Anonymous Referee #1

The authors thank very much the reviewers for their useful comments and remarks. First, a lot of corrections are made to improve the manuscript. All remarks of the reviewers are considered and some necessary changes are made in the sense of these remarks. For example: the definition of winter lightning is included and the criterion of classification revised according to the suggestions of the reviewers.

Below we include the responses to each of all referee's comments:

- Responses to Referee' #1 comments are found from page 1 to page 3.
- Responses to Referee' #2 are found from page 4 to page 14.

After page 14 we include the manuscript with tracking changes.

The paper is the first to discuss the global activity of winter-type lightning as the authors write, and is valuable to the community considering the importance of lightning protection against this type of lightning. It requires some revision, however, e.g. it lacks explanation on the definition of winter lightning, and an important aspect of winter lightning around Japan. It follows specific comments.

Fig. 1 d) does not match the explanation of page 3, 2nd paragraph, where is written that lower positive charge might not be accumulated.

Agree, the figure 1.d) shows low positive charge. It is more consistent to refer in terms of the necessity of charge of opposite polarity below the mid-level charge in order to favor the production of CG. The text is clarified. It is indicated that the reference of Montanyà et al., 2007 is for European winter storms and the case in figure 1d it is already mentioned that the charge structure belongs to the case of Japan.

Fig. 1 e) is wrong. Page 3, 3rd paragraph is explanation of downward positive flash (the cited references are for summer MCS). Fig. 1 e) has to be a cartoon of a downward positive flash.

Thanks for the comment. In figure 1e we only include upward lightning from wind turbines which can be positive flash (upward negative leader). The figure has improved adding a downward positive flash. Figure caption is clarified indicating that both positive upward and downward flashes occurs at the stratirform region of the MCS.

page 3, line 27: This paragraph refers to downward positive flashes, which rarely strike wind turbines or aircrafts in the cold season, too. Upward positive flashes are the threat to wind turbines in winter, and this is a different phenomenon from that explained in this paragraph.

Agreed, the text is clarified according to the comment. We also indicate that downward positive flashes striking close a tall structure can initiate an upward flash.

page 5, Section 3.1.1: Adachi et al. examined sprite-producing storms only. Sugita and Matsui (2008) report on other type of lighting activity in the cold season. They call it "isolated type", producing only a few lightning flashes a day, and is clearly distinguished from JPCZ-type, which is much more active (may correspond to Sugita and Matsui's coastline type). The isolated type may not produce sprites, but contributes significantly to winter thunderstorm days of over 30 around Japan. reference: Akiko Sugita, Michihiro Matsui, "Examples of winter lightning observed by the JLDN", 2008 ILDC/ILMC, Tucson, Arizona, 2008. http://www.vaisala.com/en/events/ildcilmc/Documents/Examples%20of%20Winter%20Lightning%20Observed%20by%20the%20JLDN.PDF

Thanks so much for the reference. We've included it and add the isolated type to the section.

page 5, Section 3.1.2 does not have a reference.

There is no a particular reference dealing specifically with winter thunderstorms in Europe in which the particular meteorology of these storms is described. Perhaps the best descriptions can be found in Estofex (http://www.estofex.org/). We included that reference as well Holley et al. 2014 for northern Europe winter storms.

page 6, Section 3.2, 1st paragraph: Basis is not given to the criterion of winter lightning, "temperatures equal or lower than 5 C at the 900 hPa level". Saito et al. (2012) suggest a boundary of 5.7 km of -10 C level, based on their observation. reference: M. Saito, M. Ishii, F. Fujii, M. Matsui: Seasonal Variation of Frequency of High Current Lightning Discharges Observed by JLDN, IEEJ Trans. P&E, Vol. 132, No. 6, pp. 536-541,b2012.6.

Thanks for the reference. Actually Saito et al., 2012 shows an average temperature of -10 ºC at 2.7 km (~700 hPa) for the classified thunderstorms as winter. We observed the same in Montanyà et al. (2007) in Europe and a recent publication by Warner et al. (2014) for the US.

It is difficult to establish a precise criterion and easy enough to allow the global classification of winter lightning and thunderstorms. Our criterion of temperatures equal or lower than 5 ºC at 900 hPa produce good agreement with the observations indicated in the referenced papers. But we decided to modify the criterion to (700 hPa and -10ºC) in the way to be more consistent with the references of Saito et al. (2012), Montanyà et al. (2007) and Warner et al. (2014). We choose actually, our criterion of winter lightning to be those lightning flashes occurring in cold d airmass thunderstorms. Then a criterion of -10 ºC at 700 hPa is more reasonable in order to identify airmass thunderstorms and not include those storms such as winter squall lines (common in the US) which are associated with warm and stable air above the freezing air. The results obtained are very similar with the previous criterion defined at lower altitude (900 hPa).

The advantages of this new criterion are:

- 700 hPa corresponds to ~3 km where most of the locations of the planet are lower than this altitude. It was the concern of how to use 900 hPa in high altitude regions (from a received personal comment).
- The results of using 700 hPa and -10 ºC or 900 hPa and 5 ºC do not change much qualitatively and quantitatively.
- The use of 700 hPa is more consistent with Saito et al. (2012), Montanyà et al. (2007) and Warner et al. (2014) for three different areas: Japan, Europe and US, respectively.
- The use of -10ºC is also convenient since might be related to the lower altitude of the main negative charge and it is also related to the non-inductive charging mechanisms.

page 6, Chapter 4 and Fig. 5: Tw should be "the number of winter thunderstorm days per year" and not the number of thunderstorms.
Agreed, thanks so much.

Anonymous Referee #2

The paper "Global Distribution of Winter Lightning: a threat to wind turbine and aircraft" provides new analysis of global lightning data, focusing on the distribution of winter thunderstorms, that are known to be threat to aviation and wind turbines. The data analysis approach is novel, as provides a useful comparison of the relative intensity of regions of winter thunderstorms. The quality of the analysis and report suggests that it is of a sufficient standard to be published without major corrections; however the number of minor corrections required is significant. A very high proportion of these are due to language issues, where the point made is acceptable, but the wording requires clarification. Additionally, there are also a number of scientific questions that need to be addressed.

We sincerely thank so much to Referee #2 for the exhaustive and constructive revision of the manuscript. We appreciate it.

- GENERAL COMMENTS

The use of a threshold of 5 C at 900hPa is not sufficiently explained/justified. Why isn't 4 C, or 6 C, appropriate? What is the impact of using different temperature/pressure levels? It may be that this approach has been justified in existing literature, but if this is the case, an appropriate reference would be required.

Same response as to Referee #1:

It is difficult to establish a precise criterion and easy enough to allow the global classification of winter lightning and thunderstorms. Our criterion of temperatures equal or lower than 5 ºC at 900 hPa produce good agreement with the observations indicated in the referenced papers. But we decided to modify the criterion to (700 hPa and -10ºC) in the way to be more consistent with the references of Saito et al. (2012), Montanyà et al. (2007) and Warner et al. (2014). We choose actually, our criterion of winter lightning to be those lightning flashes occurring in cold airmass thunderstorms. Then a criterion of -10 ºC at 700 hPa is more reasonable in order to identify airmass thunderstorms and not include those storms such as winter squall lines (common in the US) which are associated with warm and stable air above the freezing air. The results obtained are very similar with the previous criterion defined at lower altitude (900 hPa).

The advantages of this new criterion are:

- 700 hPa corresponds to ~3 km where most of the locations of the planet are lower than this altitude. It was the concern of how to use 900 hPa in high altitude regions (from a received personal comment).
- The results of using 700 hPa and -10 ºC or 900 hPa and 5 ºC do not change much qualitatively and quantitatively.
- The use of 700 hPa is more consistent with Saito et al. (2012), Montanyà et al. (2007) and Warner et al. (2014) for three different areas: Japan, Europe and US, respectively.
- The use of -10ºC is also convenient since might be related to the lower altitude of the main negative charge and it is also related to the non-inductive charging mechanisms.

The use of these specific criteria also means that thunderstorms at high latitudes in the summer are still classified as "winter" thunderstorms. This can be seen in Figure 4, where lightning in the meteorological summer is classified as winter lightning in North America and northern Asia (bottom left subfigure) and near to the Southern Atlantic and Southern Indian Ocean (top right subfigure). The term is appropriate in general, but this characteristic should be discussed, as it may be that these (technically) summer thunderstorms actually exhibit characteristics similar to winter thunderstorms (i.e. in terms of the heights of charged regions).

Our criteria for winter thunderstorms here is not straightly related to the year's winter season. We do not filter by season. Here our winter thunderstorms are those occurring in cold air masses and as pointed by the reviewer, certainly storms in high latitudes can have this type of thunderstorms in winter. We have clarified that in the introduction and at the beginning of section 3.2 where we introduce the methodology for obtaining the maps.

Although the comparison of the relative intensity of global regions of winter lightning activity is useful, the authors do not provide enough analysis of the global variability in WWLLN detection efficiency (DE).In page 6, line 31, they state that the DE of WWLLN "is considered to be 11%". There will be significant variations in this globally, however, based on sensor distribution. Further to this, Rudlosky and Shea (2013) showed that WWLLN is apparently three times more likely to detect a flash over the ocean than over land, based on comparison with LIS data. (Rudlosky, Scott D., and Dustin T. Shea. "Evaluating WWLLN performance relative to TRMM/LIS." Geophysical Research Letters 40, no. 10 (2013): 2344-2348)

Thanks for the comment. That is an interesting point. WWLLN data provides relative hourly DE and that might be used. Actually, we considered that but two concerns aroused: first the DE is relative, not absolute. Second, if it would be realistic for those winter thunderstorms that produce very few flashes. If i.e. a location with 0.05 relative DE has 1 stroke a simple approach would be to compensate and assume actually 20 strokes. That might be very unrealistic. Areas with low relative DE (e.g 0.05) can have strong influence. We improved the text addressing the reader to the provided references and others that discuss and provide maps of relative DE of WWLLN and the reader can do the judgment for any possible correction with DE.

