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Characteristics and distribution of intense cloud-to-ground flashes in Western Europe

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SUMMARY

This work aimed at analysing the occurrence of Intense Cloud-to-Ground (ICG) in Western Europe, including a large part of maritime areas, defined as lightning flashes exhibiting at least one return stroke peak current larger than 200 kA based on lightning data collected by EUCLID between 2007 and 2016. As expected, the rate of ICG is low in average, about 0.18 % of the total Cloud-to-Ground (CG), but because of a pronounced seasonal trend it can increase up to 1.5% in winter. Around 70% of ICG occurring over the Atlantic Ocean and the Mediterranean Sea are of negative polarity whereas, in around the same proportion, they are positive over the continental regions. The geographical distribution of ICG shows a clear enhancement of ICG occurrences during winter time along coastal areas exhibiting elevated terrain, in northern Spain and western Italy and in Balkans. In these regions ICG are mainly located in land and surprisingly their polarity is negative on the contrary to the general trend stating most ICG are positive on the Continent. The discrepancies observed in the geographical, seasonal and polarity distributions are thought to be related to the different type of thunderstorms occurring across Europe and particularly oceanic and Mediterranean winter and continental deep-convective clouds. Finally, some high-density areas along Italian or Balkan coastlines can reach up to 0.45 ICG/km²/year, both polarities combined.

KEYWORDS

Lightning Locating Systems, Intense Cloud-To-Ground, EUCLID

INTRODUCTION

Among the different lightning parameters used in the field of the Lightning Protection, the return stroke peak current is particularly important. As a result, all standards refer to the lightning peak current distribution which is used to design the earth termination system. These statistics are still based on lightning data derived from direct measurements operated by Berger in the early 70's in Switzerland. However, most of the Lightning Locating Systems (LLS) deployed around the world can collect lightning data on large areas and long periods of time. From these huge datasets, and despite some limitations related to such systems, it is then possible to compute statistics on other lightning parameters and not only that may be used in the traditional quantitative risk management methods, mainly based on global occurrence of Cloud-to-Ground (CG) discharges whatever their polarity or current intensity but also in a complementary qualitative approach considering individual lightning flash parameters such as peak current or seasonality.

Because of the Fukushima power plant disaster, industries presenting a risk for the environment have started to review their risk assessment trying to integrate the effect of the most extreme natural hazards in the calculation. In the field of lightning physics, the question about the maximum return stroke peak current that a lightning flash could produce was raised by engineers. The unpredictable nature of lightning discharges makes direct measurements of these extreme events difficult if not to say practically impossible. Thus, some authors have tried to theoretically evaluate the maximum stroke current based on physical lighting characteristic assumptions and models. Indeed, a theoretical limit of 300 kA for first negative stroke in temperate regions can be found in literature [1]. Considering remote sensing, LLS sensitive to the return stroke discharge are likely to help in collecting and providing data for studies. However, lightning current derived from electromagnetic field remote measurements are subject to some errors, mainly because of the return stroke model used to convert field into current. To assess the peak current estimation error, sensor manufacturers and LLS operators have conducted experiments aiming at comparing direct current measurements and lightning data. Unfortunately, all the different methods present some limitations to calibrate the peak current estimation for positive and first negative stroke therefore no calibration for negative first stroke and positive peak current exists.

This study aimed at characterizing the occurrence of intense cloud-to-ground flashes (ICG) across Western Europe, based on EUCLID network [3]. In this work, an ICG is defined as a cloud-to-ground flash (CG) exhibiting at least one return stroke in excess to an absolute detected value of 200 kA. This value of 200 kA is the limit considered for the design of Lightning Protection Systems according to international lightning protection standards and is also the limit considered for the associated lightning risk analysis. A probability of 1% is given in standards for currents greater than 200 kA and it is considered acceptable to disregard lightning discharges in this upper range of currents although they are regularly observed by LLS

The objective is to provide some insight on the occurrence of such extreme events as they are detected and located by EUCLID. As a result, a climatology of ICG is given completed by high resolution maps showing ICG geographical distributions. The analysis is based on lightning data collected during a 10 years' period, between 2007 and 2016, on an area covering Western Europe, including large maritime regions in the Atlantic Ocean and Mediterranean Sea. The total area is delimited by -11.00 to 19.00 degrees longitude and 35.00 to 56.00 degrees latitude.

