School of Geography and the Environment

Fieldwork Report

Essay Title: An investigation into how the differences in synoptic settings control the trade winds over Tenerife

Fieldwork Location: Tenerife

Word count: 3488

Introduction

This study aims to evaluate the differences in how the synoptic scale settings control the trade winds over Tenerife. It will do this by discussing the influence of the North Atlantic Oscillation (NAO) and neighbouring pressure systems on trade wind speed and direction. Synoptic scale systems occur over a spatial scale of hundreds to thousands of kilometres, and a temporal scale of 10 to 100 hours (Barry and Carleton, 2001), and include air masses and high- and low-pressure systems.

Background

Tenerife is situated at 28.3°N, 16.6°W (Figure 1) and is the largest of the seven Canary Islands, in terms of area (2,034km^2 (Veigasa and Iglesias, 2013)) and maximum height. It's location in the Atlantic subtropical belt puts it under the direct influence of the Azores high pressure anticyclone (Figure 2) and the trade winds (Herrera et al., 2001; Cropper and Hanna, 2014). This influence of the trade wind belt and the descending air associated with the Azores high makes Tenerife's climate generally very stable all year, with the presence of the Azores high often adding further stability by blocking Atlantic low-pressure systems from the island (Herrera et al., 2001).

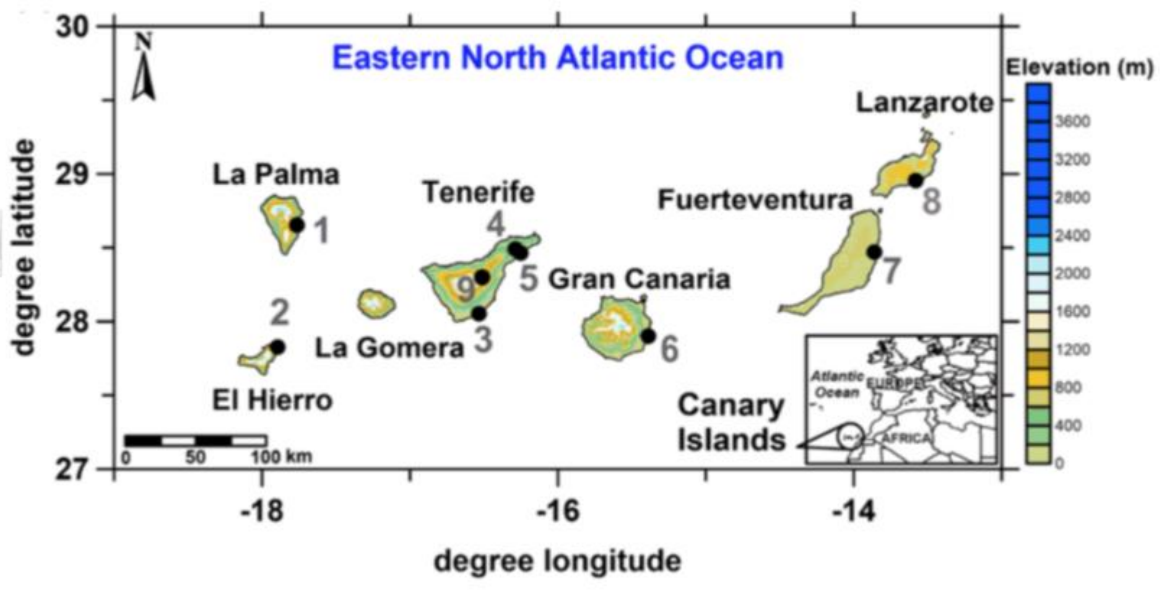


Figure 1 – Map of the Canary Islands (Azorin-Molina et al., 2018).

The presence of Tenerife's stratovolcano 'El Teide' results in orographic impacts on mesoscale and synoptic forcings. Its steep orography makes the island sensitive to minor changes in synoptic controls

(Herrera et al., 2001). The high barrier often intercepts low-level airflow (Smith, 1979) and results in the trade winds splitting and flowing around the mountain in currents (Leopold, 1949). However, this is largely dependent on the height of the trade wind inversion layer, which determines whether air can flow over the top of the mountain (Durran, 1986). The height of 'El Teide' also results in orographic lifting as cold moist air is forced to rise and is cooled adiabatically to form a belt of clouds known as the 'sea of clouds' (Sperling et al., 2004).

The position of Tenerife on a synoptic scale is very important when studying winds because of its central location between two influential circulation systems and makes the island a key region for observing wind variability associated with neighbouring pressure systems. Because of its location, the island can be affected by both north-easterly trade winds and westerly winds, with the dominance of these particular circulation features being partly determined by the strength of the NAO. During the positive phase of the NAO the Azores high is stronger than normal, there are stronger westerly winds across the midlatitude north Atlantic (Herrera et al., 2001), and north-easterlies tend to dominate the climate of Tenerife (George and Saunders, 2001). Whereas, a negative NAO often reflects a weakened influence of the trade winds. The NAO index shows the strength of the oscillation and is calculated by the anomaly difference in sea level pressure between the Azores and Iceland (Herrera et al., 2001). Neighbouring pressure systems, such as the Azores high or occasional cyclonic low-pressure systems coming from the north Atlantic (Fernandopulle, 1976), can influence the behaviour of the trade winds and alter the stability of climatic conditions around Tenerife (Azorin-Molina et al., 2018).

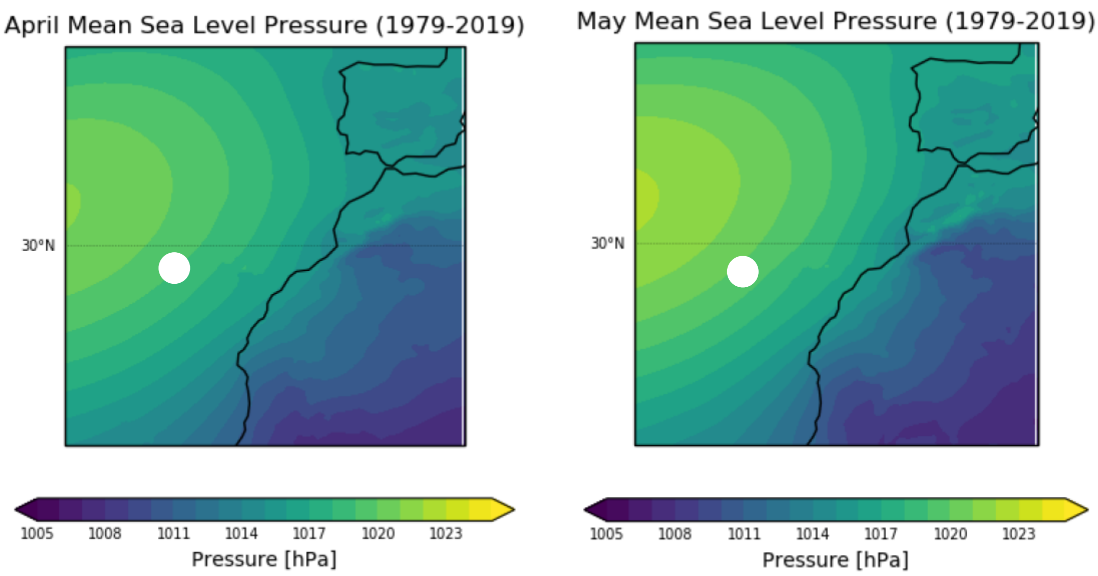


Figure 2 – Graphs showing the mean sea level pressure for April and May indicate the presence of the Azores high to the north-west of Tenerife. White dot indicates Tenerife. Generated from ERA5 monthly mean sea level pressure dataset.

