on climate then really depends on whether your reference point is at the top of the atmosphere (*TOA*) or at the Earth's surface. Optically thin cirrus clouds are known to have a warming effect on the total earth-atmosphere system (reference at *TOA*), because trapping of upwelling long wave radiation surpasses the albedo effect on average [*Meerkötter et al.*, 1999]. By means of a GCM study *Burkhardt* and *Kärcher* [2011] evaluated the *AIC* forcing at *TOA* for the year 2002. They found a global total mean radiative forcing of $+37.5$ mW/m^2 and $> +300$ mW/m^2 in high air traffic density areas (e.g. Europe and the USA). This forcing means that the atmosphere is heated. These values amount to about 1% and 10% of the total global mean anthropogenic radiative forcing, respectively [*IPCC*, 2007]. At the surface, however, these clouds will typically warm at night and cool during the day. The balance at the surface is reversed compared to at *TOA* and is anticipated to have a net cooling effect [*Meerkötter et al.*, 1999]. Locally and for a short amount of time the daytime surface radiative forcing can be in the order of -10 or -100 W/m^2, which thus means a cooling effect [*Meerkötter et al.*, 1999]. On the global scale this cooling effect will be several orders of magnitude smaller. With an increase of air transport in the future the contribution of *AIC* to anthropogenic climate change is anticipated to become more significant [*IPCC*, 2007]. This case study focuses on the effect of *AIC* on the solar irradiance, i.e. the short wave component of the total forcing by *AIC*.

Extremely high contrail and contrail-cirrus coverage occurred during January 13-17th 2012 over The Netherlands and adjacent regions, which lead to the idea of this case study. After an initial exploration it was found that January 16th and 17th are best suited for investigation. This is because of the absence of lower level clouds during those days, which may complicate interpretation of observational data. The main objective of this case study is to estimate how these clouds affect the solar short wave irradiance at the surface of the measurement site of Cabauw, The Netherlands. This thus implies a focus on the daytime of January 16th and 17th. However, this *AIC* event is looked at from different perspectives, using e.g.

satellite images, sounding data and synoptical weather charts. To estimate the effect of these clouds on the solar irradiance at the surface, we compare the radiation observations at Cabauw from January 16th and 17th 2012 to Cabauw observations from January 16th 2005, because this day was nearly free of clouds. Radiosonde data from De Bilt and uv-lidar data at Cabauw are compared to observe, whether the cloud heights and the upper-troposphere humidity conditions relate to each other. Satellite observations are used to get an overview of the cloudiness conditions during this case. The study starts with some theory on contrail formation and persistence.

2. CONTRAIL FORMATION AND PERSISTENCE

A contrail can form due to the increase in relative humidity (*RH*) in the exhaust plume of a jet aircraft because of mixing of heat and water vapour. Moist and hot exhaust air mixes with cool ambient air consequently raising the *RH* in the exhaust plume. When the ambient air is sufficiently cold with a temperature below a certain threshold value the *RH* may reach liquid saturation in the exhaust plume behind an aircraft [*Schumann*, 2005]. Then water vapour condenses, primarily on the directly emitted and produced soot and sulphate particles, to form liquid water droplets. Because of the sub-zero temperature of the ambient air the droplets freeze into ice crystals soon after a contrail has formed. Although contrails, because they consist of ice particles, can persist under lower *RH* it is generally accepted that liquid saturation must be reached in the exhaust plume for contrails to form. This mainly has to do with activation and liquid coating of aerosols to become efficient ice nuclei [*Kärcher*, 1999; *Schumann*, 2005]. Since the temperature and humidity of the engine exhaust co-determine whether a contrail will form, aircraft engine properties play a role in contrail formation as well. A more efficient engine which emits the same amount of water vapor, but with cooler exhaust, will more likely trigger a contrail [*Kärcher*, 1999; *Schumann*, 2005]. After formation contrails will either rapidly dissipate (seconds to minutes) or persist (hours up to days) depending on the relative humidity of the ambient air. If the air is ice-under-saturated a contrail soon vanishes, whereas contrails persist if the air remains ice-supersaturated. Figure 1 shows the saturation curves (liquid and ice) of partial water vapour pressure as a function of temperature (green curves). The red and blue lines in this figure represent the linear decrease of temperature and vapor pressure as exhaust and ambient air mix.

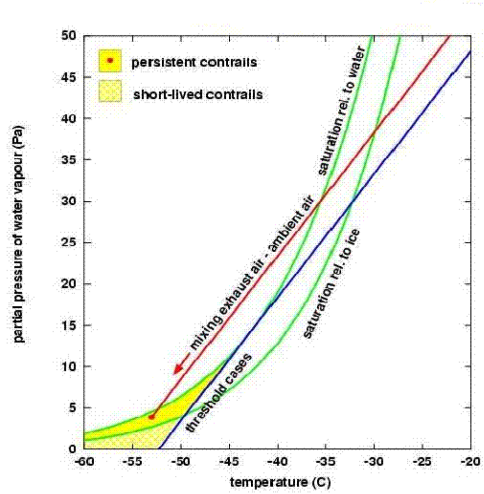

Figure 1. Liquid- and ice-saturation partial pressure of water vapour as a function of temperature. A mixing line indicating the threshold for contrail formation and a mixing line leading to persistent contrails are also drawn. See text and description inside figure for further explanation (from: "Contrails, contrail-cirrus, and ship tracks: tutorial lecture", K. Gierens, DLR).

Mixing lines terminating in the yellow zone above the ice-saturation curve, and which cross the liquid-saturation curve, lead to the formation of persistent contrails. The red mixing line exemplifies this, where the end point represents ambient conditions. The blue mixing line depicts a threshold situation for contrail formation. Short-lived contrails occur if a mixing line, after reaching liquid-saturation ends up in the yellow dashed area below the ice-saturation curve. Short-lived contrails have less of an impact on climate, because they perturb the radiative balance for a relatively short amount of time. On the other hand, when contrails persist, spread, shear and grow to contrail-cirrus clouds a more significant effect is to be expected. An example of a contrail being formed behind an aircraft and aged contrail-cirrus clouds is given in Figure 2 (photographer: Joost van Veelen). These clouds were observed over Schiphol airport during May 27th 2012. The contrail-cirrus has nearly lost its line-shaped appearance, making it hard to ascribe it to an aviation-induced origin. During January 16th and 17th 2012 contrail and cirrus coverage was intense and lasted the entire time period.

