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Towards a prediction of the intensity of a Harmattan season

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Introduction

The harmattan is a seasonal phenomena in West Africa. It is a dry and warm wind which is able to transport large dust plumes. Each year during the harmattan season, between November and March, this wind reaches parts of West Africa. Harmattan winds can transport large amounts of dust originating from the Sahara and Sahel through the atmosphere. This makes dust aerosol the most common aerosol type in West-Africa [Ochei and Adenola, 2018]. These fine dust particles transported by the harmattan winds scatter light and decrease the incoming sunlight. This results in decreased visibility and dangerous situation for aviation. In addition to affecting the visibility, the harmattan brings other negative effects as well, like health issues and crop loss.

The countries in West Africa along the Gulf of Guinea (from Ivory Coast to Nigeria) suffer most from the consequences of the harmattan due to their location relative to the harmattan winds. Not only from a health or aviation perspective, but also from an agricultural perspective these countries are affected by the harmattan, as their crops are affected by the warm, dry and dusty harmattan winds. These are countries investing in crops like cocoa pods or cashew nuts. Those crops can be largely influenced by the harmattan winds, as they are highly sensitive to dusty and dry conditions. For these farmers, a good or bad harmattan season can make a huge difference, because crop yield can decrease significantly during a bad harmattan year [Reuters, 2016].

The harmattan is a seasonal event, so it is known during which period the monsoon winds will change into harmattan winds each year. Still, it is difficult to predict how intense the harmattan season will become each season. Quite some interesting short term predictors do exist, such as the aerosol forecasts of the ECMWF [monitoring CAMS, nd]. The trajectory of a dust outbreak somewhere can be predicted quite well over a 4 day period. So on short notice, there is quite reliable information on the movement of a dust outbreak during the harmattan season. However a reliable seasonal predictor is missing, which would be optimal for farmers and investors in West Africa. It would be optimal if prior to the harmattan season, an indication about the intensity of the next harmattan season can be provided: to predict whether the next season will have extreme or light dust events.

So a seasonal predictor would be optimal for farmers in West-Africa or especially for companies like 'Opus insights' which bring services to agricultural supply chains in the Tropics (`opusinsights.co`). Part of their service consists of providing reliable weather forecasts. The harmattan is still something which is hard to predict but really important to understand, as it can have a large effect on crop growth and yield. For them it would be ideal to have seasonal predictor in the future, which could warn for a bad harmattan season based on other external triggers. This study is done in collaboration with 'Opus Insight' to see if it is possible to make a seasonal predictor of the harmattan.

To find a seasonal predictor which can predict the intensity of the next harmattan season, historical data will be analyzed. This study aims to get insight in possible triggers that may have influence on the harmattan season itself. To understand which events or circumstances could trigger certain harmattan events, first the different triggers of harmattan winds will be studied. In the end, historical data of these so called triggers will be compared to the harmattan events each year.

Pre study - Possible triggers

Some pre research is done on the harmattan and how it arises. Winds, a shifting Inter-Tropical Convergence Zone (ITCZ) or even location are some variables that are related to the harmattan. To create more insight in the harmattan itself, those areas of interest are looked into.

ITCZ

The exact location of the Inter-Tropical Convergence Zone (ITCZ) within Africa affects the direction of the main winds in West Africa. The position of the ITCZ over Africa is located where the north-easterly harmattan winds meet the south-westerly monsoon winds [Lyngsie et al., 2013]. The ITCZ has a yearly cycle which moves with the seasons. During the harmattan season (between Nocember and March) it reaches its most southern location, causing the harmattan winds to reach furthest south [Lyngsie et al., 2013]. Figure 1 [Encyclopædia Britannica, 2008] clearly shows what influence the location of the ITCZ has on the wind direction in West Africa.

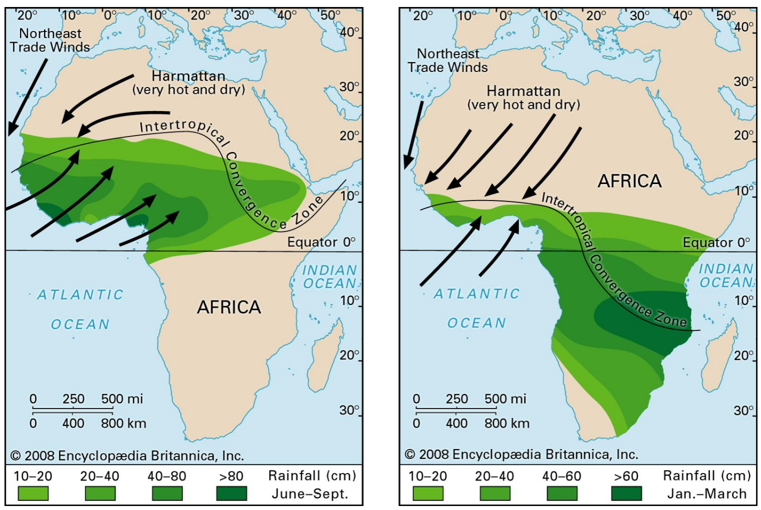

Figure 1: This figure from [Encyclopædia Britannica, 2008] shows clearly what influence the location of the ITCZ has on the wind direction in West Africa

The ITCZ can be seen as a belt of low pressure around the earth near the equator. Its latitudinal location changes due to change in solar heating which is different each season because of the tilted earth. So in the (northern hemisphere) summer, the ITCZ has a higher latitude, and in the winter it becomes lower, even possible to cross the equator. During the West African monsoon season (May-Oct), the ITCZ has a relatively high latitudinal location (Figure 1, left picture). When looking at West Africa, a high pressure in the south and lower pressure in the north (near the ITCZ) creates south-easterly trade winds due to the pressure differences and the Coriolis force. During the harmattan season (Nov-Apr), the latitudinal location of the ITCZ is closer to the equator (Figure 1, right picture). The first few months the latitudinal coordinates of the ITCZ are decreasing. This is because of higher pressures in the north of West Africa compared to the lower pressure near the ITCZ in the south. This causes north-easterly trade winds: the harmattan. This wind comes from the warmer and dryer Sahel/Sahara, causing the wind to be warmer, dryer and sometimes dusty. The harmattan winds can only reach as far as the location of the ITCZ as this is the location where the two trade winds come together. Near the ITCZ the winds are slowly directed upward. The movement of the ITCZ affects the harmattan season and may be an indicator to create a seasonal harmattan predictor.

The southern retreat of the ITCZ and the harmattan season are linked. The further the ITCZ retreats southwards the further south harmattan winds can reach. Also, the changing ITCZ is caused by changing pressure patterns over West Africa, which also influence the harmattan winds. The exact position of the ITCZ varies from year to year [Lyngsie et al., 2013]. It might be worth looking into the behavior of the ITCZ prior to each harmattan season as this could be a possible indicator of the intensity of a upcoming harmattan season.

Visibility

A variable is needed which can provide insight into the impact and intensity of the harmattan dust storms in different years. Visibility data seems to provide such data. Visibility is the most observable effect of dust aerosols in the air [Ochei and Adenola, 2018]. Historical visibility data during harmattan seasons can provide insight into the impact and strength of the harmattan dust storms in different years. Continuous historical data about the severity of harmattan seasons are hard to get by, because in situ meteorological data in (West)-Africa is scarce. Some years with extreme harmattan seasons are known (e.g. 2015/2016), but overall long records of visibility data are missing. Furthermore, the strength of a harmattan season differs spatially because dust storms follow wind patterns.

In this research two different variables are used to represent possible harmattan dust events. Visibility data and wind data are used at different locations in West Africa. Both are expected to be directly related to the harmattan dust events. This will further be explained in the next paragraphs.

Visibility data provides direct feedback on the the amount of aerosols (including dust) in the air. In West Africa, a large decrease in visibility is often caused by dust in the air. However, biomass burning also releases a fair amount of aerosols in the air [Ochei and Adenola, 2018]. A large decrease in visibility appears to occur during the harmattan season (November-March). Close to the source area (e.g. the Sahel region of Nigeria) the key factor which is responsible for a decrease in visibility is dust [Ochei and Adenola, 2018]. Large dust events cause visibility to decrease unmistakably, but the further south, the more other aerosol sources like biomass burning has to be taken into account.

Historical data from weather archives are scarce in West Africa. Visibility data from 9 different locations in West Africa from the weather archive of [Parker and Diop-Kane, 2017] is used to provide insight about decrease in visibility per season but also spatially. Figure 2 shows the location of the 9 stations. Each station has data from a harmattan season between 2010 and 2018.

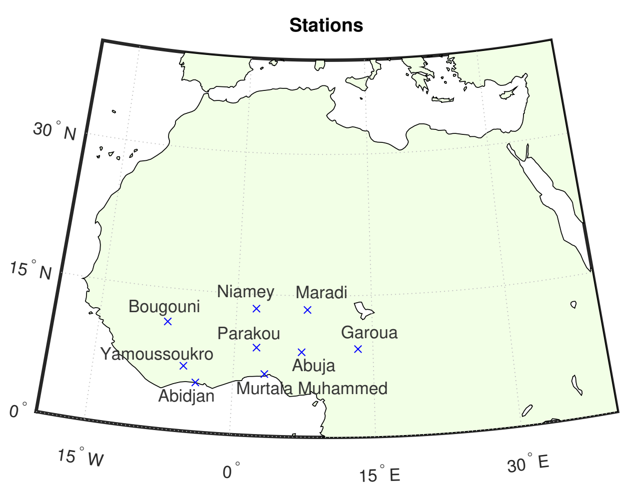

Figure 2: 9 stations from which visibility data is available from harmattan season 2010-2017.

Source regions
A important requirement for a dust storm is the injection of dust into the air. In the Sahel or Sahara, sufficient wind can cause dust to be raised into the atmosphere. Turbulent movement of the air makes sure that dust aerosols are distributed in the air. Larger dust particles will fall back to the ground, but the fine dust particles stay in the air and will be carried by the wind. Only precipitation like rainfall, dew or dry sedimentation will remove small particles from the atmosphere [Ochei and Adenola, 2018].

However, not all locations in the Sahel and Sahara are expected to create dust storms. For example, if soil moisture is too large, wind won't be able to lift the sand particles into the air. Also source area with coarse sand particles won't attribute to large dust events, because large particles will fall back to the ground once the wind decreases a little bit. Optimal conditions would be small (and dry) sand particles. Those can be lifted up into the sky at higher altitudes and won't settle that fast. Harmattan winds will bring the dusty air to other places. Potential source areas can be seen in figure 3 based on a analysis of [Formenti et al., 2011]. PSANAF-5 and PSANAF-3 are the most important dust source areas for our research area (West African countries along to the Gulf of Guinea) due to the direction of the wind during the harmattan season.