Tenerife’s lower troposphere can be separated into two layers (Alarcon et al., 2011). The cold, moist bottom layer, known as the marine boundary layer (MBL), is affected by the north-easterly trade winds which bring Mediterranean or south European air masses to Tenerife. Meanwhile the top layer is the very dry free troposphere which is affected by the midlatitude westerlies. The trade wind inversion layer (TWI) sits at an altitude that fluctuates around 900hPa (Carrillo et al., 2016), and decouples these two different layers (Alarcon et al., 2011). This inversion forms because of the interaction between convection-driven rising air from lower levels and large-scale subsiding air from the descending limb of the Hadley cell (Albrecht, 1984; Cao et al., 2007), and is characterised by a temperature inversion whereby temperature increases with height (Raes et al., 1997). The TWI height, which fluctuates diurnally, determines the depth of the trade wind layer and affects island airflow (Chen and Feng, 2001). It also caps the convective processes beneath it to prevent the MBL air from rising to the level of free convection (Stevens et al., 2001), which can be an important determinant in forcing the trade winds to flow around ‘El Teide’ rather than over it if the base height lies below the mountain peak (Leopold, 1949).

This study will look at two questions in order to investigate how the differences in synoptic settings control the trade winds:

1) How does the NAO influence the trade winds?
2) How do neighbouring pressure systems influence the trade winds?

While this study focuses on the synoptic scale forcings, trade wind flow over Tenerife is also complicated by wind regimes at a mesoscale, such as land and sea breezes and mountain-valley regimes (Leopold 1949; Jury and Spencer-Smith, 1988), which are likely to affect the results of this study.

As well as being beneficial for climatological research, this study is relevant to the development of offshore wind energy farms (Veigas and Iglesias, 2013; Mederos et al., 2011) and the impacts of African dust particles on the Canary Islands (Viana et al., 2002).

Methods

This study has chosen to focus on data over four days in April for both 2016 (24th-27th) and 2017 (23rd-26th), with this data having been collected in previous years. These years were chosen because they show some contrasting conditions which will enable the study to try to understand how differences in the synoptic setting control the trade winds. Although the time periods studied are short, it offers a dynamic range of data because April is part of the subtropical transitional season where there are large variations in the dominant synoptic scale circulations. The data used is pilot balloon (PIBAL) tracking and an automated weather station (AWS). The data was collected from two locations, Puerto de la Cruz and Guimar, as shown in Figure 3. This study will only look at the data collected from Puerto as this is on the northern side of the island where the trade winds are generally better captured when considering their direction. Radiosonde soundings and reanalysis data were also used in this study to provide further information.

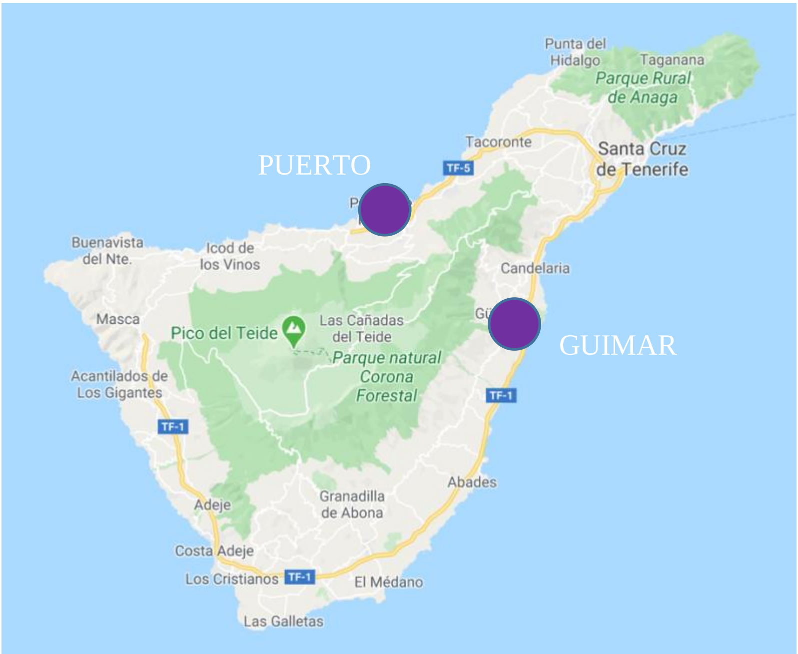


Figure 3 – A map of Tenerife, with the two purple circles indicating the sampling sites.

Pibal Tracking

Helium balloons were released roughly every half an hour throughout the day from each site, with measurements being taken at 30 second and then one-minute intervals until the balloon could no longer be tracked. A Theodolite was used to measure the azimuth and angle of elevation, and from this the ascent rate of the balloon was calculated (Equation 1) which is used to give measurements for wind speed and direction. This method is the same as used by Washington et al. (2006) to measure dust and low-level circulation over the Bodele Depression.

$$V = \frac{83.34\sqrt{L}}{(L + W)^{1/3}}$$ (Equation 1)

Identifying the inversion layer

The TWI layer was identified using raw data from radiosonde soundings taken at Guimar. Soundings were available at 00Z and 12Z for each day, however in this study only the data from 00Z is used. The inversion layer height is the altitude at which the temperature starts increasing with height rather than decreasing. This height was identified to detect which wind speeds were associated with the trade winds and which were associated with the boundary layer or the free troposphere above.

Limitations

While I did not collect the data used in this study, there are some issues that may have occurred during data collection which could result in limitations.

Balloon tracks:

- There is an assumption that the balloons have a constant ascent rate, however this is sometimes not the case. For example, turbulent eddies near the surface might alter the rate.
- Tracks are often lost early on due to the fact that they go behind heavy cloud cover, buildings or the sun. This means that the tracking profiles are often not very complete.
- The equipment is susceptible to human error.
- There are small uncertainties in calculating the lift when adding weights to the balloon.
- If the theodolite is not perfectly flat on the ground, or is not correctly calibrated to north, then the readings will be incorrect.
- Balloons are tracked by eye, and the ability to see balloons can be affected by local atmospheric conditions such as low-level fog in the morning or air pollution.