Figure 2. A young contrail and an aged contrail-cirrus deck observed by the author over Schiphol Airport during May 27th 2012. Photographer: Joost van Veelen.

3. SYNOPTICAL SITUATION

During the period of January 13th-17th a high pressure system was located over The Netherlands, which lead to fair weather conditions. Some boundary layer clouds and fields of mid-altitude clouds were observed in the first few days in addition to the contrails and contrail-cirrus. As can be seen in Figure 3 (left panel), the center of this system was directly over the country during the 16th. At that time virtually no lower level clouds were present and only contrails and cirrus remained. A frontal system arriving from the west (see: Fig. 3, right panel) again brought mid-altitude clouds at around 13 UTC on the 17th. In this study we focus on the period from January 16th until 13 UTC January 17th, when only contrails and cirrus were over the study area.

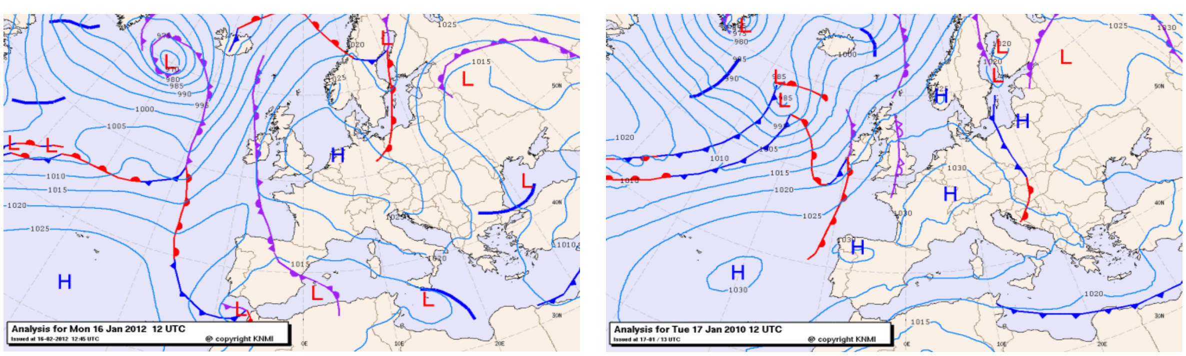

Figure 3. Weather charts showing the surface analysis of January 16th 12 UTC (left panel) and January 17th 12 UTC (right panel) [source: KNMI, Royal Netherlands Meteorological Institute].

4. SATELLITE OBSERVATIONS

Contrails and young contrail-cirrus stand out from other clouds because of their line-shaped appearance. After sufficient time these elongated shapes disappear, when contrail-cirrus spreads and becomes indistinguishable from natural cirrus. Four satellite images (January 17th 08-11 UTC) centered over The Netherlands are given below (Figure 4). These images were obtained from the SEVIRI instrument on board the geostationary MSG meteorological satellite. This instrument observes in the visible (high resolution visible band: HRV), near-infrared and infrared bands. Different image composites were used (see caption Figure 4), giving high-altitude clouds a white-blueish appearance during night and day. During daylight hours low-level clouds appear yellowish and the frontal cloud band west of The Netherlands gets a more violet coloring. In these satellite images we can discern high cirrus coverage with linear characteristics over the country and the approaching frontal system in the west (see yellow arrow in Figure 4). An interesting observation can be done looking at The North Sea. The upper-left panel (08 UTC) shows a line-shaped cloud structure consisting of one or potentially several contrails. It appears about 400 km in length. Over time it evolves to a much more extensive cirrus deck, perhaps 50 km wide. It nicely demonstrates contrail to contrail-cirrus spreading and how these cloud structures can persist for hours at the least. In the lower-right frame (11 UTC) it is not easily distinguished anymore as cirrus originating from aircraft operation (see red arrows in Figure 4).