By the way, this comment is also very interesting in relation to the use of LLS data for risk assessment. Standards such as IEC61400-24 proposes a risk assessment in order to estimate the number of lightning flashes to a wind turbine. There are interesting discussions in the group of IEC related to with standard in order how to compensate DE of LLS data and also how to deal with winter thunderstorms (e.g. March 2015, APL conference).

The figures present the results in units of strokes per square kilometer per year. Is there a reason that WWLLN fixes were not merged into flashes using suitable space/time criteria? This would make the data easier to compare with satellite data (OTD, LIS, or the upcoming GLM and MTG-LI) and other analyses of lightning density, which also generally use flashes.

Thanks for the comment. One reason why we do not group WWLLN detections in to flashes is because the computation would take much longer. The second is that we are not sure about grouping with WWLLN since it uses TOGA technique. Grouping strokes into flashes also requires some good location accuracy if the common criteria of 1 s maximum duration, 500 ms of maximum inter-stroke interval and 10 km between strokes.

The middle paragraph of the Discussion section (Page 7, lines 12-21) seems a little muddled. The authors leap from a one-sentence analysis of one area, to another area, to another. The Mediterranean and New Zealand are mentioned before North America and the North Atlantic, despite the latter experiencing much higher winter lightning densities than the former, based on Figure 3. More context in the text, i.e. peak densities or winter thunderstorms days, would make this section simpler to understand without constantly needing to refer to the figures.

The colour scales used in Figures 4 and 5 could be adjusted to allow for the appreciation of greater detail in regions of stroke densities above 0.2 strokes per square kilometer per year. Large regions of North America, North Atlantic and the North Pacific are simply displayed as block red in Figure 3. The current colour scale between 0.0 and 0.2 could be kept the same, so that 0.2 is still red, but values about that could transition into black/grey/purple, for example. See Anderson and Klugmann (2014) as an example.

We improved the figures using a non-rainbow stile color bar. We substituted the old 'jet' colorbar (rainbow type) for a non-rainbow type (e.g. Matlab 'parula') which can provide a linear representation.
(for more information see: http://www.alecjacobson.com/weblog/?tag=colormap).

There are a large number of specific comments and technical corrections that are simply due to the use of language, but do not prohibit understanding of the topics discussed. References were generally accessible and appropriate for the text, unless otherwise stated in the specific comments.

SPECIFIC COMMENTS

Page 1, line 9: "for new generation of aircraft." does not read well in English.
Suggest "for modern aircraft."
Ok, thanks.

Page 1, line 10: "That is because the use of lightweight of" does not read well in English. Suggest merging with the previous sentence: "for modern aircraft, due to the use of lightweight composite materials."
Done, thanks so much.

Page 1, line 14: "characterized for producing" does not read well in English. Suggest "characterized by a relatively high proportion of"
Done, thanks.

Page 1, line 14: "type" Should be "types"
Done, we appreciate your very detailed review.

Page 1, line 15: “However, up to now
” The however is unnecessary, and “up to”does not read well. Suggest “Until now”
Done, many thanks.

Page 1, line 17: “three maps” Actually, six maps are presented, in three figures.
Done, thanks so much.

Page 1, line 21: “provided here can be used for providing” Double use of forms of the word “provide” does not read well. Further, the information presented in the manuscript is not sufficient for an entire assessment of risk on its own. Suggest “provided here can be used in the development of a”
Done, we appreciate your very detailed review.

Page 1, line 26: “”But, although” Word “But” is not necessary.
Done, many thanks.

Page 1, line 26: “... winter thunderstorms is low” It would read better is this were put in context. Suggest “winter thunderstorms is relatively low compared with summer thunderstorms”
Done, thanks.

Page 2, line 9: “events to airplanes” does not read well in English. Suggest “events involving airplanes” or “events involving lightning connections to airplanes”
Done, thanks so much.

Page 2, line 12: “This phenomena present” Mixes singular and plural, should read“ This phenomena presents”
Agreed.

Page 2, line 13: “under this conditions.” Mixes singular and plural, should read “under these conditions.”
Thanks.

Page 2, line 15: “interactions highlighting the situations related” does not read well in English. Suggest “interactions related”
Thanks so much again.

Page 2, line 15: “That is” does not read well in English. Suggest “This is”
Agreed.

Page 2, line 21: “can receive both downward and initiate upward” The word “both” refers to receiving downward and initiating upward lightning, and so should appear earlier. Suggest “can both receive downward and initiate upward
Done, we appreciate your very detailed review.

Page 2, line 23: “We do that” does not read well in English. Suggest “We do this”
Agreed.

Page 2, line 31: Fig. 1d is referred to in the text before Figs 1b and 1c. It would make sense then to either rearrange this sentence, so Fig. 1d is mentioned after the previous figures, or to rearrange the subfigures in Figure 1 so that what is currently 1d becomes 1b, 1b becomes 1c and 1c becomes 1d.
Fixed.

Page 3, line 1: It has been contested whether IC lightning is technically a “flash” in the same way as CG lightning, as there is not a stepped leader/return stroke structure. I have debated this previously with other scientists, who prefer the term “IC discharge”. The change here is not an absolute necessity, however.

That is an interesting comment. We like more to use the term flash since lightning flashes can produce or not a ground stroke. With the lightning mapping array (e.g one of our references such as van der Velde and Montanyà, 2013) one can see the complexity of lightning flashes. There, the leaders to ground appear as another characteristic of a flash. We use the term lightning flash for all types of lightning and when there is a contact to ground we name it as CG flash and when there is no contact to ground simple IC flash to the entire complex lightning leader activity.

Page 3, line 1: “Upward induced lightning is more likely to occur” It would be useful to clarify whether this refers to absolute numbers of upward induced lightning events or relative numbers. As an arbitrary example, if the relative proportion of events drops by 50%, but the total amount of lightning increases by a factor of 4, the absolute number doubles.
That is a very interesting question and difficult for us to provide quantitative numbers. Observations such as Tom Warner in South Dakota towers most of the upward events are induced by close lightning flashes. We observed similar pattern in Europe for summer and some self-initiated (measurements at our instrumented tower) during winter thunderstorms.

Page 3, line 16: “because of the necessity of” This does not read well in English. Suggest “ because the presence of”
Thanks so much.

Page 3, line 16: “charge region necessary to” This does not read well in English. Suggest “charge region is necessary to”
Agreed.

Page 3, line 29: “turbines belongs to” Mixes singular and plural, should read “turbines belong to”
Thanks so much again.

Page 3, line 30: “raised the interest.” This does not read well in English. Suggest“ has been discussed and investigated.”
Agreed.

Page 4, line 1: “an hour especially when” Suggest inserting a comma, i.e. “an hour, especially when”
Thanks.

Page 8, line 1: “But Japan is” This does not read well in English. Suggest “Japan is”
Agreed.

Page 8, line 2: “lightning but other” This does not read well in English. Suggest“ lightning, as”
Thanks so much again.

Page 8, line 4: “The maps are helpful for risk assessment” This has not been conclusively demonstrated yet. Suggest “The maps may be of use for risk assessment”
Agreed, thanks so much again.

Page 8, line 4: “IEC”. Expand this acronym.
Done.

Page 8, line 5: “turbines can be submitted to” This does not read well in English. Suggest “ turbines can be exposed to”
Agreed, thanks.

Page 8, line 6 “for self-lightning initiation.” This does not read well in English. Suggest “for lightning self-initiation.”
Done, thanks.

Page 8, line 8: “Also high risk locations are those offshore” This does not read well in English. Suggest “Locations at the greatest risk tend to be offshore”
Agreed, thanks.

Page 8, line 9: “the new presence of” This does not read well in English. Suggest“ the installation of ”
Thanks, agreed.

Page 8, line 11: “winter lightning will allow to conduct further.” This does not read well in English. Suggest “winter lightning may be beneficial in conducting”

Agreed, thanks so much.

Page 8, line 12: "on local lightning data and meteorological data." This does not read well in English. Suggest " on local combined lightning and meteorological data."

Agreed, many thanks.

Page 9, lines 21-23: Montanyà el al. (2011) reference not generally available online.

This is a conference reference that we can provide under request.

Page 9, line 29: Murooka (1992) reference not accessible unless via web page in Japanese.

Agree, a summary of the observations of Murooka (1992) can be found in other papers and books (e.g. Lightning protection of aircraft, by Franklin A. Fisher, J. Anderson Plumer, Rodney A. Perala).

Page 10, line 21-22: Wang and Takagi (2011) not generally available online.

ICAE conference papers can be easily obtained by request to the secretary of the ICAE: http://icae.jp/

Figure 1: Subfigures 1a and 1b imply that the CG lightning is initiated from the small positively charged region at the base of the cloud. Assuming these figures represent negative CG lightning, it would be better if the branching of the lightning were to extend further into the negatively charged region, and were to spread out within that region (Montanya et al. 2014a, Figure 3 demonstrates the extent of a CG flash within a cloud nicely).