AWS data:

- At Puerto the data was taken on a hotel roof which was at a higher altitude and much further inland than the theodolite, meaning it is likely that there are inconsistencies between PIBAL and AWS wind data.

Radiosonde soundings:

- This study uses the Puerto site for the rest of its data, but radiosonde soundings are only taken from Guimar. However, this should not affect the conclusion because the inversion is a largescale feature of the general circulation and so it is a fair assumption that its altitude does not change between the different sites.
- On 25/04/16 no data was available and so the inversion height is extrapolated from the previous day.

Results

Recorded wind patterns using PIBAL tracking

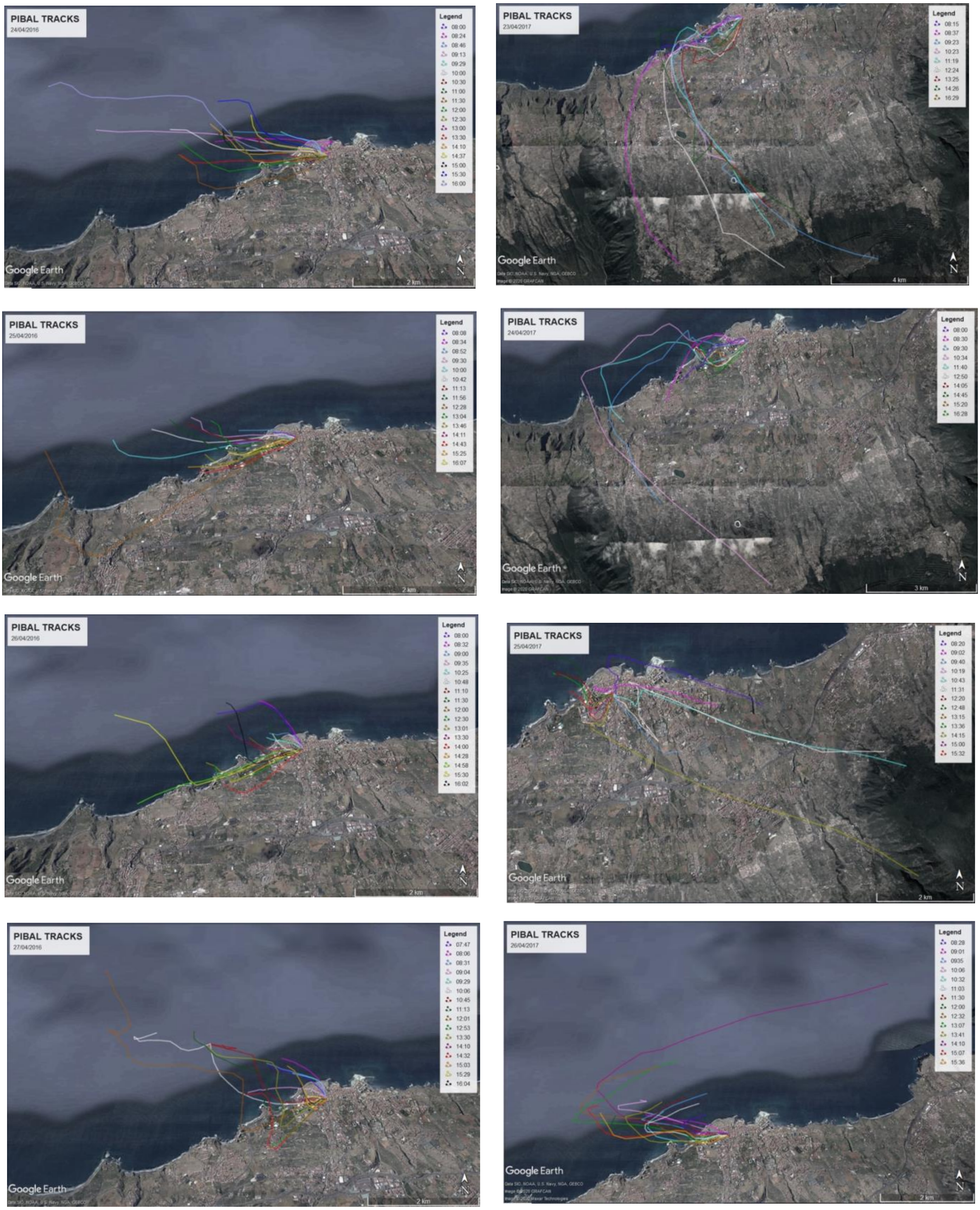
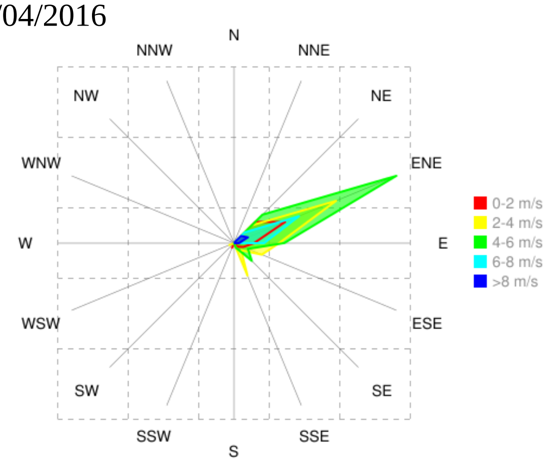


Figure 4 – PIBAL data overlying Google Earth to show the pathways of tracked balloons for 2016 and 2017 datasets. The legend shows the time of each balloon track. Plots created using Google Earth.

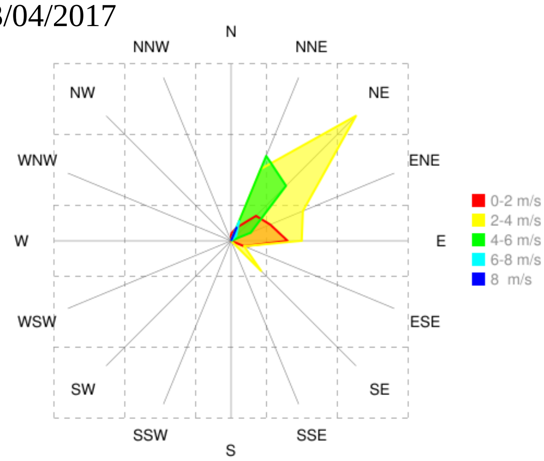
Figure 4 shows the PIBAL tracks recorded from Puerto in 2016 and 2017. Neither the 2016 nor 2017 plots show the expected north-easterly direction of the trade winds. For 2016 the direction of the trade winds are quite consistently easterly. Meanwhile, the 2017 plots show a range of directions that begin with northerly on the 24th and move to north-westerly for the 25th and 26th. On the 27th the wind's direction seems to reverse what is seen earlier in the week. The deeply incised topography of the island above Puerto forces the balloons offshore, with the tracks turning at different points being largely explained by the fact that balloons are different sizes which affects their ascent rate, with the topography having different influences at different heights.