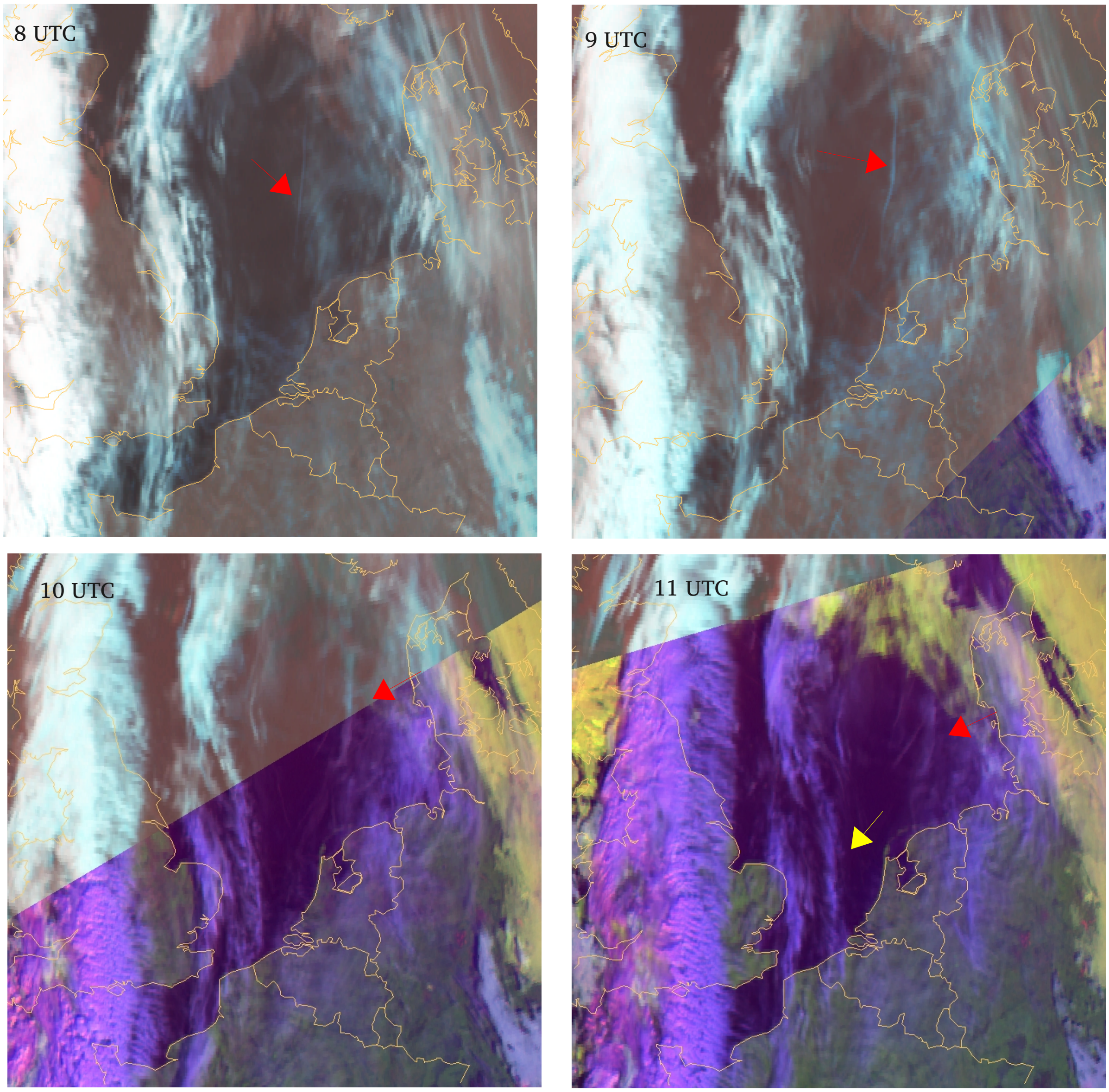

Figure 4. Satellite composite images (MSG satellite, SEVIRI instrument and HRV-band) of January 17th 08-11 UTC in frames of 1 hour. During daytime composite is R 0.4-1.1, G 1.6 and B 10.8 micron. During the night: R 3.9, G 10.8 and B 12.0 micron. Red arrow points at evolving contrail-cirrus. Yellow arrow points at approaching frontal cloud band.

5. RADIOSONDE AND LIDAR DATA

As mentioned previously contrails can persist as long as the relative humidity with respect to ice (*RHi*) exceeds 100%. By taking up water vapor from the ambient air, while being spread out by wind shear, the contrails often grow to considerable contrail-cirrus decks as Figure 4 demonstrates. It is therefore interesting to get an idea of the humidity conditions of the upper-troposphere. From sounding data at De Bilt we have calculated *RHi* at four times during the period under study. We start with:

$$e_{s(l)} = e_0 \, exp \, [\, \frac{L_v}{R_v} \, (\frac{1}{T_0} - \frac{1}{T}) \,] \tag{1}$$

which is an approximation [*Stull*, 2000] to the Clausius-Clapeyron relation describing the liquid-saturation water vapor pressure, $e_{s(l)}$ (kPa), as a function of absolute temperature T (K). Constant parameters are: $T_0 = 273$ K, $R_v = 461$ J K^{-1} kg^{-1} being the gas constant for water vapor, $e_0 = 0.611$ kPa and $L_v = 2.5\text{x}10^6$ J kg^{-1} is the latent heat of vaporization. Temperature profile data from the soundings in [°C] are converted to [K] in order to obtain T. Next, since *RH* with respect to liquid water (RH_l) is available in the sounding profiles, we can calculate the actual vapor pressure (e) data from:

$$e = e_{s(l)} \, \frac{RH_l}{100} \tag{2}$$

Finally, the *RHi* data are obtained as shown in the following expression:

$$RH_i = 100e \, [\, e_0 \, exp \, [\, \frac{L_d}{R_v} \, (\frac{1}{T_0} - \frac{1}{T}) \,] \,]^{-1} \tag{3}$$

Equation (3) also incorporates the Clausius-Clapeyron approximation [*Stull*, 2000], but uses a constant $L_d = 2.83$ J kg^{-1}, which is the latent heat of deposition to give us the saturation pressure over ice surfaces.

Figure 5 shows the vertical *RHi* profiles of 00UTC and 12UTC during both January 16th and 17th. These data indicate the presence of ice-supersaturated air, which confirms the potential for contrails to be persistent. Values up to ~130% are reached. Subsonic aircraft (i.e. airlines) cruise at levels ranging from 8 to 13 km. This is also the altitude range where contrail formation typically occurs at mid-latitudes, considering average temperature and humidity profiles of the upper-troposphere and tropopause. From Figure 5 can be inferred that contrails can persist above approximately 10-11 km, but no higher than about 12-13 km during this period. The sounding of 00UTC of January 17th also shows RHi > 100% at about 9 km and 5 km height. The January 17th 12UTC sounding nearly touches the 100% boundary. Obviously, these humidity data do not tell a complete story. The ascending sounding balloons merely take

4 'snapshots' of small parts of the atmosphere we are interested in. To give some more information about the upper-troposphere/tropopause conditions we compare the soundings to data from a UV-lidar, which is located at the Cabauw site (Figure 6).