THE LIGHTNING DATA

EUCLID is the result of a cooperation among national LLS operators who decided to join their systems in one larger and uniform pan-European network. Since 2001, lightning data have been continuously collected and archived in a database. In 2007, EUCLID was composed of 131 sensors covering Portugal, Spain, Italy, France, Germany, United Kingdom, Benelux, Switzerland, Austria, Scandinavian countries, Slovenia, Czech Republic, Hungary and Poland.

The performances have been extensively analysed over the last decade against ground truth data collected by either direct measurements on the Gaisberg's tower or high speed video and field recording system (VFRS). The resulting Detection Efficiency (DE) was determined to be 97% for flashes containing at least one stroke with a peak current greater than 5 kA and 80% for strokes with peak currents greater than 10kA [3]. The median value of the absolute location Accuracy (LA) was measured at the Gaisberg Tower in 2014 to reach a median value of 90 meters which is consistent with the results obtained at larger scales based on VFRS data [3]. The stroke peak current is estimated from the magnetic field remotely detected by the sensors. The Transmission Line Model (TLM) is used to model the return stroke and convert remote electromagnetic field measurements to lightning current. Because the return stroke velocity used by the model varies from discharge to discharge an error is committed on the peak current calculation. The error is expected to be about 10% according to the manufacturer (rocket triggered lightning data) and findings based on direct measurements at Gaisberg [2].

ICG OCCURRENCES ANALYSIS

During the 10 years' period, EUCLID collected a total of 30779 +ICG and 32790 -ICG respectively corresponding to 0.45% and 0.12% of the total number of +CG and -CG. Globally, ICG account in average for about 0.18% of the total of CG flashes observed in Western Europe. It must be noted, that the total number of observed +ICG and -ICG are so similar by chance, while most of the annual results reveal discrepancies in favour of either positive or negative events. However, ICG occurrences highly depend on the analysed region and particularly when differentiating between continent and sea/ocean. Thus, most of -ICG, about 70% and 63% of them, are found over the Atlantic Ocean and the Mediterranean Sea respectively. On the contrary, almost 70% of the ICG are +ICG when considering continental land areas.

From the previous results, and this it is not a surprise, one can consider that ICG are rare events. However, the monthly distribution of ICG compared to the total of CG (Fig. 1) presents significant variations due to a clear seasonal trend. The proportion of ICG occurrences is much higher during winter than summer which is the main lightning season in Western Europe. Interesting to note, the distributions of +ICG and -ICG exhibit a similar pattern, although the magnitude for the first one is about 2 to 3 times larger than for the second despite the number of occurrences in each dataset is very comparable. This is expected as positive discharges are known to be more intense than negative. When combining both polarities, the monthly percentage of ICG over total observed CG can increase up to 1.5% in January and February which is close to one order of magnitude more than the annual average.

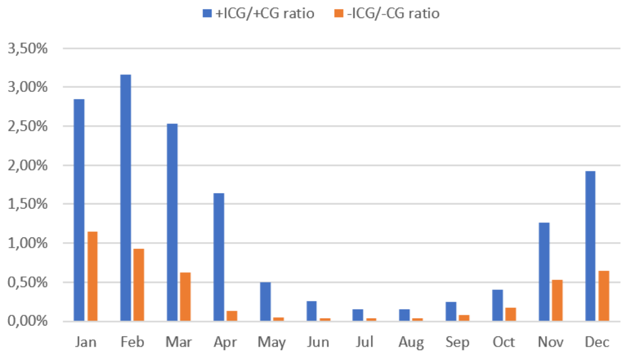

Fig 1- monthly distribution of +ICG/+CG and -ICG/-CG ratios

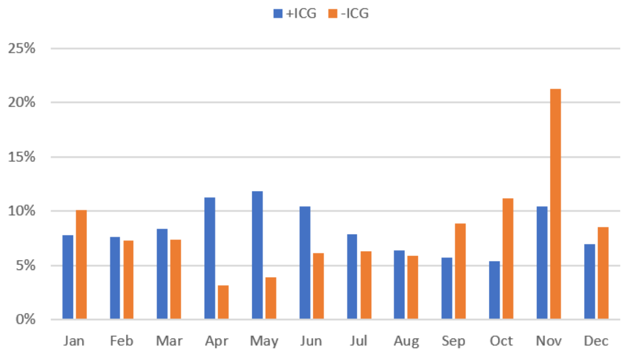

Fig 2 - probability distribution of +ICG and -ICG computed as monthly percentages