The sketch has been adapted according the reviewer's suggestion. The initiation is between the positively and negatively charged regions and we included some branches extended into the negatively charged region.

Figure 1, caption: Remove "(Case of Japan)", this does not make sense.

This text is clarified. It is substituted by: "charge distribution as observed winter storms in Japan" since the plotted electric charge structure corresponds to the winter thunderstorms in Japan which are characterized by the production of positive CG flashes. That might be not the same case for other regions like in Europe where most of the lightning flashes in winter storms are negative.

Figure 1, caption: "Proportions are not meet in the representations." This does not read well in English. Suggest "Proportions in these diagrams are not to scale."

Done, thanks.

Figures 3-5: The font within the figures is slightly too small, and difficult to read. The coastlines and edges of the plots are also very fine. It may be that the figures were created at one size, then had to be scaled down to fit the page. It would be preferable to scale down the original image, so that when it is reproduced in print, the text and edge lines appear less fine.

The figures have been improved according to this comment.

Figure 4: I have a suspicion that the values of the flash densities in this figure are wrong. If flash densities across North America/Japan are well in excess of 0.2 flashes per square kilometer per year annually, and there are seasons where the values are well below this level, there must be seasons where the flash density is significantly greater than the annual average. Looking at the peak densities in Figure 4, this is not the case. What I suspect has happened is that the number of flashes per grid box have only been divided by the area, to give units of flashes per square kilometer per season. In fact they must then be divided by the number of days in the year and multiplied be the number of days in the season to convert the units to flashes per square kilometer per year. This means that all of the densities are too low by a factor of four.

Thanks for the comment. The values in Fig. 4 are calculated for each grid box as the number of strokes divided by the area and averaged for the 5 year period. In such case, for a particular grid box, the addition of the four values sums the density in Fig 3. That is clarified in the text. We see the reviewer's point and agree that we should take into account for calculating the density the period of three months instead and entire year. However, we prefer to keep as we calculated in order to keep the addition of the four periods as the total annual density. We have indicated and clarified now this in the text and in the caption.

Figure 4: Subfigure titles contain "900 05": Presumably these are the temperature height and cut-off settings for the data. These would preferably be removed.

These labels have been removed. Thanks.

Figure 4: The details in the maps are hard to see in this plot. There are two options that would improve this situation. One would be to use a single large, narrow colorbar to the right of all four figures, as the same scale is used in each, and the amount of whitespace could also be reduced, to make better use of the available space. Alternatively, the maps could be rotated by 90 degrees to fill a page sideways, which would allow for a lot more detail to be visible.

The figures have been improved according to this comment. The text fonts are enlarged. As indicated before, we substituted the 'jet' colorbar (rainbow type) for a non-rainbow type (e.g. Matlab 'parula') which can provide a linear representation (for more information see: http://www.alecjacobson.com/weblog/?tag=colormap).

- TECHNICAL CORRECTIONS

We sincerely appreciate the very detailed review and the time dedicated to improve our paper. We have adopted all the following suggestions.

- **Page 1, line 24: “et al.,2015” should include a space after of comma, i.e. “et al., 2015”.**
- **Page 1, line 24: “Anderson and D. Klugmann” should not include initial, i.e. “Anderson and Klugmann”.**
- **Page 1, line 25: “Poleman” should be spelt “Poelman”.**
- **Page 1, line 29: “(Montanyà et al., 2014)”. There are two Montanyà et al papers in**
- **2014, this reference presumably refers to Montanyà et al., 2014a?**
- **Page 1, line 29: “Honjo, 2014”. Wrong year, should read “Honjo, 2015”.**
- **Page 2, line 10: “Wilkinson et al., (2009) concluded” Comma should be removed.**
- **Page 2, line 10: “Wilkinson et al., (2009) concluded” Incorrect year: should be 2013.**
- **Page 3, line 31: Missing caron and acute from name of author: Radicevic should read “Radicevic”.**
- **Page 3, line 33: “Recently Montanyà et al. (2008) ”No such reference: suggest Montanyà et al. (2014a).**
- **Page 3, line 34: “Fig. 1 f”. Space between figure number and subfigure letter should be removed.**
- **Page 4, line 4: “Fig. 1b” should refer to “Fig. 1d”.**
- **Page 4, line 8: “Fig. e and d” should refer to “Fig. 1e and 1f”.**
- **Page 4, lines 9-10: “Montanyà et al. (2014)”. There are two Montanyà et al papers in 2014, this reference presumably refers to Montanyà et al. (2014a)?**
- **Page 4, line 11: “Lightning” misspelled as “Lighnting”.**
- **Page 5, line 16: “mid winter” should be “mid-winter”.**
- **Page 5, line 25: “were” should be “where”.**
- **Page 5, line 27: “artic” should be “Arctic”.**
- **Page 5, line 27: “Holle and Watson, 1992”. Wrong year, should read “Holle and Watson, 1996”.**
- **Page 7, line 1: “Fig. 2 and 3” should be “Fig. 3 and 4”.**
- **Page 7, line 25: Missing closing parenthesis.**
- **Page 8, line 19: Page numbers not needed in Abarca et al. (2010) reference.**

- **Page 8, line 22: Reference requires full title of paper: “A European lightning density analysis using 5 years of ATDnet data”**
- **Page 8, line 23: Incorrect year in Anderson and Klugmann (2013) reference: should be 2014.**
- **Page 8, line 26: Missing “and” between second to last and last author.**
- **Page 8, line 33: Incorrect year in Holle and Watson (1992) reference: should be 1996.**
- **Page 9, line 6: Page numbers not needed in Hutchins et al. (2012) reference.**
- **Page 9, line 25: Missing space in journal title: “Res.Atmos.” should read “Res. Atmos.”**
- **Page 9, line 30: Reference requires full title of paper: “The European lightning location system EUCLID – Part 2: Observations”**
- **Page 10, line 1: Missing caron and acute from name of author: Radicevic should read“Radicevic”.**
- **Page 10, line 1: Missing space after colon: “Badea, I:Impact” should be “Badea, I:Impact”**
- **Page 10, line 10: Incorrect page range: “2653-2673” should be “2653-2674”.**
- **Page 10, line 29: Missing space and full stop in author’s name: “Williams, E.R,” should be “Williams, E.R.,”**
- **Page 10, line 34: Missing indent at start of line.**
- **Figure 2: Caption reads “artic”, should read “Antarctic”.**

Global Distribution of Winter Lightning: a threat to wind turbines and aircraft

J. Montanyà[1], F. Fabró[1], O. van der Velde[1], V. March[2], E. R. Williams[3], N. Pineda[4], D. Romero[1], G. Solà[1] and M. Freijo[1]

[1]Department of Electrical Engineering, Universitat Politècnica de Catalunya, Terrassa (Barcelona), 08222, Spain
[2]Gamesa Innovation & Technology, Sarriguren, (Navarra), Spain
[3]Massachusetts Institute of Technology, Cambridge, MA, USA
[4]Meteorological Service of Catalonia, Barcelona, Spain

Correspondence to: J. Montanyà (montanya@ee.upc.edu)

Abstract. Lightning is one of the major threats to multi-megawatt wind turbines and a concern for ~~new~~ modern~~generation of~~ aircraft, due to~~. That is because~~ the use of lightweight ~~of some~~ composite materials. Both wind turbines and aircraft can initiate lightning and very favourable conditions for lightning initiation occur in winter thunderstorms. Moreover, winter thunderstorms are characterized by a relatively high production of ~~for producing~~ very energetic lightning. The paper reviews the different types of lightning interactions and summarizes the well-known winter thunderstorm areas. ~~However, up to~~Until now comprehensive maps of global distribution of winter lightning prevalence to be used for risk assessment have been unavailable. In this paper we present the global winter lightning activity for a period of 5 years. Using lightning location data and meteorological re-analysis data, ~~three~~ six maps are created: annual winter lightning stroke density, seasonal variation of the winter lightning and the annual number of winter thunderstorm days. In the northern hemisphere, the maps confirmed Japan to be one of the most active regions but other areas such as the Mediterranean and the US are active as well. In the southern hemisphere, Uruguay and surrounding area, the southwestern Indian Ocean and the Tasman Sea ~~In the southern hemisphere, Argentina and New Zealand~~ experience the highest activity. The maps provided here can be used ~~for providing~~in the development of a risk assessment.

1 Introduction

Storms and lightning differ from one geographic area to another. In Europe, lightning activity is concentrated during the "warm season" since it is related to solar heating and availability of atmospheric water vapour (e.g. Poelman et al., 2015; Anderson and ~~D.~~ Klugmann, 2013). Poel~~e~~man et al. (2015) found that winter months account only for 3 % of the annual lightning in Europe. A~~But, a~~lthough globally lightning activity associated to winter thunderstorms is relatively low compared ~~,~~ with summer thunderstorms these storms can produce very energetic lightning events and a large amount of damage (e.g. Yokoyama et al., 2014). Moreover, winter storms present the most favourable conditions for the initiation of upward lightning flashes from sensitive tall structures such as wind turbines (e.g. Montanyà et al., 2014a) and for flying aircraft (e.g. Wilkinson et al., 2013). A recent study by Honjo (2015~~4~~) ~~o~~of a sample of 506 lightning currents to wind turbines in Japan concludes that winter lightning currents tend to feature longer duration currents, often bipolar, and that some particular wind turbines can be struck by lightning repeatedly in short periods of time. From the data, in about 5 % of the cases the charge transferred by lightning exceeded 300 C. Wang and Takagi (2011) analysed a sample of 100 records and summarized that 67.6 % of the cases presented negative polarity, 5.9 % presented positive polarity and 26.5 % presented bipolar currents. In that study they also found that about a 50 % of the cases were self-initiated by the wind turbine and approximately the same percentage of flashes were initiated by other lightning activity. The authors noted that active thunderstorms produced more induced lightning than those storms with lower lightning activity. Additionally Wang and Takagi (2011) noted that strong wind conditions common in winter storms may favour upward lightning initiation.