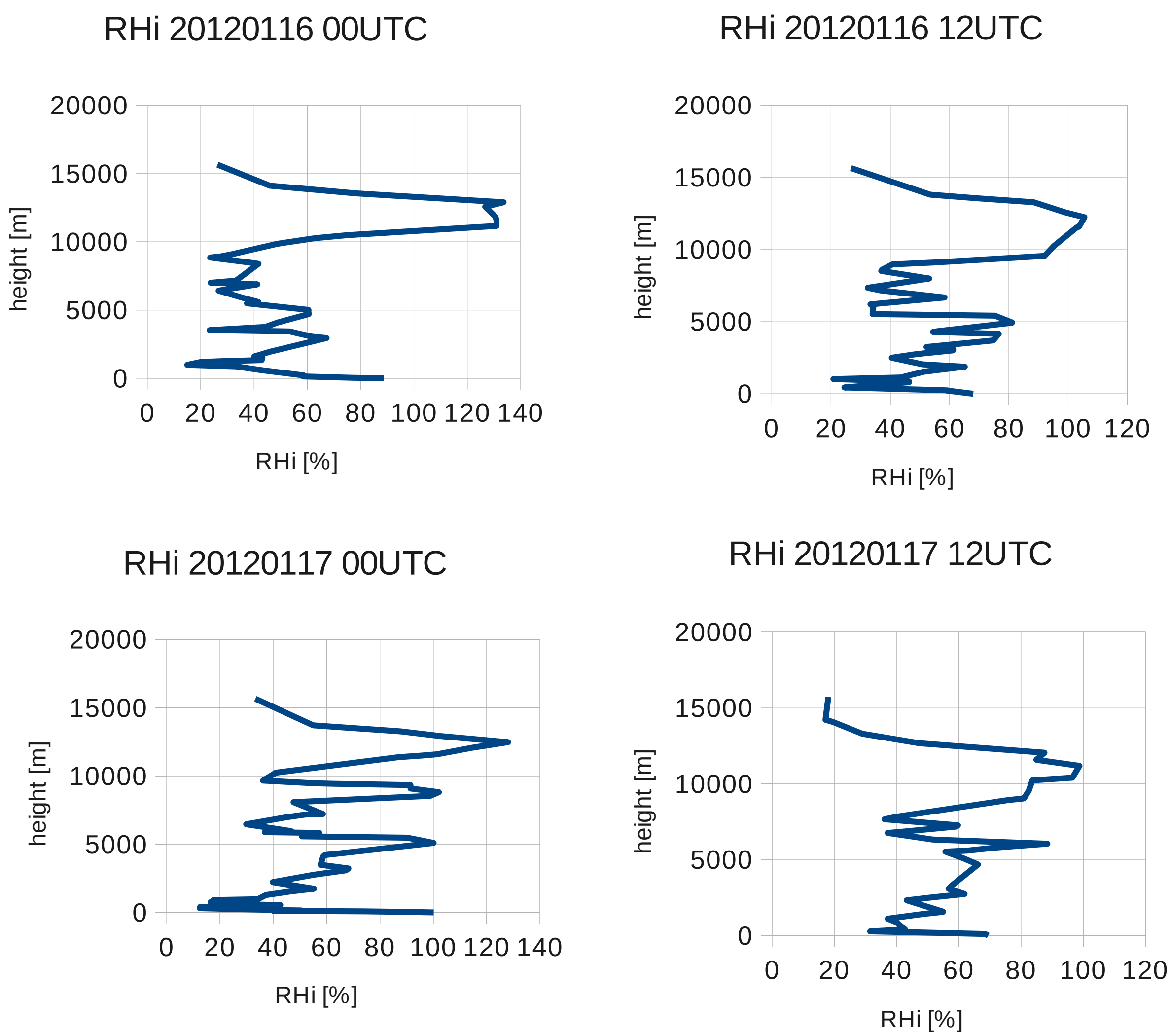

Figure 5. Relative humidity with respect to ice, RHi (%), as a function of height (m) for January 16th (upper panels) and 17th (lower panels). Panels on the left are for 00UTC and right ones for 12UTC (see panel titles).

It is virtually impossible to compare the sounding and lidar data in great detail. Firstly, there is a considerable geographical distance between the lidar location (Cabauw) and the starting point of the sounding (De Bilt). Secondly, the chance that an air mass measured by the lidar will be intercepted by the ascending balloon, while being transported downwind, is minute. Even if this would happen, there is a timing difference in which the air mass containing contrails and cirrus will have changed. Therefore, the lidar data and sounding data represent air volumes of different characteristics. However, the height intervals where contrails can persist as inferred from the soundings agree reasonably well with the lidar images (Figure 6). Figure 6 suggests the presence of high-altitude clouds during nearly all hours of January 16th (upper panel) and 17th (lower panel). After 13UTC on the 17th the cloud base drops, because of the approaching frontal system.

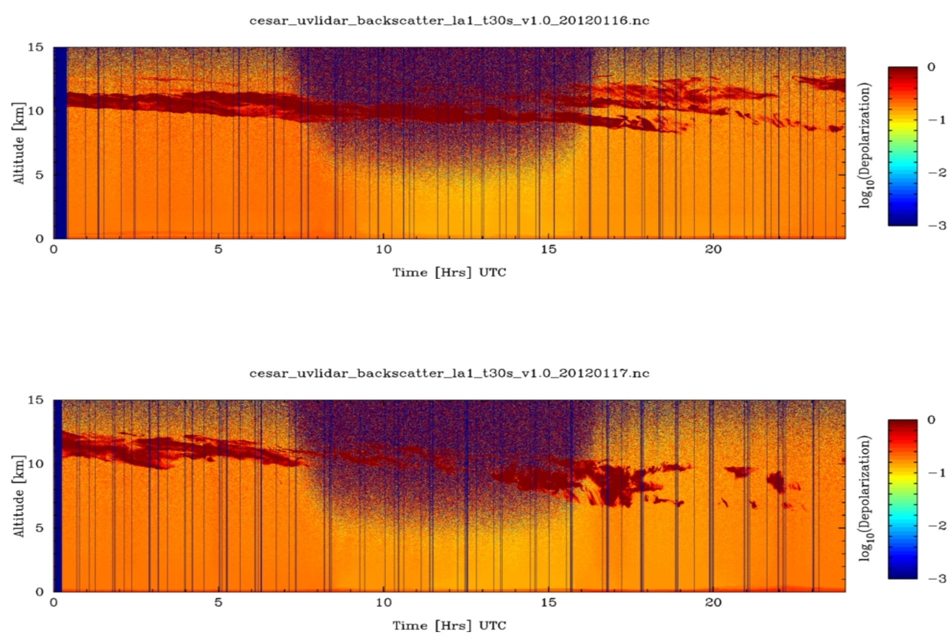

Figure 6. UV-lidar depolarisation backscatter over time (UTC). Upper panel shows January 16th, lower panel shows January 17th.