The ICG monthly probability distributions (fig. 2) are computed as the percentage of the number of ICG per month compared to the total of ICG in respect to their polarity. The analysis shows that +ICG tend to occur more often during spring time (April to June) whereas -ICG are produced preferably during autumn (October to December) with a large peak in November representing more than 20% of the total -ICG. Interesting to note, +ICG exhibit again a peak in November but with a smaller amplitude. These results, shows that ICG are preferably produced in the periods before summer and winter, which can be explained by different thunderstorms characteristics related to the changing meteorological conditions during these transition periods.

The spatial distributions of ICG are shown in high-resolution maps (Fig. 3 to 6) as a function of the polarity of the current and the season. In this study, winter is defined by a 3 months' period ranging from January to March and summer from July to September. The maps represent the cumulated number of -ICG or +ICG counts on the 10 years' period over Western Europe in 10 x 10 km grid cells. All the maps have the same colour code that ranges from blue to brown, the latter representing a maximum of 9 events per grid cell. Thus, the regions coloured with warmer colours highlight the areas where thunderstorms often produce ICG.

During winter time (Fig. 3 and 5), most of the ICG are concentrated in the southern part of the Gulf of Biscay, the eastern Mediterranean Sea and in a lesser extent in the Channel. When looking more

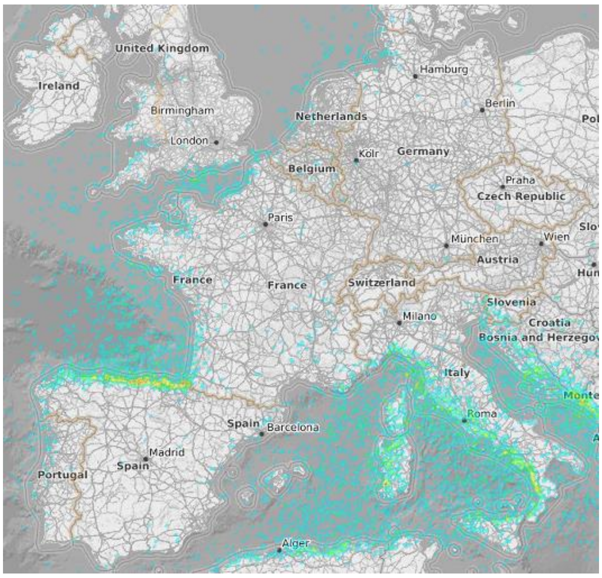

Figure 3- distribution of -ICG counts in winter

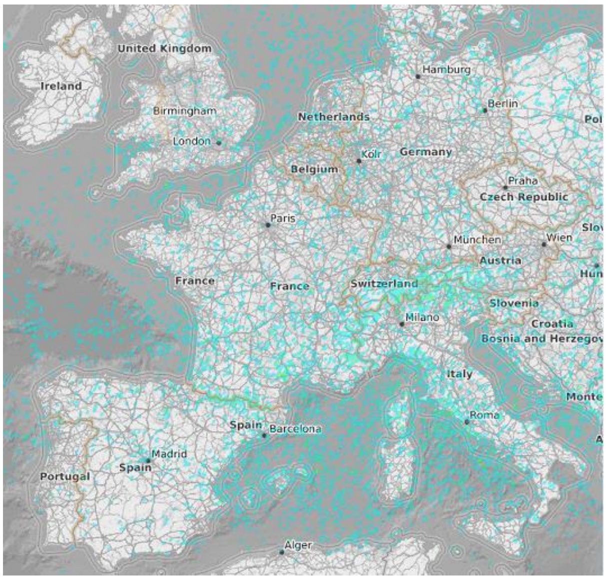

Figure 4 – distribution of -ICG counts in summer