Regarding aircraft, Murooka (1992) showed how lightning strikes to airplanes typically occur at lower altitudes during winter compared to summer. Gough et al. (2009) identified that 40 % of the studied lightning events involving~~to~~ airplanes occurred during the “cold season” which is not the period of the most frequent thunderstorm activity. Moreover, Wilkinson et al. (2013~~09~~) concluded that because the lightning strike rate to helicopters at the North Sea during winter was much higher than expected, the presence of a helicopter actually triggers lightning. This phenomena presents a significant safety risk to helicopters doing operations under these~~is~~ conditions.

The main goal of this paper is to present a global map of winter lightning occurring in cold airmass thunderstorms (our criterion is < -10°C at 700 hPa). ~~The main goal of this paper is to present a global map of winter lightning. First~~, we summarize the lightning interactions ~~highlighting the situations~~ related to winter storms. This~~at~~ is an important aspect which can vary according to the climatology of the thunderstorms for a particular area. Second, a global overview of winter storms is presented as well the resulting lightning maps that have been computed from global lightning data. These maps will provide a tool to identify risk areas of winter lightning when performing risk assessment.

2 Lightning interactions

Risk assessment can only be done effectively with a complete understanding of the interactions between lightning and the struck object. Wind turbines are tall structures and in this way can both receive ~~both~~ downward and initiate upward lightning. In the case of an aircraft lightning is initiated in a bidirectional way (positive and negative leaders) from itself when flying in or beneath a thunderstorm. In this section we review the types of lightning related to wind turbines and aircraft. We do this~~at~~ because the mechanisms of lightning interaction with wind turbines and aircraft can differ from winter thunderstorms to summer storms (storms associated with deeper convection).

First of all, downward lightning to wind turbines (Fig. 1a) can be more common in relation to deep convective situations (e.g. summer storms in the northern hemisphere and tropical storms). Downward lightning is the most frequent type of lightning and is also a threat to wind turbines and aircraft. The number of downward lightning events to a particular wind turbine will depend on the exposure of the turbine and the regional ground flash density.

In the case of upward lightning two situations are distinguished regarding the triggering of an upward leader from the turbine: induced (Fig. 1b and 1c) and ~~.~~self-initiated (Fig. 1d). ~~and induced (Fig. 1b and 1c).~~ We use the term induced lightning when it is related to the occurrence of another lightning flash which does not strike the turbine. In the case of induced upward flashes, a nearby CG flash or an IC flash can provide the conditions for the inception of an upward leader. Upward induced lightning is more likely to occur during warm season storms because the high occurrence of lightning. Fig. 1b and 1c depict that situation. Under a thunderstorm, due to the intense electric fields produced by cloud charges, wind turbines can produce corona discharges. By means of corona, electric space charge is produced (positive for a typical dipole or tripolar charge structure as discussed Williams, 1989). As indicated by Montanyà et al. (2014a) this space charge screens the electric field at the turbine tip thereby preventing the initiation of a leader. In order to produce a stable leader, the field needs to increase at the tip of turbine (Bazelyan and Raizer, 1998). This increase of the electric field can be produced thanks to the fast neutralization of charge produced in a CG (e.g. Warner et al., 2012 and Montanyà et al., 2014b) or an IC flash. Because of the slow ion mobility of the space charge at the tip of the turbine, the electric field is not screened and it is increased. In the case of wind turbines, the most favorable conditions for induced triggered lightning will be the case of a fast and large charge neutralization in nearby CG and IC flashes and with enhanced electric fields due to the terrain height (close to the cloud charge) and orography (e.g. on mountain peaks).

A more favourable situation for self-initiated upward lightning is present in winter thunderstorms (Fig 1d). Resulting from the dependence of the electrification processes on temperature (e.g. Takahashi, 1984 and Saunders et al., 2006), in winter the cloud charges are located closer to the ground. But, even with the lower height of the cloud charges, winter storms are not prolific generators of downward lightning (Michimoto, 1993; López et al., 2012, Bech et al., 2013 and Hunter et al., 2001). That might be explained because of the presence~~of the necessity~~ of opposite polarity charge under the mid-level~~ain negative~~ charge region is necessary to initiate a leader in the cloud (Krehbiel et al., 2008). In the case of winter storms in Europe, Montanyà et al. (2007) showed that, because the low altitude of the freezing level (even at ground), the lower positive charge center in the cloud might not be accumulated and then downward lightning may not be initiated. But prominent objects on the ground or at mountain tops have favourable conditions to initiate an upward leader (e.g. Warner et al., 2014).

Another special situation characterized by energetic lightning is produced in relation to the stratiform regions of Mesoscale Convective Systems (MCS) (Fig. 1e). MCS are also common in winter storm structures (e.g. Mediterranean storms). MCS can present a higher percentage of positive CG lightning activity and higher peak currents than produced by cellular summer storms (e.g. MacGorman and Morgenstern, 1998). It is well known that intense +CG flashes occur in the stratiform regions of MCSs which also excite sprites in the mesosphere (e.g. Lyons, 1996; Williams et al., 2010; van der Velde et al., 2010 and Montanyà et al., 2011). These intense positive CG flashes can transfer hundreds of Coulombs of charge with continuing currents lasting up to tens of milliseconds (e.g. Li et al., 2008). ~~which makes them~~Although downward positive flashes to wind turbines or aircraft are not common, these can induce the inception of upward flashes.~~ a major threat to wind turbine and aircraft. ~~However there is significant variation from one MCS to another.

Since most of the winter lightning strikes to turbines belong~~s~~ to the upward lightning type (Honjo, 2015), the effect of rotation on the enhancement of lightning inception ~~raised the interest~~has been discussed and investigated (e.g. Rachidi et al., 2008, Wang et al, 2008, Montanyà et al., 2014a and Radičević~~Radicevic~~ et al., 2012). However, there is no clear evidence that the number of lightning flashes increases significantly with the effect of rotation. In the studies by Wang et al. (2008) and Wang and Takagi (2011) in Japan the authors noted slightly larger number of strikes to rotating wind turbines than to a nearby protecting tall tower. Recently Montanyà et al. (2014~~08~~a) showed corona/leader activity associated with rotating wind turbines (Fig. 1~~-~~f). This activity can last for more than an hour, especially when the turbines are under an electrically charged stratiform region. This activity, even if it may not result in a complete lightning flash, can stress the dielectric properties of blades and needs to be considered in lightning protection standards.

In the case of aircraft, Fig. 1d~~b~~ would correspond to those cases of encounters between aircraft and lightning or the cases of lightning initiated by the aircraft. There is no information about the occurrence of lightning that is initiated by the aircraft but induced by another lightning flash (Fig 1b and 1c). Initiation by aircraft can be more efficient when thundercloud charges are closer to the ground and charge may be larger because of less frequent discharging by lightning. That is the case of winter thunderstorms (Fig. 1d) and also the conditions under stratiform regions of MCS (Fig. 1e and 1f~~d~~.). Regarding the situation in Fig. 1e also happens to aircraft where continuous corona discharges without resulting in lightning occurs. Montanyà et al. (2014a) showed an example.

3 Winter thunderstorms and global winter ~~lighnting~~lightning

3.1 Meteorology of winter thunderstorm areas

Thunderstorms develop as convective clouds to altitudes where it is cold enough for graupel and ice crystals to form and separate, creating layers of opposite cloud charges. Their development depends on the presence of conditional stability, with temperatures decreasing with height over a large depth of the troposphere (steep lapse rates) while the boundary layer must contain sufficient amounts of water vapor whose latent energy is released in ascending parcels, causing positive buoyancy (see Wallace and Hobbs, 2006). In summer, water vapor is supplied by large evapotranspiration while diurnal heating is strong enough over land to create the needed vertical temperature gradients, often with help from the dynamics within low pressure systems. Convergence and ascending air near the surface is required to carry parcels to their level of free convection.

In the winter period, diurnal heating is weak and moisture content is much reduced over land. Low pressure systems are more vigorous and bring cold airmasses from polar and arctic regions southward to mid-latitudes, creating strong vertical temperature gradients as cold continental air flows over relatively warm seas and ocean currents. Air parcels near the surface then experience no inhibiting warm layers on their way to the equilibrium level, often the tropopause, and occur over large regions over sea behind cold fronts. The tropopause is found between 10-15 km at mid-latitudes in summer, but can descend to 5-10 km in winter, limiting the vertical extent of convection. Just as in summer, low-level convergent winds organize the triggering of storms, but over sea these are often found near upwind coastlines, where enhanced friction and sloping terrain creates a relative stagnation and ascending flow.