The high-altitude cloud decks are alternately single-layered and multi-layered. Their cloud bases are in the height range of 10-11 km, which corresponds with the lower-bound of the ice-saturation zones in the sounding data. The cloud tops as can be seen in the lidar images and the tops of the ice-saturation layers are also very similar. These are both in between heights of 12 and 13 km. In the case of January 17th 00UTC the observed saturated layer around 9 km height is reflected by lidar backscatter around the same time and height. It thus appears that, although different air masses are being measured, there is still some homogeneity of the upper-air in terms of humidity and the resulting cloudiness. For this case study it would be comfortable to say that all the upper-air cloudiness during these two days has resulted from aircraft operations. Unfortunately, we cannot exclude a contribution by natural cirrus. Natural cirrus formation occurs at temperatures below -38°C and at a certain supersaturation level [*Ström et al.*, 2003]. During the entire period under study temperatures were <-38°C above heights of 7-8 km. It is believed that a typical *RHi* threshold for natural cirrus formation is roughly 130-140% if homogeneous freezing mechanisms dominate [*Ström et al.*, 2003]. These involve freezing of water droplets in which the ice nuclei are dissolved substances. Somewhat lower threshold *RHi* is anticipated if heterogeneous mechanisms are the cause for ice cloud formation (ice particle forms around a solid nucleating particle), perhaps around 120% [*Spichtinger et al.*, 2004]. Values of $>120\%$ have been observed in the soundings, and air masses not intercepted by the sounding balloons could have had even higher *RHi*. In addition, it is possible that after sufficiently high *RHi* was reached, and natural cirrus was formed, the humidity decreased because the ice cloud particles grew and depleted the ambient water vapor. So, we cannot exclude a contribution in the surface radiative budget by natural cirrus during this case. Nonetheless, it is worthwhile to make an estimation of the impact on the shortwave irradiance from the clouds that were present. It then serves as a test-case for a hypothetical situation, where all cirrus clouds are due to aircraft. Since it often happens that only *AIC* is present and the *RHi* is too low for natural cirrus formation [*Schumann*, 2005], this view point is not far-fetched. Having seen and described this case from different perspectives, we will now focus on estimating the short wave forcing by these clouds at the land surface.

6. SHORT WAVE FORCING ESTIMATION

Down-welling short wave radiation is observed at the Cabauw site using pyranometers. The total short wave surface irradiance is measured, but also the individual components, being direct and diffuse radiation. Global irradiance (*G*) as W/m^2 (i.e. short wave down radiation) is the intensity of short wave radiation at the land surface:

$$G = cos(\Theta)\ I_{dir} + I_{dif} \tag{4}$$

I_{dir} is the short wave irradiance (W/m^2) on a ground-based plane normal to the sun rays, i.e. looking directly at the Sun from the surface. θ is the solar zenith angle, and I_{dif} is the diffuse short wave irradiance (W/m^2) at the surface. Figure 7 shows the global (*swd*), direct (*dir*) and diffuse (*dif*) irradiance during January 16th (lef panel) and 17th (right panel). In addition, Figure 7 shows output from a model estimating the global irradiance for a cloudless sky (*mod*). This model is based on work from *Raaf* [1987] (see also: [*Bosveld*, 2010 – online documentation]). We can see that both the direct and diffuse components contribute to the global irradiance, which means that the clouds are semitransparent, since they also allow for direct radiation to reach the surface. During parts of the day when clouds obscure the sun rays or become thicker the contribution by direct irradiance decreases. It can be observed that diffuse irradiance generally goes up, when direct radiation goes down. We can also clearly see that the clear sky-model gives lower values for *G* than do the observations, during most of the time. This would suggest that during these cloudy days more sunlight reaches the surface than in a cloudless case. Such an effect can be related to a 'positive cloud feedback', where clouds in the vicinity reflect a lot of solar radiation towards the measurement point, and the attenuation by clouds in the direct solar beam is minor [*Long* and *Ackerman*, 2000]. However, it is known that the model used here incorporates an atmospheric aerosol load from a time when air pollution was severe. Nowadays, the air is much cleaner and so the model output is somewhat outdated. It is thus anticipated that this model is biased towards relatively low values for *G*.

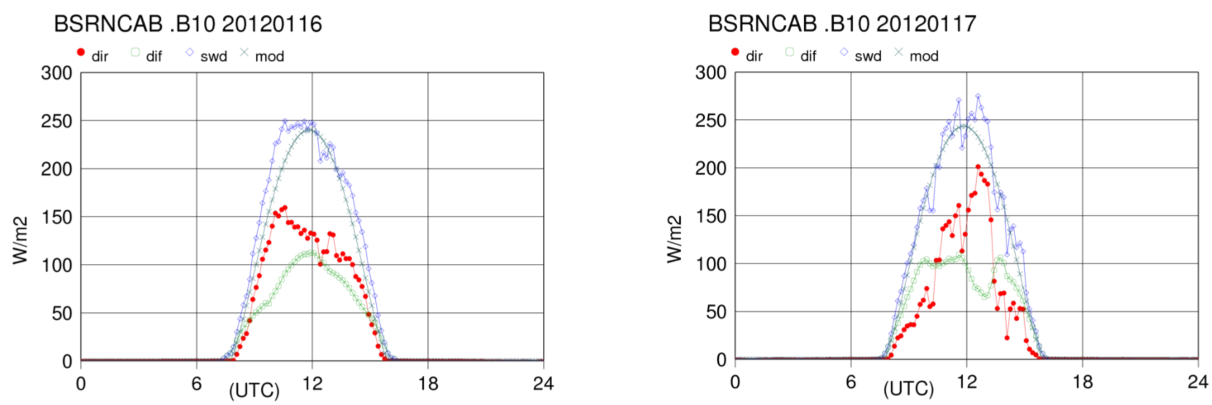

Figure 7. 10-minute radiation measurements (W/m^2) at Cabauw over time (UTC) during January 16th (left panel) and 17th (right panel). Measurements are denoted in the upper-left corner of a plot (dir = direct irradiance; dif = diffuse irradiance; swd = global irradiance observed; mod = global clear sky irradiance modeled).

Directly using this model in estimating the short wave forcing during these days would therefore not be an optimal choice. Another approach was chosen here to arrive at a clear sky estimation, by using radiation observations from January 16th 2005. From the nearly bell-shaped curve of *G* during this day was derived that it was almost cloudless. The global irradiance was also higher than the model output, giving confidence that this may be a more accurate representation of clear sky conditions. A few clouds were present during the morning, which caused some anomaly from the desired 'clear sky curve'. But, the anomalous data points were removed to smoothen the result. After linear interpolation, we obtained a 'clear sky curve' which is shown below (Figure 8).

