Influence of atmospheric patterns and North Atlantic Oscillation (NAO) on vegetation dynamics in Iceland using Remote Sensing

Haraldur Olafsson\textsuperscript{a}\textsuperscript{*} and Iman Rousta\textsuperscript{b,c}

\textsuperscript{a}Institute for Atmospheric Sciences-Weather and Climate, Department of Physics, University of Iceland and Icelandic Meteorological Office (IMO), Reykjavik, Iceland; \textsuperscript{b}Department of Geography, Yazd University, Yazd, Iran; \textsuperscript{c}Department of physics, Institute for Atmospheric Sciences - Weather and Climate, University of Iceland and Icelandic Meteorological Office (IMO), Reykjavik, Iceland

\textbf{ABSTRACT}

In this study, the relationship between vegetation dynamics and atmospheric patterns over Iceland from 2001-2019 has been assessed using remote sensing. This study is based on MODIS NDVI images, NCEP/NCAR reanalysis dataset and values of the North Atlantic Oscillation (NAO). The results show that the vegetation coverage in Iceland reaches a maximum in the period from the middle of July to late August, with an average of about 65% of the total area (68858 km\textsuperscript{2}). There is not a strong relationship between NAO phases and the occurrence of the dry (less vegetation) or green months, which means that a dry year can be accompanied by a negative NAO phase (i.e. July 2009 with NDVI anomaly=-3.35 and NAO=-2.15) or with a positive phase (September 2005 with NDVI anomaly=-2.23 and NAO=0.63). The most important factor influencing the occurrence of months with denser/less dense vegetation is shifting west/eastward of Greenland Low height (GL), which is accompanied by a green/dry month in Iceland, respectively. The knowledge of this can help us to understand the variations in Iceland’s vegetation and also enables us to have a closer look at the impact of changes in global atmospheric patterns on the vegetation productivity in Iceland.

\textbf{Introduction}

Vegetation is linked to air, soil, water, and other environmental components, while at the same time it is an essential component of the land surface system (Cui et al., 2009; Foley et al., 2000; Rousta, Olafsson, Zhang et al., 2020; Yuan et al., 2021). Vegetation variations can be a good indicator providing important information about the impact of global warming (Mario et al., 2003; Rousta, Saberi et al., 2020; Wu et al., 2015), land degradation, (Metternicht et al., 2010), and desertification (Symeonakis & Drake, 2004). Normalized Difference Vegetation Index (NDVI), derived from measurements of the optical reflectance of the sunlight in the red and near-infrared wavelengths is highly sensitive to ecosystem conditions (Ollinger, 2011). Therefore, it can serve as a proxy for detecting changes in vegetation activity, e.g., greening (NDVI increase) and browning (NDVI decrease) trends (Alcaraz-Segura et al., 2010; Rousta, Olafsson et al., 2020, 2020). Several studies have reported greening trends in the northern high latitudes (Vickers et al., 2016). It was shown that the NDVI-adjusted photosynthetically active radiation is closely related to the gross primary production in Iceland (Ólafsdóttir & Óskarsson, 2014).

Icelandic landscape has been historically characterized by frequent, energetic geological processes (Thorarinsson, 1967) and anthropogenic pressure on its ecosystems due to the land-use changes imposed after Iceland was settled by humans (Dugmore et al., 2009; Sigurmundsson et al., 2014). This has led to Iceland having relatively low biodiversity compared to lands at similar latitudes (Jóhannesdóttir et al., 2017). Therefore, understanding biodiversity variations in Iceland is of special importance.

However, such studies cannot ignore the influence of global climate change, which is more significant and acute for sub-arctic regions, such as Iceland. The Intergovernmental Panel on Climate Change (IPCC) highlights that high northern latitudes are warming faster than other regions on the planet (Hoegh-Guldberg et al., 2018), with some research pointing towards Polar Amplification (PA), a phenomenon, in which effects such as decreasing sea ice and lower albedo due to reduced snow cover cause the Arctic temperature to rise disproportionately under increased greenhouse gas emissions (Polyakov et al., 2003).

Iceland holds a unique position in terms of world ecosystems, mainly due to its soils. Iceland’s geology is
overwhelmingly influenced by relatively recent explosive volcanism, which forms the main parent material for the soils. On a geologic timescale, soil formation is as recent as 10,000 years ago, coinciding with the end of the last glacial period (O. Arnalds et al., 1995). The major basis for Icelandic soils is basaltic tephra (O. Arnalds, 2008), which is the term describing the material of any size and composition ejected from volcanoes.