The so called Bodélé Depression is located in PSANAF-5. This specific area is considered to be the main source area of the Harmattan dust concerning countries along the Gulf of Guinea [Engelstaedter et al., 2006, Washington et al., 2006]. The topography of this area in combination with the wind conditions makes it easier to take large amounts of dust into the air[Washington et al., 2006]. It is thus expected that PSANAF-5 will have a larger influence on harmattan dust events compared to PSANAF-3.

Both source areas, PSANAF-5 and PSANAF-3, will later be used as boundaries for a wind-data analysis.

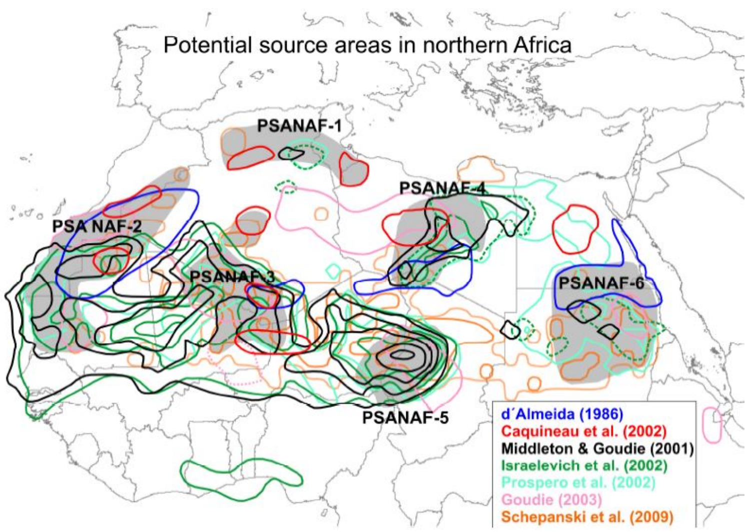

Figure 3: The figure shows the potential source areas in Northern Africa (PSANAF) [Formenti et al., 2011]. The most important regions are the grey areas.

Wind
As mentioned earlier in the paragraph 'visibility', a variable is needed which can provide insight into the impact and intensity of the harmattan dust storms in different years. Because visibility data is limited over the years, another approach is to look into wind-data and compare yearly data with each other.

Harmattan winds are a result of a change in direction of the winds in West Africa during the year. The amount of dust which can be taken along with the wind does not only depend on the location where the dust will be taken (see paragraph 'source regions') but also on the velocity of the winds. Wind is expected to be the initial cause of a possible harmattan outbreak. A large enough wind speed can cause dust particles to be injected into the air. A 10m wind speed of larger then 15 m/s located in a Sahel/Sahara location is expected to be accompanied by a significant dust event [Parker and Diop-Kane, 2017]. Once in the air, dust particles will travel in the direction of the wind. Depending on speed and direction of the wind, this causes a harmattan dust event to travel.

Wind data is available over a longer period of time. ERA5 offers globally hourly wind data based on a reanalysis from 1979 up to today [(atmospheric reanalysis ERA5), nd]. The wind data in PSANAF-5 and PSANAF-3 will be considered. If within these areas the wind exceeds 15 m/s, a significant dust event can be expected in Western Africa. If these wind events are counted every year during the harmattan season, this will give insight into the intensity of the harmattan season each year.

NAO and SOI

The North Atlantic Oscillation (NAO) and the Southern Oscillation Index (SOI) are both large scale pressure oscillations that may or may not influence the Harmattan season. The SOI, which also provides an indication of the intensity of El Nino events, is sometimes directly linked to the intensity of harmattan events [Bassompierre et al., 2018], which makes the SOI an interesting variable to study. The pressure differences of the NAO are located much closer to West Africa. This large scale pressure system could possibly influence the pressure system in West Africa which could influence the ITCZ or wind surges in the source regions. Both pressure oscillations may influence the wind events in West Africa and will therefore be taken into consideration while analyzing the harmattan events.

Methodology and data

Methodology

Resulting from the pre-study it can be concluded that changes in ITCZ, SOI and NAO may influence the harmattan season. These variables, so called 'triggers', could play a role in predicting the (intensity of the) harmattan season. To study this possible relationship, these triggers will each be compared to historical wind data.

Figure 4 provides an overview to show visually which comparisons are made in this study. Wind data from two different source areas is compared with multiple NAO, SOI and ITCZ values each harmattan year. Also the wind data is compared to the visibility data at nine different stations, although this is only a period of 8 years.

The goal is to find whether some relations are correlated with each other. if that is the case, that would be a first step towards a seasonal harmattan predictor. To find out whether there is any positive or negative relation between different data sets, a best fit line (based on least squares) is created for each data set. For this line the correlation coefficient (R), R^2 and p-value are then calculated to say something about the correlation and significance.

Often the term 'harmattan season' is used to refer to a specific time period; the harmattan season starts in November (1) and ends in March (31). When referring to the mean value within the harmattan season, all days within those dates will be taken into account.

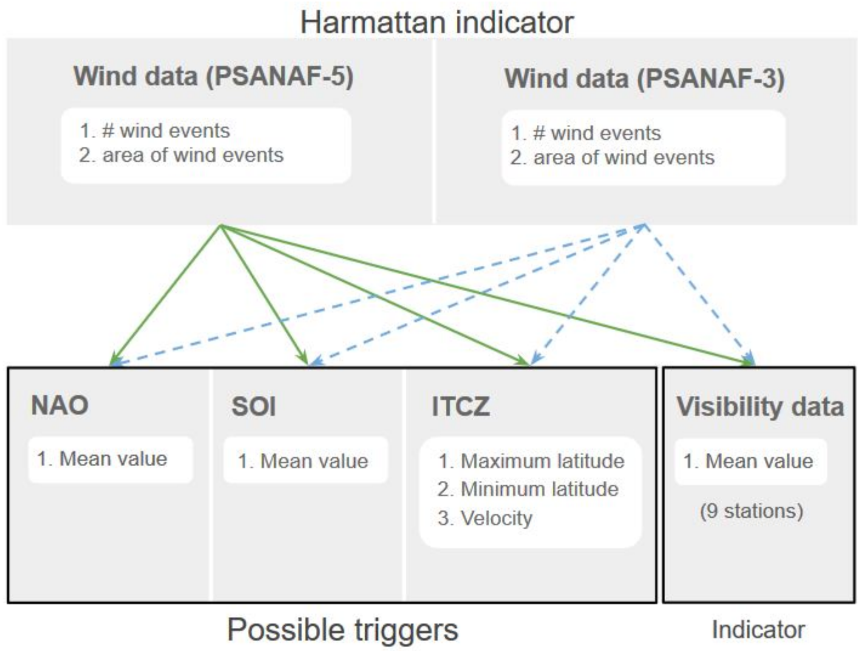

Figure 4: This figures shows the comparisons which are made. The wind data (top) is an indicator for the harmattan and will be compared with possible triggers: NAO, SOI and ITCZ (bottom left). The visibility data (bottom right) is an indicator as well but because of the limited amount of years, this will be compared to the wind data as verification.

Data sets

Below a short description of all used data sets can be found. Table 1 shows an overview of these data sets and the amount of harmattan seasons they cover. If two data-sets are compared, only the the number of overlapping years will be used.

Table 1: The amount of harmattan seasons that is covered per data set.

	Data available during harmattan season		Years of data
	From	*to*	-
PSANAF-5 wind data	1979/1980	2017/2018	39
PSANAF-3 wind data	1979/1980	2017/2018	39
ITCZ	1989/1990	2017/2018	29
NAO	1821/1822	2017/2018	197
SOI	1866/1867	2017/2018	152
Visibility	2010/2011	2017/2018	8

Wind data
ERA5 offers globally hourly wind data based on a reanalysis from 1979 until today [(atmospheric reanalysis ERA5), nd]. This wind data is analyzed within the borders of PSANAF-5 and PSANAF-3 (see Figure 5).

Per harmattan season, the number of 'large wind events' needs to be known within each source area. A large wind event is defined as 'the number of times the wind velocity (within the chosen boundaries) exceeds 15 m/s'. The exact location within the chosen boundaries and the amount of pixels exceeding the limit are not taken into account.

As mentioned earlier in the paragraph 'wind', a wind velocity which exceeds 15 m/s in a source area is expected to be accompanied by a significant dust event. We hereby establish the link between wind and dust events.

The total number of pixels which exceed a wind velocity of 15 m/s are also counted each season. A pixel represents a data cell with the smallest spatial resolution of the wind data set. Counting the total number of pixels of all large wind events per season gives some insight about the total area that plays a role while creating a dust event.

As a result, each source area (PSANAF-5 and PSANAF-3) will have two values which will be studied:

- The number of large wind events per harmattan season
- The number of pixels (= area of wind events) of all the wind events per harmattan season

These values will later compared to the possible triggers (NAO, SOI, ITCZ).

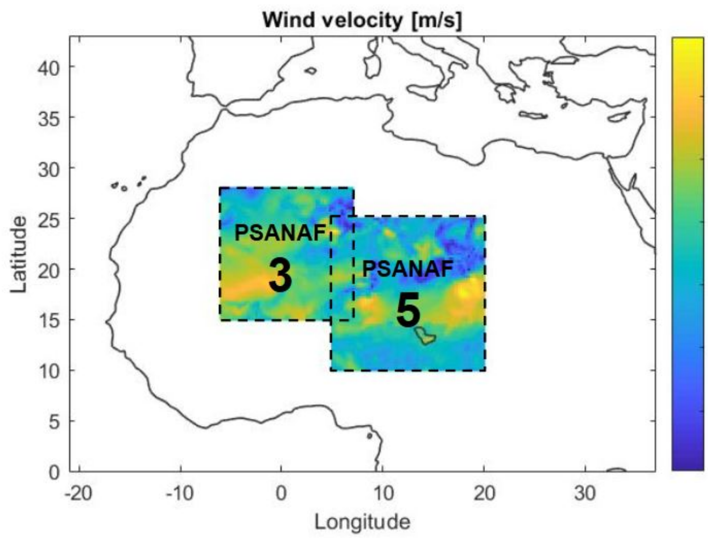

Figure 5: The figure roughly shows the area of PSANAF-5 and PSANAF-3. The area which is visible is used as input region for the wind-data.