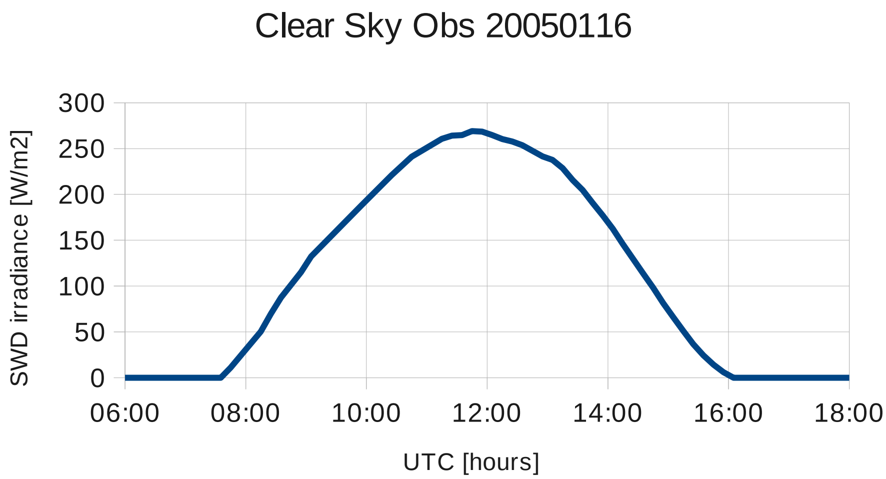

Figure 8. Smoothed 10-minute observations of the global irradiance (W/m^2) over time (UTC) of an almost cloudless sky during January 16th 2005.

These results were then used to estimate the short wave radiative forcing during January 16th 2012, by assuming that the 2005 observations provide us with a reasonable baseline for clear-sky conditions. The short wave radiative forcing (*RF*) as W/m^2 then follows from:

$$RF = G_{(obs,\,2012)} - G_{(obs,\,2005)} \quad (5)$$

Equation (5) shows that the radiative forcing is taken as the difference between the global irradiance observations from January 16th 2012, $G_{(obs,\ 2012)}$, and the smoothed observations of January 16th 2005, $G_{(obs,\ 2005)}$. These results are plotted in Figure 9 and suggest that the forcing was both negative (cooling) and positive (warming) during parts of the day. Positive values go up to $\sim+20$ W/m^2 and negative ones reach $\sim$-50 W/m^2 at the most. Interestingly enough, the forcing is appears to be positive at low solar angles and negative around midday. Looking at these numbers the maximum forcing is in the order of about 20% of the clear sky irradiance.

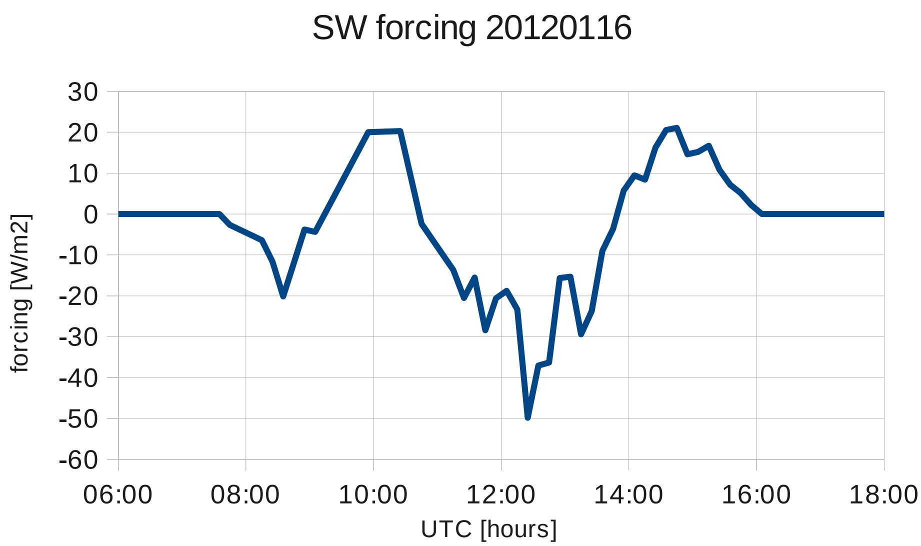

Figure 9. Estimated short wave radiative forcing (W/m^2) over time (UTC) during January 16th 2012.

In Figure 10 the relative contribution by the direct and diffuse components to the total short wave irradiance is plotted for January 16th. At times, when the forcing peaks to positive values (Figure 9), direct solar radiation is relatively high. The lowest point of the forcing curve (negative forcing) coincides with an equal contribution by direct and diffuse radiation. Direct radiation will be relatively high if cirrus clouds in the path towards the measurement instruments become optically thinner or just absent. If the direct solar beam passes through cirrus clouds with increasing optical thickness, this causes the ratio of direct/diffuse to decrease. In this case, although clouds were present during most hours, a major contribution to *G* was still made by direct solar radiation.

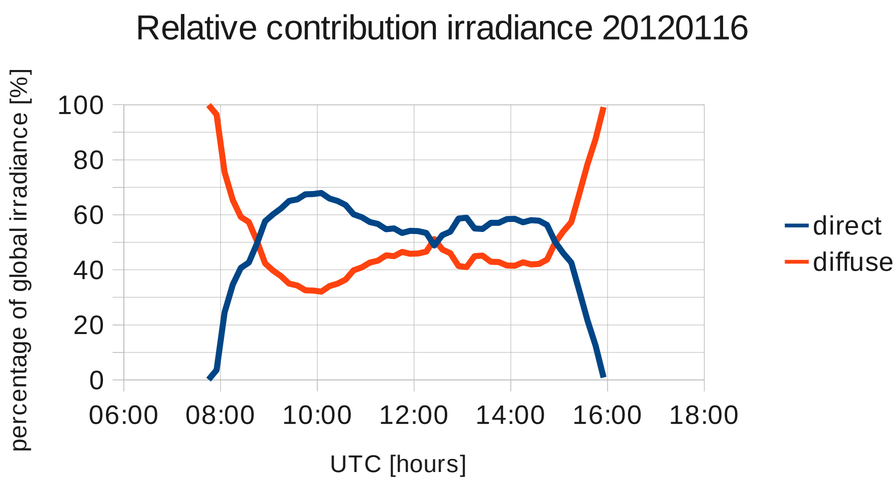

Figure 10. Relative contribution (%) by direct (blue line) and diffuse irradiance (orange line) to the global irradiance during January 16th 2012.