Trade wind direction

24/04/2016



23/04/2017



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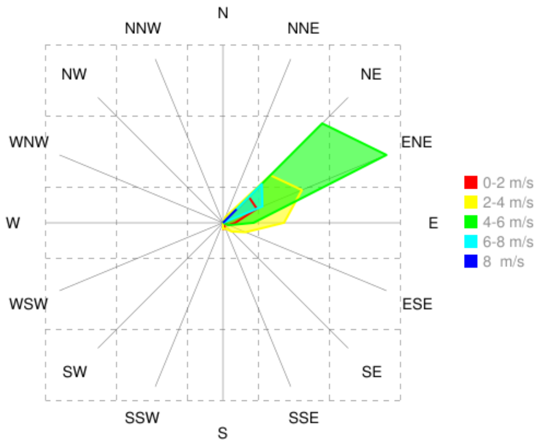

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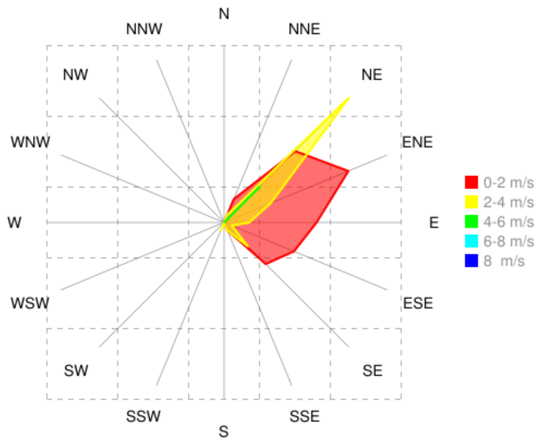

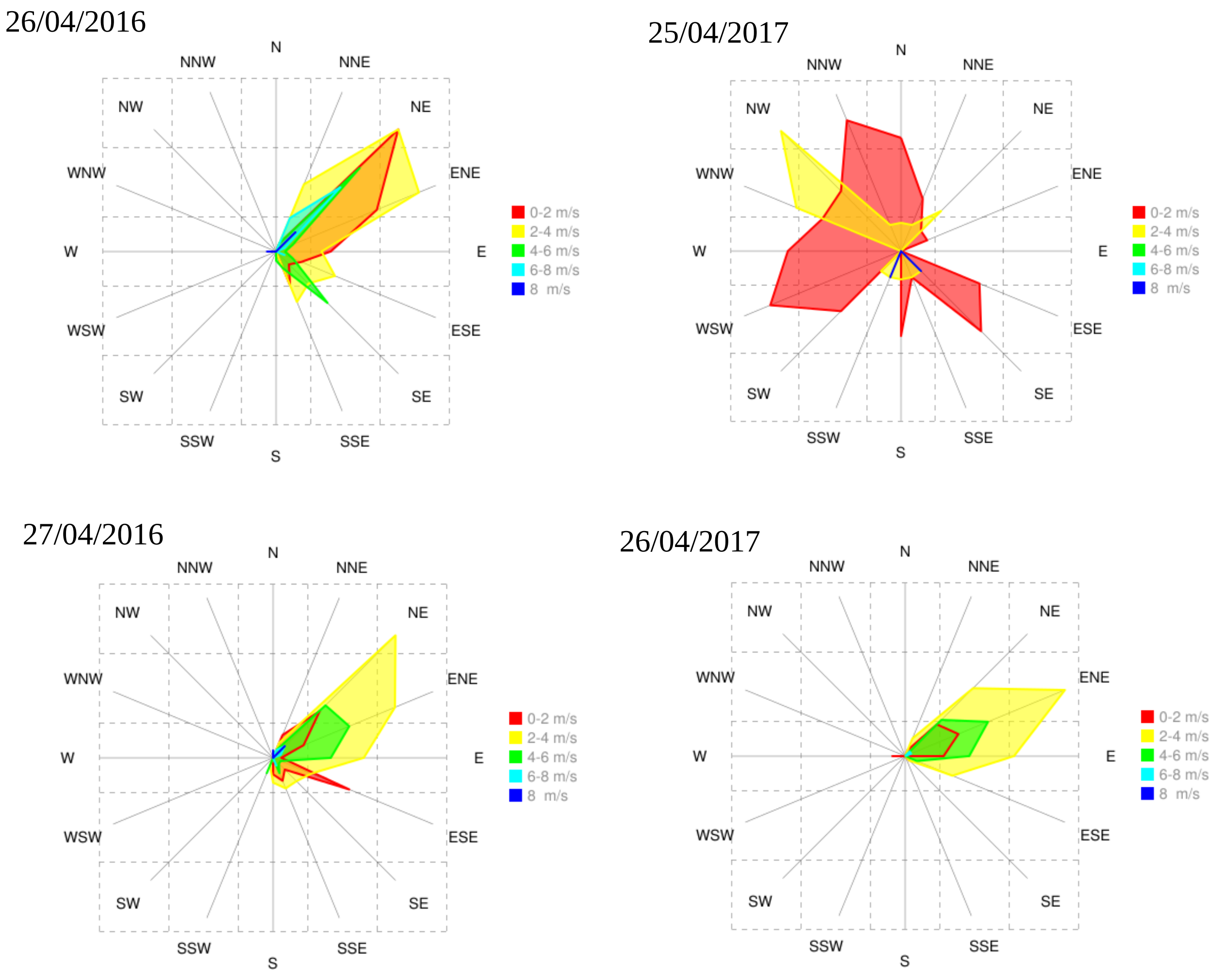

Figure 5 – Wind roses to show the average trade wind speed and direction of the recorded data for 2016 and 2017. Wind roses generated on www.enviroware.com.

Figure 5 shows that NE and ENE trade winds dominated in both 2016 and 2017. Although on 25/04/2017 wind direction shifts to a mainly northly to westerly direction. Wind speed averages are seemingly more variable than direction. 2016 wind speeds tend to range between 2 and 6 m/s, whereas for 2017 the 23th and 26th see similar speeds to 2016 but the 24th and 25th see slower speeds of mainly 0-2m/s.