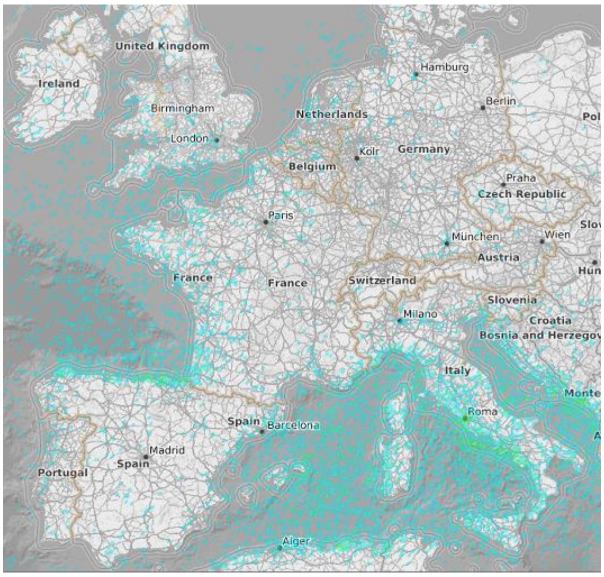

Figure 5- distribution of +ICG counts in winter

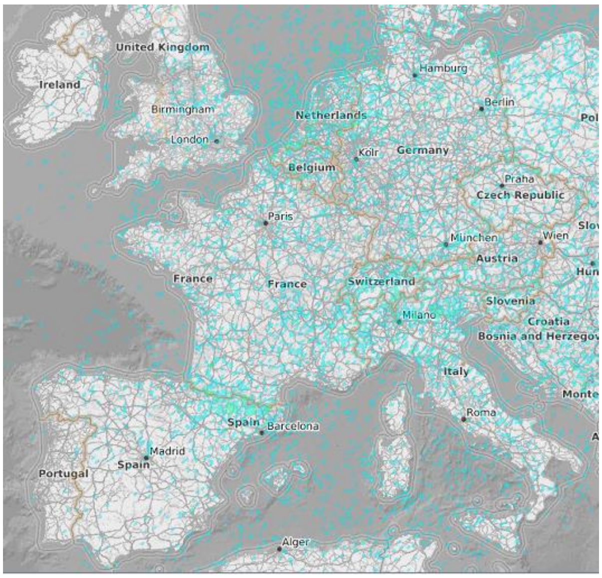

Figure 6 – distribution of +ICG counts in summer

closely at those areas, the maximum of the ICG activity is observed to be located along the coasts presenting a mountainous terrain. On the western Italian and northern Spanish coastlines, more than 90% of ICG are observed during winter and autumn periods. In the Balkans, the monthly probability distribution is more balanced with 75% of ICG produced during winter and autumn and 22% still occurring in spring. These spatial distributions significantly change in summer (fig. 4 and 6) where the ICG occurrences weaken over ocean/sea regions while on the contrary strengthen on the continent. The trend is more pronounced for -ICG as the hotspots clearly visible in winter totally disappear in summer.

The analysis of the areas where high rates of ICG are detected in northern Spain, western Italy and Balkans permits to refine the monthly distributions. It shows (Fig. 7) that the seasonal effect is even more pronounced compared to the general trend observed on all Western Europe (Fig. 1). The proportion of ICG relative to the total CG considerably increases in winter for the northern Spain coastlines reaching up to 9% mostly composed of -ICG. The relatively low amplitude of the Italian and Balkan ratios is not due to a smaller count of ICG but more because of a higher number of CG. This result is interesting as it shows a difference between Atlantic Ocean and Mediterranean regions. The sea surface temperature in winter on the western Mediterranean Sea is in average 2°C hotter than on the Atlantic Ocean, which could lead to a difference in the electrification of the winter thunderstorms.