Increases in vegetation for northern latitudes have been documented using satellite data since the 1980s (Bokhorst et al., 2009; Liu et al., 2015; Merrington, 2019; Raynolds et al., 2015; Slayback et al., 2003). Increases in the NDVI were found to be correlated with increases in summer surface temperature in most parts of the Arctic (Chen & Yang, 2020; Elmendorf et al., 2012; Wang et al., 2020). From 1990 to 2010, a straightforward relationship between plant and climate change has been revealed, with increasing temperatures caused by higher vegetation productivity and, at the same time, being the reason for the longer growing seasons (De Beurs & Henebry, 2010; Li et al., 2020; Zhou, 2020).

In some parts of northern European countries, a decreasing trend in NDVI has been discovered recently. This trend can be associated with both winter warming events, which affect and reduce the protective role of snow cover (Bokhorst et al., 2009), and with insects or lack of optimal condition for vegetation grow in the summer season (Bjerke et al., 2014). The role of NDVI in vegetation dynamics and drought monitoring has been described several times during the last few decades (Ji & Peters, 2003; F. F. Kogan, 1991; F. N. F. N. Kogan, 1995; McVicar & Bierwirth, 2001; Wan et al., 2004; Yang et al., 1998). Gong and Ho (2003) analyzed the relationship between NDVI and atmospheric temperature over Eurasia and North America in spring for the period of 1982–2000 and revealed that a significant relationship between them exists. They also showed that temperature is a focal factor influencing vegetation activity (Gong & Ho, 2003). Vicente-Serrano and Heredia-Laclaustra (2004) have studied the relationship between climatological factors and vegetation on the Iberian Peninsula. They revealed that winter NAO had an important role on the vegetation, especially in the southwest region, mainly because it is a factor highly responsible for the precipitation (Vicente-Serrano & Heredia-Laclaustra, 2004). In the decade of the 90s, the NAO index showed a positive trend; however, a response in the climatological factors and ecosystem variations were varied (Chmielewski & Rötzer, 2001). NOA’s variations have had an important effect on the precipitation, agriculture, vegetation activity, forest fire, and droughts in the Mediterranean areas in the 1990s (González-Hidalgo et al., 2009).

The North Atlantic Oscillation is responsible for the main part of inter-annual variability in the atmospheric circulation of the western European areas, which is caused by changes in the surface westerlies across the North Atlantic onto Europe (Hurrell, 1995). There are several definitions for NAO, but it is always associated with the north to the south-oriented bipolar distribution in the pressure over the Atlantic Ocean, that can be recognized by different methods and that is usually summarized as the normalized pressure difference between a station in the Azores and one in Iceland (Jones et al., 1997). Positive NAO years are accompanied by a decrease in humidity conditions and drought periods in the south part of Europe and the Mediterranean regions. In NAO’s negative phases, increased moisture conditions are recorded in these areas (Hurrell & Van Loon, 1997).

Since NAO has a great impact on the temperature and precipitation variability over various regions, it directly affects vegetation growth, agricultural activities, fish inventories, and water management (Hurrell, 2003). Changes in the NAO can influence the transport of humidity in western European regions. So, the NAO can be linked straightforwardly to changes in regional moisture and precipitation. Monitoring climate change effects on vegetation by using pressure patterns is very promising because changes in meteorological elements can be firstly recognized from atmospheric patterns (Houghton et al., 2001). A strong positive correlation between accumulated growing degree-days and NAO in Estonia, Latvia, Lithuania, and the middle of Finland was already shown (De Beurs & Henebry, 2008).

The increasing temperature rates in the tundra ecosystem of Greenland are accompanied by an increasing trend of vegetation productivity over a large part of the Arctic indicated by the remote-sensing data (Elmendorf et al., 2012; Forbes et al., 2010). There is a significant relationship between the Russian heatwaves and negative NAO. A negative NAO index in April, May, and June can have a decreasing effect on productivity in Eurasian Wheat Belt (Wright et al., 2014).