Trade wind speed and daily NAO index

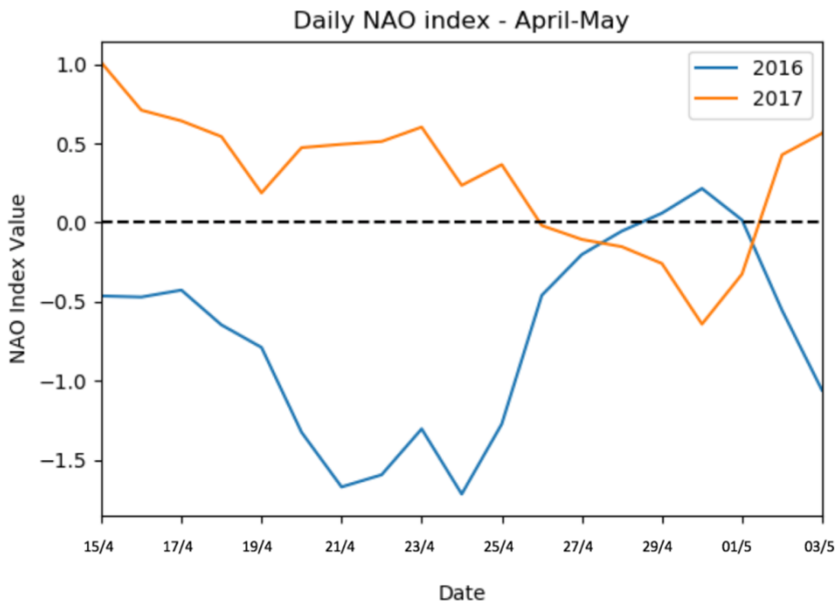

Figure 6 – Daily NAO index values for 2016 and 2017. Source: ftp://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.index.b500101.current.ascii.

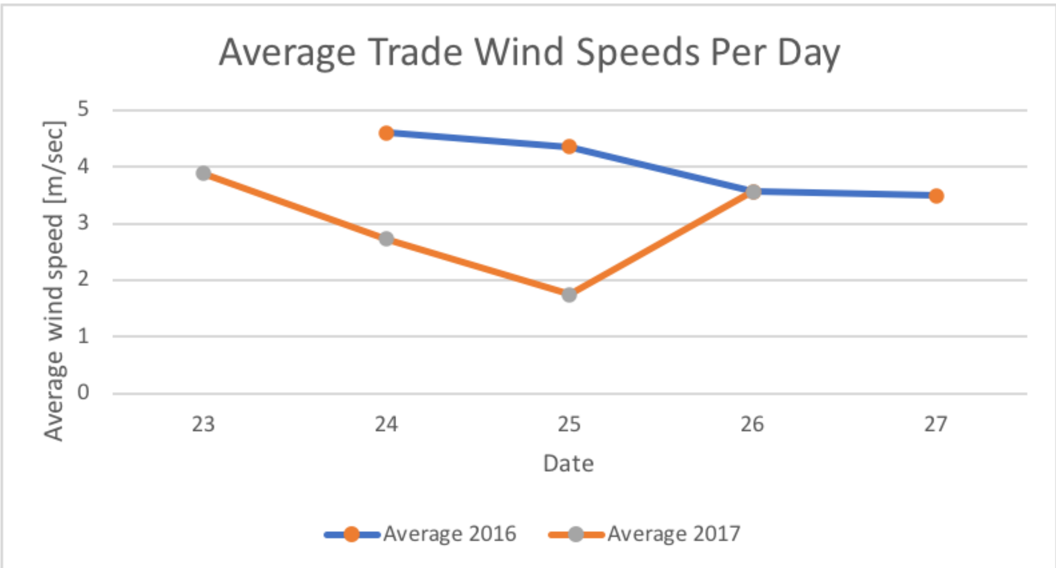

Figure 7 – Average daily trade wind speed for the 2016 and 2017 datasets based on averaged PIBAL data.

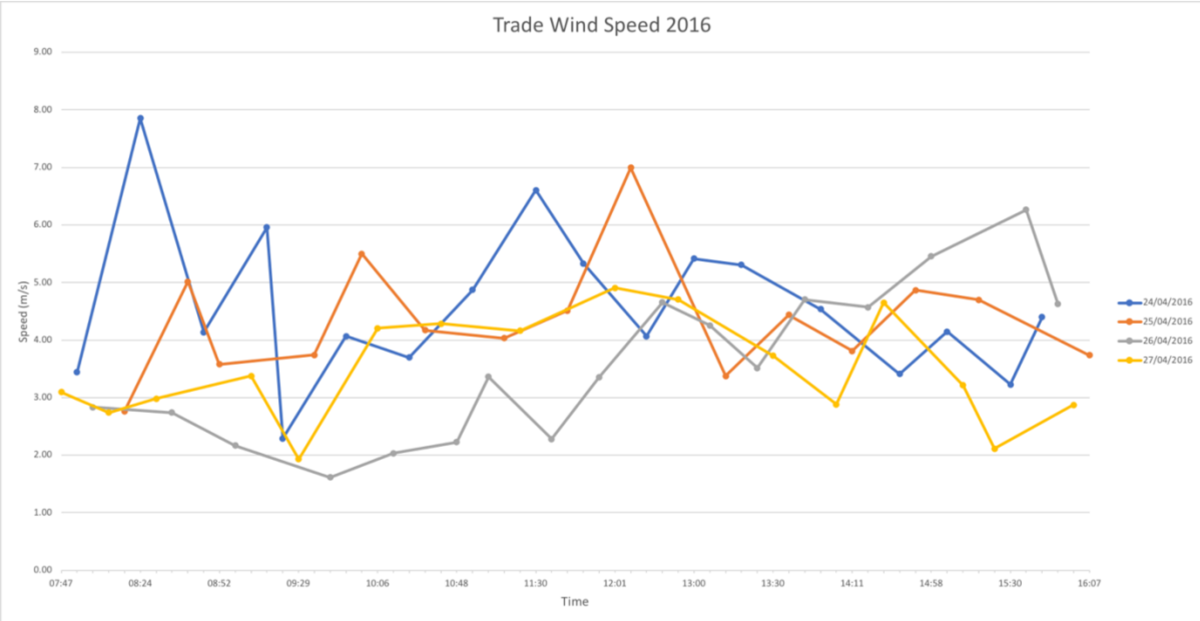

Figure 8 – Average trade wind speed by time of day based on averaged PIBAL data, for all four days for 2016.