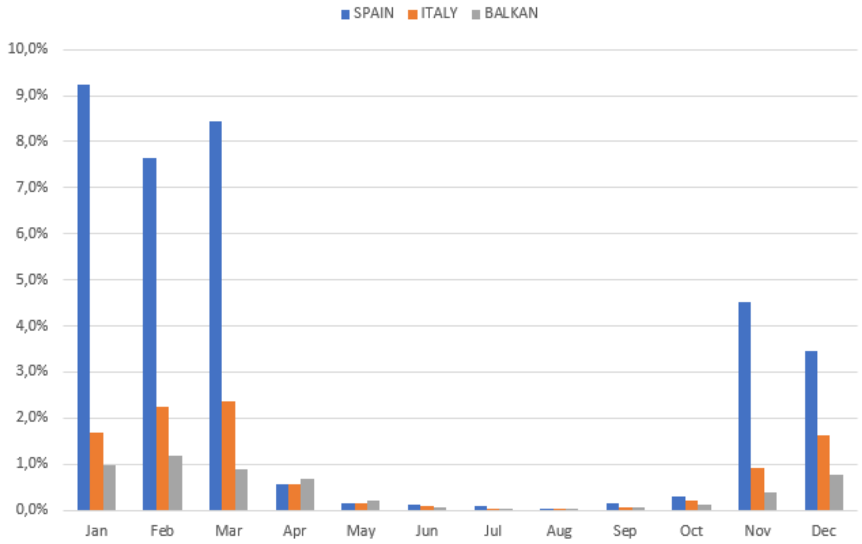

Figure 7 - percentages of ICG (ICG over total CG) in the hotspot regions

The relative low number of ICG occurrences, about an average of 80 to 100 events a year in the most exposed areas should not underestimate the real threat these kind of lightning flashes represent. Indeed, some annual maximum lightning density values can reach values up to 0.45 ICG/km²/year like in the region of Amalfi in Italy and around 0.3 ICG/km²/year in Montenegro, and northern Spain.

DISCUSSION

The limitation of the LLS regarding the return stroke peak current measurements might be an issue in such a study because only negative subsequent return strokes peak currents are calibrated, whereas most of ICG flashes are single stroke flashes. Therefore, considering the absolute value of currents might result in a bias, but this study aimed at comparing different areas in terms of relative quantity to derive percentages of occurrences of discharges exhibiting “large” peak currents regardless of the accuracy of the single measurement.

Several authors have observed that the first negative return stroke in a flash tends to exhibit a much higher peak current when they produce over the oceans than on continental areas [4][5][6][7][8]. Moreover, Füllekrug et al. [9] analysed the magnetic fields from intense lightning discharges at a planetary scale, concluding that most of the intense lightning flashes on planet Earth occur in coastal areas, which is consistent with the findings in this study.

Interestingly, we found out that most of the ICG observations are located during winter with strong enhancement along coastlines presenting elevated terrain. It must be noted, this condition on the topography seems not to be sufficient for producing a high rate of ICG occurrence since coastal regions in Catalonia (Spain) and Cote d'Azur (France) do not exhibit a strong ICG rate whereas they are close to mountains. It is likely that these natural barriers act as obstacles to the propagation of cold air masses forcing an ascending flow and initiating the convection of the warm air present at the surface of the ocean or the sea. During winter, low pressure systems are generally located over UK generating a cold polar air stream moving anticlockwise. This explains why northern Spain and Western Italian/Balkan coastlines are in the wind whereas eastern Catalonian and South French coast are downwind.

It is found that ICG occurring in the sea/land boundaries with high ICG rates are mainly of negative polarity and produced inland. This observation seems in contradiction with the result stating that most of the ICG occurring over the continent, about 70%, are positive. The different characteristics between winter and summer thunderclouds could explain this discrepancy. In summer, thunderstorms are mainly based on deep convection and orographic conditions. Most of them are highly electrified because of the presence of strong updrafts and large quantity of water content. These systems present a stratiform region at the dissipating stage that is mostly composed of positive charges leading to the production of intense +CG. Also, these systems are mostly producing over land compare to oceans because of the big difference of temperature between the ground heated by the sun and the atmosphere. As a result, summer storms could favour the +ICG over land. On the contrary, winter thunderstorms are known generally to exhibit a low altitude base and top height, because the Convective Available Potential Energy (CAPE) is smaller than in summer and the tropopause altitude is lower, around 5-6 km. Finally, it is likely that the sea-salt particles and the large number of marine aerosols observed in maritime clouds [10] play an important role in the cloud electrification process leading to intense negative lightning discharges. It is then possible that the excess of -ICG along the coast results from the electrification of the maritime thunderclouds over the Gulf of Biscay or the Mediterranean Sea.