No studies have focused on the relationship between vegetation productivity and atmospheric circulation in Iceland. There is a strong need for large-scale studies assessing the impact of atmospheric circulation variations on land surface climate and related vegetation dynamics of Iceland. A large part of the vegetation in Iceland is located in coastal and human settlement areas. The vegetation in Iceland, like in all of the sub-arctic and arctic regions, are of high
importance for wild and human life. Studying vegetation dynamics and its link to atmospheric patterns and global warming is very important to the ecological sustainability of this country. In Iceland, the differences in NAO influence on climate are significant, and knowledge on how these differences and atmospheric patterns influence vegetation production are of special interest. In this manuscript, the vegetation production trends in Iceland and their relationships to the NAO index and atmospheric circulation patterns were analyzed. It allows us to understand the response of local vegetation production to global climate patterns and future climate changes.

Material and methods

Study area

Iceland is an island with an area of 103,000 km². It is located in the N-Atlantic between latitudes 63–67°N, and longitudes 25–13°W. Iceland has 360,000 inhabitants. Reykjavik is the capital and largest city of the country. Reykjavik, along with its southwest part of the island, is the home of approximately 66% of the population of Iceland. The country is geologically and volcanically dynamic and consists of a plateau characterized by mountains, sand and lava fields, and glaciers. Through the lowlands, many glacial rivers flow to the sea. Despite a high latitude, Iceland has a temperate climate, and marine influence keeps summers chilly, with a tundra climate. The coldest part of Iceland is the central highlands, snowfall in winter is more common in the north than south. The south coast of the island is warmer, wetter, and windier compared to the north coast. Einarsson (1984) and Ólafsson et al. (2007) have described Iceland’s climate in greater detail (Figure 1).

Methodology and data collection

To explore the seasonal variability of Iceland’s vegetation coverage, NDVI and maximum snow extent images derived from MODIS satellite data were used. The images were retrieved by using Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) software from https://lpdaacsvc.cr.usgs.gov/appears (Didan, 2015). MODIS products used for this research included MOD13Q1.006 at 250 m spatial resolution with a sampling period of 16-day and MOD10A2.006_Maximum_Snow_Extent_8_days_500 m. The research covered the period from 1 January 2001 to 1 November 2019. The study used a total of 361 NDVI and 722 maximum snow extent images covering the whole study area. To analyze the atmospheric circulation patterns of the days selected in the study and to try to relate them with vegetation variations in Iceland, the HGT of 500 hPa and air temperature (hereafter T) and 500 hPa air temperature (hereafter T500) data for 80°W–40°E and 30–90°N, were extracted from the NCEP/NCAR reanalysis database (Kalnay et al., 1996). The spatial resolution of the data is 2.5 × 2.5 angular degrees. The spatial and statistical analysis was performed using ESRI ArcGIS 10.7 and R 2018 and GrADS 2.0 software.

Normalized Difference Vegetation Index (NDVI)

NDVI index is useful for estimation of biomass potential, which is measured with leaf area index (LAI) and production pattern (Dutta et al., 2015; Gitelson et al., 2003; Tarpley et al., 1984; Thenkabail & Gamage, 2004). Over the recent years, NDVI has been used by many scientists in different studies based on vegetation classification, land use/cover changes, vegetation phenology, mapping of continental land cover, and vegetation dynamics (Geerken et al., 2005; Martinez & Gilabert, 2009; Moulin et al.,

Figure 1. Study area with the elevation profile included.
NDVI is one of the suitable indices for monitoring drought, estimating the healthy status of vegetation, crop growth conditions, and crop yields (Dabrowska-Zielinska et al., 2002; Dutta et al., 2015). The basic concept of NDVI is based on the fact that the internal mesophyll structure of healthy green leaves highly reflects Near-Infrared (NIR) radiation whereas the leaf chlorophyll and other pigments absorb a large proportion of the red visible (VIS) radiation. This function of internal leaf structure becomes reversed in case of unhealthy or water-stressed vegetation (Dutta et al., 2015; Ghaifarian Malamiri et al., 2018). NDVI is the difference of the reflectance in the near-infrared (NIR) and visible red (VIS) band of the electromagnetic spectrum.

The value of NDVI ranges between −1 and +1. The very low values of NDVI (≤0.1) corresponds to snow, sand, or rocky or bare ground areas. Moderate NDVI values from 0.2 to 0.3 represent shrubs and grasslands, while high NDVI values (0.6 to 0.8) indicate dense vegetation. The negative NDVI values correspond to water bodies (Gandhi et al., 2015).