ITCZ

Decadally averaged ITCZ coordinates from 1989-2018 are used to analyze the trends of its movements every year (received from [data archive NOAA, nd]). The ITCZ migration will be analyzed within the boundaries of Africa. The ITCZ moves in a north-south direction and retreats southwards in the months prior to the harmattan season. The focus will therefore be on the latitudinal change of the ITCZ. Three different aspects of the ITCZ migrations will be studied, because all three are specific variables which can influence the wind within West Africa:

- The Maximum latitude of the ITCZ before the southern retreat of the ITCZ starts. This maximum is usually reached at the start of August. [Referred to as 'Maximum latitude']
- The latitude of the ITCZ prior to the start of the harmattan season, at the end of October. [Referred to as 'Minimum latitude'].
- Velocity of the ITCZ prior to the the harmattan season (between its maximum and minimum latitude) [Referred to as 'Latitude velocity']

NAO and SOI

The NAO and SOI data (received from [climate timeseries NOAA, nd]) both have a long historical data set. However, both will be compared to the wind data set, so in the end only the overlapping years are considered. Per harmattan season, the mean values of the NAO and SOI were calculated, so one value per variable represent each harmattan season.

Visibility

A large record of dust events over West-Africa is not available. For this research, visibility data of 9 different locations all over West-Africa from the weather archive of [Rp5, 2019] was considered. This dataset contains data from 2010 to 2019. Because the harmattan season is from November until March, only the data from harmattan season in the years 2010/2011-2017/2018 was used, resulting in 8 consecutive harmattan seasons. Per harmattan season, the mean visibility was calculated to create one value to represent each harmattan season.

Results

Visibility data

The visibility data by itself, without comparing it to other data, shows a decrease in visibility during the harmattan season. Figure 6 shows that location matters a lot (See Figure 2 for the exact location of each station). The visibility does not decrease significantly for locations that are too far to the west (e.g. Bougouni). Figure 7 shows the mean visibility of each location per harmattan season. The harmattan season 2015/2016 is known to be one of the strongest harmattan seasons in years. Figure 7 shows that this year has a really low visibility for almost every location. The harmattan dust events sure had a big impact that season.

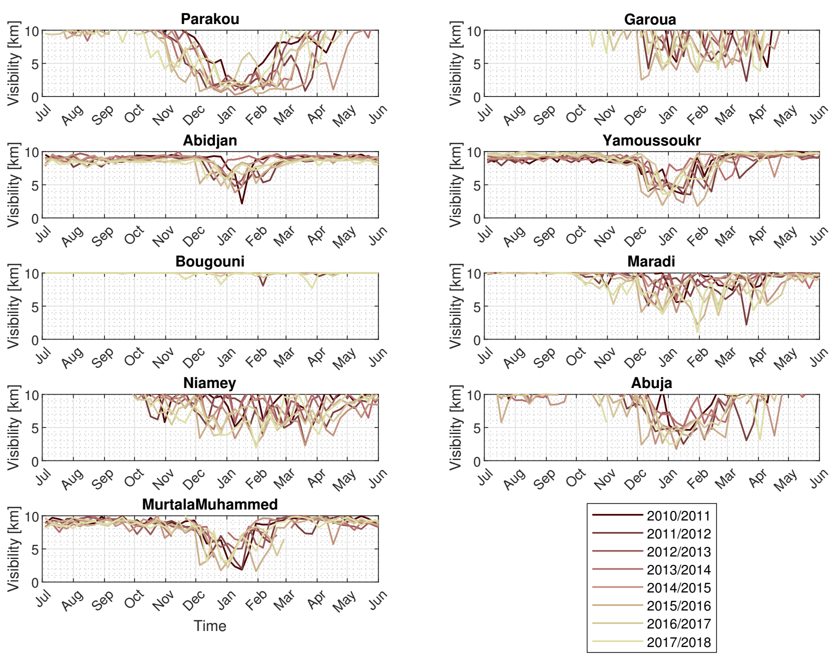

Figure 6: Visualisation of the visibility over time at 9 stations for harmattan season between 2010/2011 and 2017/2018

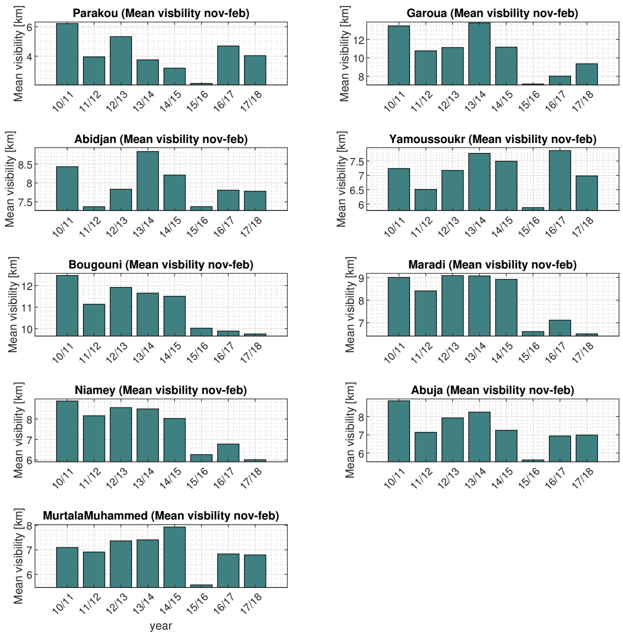

Figure 7: Mean visibility during a harmattan season at 9 stations

Wind data vs triggers

On average there are 0 to 6 large wind events each harmattan season in PSANAF-5 and 0 to 3 large wind events in PSANAF-3. The total area that is part of those large wind events (the number of pixels) is larger in PSANAF-5 compared to PSANAF-3.

This wind data over the years is compared to the triggers (NAO, SOI, ITCZ). Table 2 shows the p-value for every comparison which determines whether a possible correlation is significant or not. A short recap on why the p-value is of interest: The correlation between two variables can be visualized by drawing a best fit line based on the data-set. The correlation itself is given by the correlation coefficient [R], which can be positive or negative depending on the correlation. (The outcome of the correlation coefficient [R] for each comparison can be found in Appendix Table 4 and 5.) The p-value helps to determine the significance of these results. The correlation coefficient is called statistically significant if the p-value is smaller then this significance level ($p < 0.05$).

Due to the large amount of comparisons, all the plots of data sets and their linear (best fit) line can be found in the appendix.

- Wind data vs ITCZ: Appendix Figure 14-19
- Wind data vs NAO: Appendix Figure 20-21
- Wind data vs SOI: Appendix Figure 22-23

Table 2 shows one p-value which is small enough to be significant. The number of wind events in PSANAF-5 versus the maximum latitude of the ITCZ has a p-value of 0.016 (Table 2). The corresponding correlation coefficient [R=0.445] shows a positive relationship between the two given variables. The plot of this comparison and its linear fit can be seen in figure 8. This figure visualizes the relation between the maximum ITCZ value prior to the harmattan season ('maximum ITCZ value') and the number of wind events per harmattan season. PSANAF 5 is used as source region of the wind data. A larger 'maximum ITCZ' seems to indicate a larger number of dust events. Due to the significant p-value, this correlation can be accepted.

Table 2: P-value of data points and its linear fit (least squares)

P-value linear trend		NAO	SOI	ITCZ		
		Mean value	*Mean value*	*Maximum latitude*	*Minimum latitude*	*Velocity*
Wind data PSANAF-5	*# wind events*	0,180	0,703	0,016	0,470	0,217
	area of wind events	0,520	0,892	0,488	0,127	0,059
Wind data PSANAF-3	*# wind events*	0,616	0,286	0,360	0,548	0,734
	area of wind events	0,497	0,862	0,770	0,822	0,430

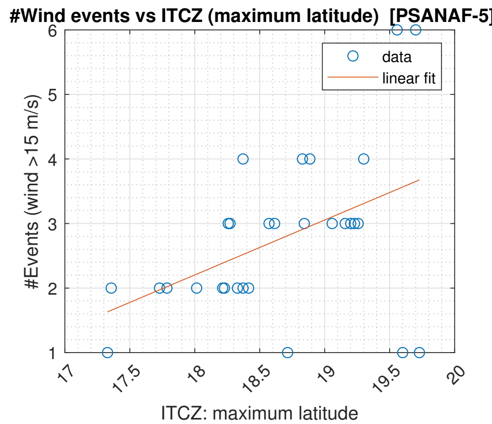

Figure 8: The plot shows the relation between the maximum ITCZ value prior to the harmattan season ('maximum ITCZ value') and the number of wind events per harmattan season. PSANAF 5 is used as source region of the wind data.

Wind data vs visibility

Wind data over the years is compared to the visibility data at 9 different locations. Table 3 shows the p-value for every comparison which determines whether a possible correlation is significant or not.

Due to the large amount of comparisons, all the plots of data sets and their linear (best fit) line can be found in the appendix as Figures 10-13.

Table 3 shows one p-value which is small enough to be significant. The total number of pixels (which are involved in a large wind event) in PSANAF-5 versus the mean visibility in Parakou has a p-value of 0.028 (Table 3). The corresponding correlation coefficient [R=-0.186] shows a small negative relationship between the two given variables. The plot of this comparison and its linear fit can be seen in figure 9. This figure visualizes the relation between both variables. PSANAF 5 is used as source region of the wind data. An increase in the number of pixels (= area of the wind-events) seems to indicate a decrease in visibility in Parakou. Due to the significant p-value, this correlation can be accepted.