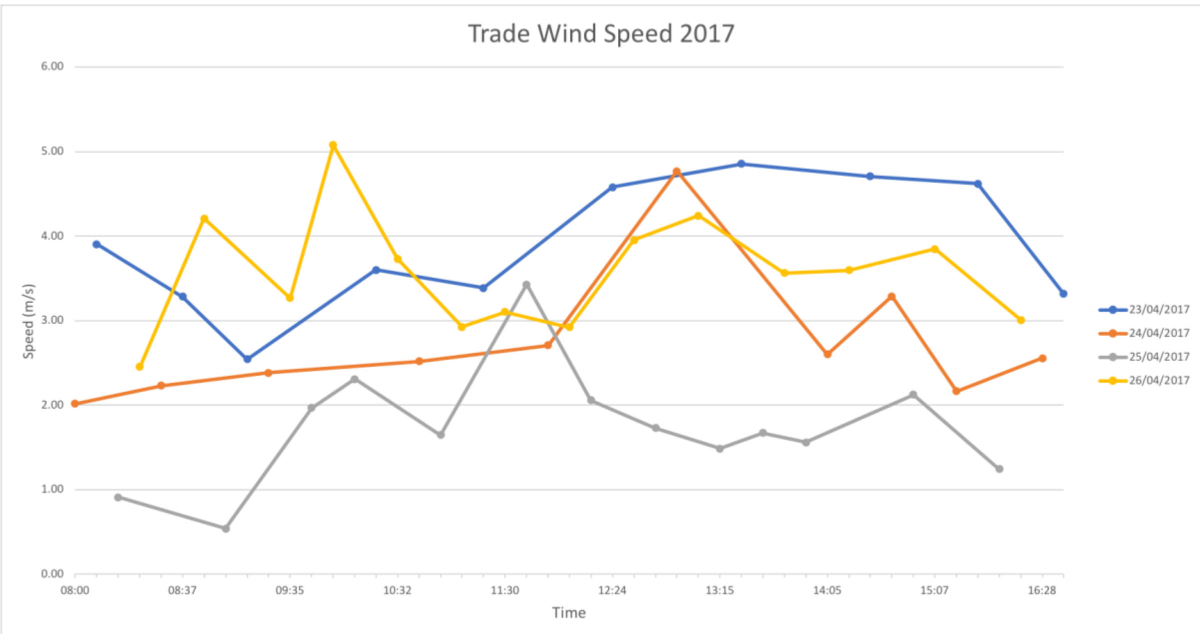

Figure 9 – Average trade wind speed by time of day based on averaged PIBAL data, for all four days for 2017.

Figure 6 shows the difference in the NAO index for 2016 and 2017. 2016 experienced a largely negative NAO phase, with the index during the study period of 24th-27th showing an increase from -1.716 to -0.202. Meanwhile, the study period in 2017 (23rd-26th April) showed a generally weak positive phase with the index decreasing from 0.603 to -0.019.

Figure 7 indicates the average trade wind speeds per day. 2016 speeds were more consistent and higher, reaching a maximum average speed of 4.6 m/s on the 24th April and a minimum speed of 3.49 m/s on the 27th. 2017 speeds fluctuated, decreasing quite significantly from the 23rd April (3.88 m/s) to the 25th (1.74 m/s), before then increasing again to 3.56 m/s on the 26th.

The average trade wind speeds by time of day (Figures 8 and 9) indicate that for 2016 the trade wind speeds ranged from 1.62 – 7.85 m/s and for 2017 the range was 0.54 - 5.08 m/s. These ranges are quite similar, with 2016 having a slightly higher overall trade wind speed average throughout the day than 2017.

An equal variance two-tailed two sample t-test was undertaken to test for a statistically significant difference between the average wind speeds per day in 2016 and 2017. This test was chosen because it allows us to determine whether the means of two sample data sets are different. A t_{stat} of 1.842 and a $t_{critical}$ of 2.447 (at 5% significance level) indicated that there was no significant difference between average wind speeds in 2016 and 2017. This was also the case at a 10% significance level.

A Pearson's Correlation Coefficient test was conducted to test the strength of the relationship between the NAO index and the average trade winds speeds per day for 2016 and 2017. This test was chosen because it provides a measure of the intensity of the linear relationship between two variables. For 2016 there is a significant inverse (negative) correlation between these two variables at a 1% significance level ($r = -0.992$, $t = -11.11$, $p<0.01$). However, for 2017 there is no significant correlation ($r = 0.0303$) at any significance level. The test deemed that NAO did have an effect on the trade wind speed measured in 2016 but not in 2017.

Discussion

Synoptic influence of the NAO on the trade winds

The Azores high drives the predominant north-easterly trade winds that influence the climate of Tenerife, and these winds have a significant effect on precipitation distribution and TWI layer characteristics. Therefore, it is important to understand the influence of synoptic scale factors such as the NAO on the trade winds and their speeds.

During the 2016 study period the NAO was in its negative phase (Figure 6), which generally means a weaker Azores high, weaker midlatitude westerlies and a weakened influence of the easterly trade winds on the climate of Tenerife. However, for the 2017 study period the NAO was in its positive phase which indicates that the Azores high and the westerlies were stronger than usual, and there was a stronger influence of the trade winds on Tenerife. A statistical test was conducted which showed a strong negative correlation between the NAO index and average trade wind speed data in 2016, with the conclusion suggesting that as the NAO became less negative the average trade wind speed decreased. This does not coincide with the idea that a more positive NAO phase results in stronger trade winds in the subtropical Atlantic that affect the Tenerife climate. Furthermore, there was no significant correlation between NAO index and average trade wind speed in 2017, which puts into question what this data shows about the synoptic scale influence of the NAO on the trade winds flowing over Tenerife.

Average trade wind speeds in 2016 are generally slightly higher than those seen in 2017, despite the fact that the positive NAO phase (and thus expected stronger influence of the trade winds) is seen in 2017. Also, the paired t-test conducted indicates no significant differences between the speeds in 2016 and 2017, yet there are significant differences between the NAO index values for these two years.

Herrera et al. (2001) suggested that the NAO is a key control of Tenerife's climate and has a significant influence on trade wind variability. However, the results concluded from the data used in this report do not support this. For the 2016 study period there is a significant relationship between the NAO index and average trade wind speed, however this correlation is not in the direction that is expected (where a more positive index results in faster trade winds) given the understanding of how the NAO influences the winds. As for 2017, there seems to be no correlation between the average trade wind speeds and the NAO index, which not only questions the direction of influence the NAO has on trade winds, but also questions whether the influence exists at all. The understanding of how the NAO controls the climate of Tenerife is well studied (e.g. Herrera et al., 2001), and therefore it is most likely that either the data collected was not representative of the climate at the time, or there were other influences affecting the trade wind speeds, for example mesoscale impacts such as onshore and offshore sea breezes or topographic impacts from ‘El Teide’. George and Sanders (2001) indicated that NAO variation only has a partial effect on trade wind variation, and so another plausible explanation could be that during the 2017 study period the dominant controlling synoptic factor on trade wind direction over Tenerife was the low-pressure system (seen in Figure 11) which superseded the influence of the NAO.