**Calculation of anomalies**

Based on the MODIS 16-day NDVI images with a 250-m resolution, monthly and annual NDVI, as well as inter-monthly and inter-annual anomaly of NDVI were calculated. They were calculated for each pixel in the study area during 2001–2019. Anomalies have been calculated using Eq. 1 as below:

\[
\text{Anomaly}(t) = \frac{\text{Variable}(t) - \text{avg}(\text{Variable})}{\text{Stdev}(\text{Variable})}
\]

where Variable(t) is the monthly NDVI, T500 and, T and avg(Variable) is the average of NDVI, T500 and, T for that month in the whole study period (2001–2019), and Stdev is the standard deviation of NDVI, T500 and, T for that specific month during the whole study period. In the current study, the anomalies were calculated for the months from January to October, because for the last 2 months the NDVI images were not having enough quality.

**Results**

**Changes in NDVI coverage**

Figure 2 shows that the NDVI coverage is rising rapidly from the midst of February; however, in mid-March the rising is slowing down slightly (12,948 km²). The vegetation coverage is increasing from late March and reaches 33,524 km² at the end of April. This trend remains increasing in the next months and NDVI achieves its maximum coverage (66,858 km²) in the midst of July and stays high up to late August. Afterward, the green vegetation is decreasing rapidly. Therefore, the growing season (GS) begins on 23rd March and ends in late August (Figures 2–3).

In Figure 4 NDVI classes based annual normal vegetation distribution is shown. Overall, no distinguished trend in the NDVI coverage was found during 2001–2019, but significant interannual variability has been found. The maximum coverage was 42,114, 41,136, 41,028, and 41,021 km² in the years 2003, 2004, 2017, and 2019 respectively, whereas the minimum vegetation coverage was 32,919, 33,349, 34,046, 33,357, and 33,911 km² in the years 2008, 2009, 2013, 2014, and 2015 respectively (Figure 4).

**Relationship between NAO and vegetation coverage**

Table 1 presents the Z score of monthly NDVI coverage and NAO index for months from January to October from the period 2001–2019. As indicated in Figure 2, the coverage in the study area achieves its maximum from July to August and the minimum coverage falls on January/February, and October (NDVI is covering with 3, 8, and 19% of the whole.

![Figure 2](image-url) Average of NDVI (≥ 0.2) coverage in Iceland for 2001–2019 (error bars showing ± 2 Stdev of the mean).
country, respectively). Vegetation coverage of each year can be easily affected by variations in summer season atmospheric patterns, which can help the vegetation to grow up in a situation higher than or lower than normal. In Table 1, the years with NDVI or NAO two standard deviations higher or lower than normal (≤−2 and ≥2) have been indicated. Most of them occur in the summer season months, which simultaneously are the months with the highest vegetation coverage. It seems that during the study period, in each year with June, July, and August having an NAO’s Z score higher than normal is also a year with vegetation coverage higher than normal. This relation is more evident for July than for two other months, but it can be affected by other atmospheric parameters, which is discussed in the following sections. However, no obvious general relations between NAO positive/negative phases and the positive or negative anomaly of NDVI in the study area were spotted. In some years positive NAO is accompanied with the negative NDVI (May 2013), and negative NAO with the positive NDVI (May 2019). In others, the positive NAO is accompanied with the positive NDVI (Jan 2001), or negative NAO with the negative NDVI (Jul 2009). To discuss in detail the relationship between NAO or atmospheric patterns and NDVI coverage dynamics...
in the study area, all the months with an anomaly two standard deviations higher or lower than normal (± 2) were selected. Finally, 7 months were selected (bold numbers in Table 1) and atmospheric patterns related to NAO and NDVI variations were assessed (Figure 5).

Table 2 presents the correlation between monthly NDVI coverage and the NAO index. The correlation coefficients R were calculated for each month of the year from individual month’s time series from 2001 to 2019. Negative but insignificant correlations between NDVI coverage and NAO were observed
from January to March and in May, and a negative but significant correlation was spotted in September (R = −0.6 with p = 0.05). Also, there were insignificant positive correlations between the NDVI coverage and the NAO in Apr, Jun, Jul, Aug, and Oct. The correlation for Jul was higher than for other months (R = 0.43) (Table 2).