Table 3: P-value of data points and its linear fit (least squares)

P-value		**Visibility data** (mean value)								
linear trend		*Parakou*	*Garoua*	*Abidjan*	*Yammoussoukr*	*Bougouni*	*Maradi*	*Niamey*	*Abuja*	*MurtalaM,*
Wind data	*# wind events*	0,475	0,481	0,516	0,735	0,345	0,351	0,266	0,398	0,885
PSANAF-5	*area of wind events*	0,028	0,385	0,473	0,098	0,331	0,241	0,194	0,102	0,276
Wind data	*# wind events*	0,971	0,511	0,362	0,720	0,601	0,732	0,741	0,661	0,603
PSANAF-3	*area of wind events*	0,660	0,557	0,380	0,489	0,516	0,429	0,653	0,789	0,121

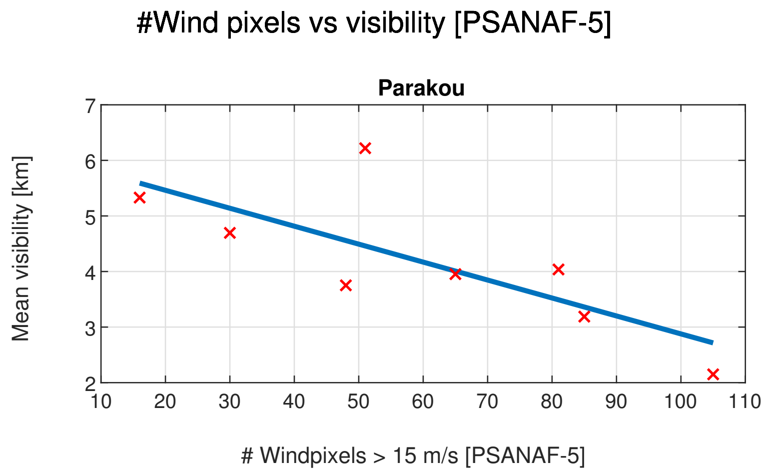

Figure 9: The plot shows the relation between the number of pixels of large dust events and the mean visibility in Parakou. PSANAF 5 is used as source region of the wind data.

Conclusion and Discussion

The results are briefly discussed within 6 paragraphs focusing on different aspects.

Visibility data

The visibility data per location creates an interesting view on how the visibility decreases over time during the harmattan season. The lowest value of visibility is around January for almost all locations. The cycle seems the same for all locations. However the amount of decrease in visibility differs spatially. If you go further to the west, the decrease in visibility becomes less. Also locations near the coast have a smaller decrease compared to locations north of it. This can be explained by the location of the ITCZ which only reaches as low as 5 degrees latitude for only one or two months each harmattan season. Only during this period, harmattan winds are able to reach coastal regions. But, keep in mind that part of the decrease in visibility can also be caused by other aerosols in the air (e.g. from by biomass burning).

Wind data vs triggers

The correlation between the 'maximum latitude' of the ITCZ prior to each harmattan season and the 'number of dust events in PSANAF-5' is found to be significant. An full explanation for this correlation is not yet found. It however is plausible that the ITCZ in one way or another affects the number of dust events. The location of the ITCZ does influence the wind direction but also affects the probability of large wind speeds. For example, it is unlikely that large wind speeds occur near the ITCZ because the small pressure differences near the ITCZ won't be able to cause such large wind speeds. The location of the ITCZ is thus important. Also, a large velocity of the ITCZ is accompanied by changing pressure field over West Africa. Both could influence the number of dust events. The interesting part is that in this study only the maximum latitude has a significant correlation with the wind events, the minimum latitude and velocity of the ITCZ are both not significant with the number of wind events. However, the goal of the study was to find possible triggers which could predict the intensity of the harmattan season. It would be good to look into this correlation an maybe combine different ITCZ values which would give an even stronger correlation. This might provide some new interesting results.

Wind data vs visibility

The correlation between the visibility data (in Parakou) and the number of pixels of large wind events is found to be significant. At first this seems very interesting, because this confirms the assumption that larger wind events cause lower visibility during a harmattan season. However, as stated before, only 8 data points (8 years) where used with this comparison. Although the correlation is significant, it is not wise to accept this correlation as the truth because of the few years of data available. For this to be acceptable, more years of data are needed.

The results shows also that none of the other comparisons between wind data and visibility data give a significant result. This is not surprising based on the same reason; there is a limited amount of data. However, it would be really interesting to link these two data sets. Visibility data are scarce, but if possible, it would be a good idea for a next study to find at least one location where visibility data has a long historic history.

COMPARE PSANAF-5 with PSANAF-3

Due to only two comparison being significant, it is hard to compare the two source areas (PSANAF-5 and PSANAF-3). Still the p-values of the different source areas are compared with each other. The average of the p-values of PSANAF-5 is lower than the average of PSANAF-3. Overall the significance of comparisons with PSANAF-5 seems to be a little better. This might be an indication that PSANAF-5 has a larger effect on harmattan in West Africa. But it has to be taken into account that these values are all not significant, so it is only an assumption which could be checked with additional data. It was assumed earlier that PSANAF-5 would contribute more to the harmattan dust compared to PSANAF-3 because of the location and the Bodélé Depression which is located in PSANAF-5. It would be good to check to what extent this assumption is true.

On average there are 0 to 6 large wind events each harmattan season in PSANAF-5 and 0 to 3 large wind events in PSANAF-3. The total area that is part of those large wind events (the number of pixels) is larger in PSANAF-5 compared to PSANAF-3. PSANAF-5 has therefore more potential to be of significance.

If one of the areas can easily be excluded, it will be easier to work towards a prediction of the harmattan. This study does not give a clear exclusion of one of the areas, but does give an indication that PSANAF-5 might be more important.

Direction of the wind

In this research, the two dust source areas (PSANAF-5 and PSANAF-3) are used as input for the wind events. Within the borders of the source areas, all wind events (>15 m/s) are taken into account. This was done to give quick results on a possible correlation. However, it would be more precise if these comparisons are made combination with the (exact) wind direction. For example; wind surges in PSANAF-3 would only be interesting for Ghana if wind blows from the north, because only then dust plumes will reach that exact area. So the direction of the wind is an important aspect and can make the comparison much more reliable. Although, due to large scale wind-system, the wind is not expected to change drastically. The wind won't just turn 180 degrees, but a change of 20 degrees could already exclude specific locations. A next study that makes the same comparisons but takes the wind direction into account, is expected to see slightly improved results.

Seasonal predictor

The results of this study do not provide a direct solution for a seasonal harmattan predictor. It gives some potential ideas for successive studies. The comparison with the maximum latitude of the ITCZ gives hope for a possible predictor, but needs more research. In addition, the current comparisons can be improved by using extensive data sets or including new variables.

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Appendix

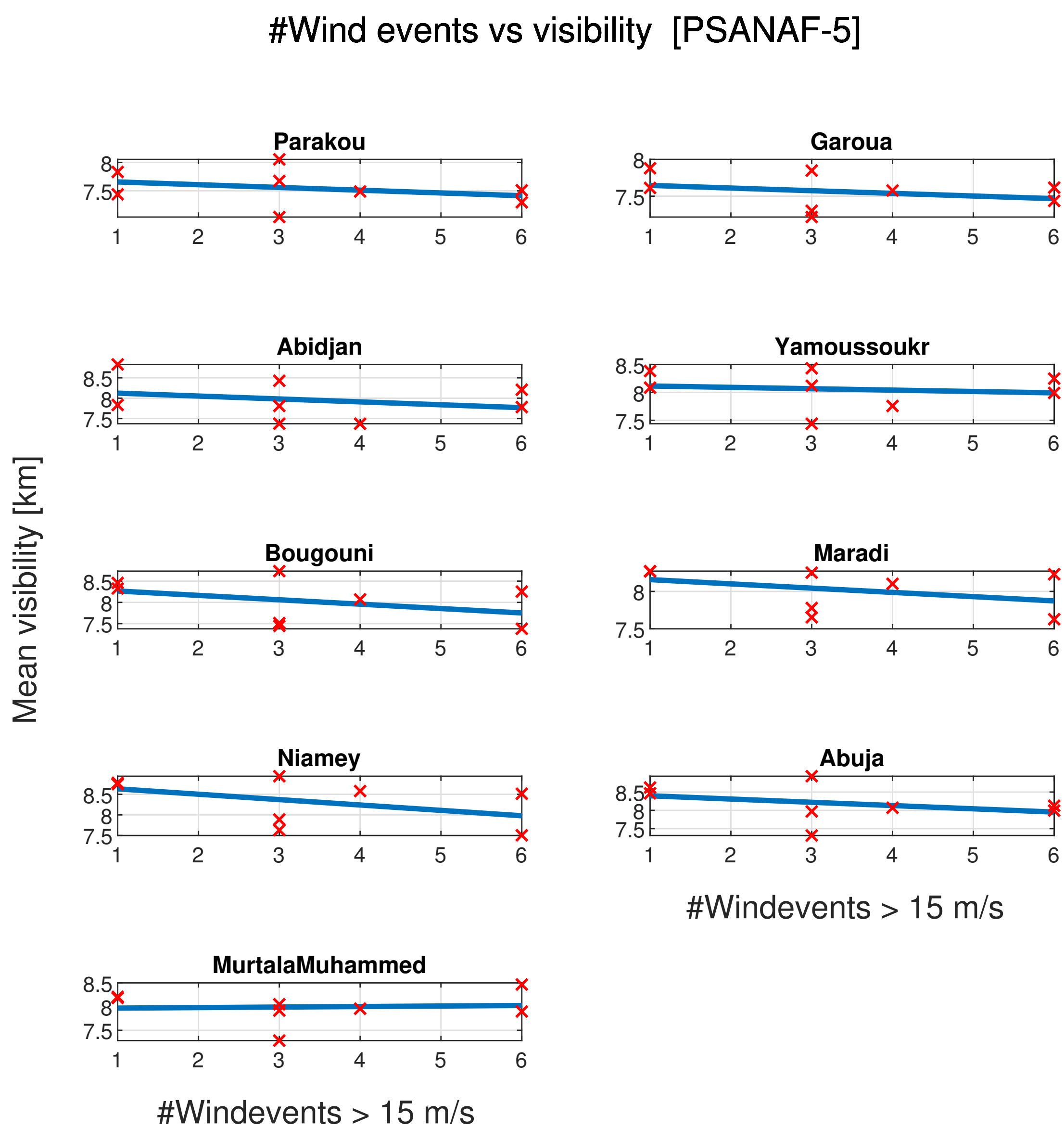


Figure 10: The plots above show the relation between the mean visibility data and the number of wind events per Harmattan season. Each plot shows the outcome of a different location. PSANAF 5 is used as source region of the wind data. The blue line shows a linear fit of the data points.