A cloud-free day for January 17th of a different year than 2012 was not found in the data set. Therefore, a different approach was chosen to obtain a clear sky baseline, in order to estimate the short wave radiative forcing during January 17th. For this case we again used the smoothed observational data from January 16th 2005, but correct for the differences in solar angle (different day of the year) by using the clear sky model [*Raaf*, 1987; *Bosveld*, 2010 – *online documentation*] mentioned previously. Ten-minute clear sky data for January 17th, $G_{(clr,\ 17th)}$, is calculated as:

$$G_{(clr,\,17th)} \;=\; \frac{G_{(mod,\,17th)}}{G_{(mod,\,16th)}}\,G_{(obs,\,2005)} \tag{6}$$

Applying Equation (6), each 10-minute measurement of G during January 16th 2005, $G_{(obs,\ 2005)}$, is multiplied by a different conversion factor, $G_{(mod,\ 17th)}$ / $G_{(mod,\ 16th)}$, which denotes the ratio of the 10-minute model values for January 17th and 16th 2012. Differences in clear-sky radiation between the two consecutive days, January 16th and 17th, amounts to 3 W/m^2. The actual short wave forcing (W/m^2) is then estimated by taking the difference between the observational and the $G_{(clr,\ 17th)}$ data:

$$RF = G_{(obs,17th)} - G_{(clr,17th)} \tag{7}$$

This gives the following result for the radiative forcing during January 17th 2012, shown in Figure 11. In this case we should focus on the hours before 13UTC, because of the arrival of non-cirrus clouds associated with the frontal system.

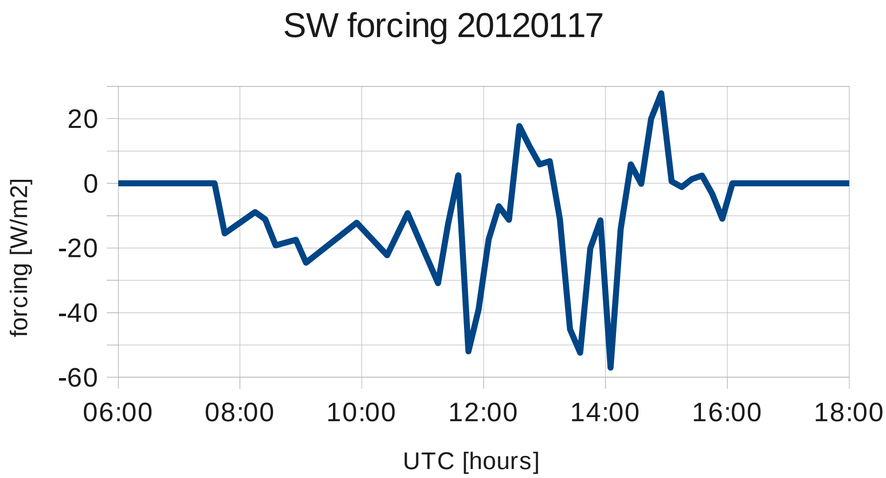

Figure 11. Estimation of short wave radiative forcing (W/m^2) over time (UTC) during January 17th 2012.

This day started with negative forcing, i.e. a cooling effect, which continues up to about 12:30UTC. The positive peaks, which were seen in the January 16th plot, do not show here during the time period of all-cirrus clouds. These data suggest that, when only contrails and cirrus clouds were over the measurement site, a cooling effect of about -20 to -50 W/m^2 was experienced. So, in the order of ~10% or ~20% of the solar radiation under a clear sky, does not reach the surface. From approximately 12:30UTC the forcing becomes alternately positive and negative with maximums about +15-25 W/m^2 and minimums of almost -60 W/m^2. The relative contributions by direct and diffuse irradiance during this day are plotted in Figure 12. The contribution by direct radiation remains relatively small during the morning hours up to ~10UTC, whereas this would strongly increase in a clear sky situation. This confirms the presence of cirrus in the direct solar beam and this period also coincides with the negative forcing shown in Figure 11. Around the same time that the positive forcing peak occurs at 12:30, direct radiation contributes ~70%, which suggests a minor role for clouds in the direct solar beam.

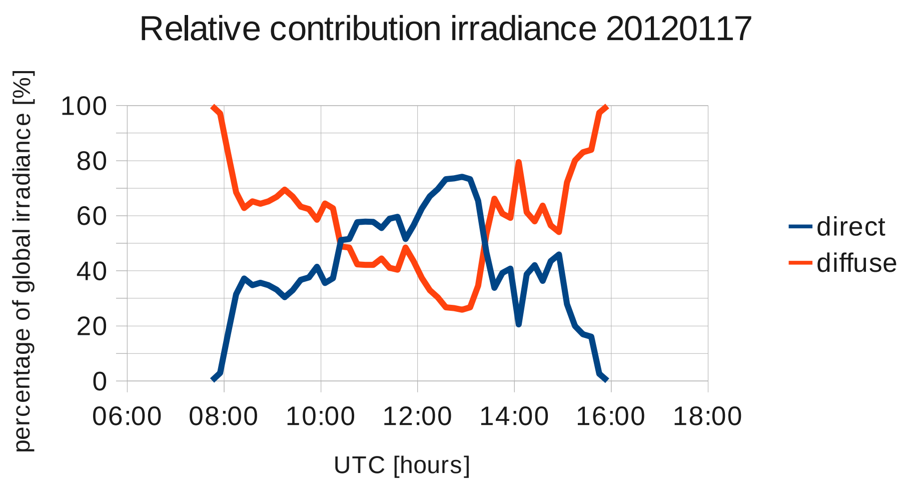

Figure 12. Relative contribution (%) by direct (blue line) and diffuse irradiance (orange line) to the global irradiance during January 17th 2012.