Table 3 presents the correlations between yearly NDVI coverage and the NAO index for the study area during 2001–2019. The correlation coefficients R were calculated for all 10 months of the year (Jan–Oct) from individual year’s time series for the whole study period. There is a negative but insignificant correlation between these quantities in the year 2002, 2012, 2013, 2015, 2016, and 2017 and a negative significant correlation in years 2005, 2008, and 2019 (p = 0.05). Also, there is an insignificant positive correlation between NDVI coverage and NAO in the years 2001, 2003, 2004, 2006, 2007, 2009–2011, and 2018. The correlation for 2011 is higher than other years (R = 0.48). And also there is a positive significant correlation in the year 2014 (R = 0.51 and p = 0.05) (Table 3).

**Atmospheric patterns**

As it is indicated in Table 1, January of 2001 is a month with 2.91 std NDVI coverage above the average for this specific month during the study period. This is accompanied by an NAO equal to 0.25, that is indicating a positive phase with a bit more powerful Icelandic Low pressure (IL) than the average one and also a bit stronger Azores High pressure (AH) than the average one (Table 1). Analysis of 500 hPa HGT and temperature (Figure 6) revealed that in January 2001 the Greenland low height (GL) has moved to the west and merged with Canada Low height (CL). Therefore, there was a long trough over Canada, which extended to the western part of Greenland (trough axis is indicated by a white line). In such a situation, westerlies have to move to lower latitudes (about 40°N), and therefore, after passing the trough, warmer air traveled to Iceland (dashed white line). The anomaly of surface temperature confirms the above reasoning, as a temperature about 0.5 std higher than average was recorded in most of the study area. Finally, the vegetation had the chance to grow

---

**Figure 5.** The relationship between extreme NDVI anomalies (≤ −2 and ≥ 2 std) and the NAO index during 2001–2019 (error bars showing ± 2 Stdev of the mean).

**Table 2.** The correlation coefficients R between monthly NDVI and monthly NAO calculated for each month of the year from individual month’s time series from 2001–2019.

| Month | Cor | Month | Cor | Month | Cor | Month | Cor | Month | Cor |
|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|
| Jan   | −0.37 | Mar   | −0.24 | May  | −0.35 | Jul   | 0.43 | Sep   | −0.60* |
| Feb   | −0.41 | Apr   | 0.12  | Jun  | 0.25  | Aug   | 0.09 | Oct   | 0.32  |

* denotes significance level at p = 0.05

**Table 3.** The correlation coefficients R between yearly NDVI and yearly NAO calculated for all 10 month (Jan-Oct) of the year from individual year’s time series from 2001–2019 Year.

| Cor | Year | Cor | Year | Cor | Year | Cor | Year | Cor | Year | Cor |
|-----|------|-----|------|-----|------|-----|------|-----|------|-----|
| 0.24 | 2005 | −0.51* | 2009 | 0.04 | 2013 | −0.23 | 2017 | −0.29 |
| −0.45 | 2006 | 0.07  | 2010 | 0.04 | 2014 | 0.51* | 2018 | 0.13 |
| 0.18  | 2007 | 0.07  | 2011 | 0.48  | 2015 | −0.06 | 2019 | −0.55* |
| 0.18  | 2008 | −0.71* | 2012 | −0.03 | 2016 | −0.41 |      |      |      |

Note: * denotes significance level at p = 0.05
faster than in other years, especially at the coast. However, the observed atmospheric pattern couldn’t greatly influence the average vegetation coverage in 2001 because the vegetation coverage in January has a very low value (Figure 6).

September of 2005 was one of the driest years, with the vegetation coverage for 2001–2019 being −2.23 std lower than average during the whole study period. In this month the NAO equal 0.63 was recorded. The maps of the higher atmosphere and surface (Figure 7) show that the polar vortex had penetrated horizontally from northern Europe to the East of Canada and covered all of Iceland (white line). At the same time, the anomaly of the temperature of 500 hPa and also surface temperature showed a −2 std for the study area comparing to the value for this month during the whole study period. Because of this atmospheric pattern and the weather colder than usual, the vegetation coverage couldn’t expand enough and this year has been another one of the driest years in terms of vegetation coverage during 2001–2019 (Figure 7).