3.1.1 Japan

In the northern hemisphere a well-known area of winter storms is found in Japan. There, three types of winter thunderstorms are identified in Adachi et al. (2005): thunderstorms associated with cold fronts crossing the Sea of Japan; thunderstorms systems originating in low-pressure areas over the Pacific Ocean; and thunderstorms originating in the Japan Sea Polar Air Mass Convergence Zone (JPCZ). The storms originating in the JPCZ are due to advection of dry and cold air masses from the Eurasian continent. The interaction of these cold and dry air masses over the Sea of Japan leads to increases in the water vapor content by evaporation. Arriving on the Japan mainland, convergence with horizontal winds due to topographic effects produces strong updrafts supporting the formation of thunderstorms. A fourth type of winter thunderstorms is described by Sugita and Matsui (2008). This type corresponds to isolated storms, which might have significant contribution to the number of winter thunderstorm days. Winter storms in Japan are known for the high occurrence of positive lightning compared to negative and bipolar lightning (e.g. Wu et al., 2014). This situation results in energetic lightning in terms of total charge transfer and the numerous damages to wind turbines (Yokoyama et al., 2014 and Honjo, 2015).

3.1.2 Europe

In Europe, the prevailing Icelandic low and the Azores high pressure systems can produce intense low-pressure systems developing over the warm Gulf Stream (e. g. Holley et al., 2014). The largest amplitude systems transport cold unstable arctic airmasses into Western Europe at their rear side and often stagnate in the area of the Mediterranean Sea, forming Genoa lows with a high activity of fall/winter thunderstorms. In mid-winter, stable cold continental airmasses over Central Europe via the Balkans and France may also slide into the Mediterranean and produce shallow winter thunderstorms over the prevalent warm water there. Estofex (http://www.estofex.org/) provides a comprehensive archive of thunderstorms including winter.

3.1.3 North America

In the United States, large winter depressions develop over the Gulf Stream and move north along the eastern coast (e.g. Dirks et al., 1988) before reaching Canada. The energy to feed these storms originates in the air-sea interaction from the warm Gulf Stream water and baroclinic instability within the cold airmass over the continent. Blizzards form over the northeastern US and thunderstorms are produced as the cold front and cold continental airmasses flow out over the Great Lakes (with lake effect snow) and the warm Gulf Stream, where the cold front collides with warm subtropical air, producing linear thunderstorm systems. The west coast of the continent experiences similar conditions as western Europe, with cold unstable maritime airmasses reaching mainly the shores of western Canada where lifting by the Rocky Mountains can initiate electrified convection.

Another cause of winter storms in Canada and the central US are outbreaks of A~~a~~rtic fronts (e.g. Holle and Watson, 1996~~2~~) in which cold A~~a~~rtic air masses move from north to south, meeting warm humid air from the Gulf of Mexico. Along these cold fronts thunderstorms are formed in the warm elevated layer producing frozen precipitation at the surface.

3.1.4 General effect of ocean gyres

Every major ocean basin (North Atlantic, North Pacific, South Atlantic, South Pacific etc) contains a basin-scale rotating current flow—a gyre—with clockwise (counterclockwise) rotation in the northern (southern) hemisphere (Fig. 2). The primary drive for these gyres is the zonal wind stress from prevailing easterly winds in the tropics—otherwise known as the trade winds. In this near-equatorial portion of the gyre, the ocean surface is warmed substantially by sunlight and at the western limit of this equatorial transit, this warm oceanic flow is diverted northward and southward, depending on hemisphere. Since the surface air over continents is increasingly colder away from the equator and tends to be moving eastward off the continents at mid-latitude, one has a consistent situation in all gyres that warm ocean water in this poleward current is found beneath colder air away from the equator. This configuration is inherently unstable and can produce vigorous atmospheric convection and thunderstorm activity. The Gulf Stream along the North American coast and the Kuroshio Current along the eastern coast of Asia (China, Japan, Korea and Russia) are prime examples in which lightning activity over warm ocean water is prevalent during winter. In contrast, the return current on the eastern boundaries of oceanic gyres, and moving equatorward, is colder than the air overlying it. This situation is stable against convection and lightning is absent. A prime example is the Eastern Pacific Ocean. Similar behavior is present in the gyres of the southern hemisphere.

3.2 Global maps of winter lightning

In this section, we present maps of global winter thunderstorms that are useful for risk assessment. As already mentioned at the introduction, we will refer as winter thunderstorms to those thunderstorms occurring in cold air masses and not necessarily occur in the corresponding winter season. In order to process the maps we used a simple criterion to define winter lightning conditions: temperatures equal or lower than -10°C at the 700 hPa level (~3 km above mean sea level). This criterion matches with the observations by Montanyà et al. (2007), Saito et al. (2012) and Warner et al. (2014) for the analysed winter flashes and thunderstorms.~~In this section we present maps of global winter thunderstorms that are useful for risk assessment. In order to process the maps we used a simple criterion to define winter lightning conditions. The criterion to classify a lightning stroke as winter lightning is if it occurred in meteorological conditions with temperatures equal or lower than 5°C at the 900 hPa level (about 1 km above mean sea level).~~ Temperature data at this pressure level is obtained on a 1°×1° grid from ECMWF Re-Analysis (ERA-Interim). Global lightning data were provided by the World Wide Lightning Location Network (WWLLN) (Rodger et al., 2006). The period of analysis correspond to five years (2009-2013). The results are presented in three maps:

average annual stroke density, seasonal variation of the lightning stroke density and average number of winter thunderstorms per year.

Fig. 3 displays the global winter lightning distribution. The maximum annual stroke density was found to be no higher than 0.5~~8~~ strokes·km^{-2}·year^{-1}, in order to present a more clear map, Fig. 3 has been limited to 0.2 strokes·km^{-2}·year^{-1}.

The map in Fig. 3 clearly shows the previously discussed areas of winter lightning (Japan, east of US, Mediterranean) and other areas with wind farms such as ~~northeastern Argentina~~Uruguay and surroundings, southwest of the Indian Ocean ~~southeastern Australia~~and Tasmanian Sea~~ and western New Zealand~~. Fig. 4 plots the seasonal variation of the global winter lightning activity.~~ ~~In this case, each grid cell corresponds to the five-year average value of the number of strokes divided by the cell area for the corresponding period. ~~as stroke density~~.

The average stroke densities shown in the maps in Fig. 3 and 4 are influenced by the detection efficiency of the WWLLN. As any long range VLF lightning location system, WWLLN has a detection efficiency for each location that changes during the hours of the day due to VLF wave propagation, and also during time due to network upgrades, sensitivity of the sensors and data processing methods. The estimated overall stroke detection efficiency of WWLLN is considered to be 11 % according to Hutchins et al., 2012, Abarca et al. (2010) and Rodger et al (2009). Although the relative detection efficiency is provided periodically, we did not apply any compensation. For further information relative to the detection efficiency, see Hutchins et al. (2012). ~~ ~~Moreover, the WWLLN makes no distinction between cloud-to-ground flashes and intra-cloud flashes. Then, the results presented in Fig. 3~~2~~ and 4~~3~~ are relative to WWLLN detections and cannot be adopted as absolute values.

Probably the most useful metric for evaluation of the winter lightning risk is the average number of winter thunderstorm days per year (T_w). Here T_w is obtained in a 1°×1° grid. A winter thunderstorm day in a grid cell is counted if at least one lightning stroke agreeing with the presented temperature-pressure level criterion is detected within the cell. The T_w map is depicted in Fig. 5.

4 Discussion

Areas of winter lightning are well defined outside the ITCZ. The resulting maps show that contrary to what occurs with deep convective storms, winter lightning activity is more distributed over the oceans than over continental areas. One of the reasons is the role that warm oceanic water plays to produce energy for convection during cold seasons. In Fig. 2 we resumed the main oceanic current gyres. Note how this simple picture goes a long way in explaining the patterns of winter lightning in Fig. 3 and 5. The preference for oceanic and coastal areas is an important aspect for coastal onshore and offshore wind farms.

Regarding winter thunderstorm activity and risk assessment, the maps indicate some particular areas more critical to winter lightning because of prevalence in larger areas onshore in proximity to active ocean areas. The Japan mainland is surrounded by winter thunderstorms, the map in Fig. 5 shows how especially the west coast is particularly active reaching in some areas about ~~30 ~~24 days of winter thunderstorms per year. Another particularly active region that affects extensive onshore areas is found in the Mediterranean Sea (e.g. South Italy and the Balkans).~~ and in New Zealand~~. In the case of North America, the highest number of annual winter thunderstorm days per year is located in the Atlantic Ocean. Although the central eastern regions of the US (Great Lakes) the number of winter thunderstorms per year are not so high, the lightning stroke densities are significant. Other areas sensitive to winter thunderstorms because present installations and also ongoing offshore farms, range from the northern coast of Spain, western coast of France, and the European coast in the North Sea. In addition, ~~northeastern Argentina~~Uruguay and its surroundings, ~~and southern Australia~~southern New Zealand, southern west coast of Chile and Southeast Alaska ~~-~~must be highlighted as well.

For risk assessment it is convenient to consider the T_w provided in Fig. 5 as the first indicator of risk to winter lightning activity. In addition to identification of winter thunderstorm areas, the seasonal variation of the winter lighting activity (Fig. 4) is another aspect deserving attention for planning purposes, for equipment maintenance or to setup lightning warnings (e.g. European standard EN 50536, ~~(~~2011~~)~~). That is also important when working with tall cranes. In the northern hemisphere the activity is concentrated from October to June whereas in the southern hemisphere the activity if significant from April to September.