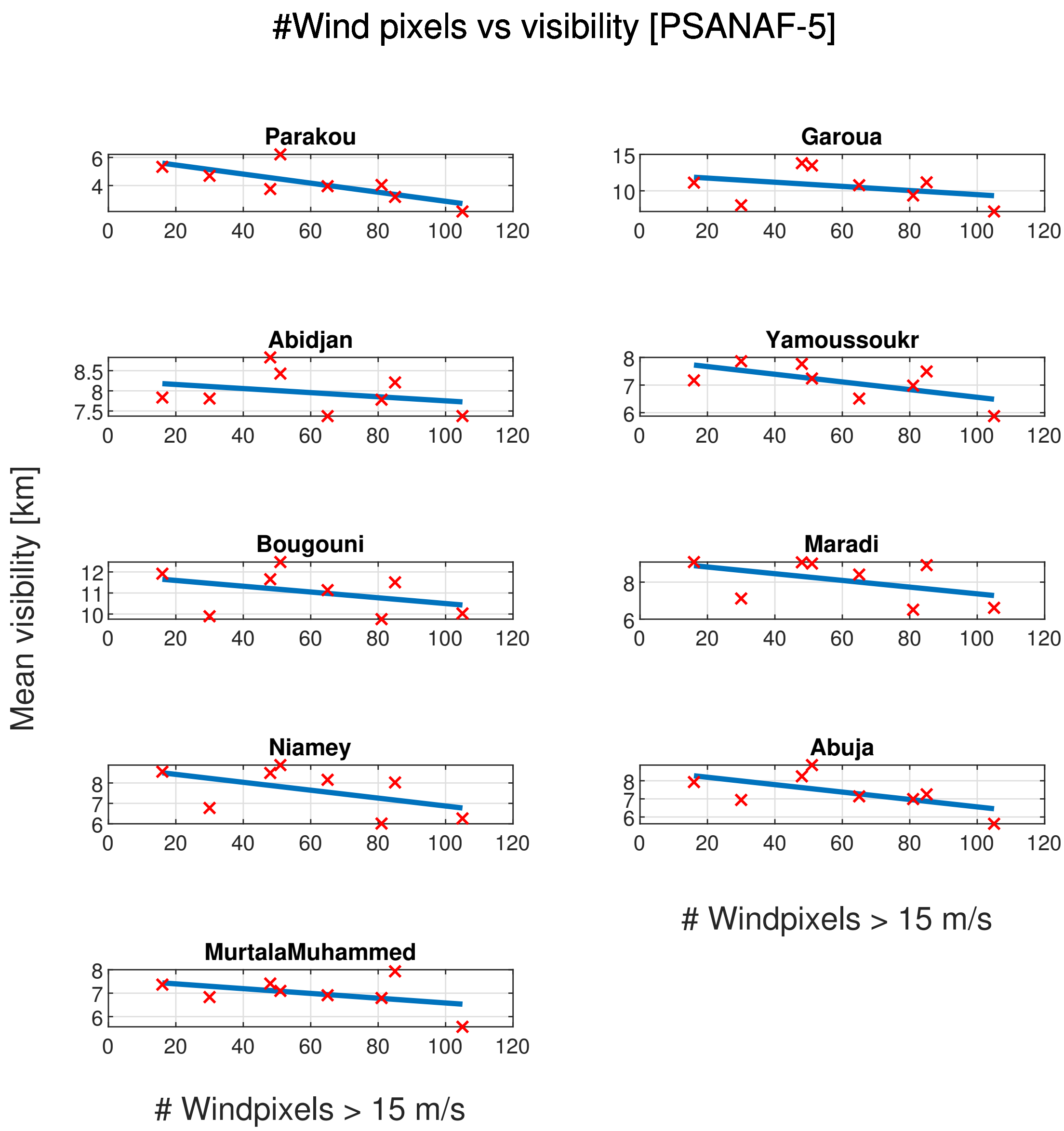


Figure 11: The plots above show the relation between the mean visibility data and the number of wind pixels of the wind events each Harmattan season. Each plot shows the outcome of a different location. PSANAF 3 is used as source region of the wind data. The blue line shows a linear fit of the data points.

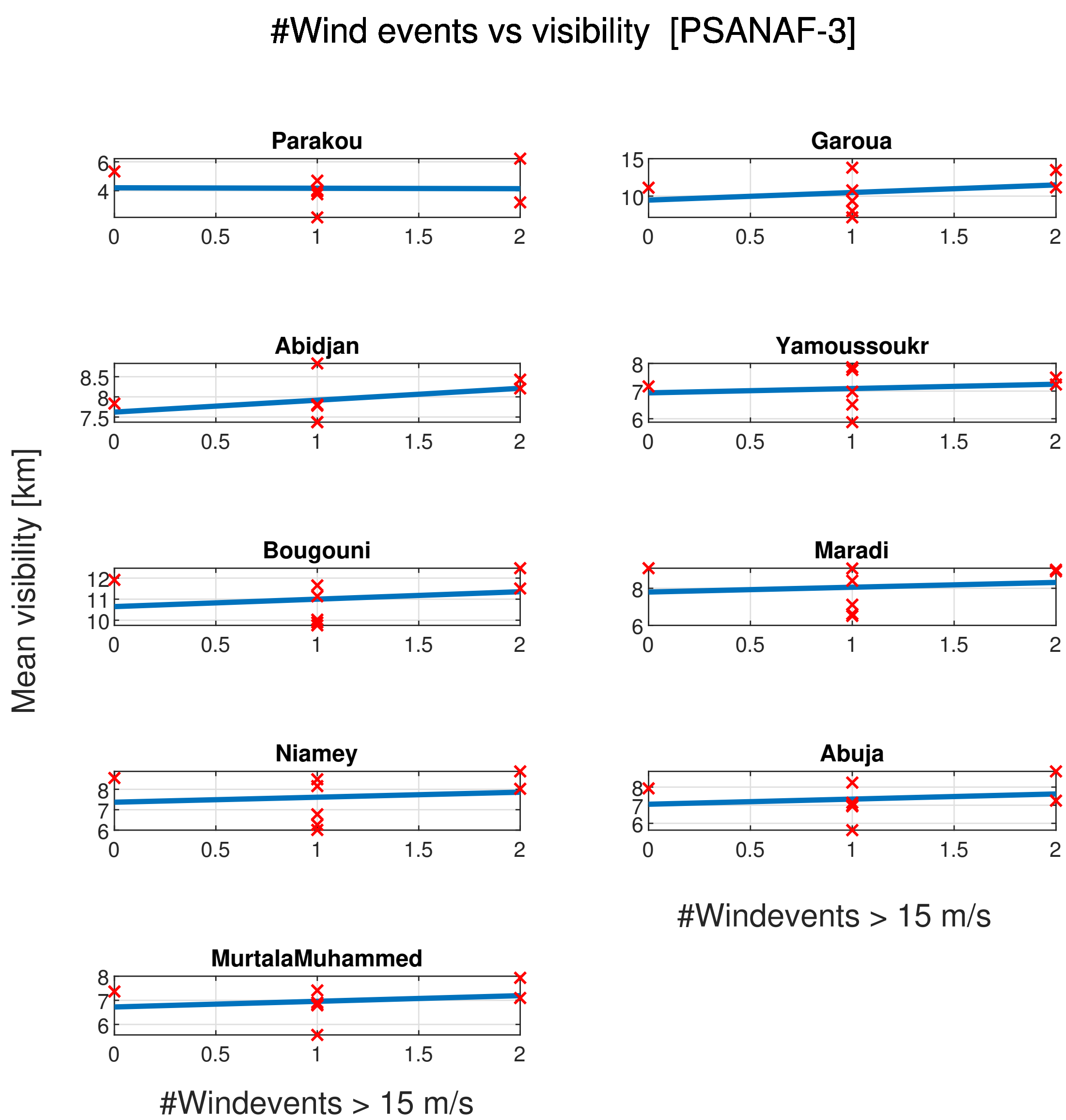


Figure 12: The plots above show the relation between the mean visibility data and the number of wind events per Harmattan season. Each plot shows the outcome of a different location. PSANAF 3 is used as source region of the wind data. The blue line shows a linear fit of the data points.