February of 2006 has been one of the greenest years in terms of vegetation coverage during 2001–2019, with the value 2.77 std higher than average for the whole study period. It was accompanied with an NAO equal to −0.51. The maps of higher atmosphere and surface (Figure 7) reveal that there is a long ridge located near the study area (ridge axis indicated by a white line) that advected the warmer air from lower latitudes (30–40 °N) toward the study area. Since the study area is located in the back of the ridge, therefore it received the warmer air from the lower latitudes and finally, vegetation in the study area has had the needed temperatures to grow (Figure 7).

July of 2009 has been another one of the driest years in terms of vegetation coverage during 2001–2019 with the value of −3.35 std lower than average for the whole study period. In this month an NAO equal to −2.15 was recorded. The maps of higher atmosphere and surface (Figure 8) show that there is a dipole blocking near the study area, with the high altitude of the dipole located on Greenland, and the low altitude located in Northwestern Europe and to the south of the study area (white bracket indicates the dipole block). Because of the blocking, and the fact that in the Northern hemisphere the high altitude centers rotate clockwise, it caused to advect cold and dry air to the study area and vegetation coverage hasn’t had high enough temperatures to grow. The anomaly of the temperature of 500 hPa, and also surface temperature...
Figure 8. HGT 500 hPa (black contour with blue number), Z score air Temperature (shaded) and Z score temperature of 500 Hpa (red contour) for July 2009 and May 2013.

confirms that (with −0.6 and −1 std lower than in the average during the study period, respectively) (Figure 8).

May of 2013 has been another one of the driest years in terms of vegetation coverage during 2001–2019, with a value −2.41 std higher than the average for the whole study period, accompanied with an NAO equal to 0.57. The maps of higher atmosphere and surface show (Figure 8) that the GL was stronger than usual and merged with CA low, creating a large area with a low height. Subsequently, AH was also powerful, but extended eastward to the north of Africa and covered the area from Western European countries to the south of the study area. Therefore, a horizontal air advection is present in the study area, advecting the colder air from higher latitudes (60°N and above), causing limiting conditions for vegetation growth (white arrow). There are the reasons why in 2013 the low vegetation coverage was observed (Figure 8).

October of 2016 and April of 2019 have been two of the greenest year in terms of vegetation coverage during 2001–2019, with 2.19 and 2.04 std higher than average for the whole study period, respectively, and it’s accompanied with an NAO equal to 0.41 and 0.47, respectively. These 2 years have the same atmospheric pattern. The maps of higher atmosphere and surface (Figure 9) for those years show that the GL shifted westward to the north of Canada and a ridge could expand northward, covering all of the study area. This caused advecting warmer air to the region (ridge axis indicated by a white line). Anomaly air 500 hPa shows a value 2 std above the average for the whole study period and surface temperature a value 1.5 std above the average. Because of these atmospheric patterns, the vegetation has had good conditions to grow (Figure 9).

Discussion

The present study attempts to identify the relationship between atmospheric patterns and NAO and vegetation dynamics in Iceland using remotely sensed NDVI MODIS images and NCEP/NCAR reanalysis datasets for 2001–2019. It was found that MODIS NDVI images could be useful for monitoring the vegetation dynamics in Iceland. There have not been many studies on the relationship between atmosphere dynamics with monthly vegetation variations in Iceland.

The extremely high vegetation coverage in Iceland was found between midst of July to late August, with around 65% of the country area covered (66,858 km2 on average). It was also found that the average length of the growing seasons spans from late March to the end of August.

In the years 2001–2019, the highest value of the NAO index was recorded in April 2011 and 2018, having 2.48 and 2.12, respectively, and the lowest value of the NAO index was observed in May 2019 (−2.62), June 2012 (−2.53), July 2009 (−2.15) and 2015 (−3.18), and October 2002 (−2.28), 2006 (−2.24) and 2012 (−2.06). The highest positive anomaly of NDVI coverage occurred in January 2001 (2.91), February 2006 (2.77), October 2016 (2.1), and April 2019 (2.04), whereas the highest negative anomaly of NDVI coverage occurred in September 2005 (−2.23), July 2009 (−3.35), and

Figure 9. HGT 500 hPa (black contour with blue number), Z score air Temperature (shaded) and Z score temperature of 500 Hpa (red contour) for October 2016 and April 2019.
May 2013 (−2.41). No straightforward relationship between positive/negative phases of NAO and positive/negative anomalies of the NDVI coverage in the study area during the study period was observed.