5 Conclusions

Winter lightning poses a critical risk to tall objects such as wind turbines and also to flying aircraft because these have favourable conditions for self-lightning initiation. In this paper we presented for the first time world maps with winter lightning activity. The maps shows that winter lightning occurs in extratropical regions with preference for oceanic and coastal areas in the western limits of permanent oceanic gyres. As a general conclusion, winter lightning maps presented in this work suggest that winter activity in Japan may be the highest, as supported by the previously discussed works. ~~But~~ Japan is not an exclusive region for winter lightning, as~~but~~ other areas such as the Mediterranean and the US are active as well. In the southern hemisphere, ~~Argentina~~ Uruguay and its surroundings, the southwestern Indian Ocean and the Tasman Sea experience the highest activity.~~and New Zealand experience the highest activity.~~

The maps ~~are~~ may be of use for ~~helpful for~~ risk assessment analysis such as proposed in standards (e.g. the International Electrotechnical Commission, IEC~~IEC~~) providing a tool to identify areas of winter lightning activity. In these ~~areas~~areas, tall structures such as wind turbines can be exposed~~submitted~~ to very energetic lightning and to an environment favourable for lighnting self~~- lightning~~ initiation. Risk assessment of the effect of winter lightning shall also include the exposure. In the case of wind turbines, those turbines located in areas influenced by winter lightning at high altitudes can experience very high number of lightning flashes. Locations at the greatest risk tend to be ~~Also high risk locations are those~~ offshore (e.g. offshore wind turbines, platforms and helicopter operations at those sites). In these ~~situations~~situations, the ~~new presence~~ installation of a tall object can significantly increase the winter lightning activity.

Finally, the simple methodology employed to classify a lightning stroke as being winter lightning may be beneficial in conducting ~~will allow to conduct~~ further risk assessment based on local combined lightning ~~data~~ and meteorological data.

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References

Abarca, S.F., Corbosiero, K.L., and Galarneau, T.J.: An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth, J. Geophys. Res., 115(D18),~~, 1–11~~, 2010.

Adachi, T., Fukunishi, H.,Takahashi, Y., Sato, M., Ohkubo, A., and Yamamoto, K.: Characteristics of thunderstorm systems producing winter sprites in Japan, J. Geophys. Res., 110, D11203, 2005.

Anderson, G. and Klugmann D.: A European lightning density analysis using 5 years of ATDnet data, Nat. Hazards Earth Syst. Sci. Discuss., 1, 6877–6922, 2014.~~3~~

CENELEC, “Protection against lightning - thunderstorm warning systems,” European Standard, EN 50536, 2011.

Bazelyan, E.M.~~,~~ and Raizer, Y. P.: Spark Discharge. CRC Press Inc., 1998.

Bech, J., Pineda, N., Rigo, T. and Aran, M.: Remote sensing analysis of a Mediterranean thundersnow and low-altitude heavy snowfall event, Atmos. Research, 123, pp. 305-322, 2013.

Dirks, R.A., Kuettner, J.P., and Moore, J.A.: Genesis of Atlantic Lows Experiment (GALE): An overview, Bull. Amer. Meteor. Soc., 69, pp. 148-160, 1988.

Gough, W. R., Hemink, J., Niemeijer, S. and Fahey, T. H.: The prediction and occurrence of aircraft lightning encounters at Amsterdam-Schiphol Airport, in Proc. 47th AIAA Aerospace Sciences Meeting, 2009.

Holle, R.L. and Watson, A. I.: Lightning during Two Central U.S. Winter Precipitation Events, Wea. Forecasting, 11, pp. 599–614, 1996~~2~~.

Holley, S. M., Dorling, S. R., Steele, C. J., and Earl, N.: A climatology of convective available potential energy in Great Britain, Int. J. Climatol., 34, pp. 3811–3824, 2014.

Honjo, N.: Risk and its reduction measure for wind turbine against the winter lightning, in Proc. Asia-Pacific Intl. Conf. on Lightning, 2015, pp. 665-670, 2015.~~.~~

Hunter, S. M., Underwood, S. J., Holle, R. L., and Mote T. L.: Winter lightning and heavy frozen precipitation in the southeast United States, Weather and Forecasting, 16, pp. 478-490, 2001.

Hutchins, M.L., Holzworth, R. H., Brundell, J. B., and Rodger, C. J.: Relative detection efficiency of the world wide lightning location network, Radio Sci., 47(RS6005)~~, pp. 1–9~~, doi:10.1029/2012RS005049, 2012.

Li, J., Cummer, S. A., Lyons, W. A., and Nelson, T. E.: Coordinated analysis of delayed sprites with high speed images and remote electromagnetic fields, J. Geophys. Res., 113, D20206, doi:10.1029/2008JD010008, 2008.

López, J., Montanyà, J., Maruri, M., De la Vega, D., Aranda, J. A., Gaztelumendi, S.: Lightning initiation from a tall structure in the Basque Country, Atmos. Research, 117, 28–36, 2012.

Lyons, W. A.: Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, J. Geophys. Res., 101, 29641–29652, 1996

Krehbiel, P.R., Riousset, J. A., Pasko, V. P., Thomas, R. J., Rison, W., Stanley, M. A., and Edens, H. E.: Upward electrical discharges from thunderstorms, Nature Geoscience, 1, 233 – 237, 2008.

MacGorman, D., and Morgenstern C. D.: Some characteristics of cloud to ground lightning in mesoscale convective systems, J. Geophys. Res., 103(D12), 14011–14023, 1998.

Michimoto, K.: A study of radar echoes and their relation to lightning discharges of thunderclouds in the Hokuriku district. II: Observation and analysis of "single-flash" thunderclouds in midwinter, J. Meteorol. Soc. Jpn., 71, 195–204, 1993.

Montanyà, J., Soula, S., Diendorfer, G., Solà, G., and D. Romero, D.: Analysis of the altitude of the isotherms and the electrical charge for flashes that struck the Gaisberg tower, in Proc. Intl. Conf. on Atmospheric Electricity, 2007.

Montanyà, J., Fabró, F., van der Velde, O., and Hermoso, B.: Sprites and Elves as proxy of energetic lightning flashes in winter. What can we learn from mesospheric discharges for the protection of wind turbines?, in Proc. Intl. Symp. on Winter Lightning (ISWL 2011), 2011.

Montanyà, J., van der Velde, O., and Williams, E. R.: Lightning discharges produced by wind turbines, J. Geophys. Res. Atmos., 119, 1455–1462, 2014a.

Montanyà, J., Fabró, F., van der Velde, O., Romero, D., Solà, G., Hermoso, J. R., Soula, S., Williams, E. R., and Pineda, N.:Registration of X-rays at 2500 m altitude in association with lightning flashes and thunderstorms, J. Geophys. Res. Atmos., 119, 1492–1503, 2014b.

Murooka, Y.: A Survey of Lighting Interaction with Aircraft in Japan, Res. Lett. Atmos. Electricity, 2, 101–106, 1992.

Poelman, D. R., Schulz, W., Diendorfer G. and Bernardi, M.: The European lightning location system EUCLID –Part 2: Observations, Nat. Hazards Earth Syst. Sci. Discuss., 3, 5357–5381, 2015.

Rachidi, F., Rubinstein, M., Montanyà, J., Bermudez, J. L., Rodriguez, R., Solà, G., and Korovkin, N.: Review of current issues in lightning protection of new generation wind turbine blades, IEEE Trans. Ind. Electron., 55(6), 2489–2496, 2008.

Radičević~~Radicevic~~, R.M., Savic, M. S., Madsen, S. F., and Badea, I.: Impact of wind turbine blade rotation on the lightning strike incidence – A theoretical and experimental study using a reduced-size model, Energy, 45, 644-654, 2012.

Rodger, C.J., Werner, S., Brundell, J. B., Lay, E. H., Thomson, N. R., Holzworth, R. H. and Dowden, R. L.: Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): initial case study, Ann. Geophys., 24, 3197–3214, 2006.

Rodger, C.J., Brundell, J. B., Holzworth, R. H., Lay, E. H., Crosby, N. B., Huang, T.-Y., and Rycroft, M. J.: Growing detection efficiency of the world wide lightning location network, AIP Conference Proceedings, 1118, ~~pp.~~ 15–20, doi:10.1063/1.3137706, 2009.

Saito, M., Ishii, M., Fujii, F., Matsui, M.: Seasonal Variation of Frequency of High Current Lightning Discharges Observed by JLDN, IEEJ Trans. P&E, Vol. 132, No. 6, 536-541, 2012.

Saunders, C.P.R, Bax-Norman, H., Emersic, C., Avila, E.E., Castellano, N. E.: Laboratory studies of the effect of cloud conditions on graupel/crystal charge transfer in thunderstorm electrification, Q. J. R. Meteorol. Soc., 132, 2653–2674~~3~~, 2006.

Siedler, G., Griffies, S. M., Gould, J., and Church, J. A. (Editors): Ocean Circulation and Climate A 21st century perspective. International geophysics series, 103, Amsterdam Academic Press, 2013.

Sugita, A., Matsui, M.: Examples of winter lightning observed by the JLDN, in Proc. of 2008 ILDC/ILMC, Tucson, Arizona, 2008

Takahashi, T.: Thunderstorm electrification-A numerical study, J. Atmos. Sci., 41, 2541-2558, 1984.

van der Velde, O.A., Montanyà, J., Soula, S., Pineda, N., and Bech, J.: Spatial and temporal evolution of horizontally extensive lightning discharges associated with sprite-producing positive cloud-to-ground flashes in northeastern Spain, J. Geophys. Res., 115, A00E56, doi:10.1029/2009JA014773, 2010

Wallace, J.M., and Hobbs, P. V.: Atmospheric science: An introductory survey. 2nd Ed., Academic Press, 2006.