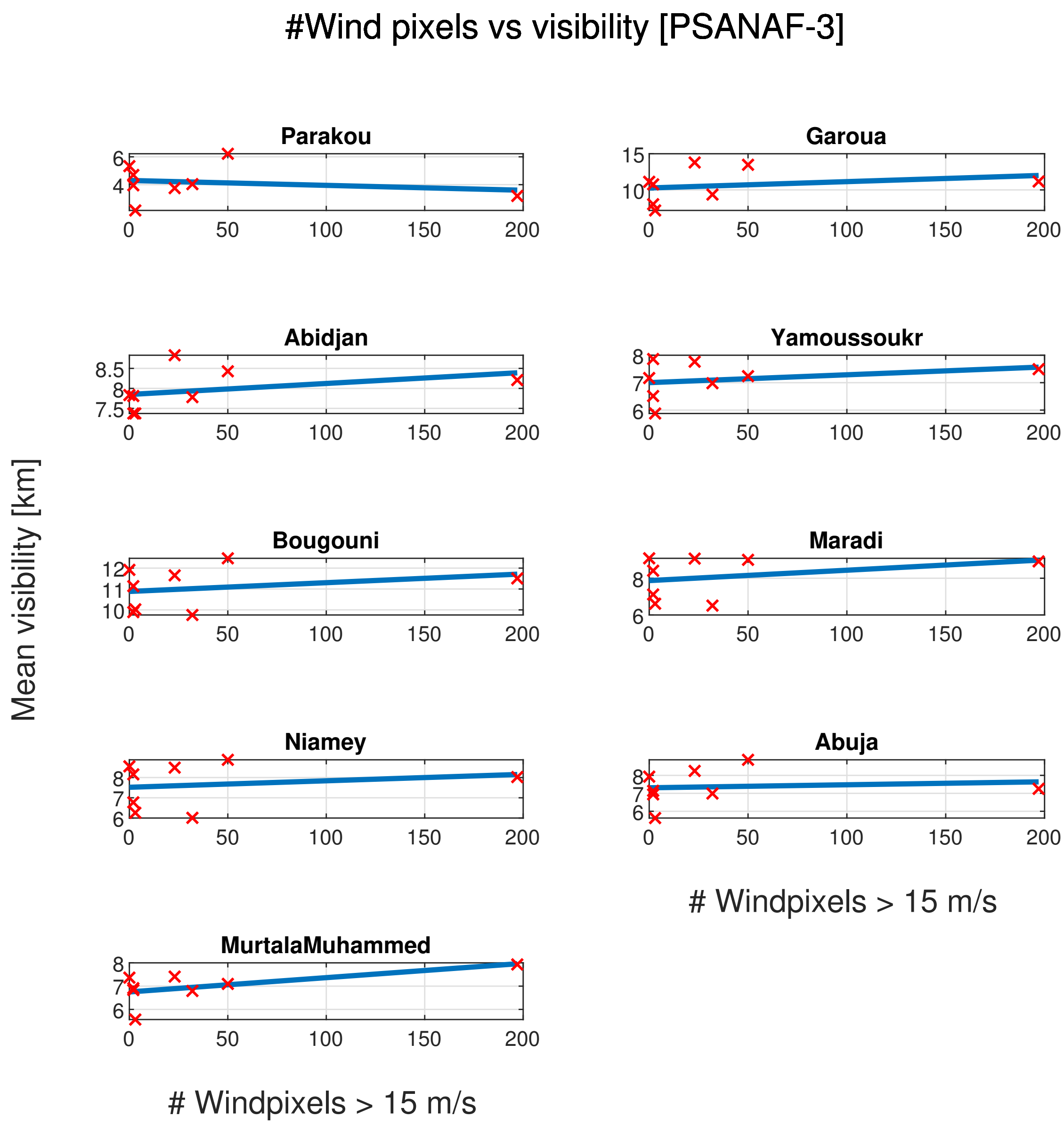
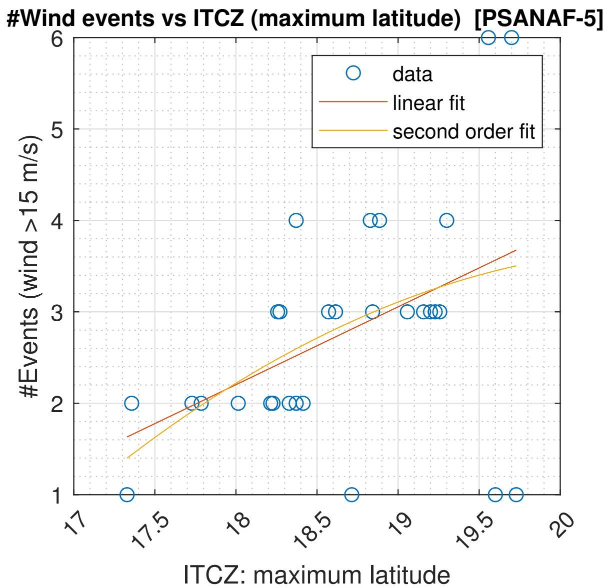
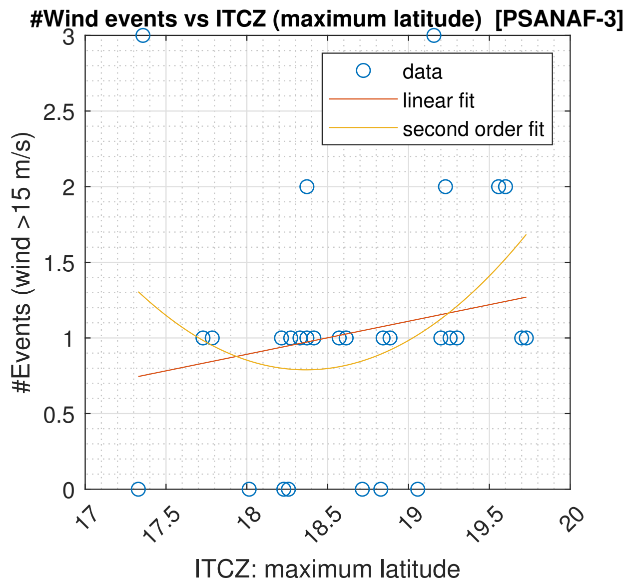


Figure 13: The plots above show the relation between the mean visibility data and the number of wind pixels of the wind events each Harmattan season. Each plot shows the outcome of a different location. PSANAF 3 is used as source region of the wind data. The blue line shows a linear fit of the data points.

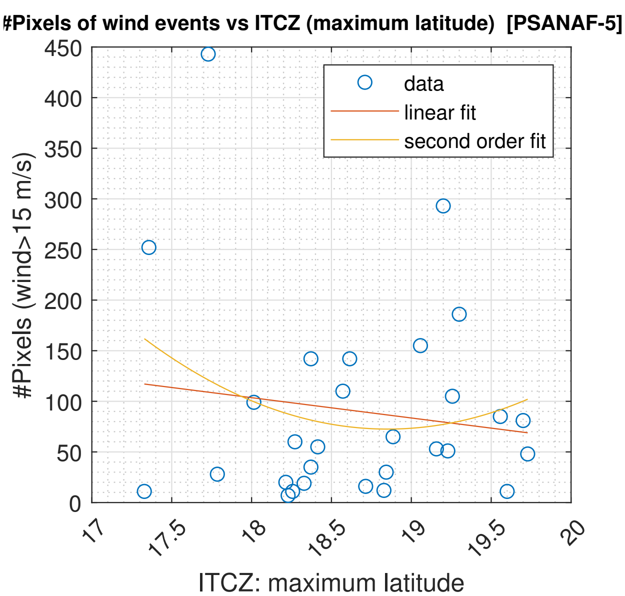


(a) PSANAF 5 is used as source region of the wind data

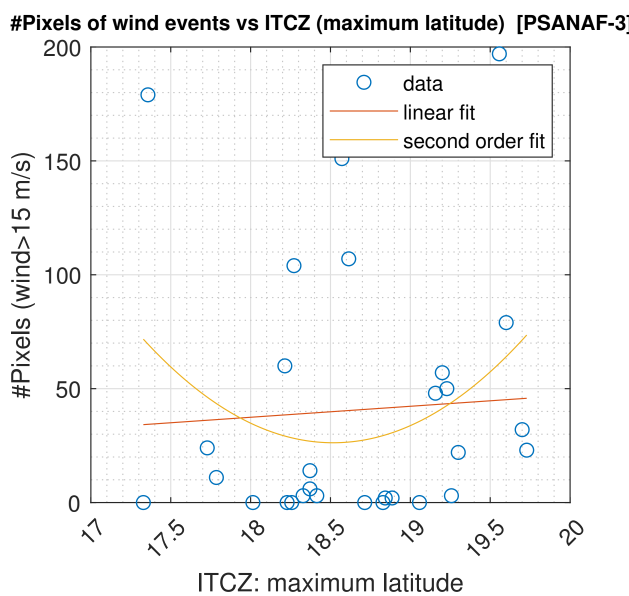


(b) PSANAF 3 is used as source region of the wind data

Figure 14: The plots above show the relation between the maximum ITCZ value prior to the harmattan season ('maximum ITCZ value') and the number of wind events per Harmattan season. PSANAF 5 is used as source region of the wind data in Figure A, PSANAF 3 is used in Figure B.

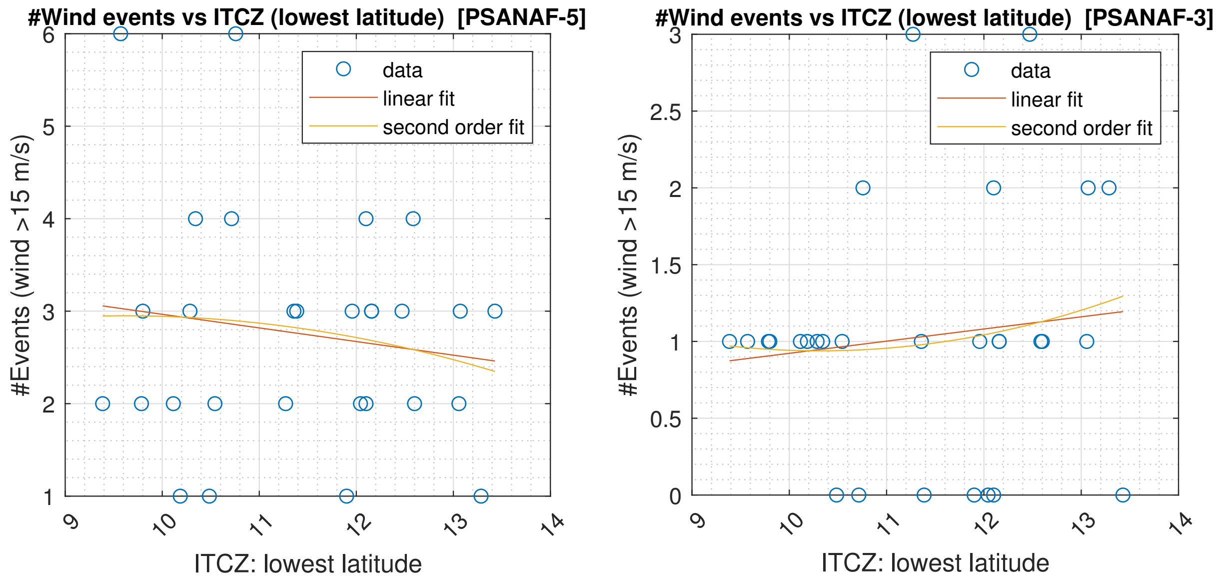


(a) PSANAF 5 is used as source region of the wind data



(b) PSANAF 5 is used as source region of the wind data

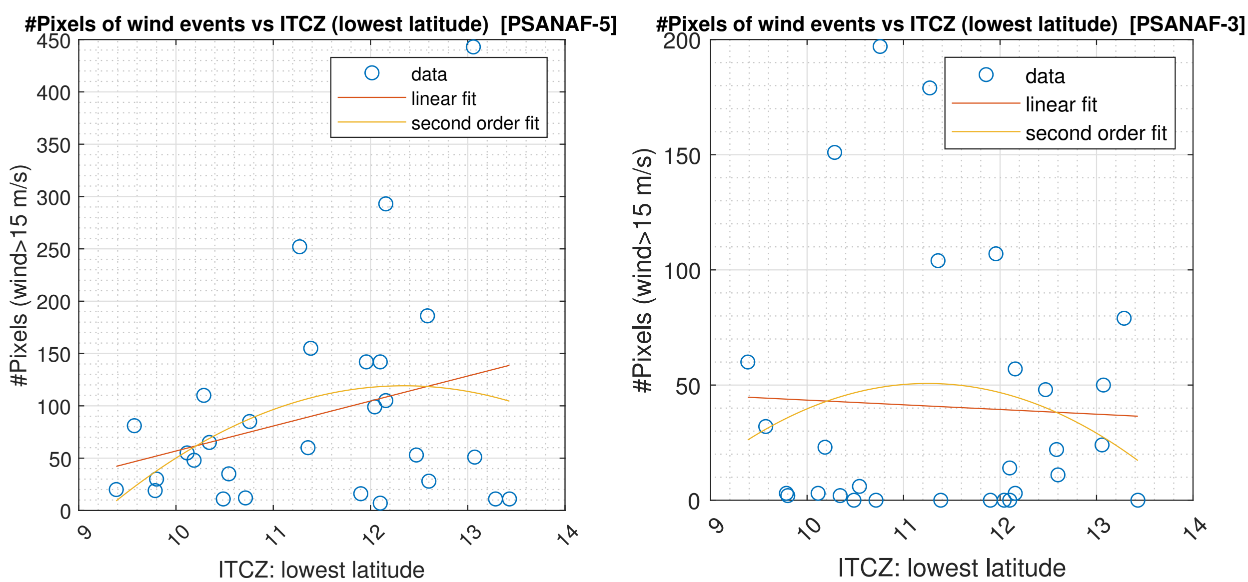
Figure 15: The plots above shows the relation between the maximum ITCZ value prior to the harmattan season ('maximum ITCZ value') and the number of wind pixels of the wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.