Synoptic influence of neighbouring pressure systems

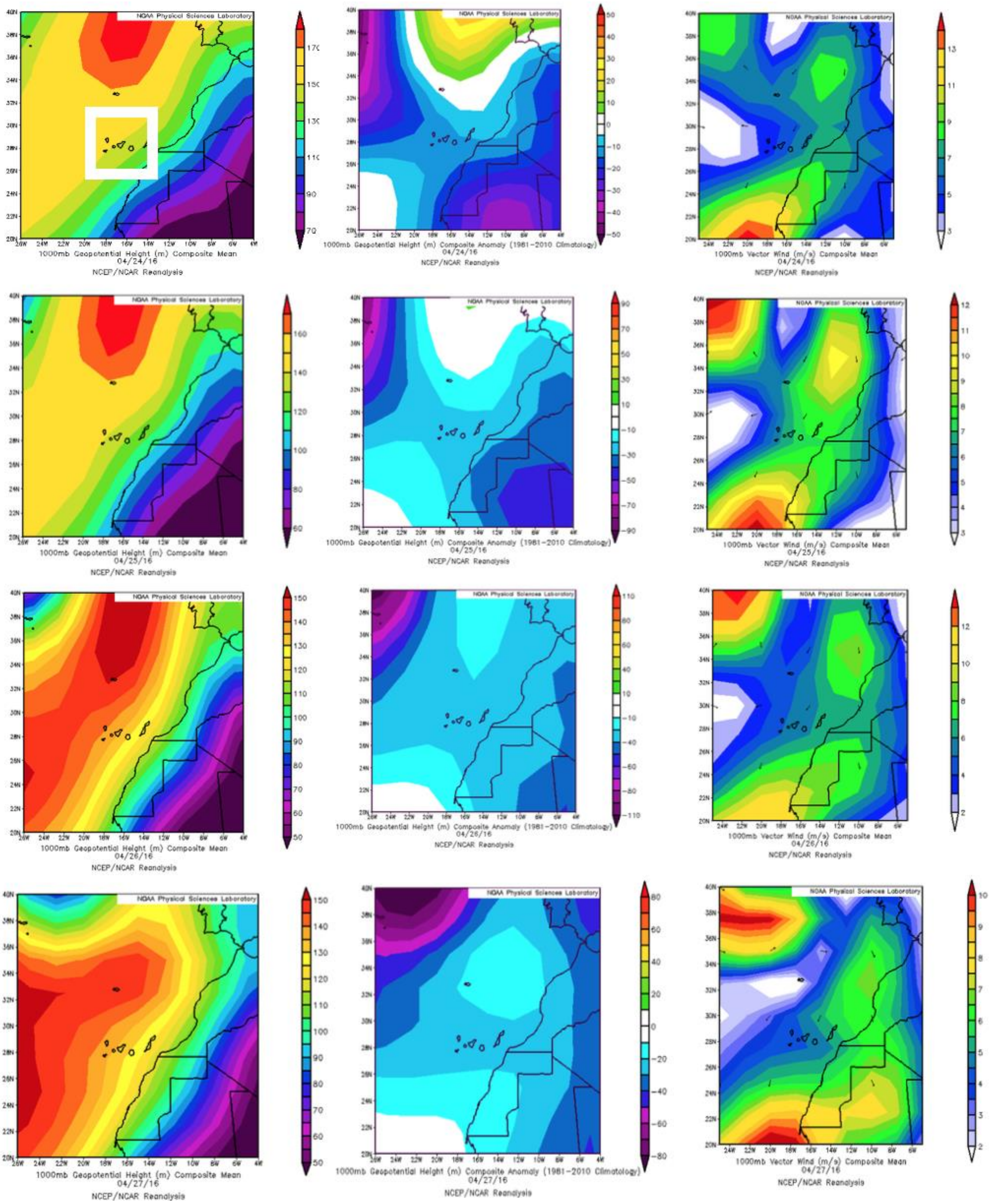

Figure 10 – The columns correspond to mean geopotential height, anomaly geopotential height, and vector wind for 24rd-27th April 2016. The white square locates Tenerife on the map.

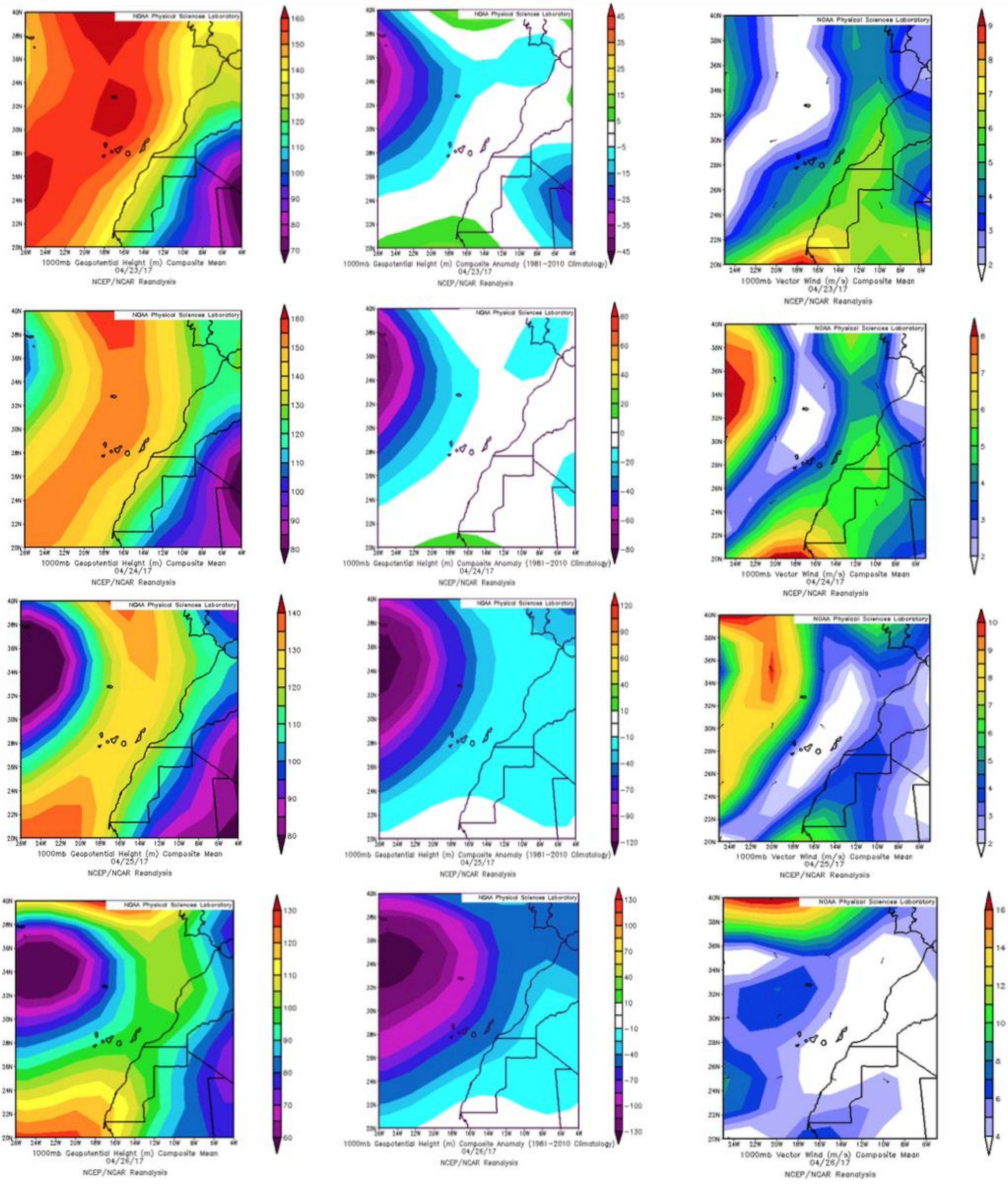

Figure 11 – The columns correspond to mean geopotential height, anomaly geopotential height, and vector wind for 23rd-26th April 2017.