Wang, D., Takagi, N., Watanabe, T., Sakurano, N., and Hashimoto, M.: Observed characteristics of upward leaders that are initiated from a windmill and its lightning protection tower, Geophys. Res. Lett., 35, L0280, doi:10.1029/2007GL032136, 2008.

Wang, D., and Takagi, N.: Typical characteristics of upward lightning observed in Japanese winter Thunderstorms and Their Physical Implications, in Proc. Intl, Conf. on Atmospheric Electricity, 2011.

Warner, T. A., Cummins, K. L., and Orville, R. E.: Upward lightning observations from towers in Rapid City, South Dakota and comparison with National Lightning Detection Network data, 2004-2010, J. of Geophys. Res., vol. 117, D19109, doi:10.1029/2012JD018346, 2012.

Warner, T. A., Lang, T. J., and Lyons W. A. :Synoptic scale outbreak of self-initiated upward lightning (SIUL) from tall structures during the central U.S. blizzard of 1–2 February 2011, J. Geophys. Res. Atmos., 119, 9530–9548, 2014.

Wilkinson, J. M., Wells, H., Field, P. R. and Agnew, P.: Investigation and prediction of helicopter-triggered lightning over the North Sea, Met. Apps, 20, 94–106, 2013.

Williams, E. R., “The tripole structure of thunderstorms,” J. Geophys. Res., 94(D11), pp. 13151-13167, 1989.

Williams, E. R., Lyons, W. A., Hobara, Y., Mushtak, V. C., Asencio, N. , Boldi, R., Bór, J., Cummer, S. A., Greenberg, E., Hayakawa, M., Holzworth, R. H., Kotroni, V., Li, J., Morales, C., Nelson, T. E., Price, C., Russell, B., Sato, M., Sátori, G., Shirahata, K., Takahashi, Y., and Yamashita, K.: Ground-based detection of sprites and their parent lightning flashes over Africa during the 2006 AMMA campaign, Q.J.R. Meteorol. Soc., 136, 257–271, 2010.

Wu, T., Yoshida, S., Ushio, T., Kawasaki, Z., Takayanagi, Y., and Wang, D.: Large bipolar lightning discharge events in winter thunderstorms in Japan, J. Geophys. Res. Atmos., 119, 555–566, 2014.

Yokoyama S., et al.: Lightning protection of wind turbine blades, Electra, 274, 43-45, 2014.

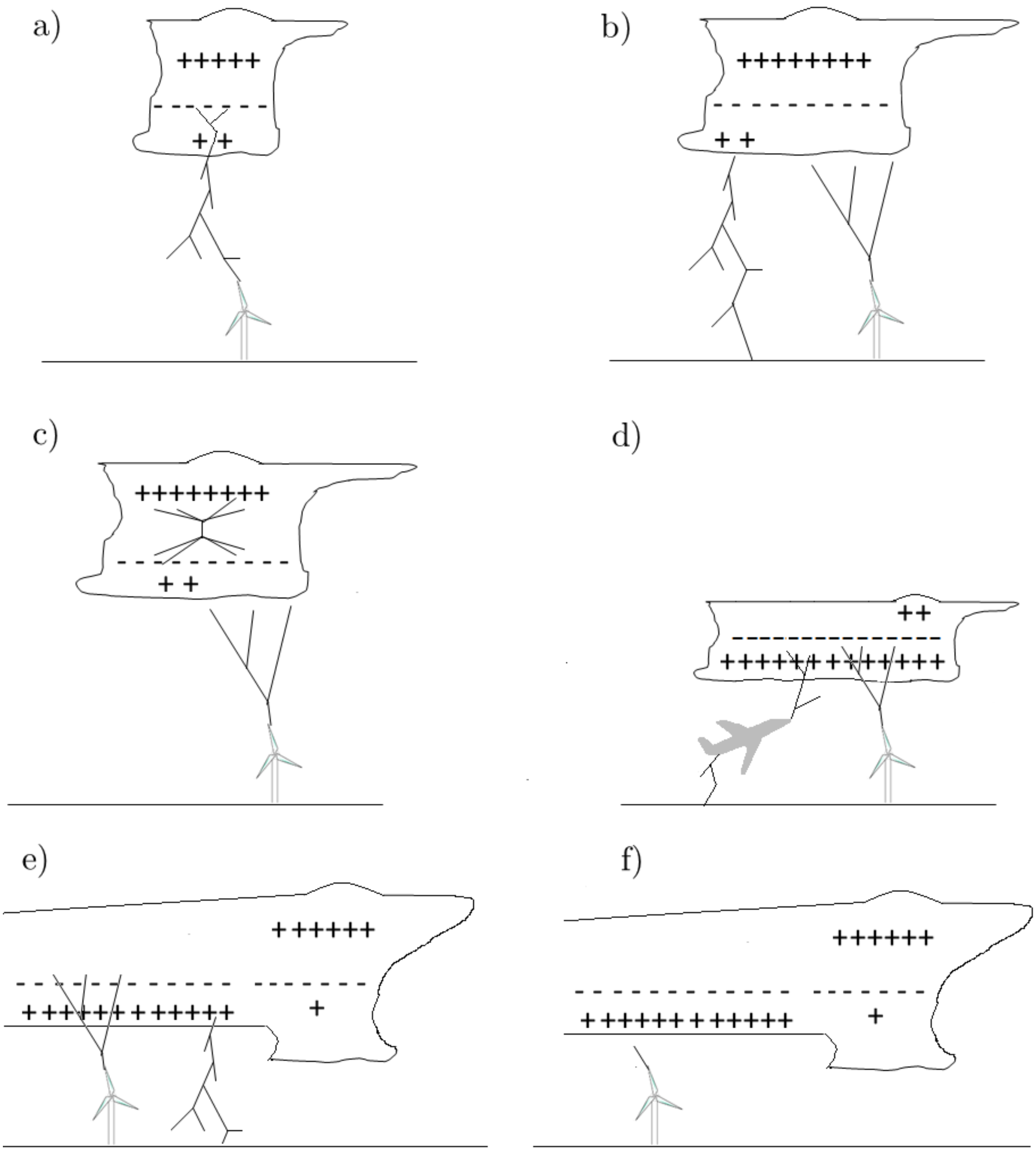

Figure 1. a) Downward lightning stroke to a wind turbine; b) Upward lightning initiated by a nearby CG flash; c) Upward lightning initiated by a IC flash; d) Upward lightning from a wind turbine and lightning initiated by aircraft in a winter storm (~~case of~~charge distribution as observed winter storms in Japan); e) Upward and downward positive flashes~~Lightning~~ in the trailing stratiform of MCS; f) Repetitive corona/leader emissions from wind turbines under storms. Proportions in these diagrams are not ~~meet in the~~to ~~representations~~scale.

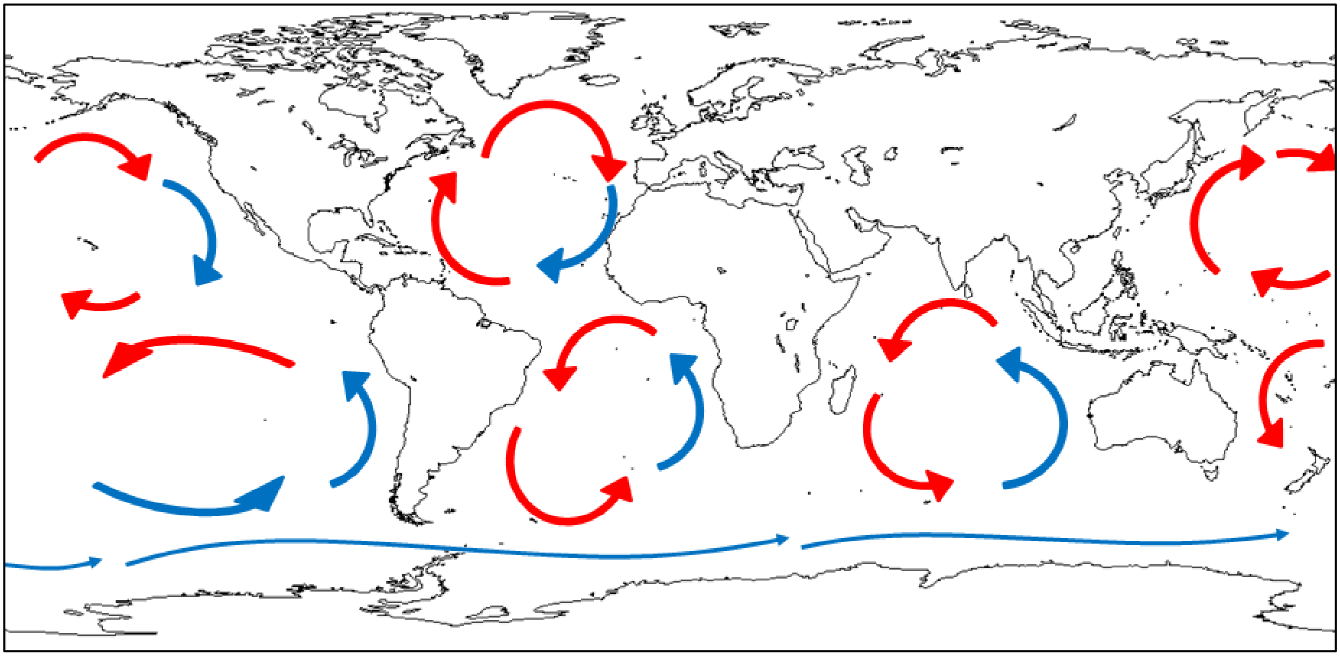

Figure 2. Simplified distribution of the most significant rotating oceanic currents: North Atlantic Gyre, South Atlantic Gyre, North Pacific Gyre, South Pacific Gyre, Indian Ocean Gyre and the An~~r~~taric Circumpolar Gyre (for more information see Siedler et al., 2013). Red and blue arrows indicate warm and cold currents, respectively.