(a) PSANAF 5 is used as source region of the wind data

(b) PSANAF 3 is used as source region of the wind data

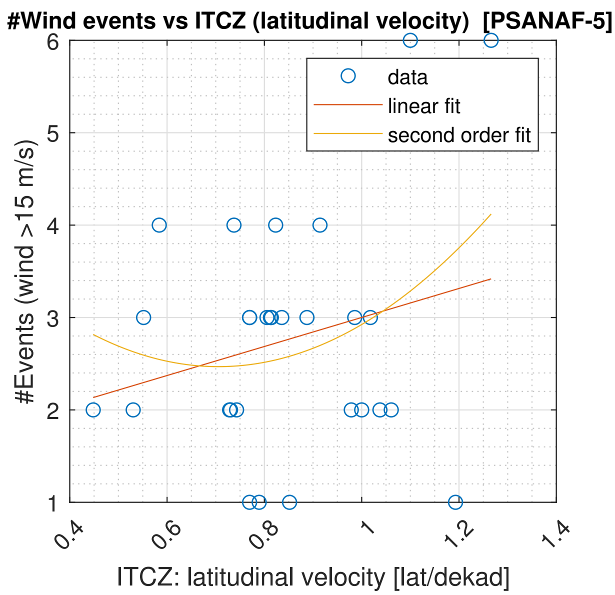
Figure 16: The plots above show the relation between the mean ITCZ value at the start of the harmattan season ('lowest ITCZ value')and the number of wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.



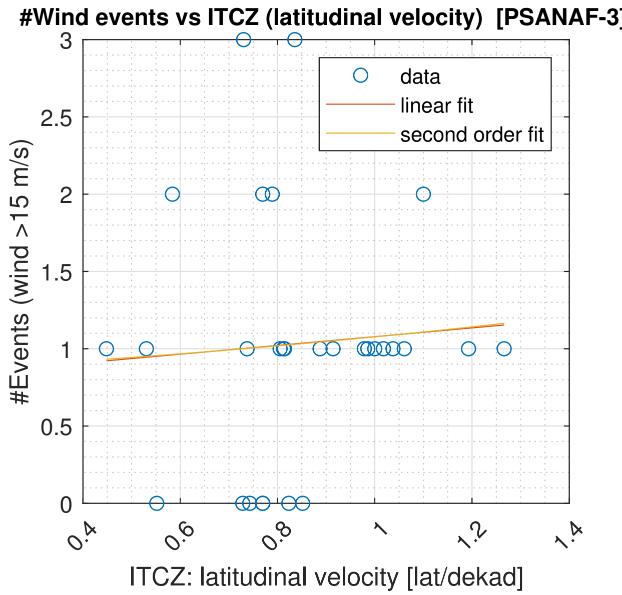
(a) PSANAF 5 is used as source region of the wind data

(b) PSANAF 5 is used as source region of the wind data

Figure 17: The plots above show the relation between the mean ITCZ value at the start of the harmattan season ('lowest ITCZ value') and the number of wind pixels of the wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.

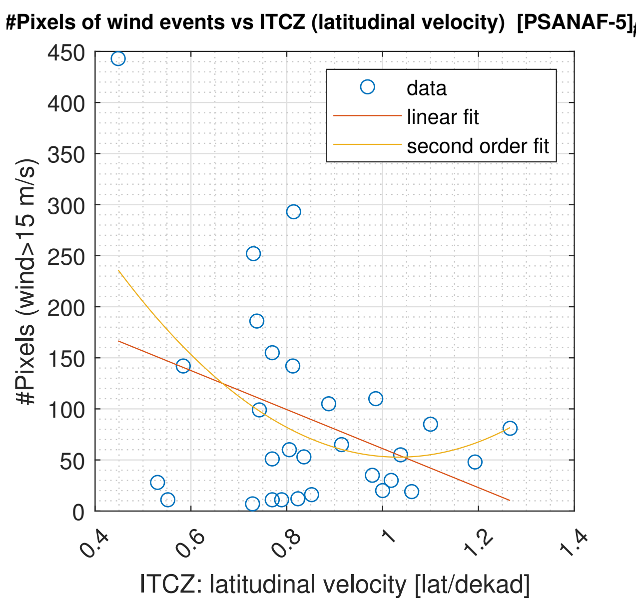


(a) PSANAF 5 is used as source region of the wind data

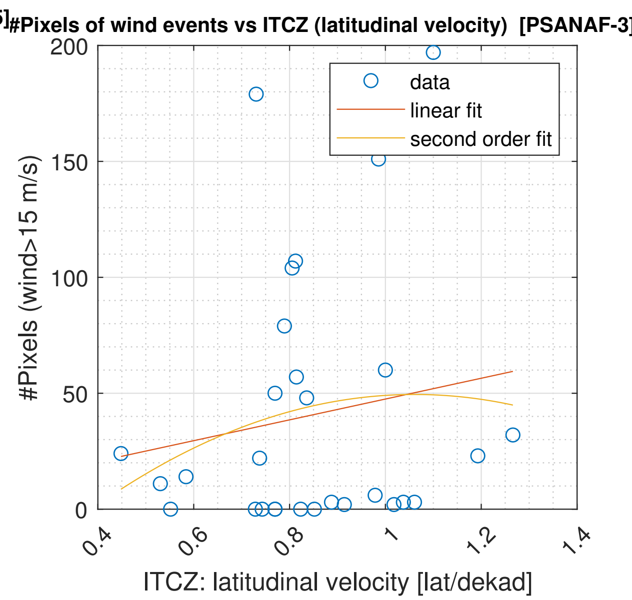


(b) PSANAF 3 is used as source region of the wind data

Figure 18: The plots above show the relation between the mean ITCZ velocity prior to the harmattan season and the number of wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.

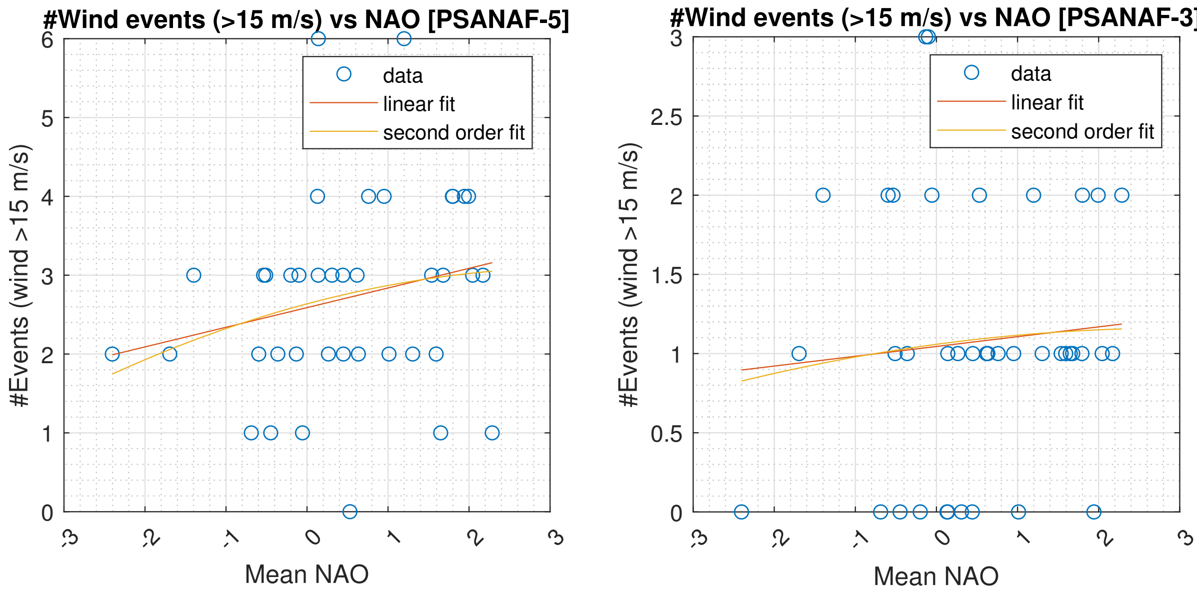


(a) PSANAF 5 is used as source region of the wind data



(b) PSANAF 5 is used as source region of the wind data

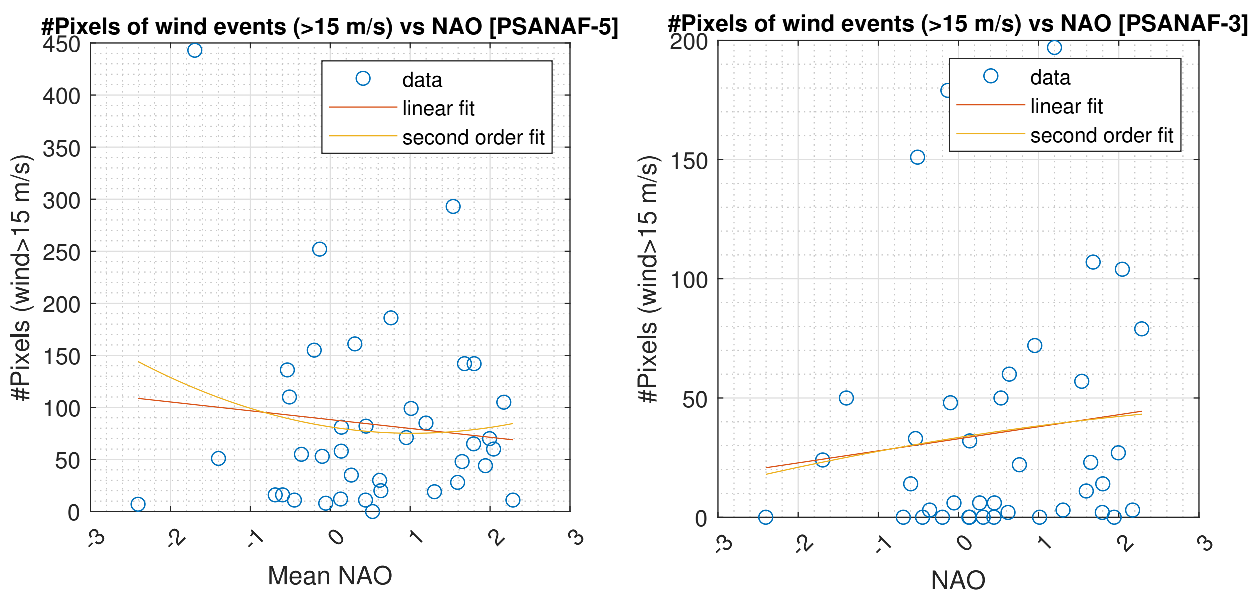
Figure 19: The plots above show the relation between the mean ITCZ velocity prior to the harmattan season and the number of wind pixels of the wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.