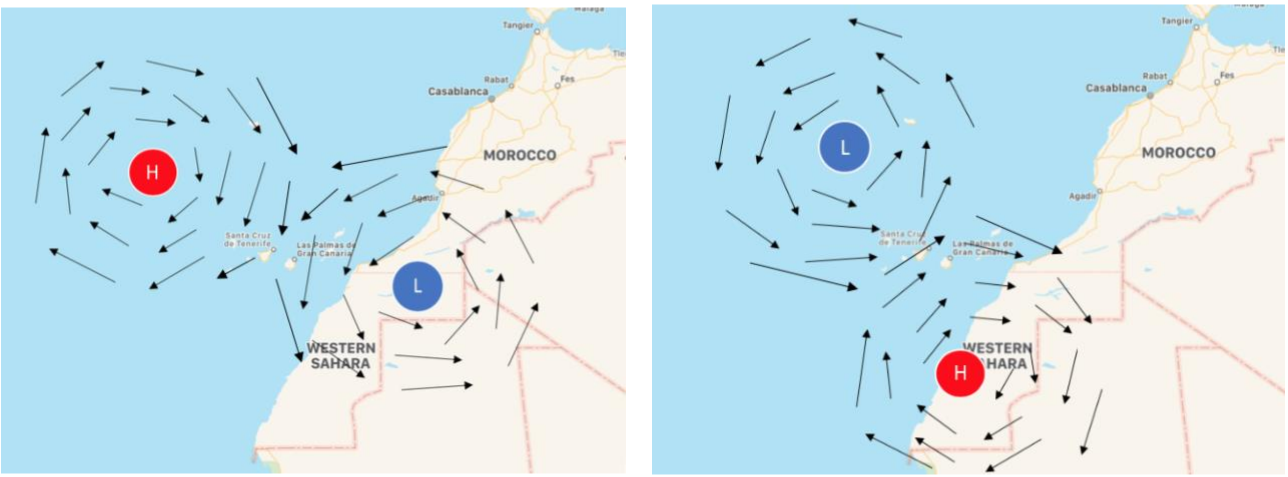

Figure 12 – Diagrams to show pressure systems over Tenerife on a synoptic scale and how they correspond to wind direction. Left: 24th April 2016. Right: 26th April 2017. Figure by the Author.

In 2016 there is a high-pressure system (with a pressure value of 1022mb (NOAA)) that features north of Tenerife on the 24th and expands south-westwards throughout the week, with the edge of the pressure system lying over Tenerife on the 26th and 27th. In 2017 there is a high-pressure system (of 1030mb (NOAA)) at the start of the week over Tenerife, which is then replaced by a low-pressure system (of 1006mb (NOAA)) coming from the west towards the end of the week. These events are shown in columns 1 and 2 of Figures 10 and 11 that show geopotential height means and anomalies for the study periods.

The Coriolis force is a deflecting force which stops wind flowing directly down a pressure gradient. In the Northern Hemisphere this effect causes clockwise anticyclonic wind flow around high-pressure system centres and anti-clockwise cyclonic wind flow around low pressure centres. This can therefore determine wind direction flowing across Tenerife (Figure 12).

In 2016 (as shown in Figures 10 and 12) Tenerife experiences north-easterly trade winds, which is the expected trade wind direction over the island. However, in 2017 trade wind flow switched from the predominant north-easterly to a westerly/south-westerly direction (Figures 11 and 12) across Tenerife as a result of the low-pressure system (which is shown to be an unusual atmospheric state from the geopotential height anomaly plots – figure 11) and the Coriolis effect. These wind direction patterns are confirmed in the vector wind reanalysis plots (Figures 10 and 11) and in the wind rose plots (Figure 5) which show average trade wind direction for the study periods, and could explain the recorded wind patterns of the PIBAL tracks (Figure 4).

The geopotential height plots, pressure values and understanding of the impacts of the Coriolis effect indicate how trade wind direction over Tenerife can be influenced by synoptic-scale forces. It is clear from this evidence that pressure systems neighbouring Tenerife can be a key control of trade wind directional variability over the island.

Conclusions

The aim of this report was to investigate how the differences in synoptic settings control the trade winds by looking at two questions:

1) How does the NAO influence the trade winds?
2) How do neighbouring pressure systems influence the trade winds?

For question 1 this report concludes that while the NAO did influence the trade wind speeds in 2016, it did not do so in the expected way. For 2017 there is no evidence that the NAO influenced trade wind speeds. However, other studies (e.g. Herrera et al., 2001) have concluded that the NAO generally does influence trade wind speeds and therefore a plausible explanation for 2017 is that the expected influence the NAO had on trade wind speeds during the study period was superseded by the influence of the synoptic neighbouring low pressure system. In order to confirm this, a Pearson's Correlation statistical test would need to be conducted to test for a correlation between surface pressure and trade wind speed. While this report has not tested this, in the future this would be an interesting focus for a research question.

For question 2 this report concludes that neighbouring pressure systems influenced the direction of the synoptic trade winds over Tenerife during the study period. When there was a high-pressure system to the north-west of the island and a low-pressure system below (seen in 2016) the trade winds came from a north-easterly direction. Whereas, in 2017 when there was a high-pressure system below the island and a low-pressure system above the trade winds came from a south-westerly direction. This is due to the Coriolis effect causing clockwise movement around high-pressure centres and anticlockwise movement around low-pressure centres.

Overall, these findings reveal that synoptic scale forcings have an effect on the trade wind characteristics experienced over Tenerife, although the influences are often not controlled by just one factor. As seen through the answering of the first research question, synoptic forcings can alter in their dominance. Therefore, the effect of synoptic scale forcings can vary. It is also important to note that the Tenerife climate is affected by mesoscale forcings which add further complexities and other spatial scales to the controls of the wind characteristics. Tenerife's climate system has many influences and hence it is often challenging to detect the determining mechanisms with confidence.

These results have useful implications in that they help to summarise influences on the trade winds which is beneficial for offshore wind farms in determining which areas are best for development. The results can also provide further understanding of how synoptic winds carry atmospheric dust to Tenerife.

To build upon the conclusions of this study, future research could be undertaken. This report has a small study period that does not provide a comprehensive annual understanding of the synoptic winds acting on Tenerife. Thus, further studies should be conducted which focus on different times of year or over longer periods. This would allow a more comprehensive investigation into the wind regimes around Tenerife and how they change on differing temporal scale.

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