From a risk analysis perspective, the current distribution in international standards is considered as fixed whatever the place is and whenever lightning discharge occur. It is well known for sensitive facilities, that the local current distribution obtained from LLS should be used to better assess the risk. For example, lightning currents lower than 10 kA can generally be accepted by a lot of metal or concrete structures when current greater than 10 kA can cause big damages. A place that exhibits a lot of lightning current lower than 10 kA (more than is considered in the standard distributions) would probably lead to a lower risk than calculated. On the reverse, a place that exhibits a lot of lightning current higher than 100 kA would probably lead to a much higher risk than calculated and the Lightning Protection System should be designed to mitigate this risk. Seasonality of the lightning current should also be considered in the risk calculation especially for activities that are not permanent all over the year. This is furthermore true for lightning current greater than 200 kA that are not considered at all in standards. For most of the applications the probability associated to such large currents is quite low and the risk can be ignored but for sensitive systems such as explosive areas or for the ultimate safety systems of nuclear plants this stress should be considered and included in the risk calculation based on local current distribution obtained from LLS;

CONCLUSION

The occurrence of ICG, defined as lightning flashes exhibiting at least one return stroke with a peak current greater than 200 kA, was analysed in detail based on EUCLID data collected during a 10 years' period over the western part of Europe. With an average rate (ICG over total CG) of about 0.18%, ICG rarely happen in comparison to the total observed CG.

However, the monthly distribution shows a clear seasonal trend where the percentage of ICG is much higher in winter and autumn than in summer, with a maximum monthly value of 1.5 % in January and February. Interestingly, most of the +ICG occur during springtime whereas the -ICG tend to be produced mostly in autumn. Spatial high-resolution seasonal maps reveal ICG of both polarities tend to occur mostly over the Ocean and the Mediterranean Sea in winter, -ICG being more numerous. In summer, this lightning activity in maritime regions significantly decreases and the lightning activity concentrates more on the continental areas. One can observe some hotspots exhibiting a strong concentration of events along the sea/land boundaries. Those regions exhibit elevated terrain oriented in the prevalent winds, like northern Spain, western Italy and Balkan. Interestingly, most of the ICG observed in those hotspots are over land, but contrary to the general trend they are of negative polarity. The differences between the characteristics of oceanic winter and continental deep-convection thunderstorms in terms of cloud electrification processes are likely to be responsible for the discrepancies between +ICG and -ICG.

Finally, in some local areas in the exposed regions, an ICG lightning density is found to be not negligible, with annual lightning density ranging from 0.3% to 0.45%.

BIBLIOGRAPHY

[1] Cooray V., V. Rakov, On the upper and lower limits of peak current of first return strokes in negative lightning flashes, JGR 2012, doi:10.1016/j.atmosres.2011.06.002

[2] Schulz W., G. Diendorfer: EUCLID network performance and data analysis, 17th International Lightning Detection Conference (ILDC), Tucson, Arizona 2002

[3] Schulz W. et al, The European lightning location system EUCLID – Part 1: Performance analysis and validation Nat. Hazards Earth Syst. Sci., 16, 595–605, 2016, doi:10.5194/nhess-16-595-2016

[4] Cummins, K. L., J. A. Cramer, W. A. Brooks, and E. P. Krider (2005), On the effect of land:sea and other earth surface discontinuities on LLS inferred lightning parameters, VIII International Symposium on Lightning Protection, São Paulo, Brazil.

[5] Orville, R., G. Huffines, W. Burrows, and K. Cummins (2011), The North American lightning detection network (NALDN)-Analysis of flash data: 2001–09, Mon. Weather Rev., 139(5), 1305–1322.

[6] Hutchins, M., R. Holzworth, C. Rodger, and J. Brundell (2012), Farfield power of lightning strokes as measured by the World-Wide Lightning Location Network, J. Atmos. Oceanic Technol., 29(8), 1102– 1110.

[7] Said, R., M. Cohen, and U. Inan (2013), Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations, J. Geophys. Res., 118, 6905–6915, doi:10.1002/jgrd.50508.

[8] Nag, A., and K. L. Cummins (2017), Negative first stroke leader characteristics in cloud-to-ground lightning over land and ocean, Geophys. Res. Lett., 44, doi:10.1002/2016GL072270.

[9] Füllekrug M., C. Price, Y. Yair, and E. R.Williams, Intense oceanic lightning, Annales Geophysicae (2002) 20: 133–137 c European Geophysical Society 2002

[10] Martensson E. M., E. D. Nilsson, G. de Leeuw, L. H. Cohen, H.-C. Hansson, Laboratory simulations and parameterization of the primary marine aerosol production, JGR vol. 108, no. D9, 4297, doi:10.1029/2002JD002263, 2003