(a) PSANAF 5 is used as source region of the wind data

(b) PSANAF 3 is used as source region of the wind data

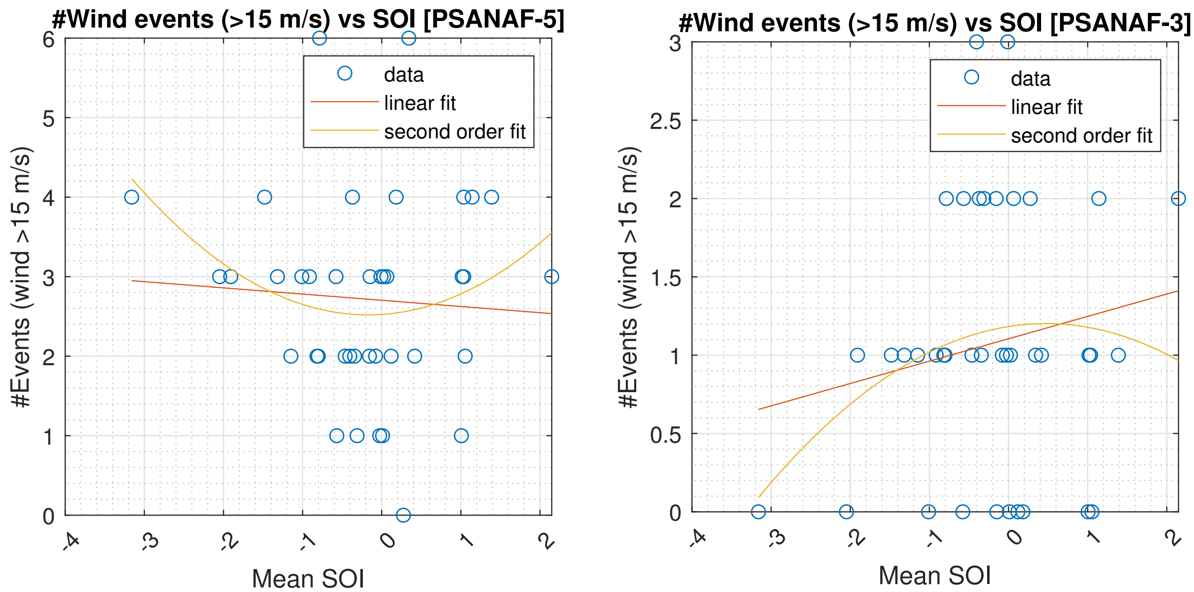
Figure 20: The plots above show the relation between the mean NAO value and the number of wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.



(a) PSANAF 5 is used as source region of the wind data

(b) PSANAF 5 is used as source region of the wind data

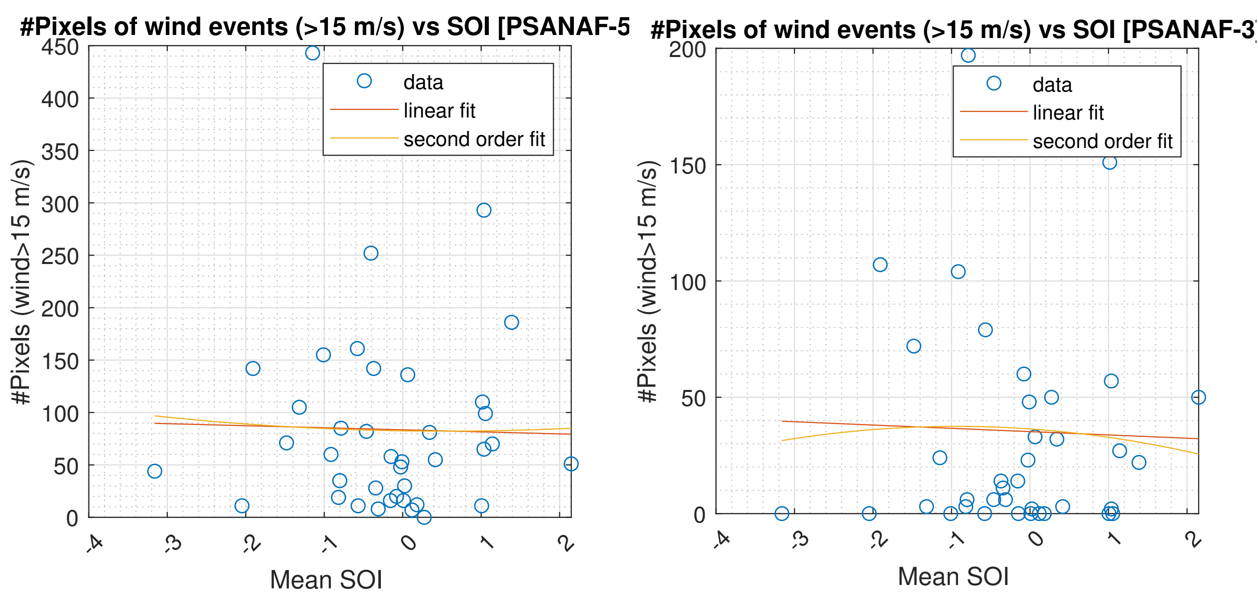
Figure 21: The plots above show the relation between the mean NAO value and the number of wind pixels of the wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.



(a) PSANAF 5 is used as source region of the wind data

(b) PSANAF 3 is used as source region of the wind data

Figure 22: The plots above show the relation between the mean SOI value and the number of wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.



(a) PSANAF 5 is used as source region of the wind data

(b) PSANAF 5 is used as source region of the wind data

Figure 23: The plots above show the relation between the mean SOI value and the number of wind pixels of the wind events per Harmattan season. PSANAF 5 and PSANAF 3 are used as source region of the wind data in Figure A and B respectively.

Table 4: This figure shows the P-, R^2- and R-values using the linear trend between two data sets.

P-value linear trend		NAO	SOI	ITCZ		
		Mean value	*Mean value*	*Maximum latitude*	*Minimum latitude*	*Velocity*
Wind data PSANAF-5	*# wind events*	0,180	0,703	0,016	0,470	0,217
	area of wind events	0,520	0,892	0,488	0,127	0,059
Wind data PSANAF-3	*# wind events*	0,616	0,286	0,360	0,548	0,734
	area of wind events	0,497	0,862	0,770	0,822	0,430

R-squared linear trend		NAO	SOI	ITCZ		
		Mean value	*Mean value*	*Maximum latitude*	*Minimum latitude*	*Velocity*
Wind data PSANAF-5	*# wind events*	0,048	0,004	0,198	0,020	0,056
	area of wind events	0,011	5,0133 e-04	0,018	0,084	0,136
Wind data PSANAF-3	*# wind events*	0,007	0,031	0,031	0,014	0,004
	area of wind events	0,013	8,3052 e-04	0,003	0,002	0,023

R linear trend		NAO	SOI	ITCZ		
		Mean value	*Mean value*	*Maximum latitude*	*Minimum latitude*	*Velocity*
Wind data PSANAF-5	*# wind events*	0,219	-0,063	0,445	-0,140	0,237
	area of wind events	-0,106	-0,022	-0,134	0,290	-0,368
Wind data PSANAF-3	*# wind events*	0,083	0,175	0,177	0,116	0,066
	area of wind events	0,112	-0,029	0,057	-0,044	0,153

Table 5: This figure shows the P-, R^2- and R-values using the linear trend between two data sets.

P-value linear trend		Visibility data (mean value)								
		Parakou	*Garoua*	*Abidjan*	*Yammoussoukr*	*Bougouni*	*Maradi*	*Niamey*	*Abuja*	*MurtalaM,*
Wind data	*# wind events*	0,475	0,481	0,516	0,735	0,345	0,351	0,266	0,398	0,885
PSANAF-5	*area of wind events*	0,028	0,385	0,473	0,098	0,331	0,241	0,194	0,102	0,276
Wind data	*# wind events*	0,971	0,511	0,362	0,720	0,601	0,732	0,741	0,661	0,603
PSANAF-3	*area of wind events*	0,660	0,557	0,380	0,489	0,516	0,429	0,653	0,789	0,121

R-squared linear trend		Visibility data (mean value)								
		Parakou	*Garoua*	*Abidjan*	*Yammoussoukr*	*Bougouni*	*Maradi*	*Niamey*	*Abuja*	*MurtalaM,*
Wind data	*# wind events*	0,088	0,086	0,074	0,021	0,149	0,146	0,200	0,121	0,004
PSANAF-5	*area of wind events*	0,581	0,128	0,089	0,390	0,157	0,220	0,263	0,382	0,193
Wind data	*# wind events*	0,000	0,075	0,139	0,023	0,048	0,021	0,020	0,034	0,048
PSANAF-3	*area of wind events*	0,034	0,061	0,130	0,083	0,074	0,107	0,036	0,013	0,352

R linear trend		Visibility data (mean value)								
		Parakou	*Garoua*	*Abidjan*	*Yammoussoukr*	*Bougouni*	*Maradi*	*Niamey*	*Abuja*	*MurtalaM,*
Wind data	*# wind events*	-0,016	0,274	0,373	0,151	0,220	0,145	0,140	0,185	0,219
PSANAF-5	*area of wind events*	-0,186	0,246	0,361	0,288	0,271	0,327	0,190	0,113	0,593
Wind data	*# wind events*	-0,297	-0,293	-0,271	-0,143	-0,386	-0,382	-0,448	-0,349	-0,062
PSANAF-3	*area of wind events*	-0,762	-0,357	-0,298	-0,625	-0,396	-0,470	-0,513	-0,618	-0,449