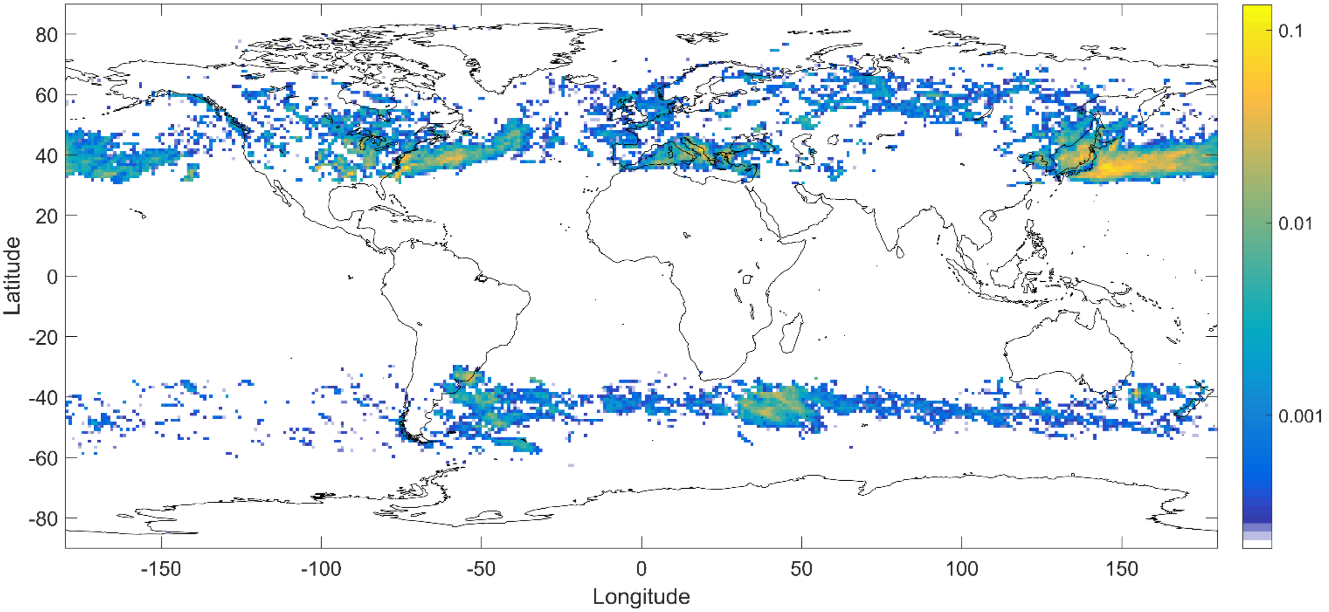

Figure 3. Global distribution of winter lightning stroke density (strokes·km^{-2}·year^{-1}) for the period 2009-2013.

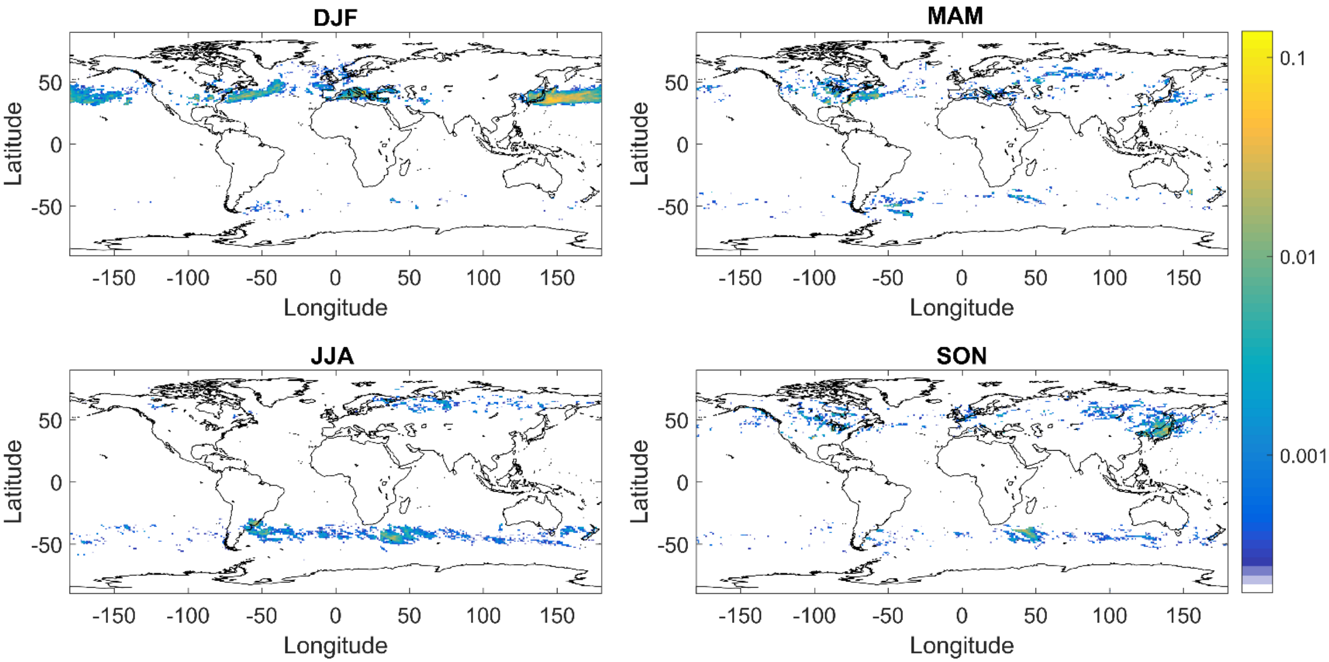

Figure 4. Seasonal variation of the winter lightning stroke density ~~(strokes·km-2·year-1)~~ distribution for the period of 2009-2013. The values are calculated as the average number of strokes for the five years in each grid cell divided by the area of the cell. Note that major shift of activity from DJF and MAM periods in the northern hemisphere to more JJA and SON periods in the southern hemisphere.

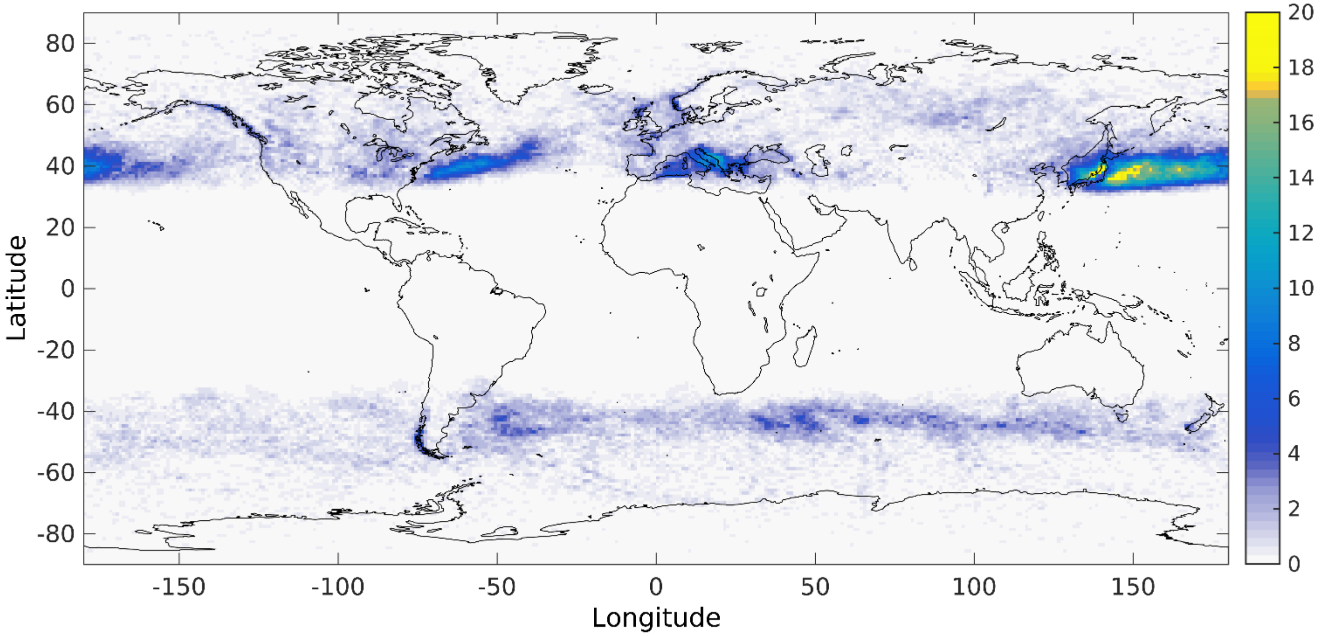

Figure 5. Average number of winter thunderstorm days per year (T_w) for the period 2009-2013.