7. CONCLUSIONS AND OUTLOOK

This case study explored a 2-day episode (January 16th and 17th 2012) of intense aviation-induced cloudiness (*AIC*) over The Netherlands. The main objective was to estimate the effect on the short wave global irradiance at the land surface of the Cabauw measurement site. In addition, we looked at satellite data, uv-lidar measurements and radiosonde data to describe this case. *AIC* includes aircraft condensation trails (contrails), contrail-cirrus evolving from contrails and also cirrus formed due to aircraft aerosol emission. During January 16th and the first part of January 17th 2012 *AIC* was, at least, a major part of the total cirrus coverage. Besides that, contrails and cirrus were the only cloud types present during this period. However, it cannot be excluded here that natural cirrus formation would have occurred in the absence of aircraft, or that the cloudiness was a mix of *AIC* and natural cirrus. This has to be concluded for this case study, because of the limited upper-troposphere humidity data that were obtained and the high relative humidity that was observed. Nevertheless, these days gave us the opportunity to assess the potential effect of these clouds on the surface short wave irradiance, assuming cloud coverage to be exclusively due to aircraft operation.

Based on an approach using 'clear sky observations' from January 16th 2005 we found that, at the measurement location of Cabauw, negative radiative forcing values (cooling effect) were typically in the order of -20 W/m^2. These cooling episodes lasted several consecutive hours. A few peaks were observed with values reaching about -50 W/m^2. This would imply that these clouds caused up to about 30% less solar short wave radiation to reach the surface compared to clear sky conditions, thus having a cooling effect. However, these results also showed two periods of positive radiative forcing during January 16th, which lasted up to 2 hours. Maximum values of approximately $+20$ W/m^2 were then reached. This thus suggests the possibility of a heating effect at the surface (compared to clear sky conditions) due to these contrails and cirrus clouds. It is known that for short time periods, under partly cloudy skies, the global irradiance on a small surface at ground-level can be higher than without clouds [*Long* and *Ackerman*, 2000]. This can happen if there are no clouds in the direct solar beam and reflectance from surrounding clouds is high. However, the clear sky estimates used here may be underestimating global irradiance, since atmospheric contents of aerosols, water vapor and e.g. ozone were unknown. It is possible that these contents were significantly higher during January 16th 2005 than during the case study days, causing a difference in atmospheric transparency. If the atmosphere was indeed relatively transparent for solar radiation during the days under study, this means that the cooling effect was actually stronger in reality than estimated here.

For future investigations into the effect of *AIC* on solar surface irradiance it is important to take the most essential (i.e. variable) atmospheric constituents into account, being aerosols, water vapor and possibly ozone. This way the clear sky solar irradiance can be more accurately calculated to estimate the short wave forcing due to *AIC*. For extending this specific case study it would be beneficial to assess these amounts and to tune a radiation model with these data. It can also be recommended to study the upper-troposphere relative humidity in more spatial and temporal detail. This may be done with a model and using radiosondes at different locations, different remote sensing sites, or perhaps satellite observations. Plotting relative humidity spatially and over time allows for better judgment, when trying to answer the question, whether the cirrus is solely *AIC* or also naturally formed cirrus. For future studies it is also recommendable to correlate the calculated radiative forcing to actual cloud coverage, and possibly cloud properties. Such detailed analysis will help to understand the radiative effect of contrails and contrail-cirrus and to improve assessments on the climate impact.

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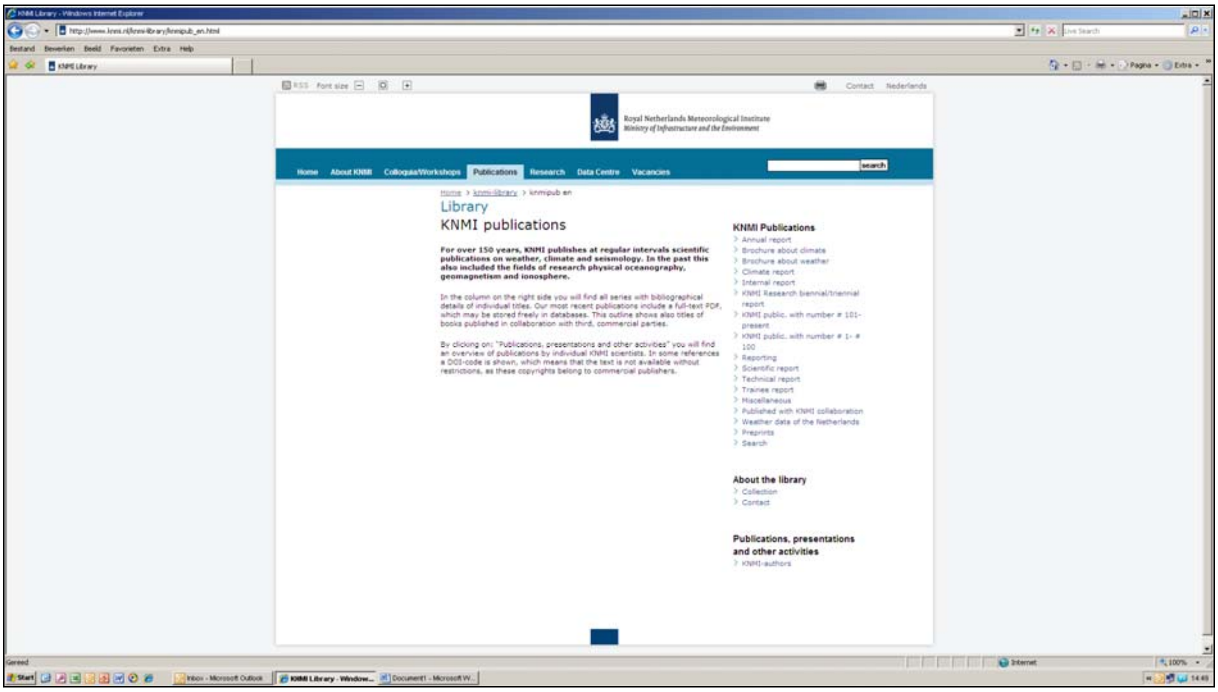

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