The main element having a strong impact on vegetation dynamics in Iceland is the atmospheric pattern of Greenland Low height (GL). When the GL is powerful and also located over Greenland and north of Canada, it can make a trough between 60–40°W, extending to latitudes of 55°N. Because of that westerlies have to shift to lower latitudes. Since the study area is located in front of such a trough, the converging warmer air from lower latitudes to the study area can help vegetation to grow up. For example, in April 2011 such an atmospheric pattern is accompanied with a positive NAO phase (2.48). In turn, when GL is weaker than normal and is at the same time shifted to western longitudes to the north of Canada, the westerlies have a large way to pass; therefore, a blocking system can be created and the warmer air from the lower latitudes makes a large ridge over North Atlantic and European countries, providing optimal temperatures for vegetation growth. For example, in April 2019 such a blocking system caused higher temperatures in the study area, and the NDVI coverage attained a positive value of an anomaly (1.74 std). In April 2019 negative NAO phase (−2.62) was observed.

Blocking systems can have different impacts on the vegetation dynamics for the study area. For example, when dipole blocking in July 2009, or omega blocking in April 2019 occurred, the response in vegetation dynamics was different. July 2009 has been the driest month during the study period (−3.35 std) and April was among the years with the most positive anomaly of NDVI (2.04 std). In July 2009 a high height center over the regions of north Iceland and northwestern and central part of Greenland (75°N) was observed and subsequently, a low height center over the south of Iceland (55°N) occurred. Therefore, the colder air advected to the study area from the higher latitudes by clockwise rotation of the height over the study area making it colder than average. In turn, the low height advected the warmer and more humid air from the lower latitudes to the study area, especially to its western part. Finally, the colder air caused snowfalls to happen more often than on average in the study area. Snow cover, accompanied by the air temperatures significantly lower than usual ones, caused the driest (with lesser vegetation) month in the study period (from 2001 to 2019) (Figure 9 and Table 4). However, in April 2019 omega blocking created a long ridge from 55° to 40°E and from 50° to 80°N, with the study area located in the back of the ridge, which was the cause why the warmer air from the attitude of 50°N was transferred toward the study area, making it warmer than average (about 2 std higher). Such atmospheric pattern has provided good conditions for vegetation growth in Iceland and has made April 2019 one of the greenest April months during the study period (2001–2019).

Table 4. Snow extent anomaly of July during 2001–2019.

| Year | snow extent anomaly | Year | snow extent anomaly | Year | snow extent anomaly |
|------|---------------------|------|---------------------|------|---------------------|
| 2001 | −0.03               | 2008 | −0.03               | 2015 | 0.88                |
| 2002 | −0.33               | 2009 | 2.04                | 2016 | −1.25               |
| 2003 | −0.65               | 2010 | 0.24                | 2017 | −0.16               |
| 2004 | −0.93               | 2011 | −1.39               | 2018 | 0.36                |
| 2005 | −0.62               | 2012 | −1.18               | 2019 | 0.26                |
| 2006 | −1.07               | 2013 | 0.82                |      |                     |
| 2007 | 0.74                | 2014 | 0.84                |      |                     |

Conclusions

On a global scale, land surface changes are a multifaceted phenomenon, which always continues to happen. They could be detected in different ways, but since the last decades, after launching first satellites, human has had an opportunity to analyze the surface phenomena with a more accurate vision than in the past. Over the last decades, a lot of researches studied plant responses to climate changes and the impacts and relationship between atmospheric patterns and vegetation (Hamann et al., 2020; Heckathorn et al., 2020; Silva & Lamberts, 2020).

In this paper, we analyze vegetation coverage trends in Iceland and their relationships with the NAO index and atmospheric circulation patterns based on remotely sensed data. This knowledge allows us to understand the response of variations in local vegetation coverage to current and future global climate patterns. Based on the NDVI values retrieved from remote sensing for the period 2001–2019, considerable inter-annual variability in the vegetation coverage in Iceland was observed. It was also revealed that in the late summer, 65% of Iceland is covered with vegetation (NDVI ≥ 0.2).

From the performed analyses it stems that the variations of vegetation coverage in Iceland can’t be assigned to just one atmospheric pattern. It results that patterns accompany each other and affect the vegetation coverage in the studied area. The study found that the main factor affecting the vegetation coverage in Island is the shift of Greenland Low height (GL). When GL is shifting eastward or westward, it affects the Canadian Low height (CL) or Siberian High (SH) pressure. Each of the atmospheric patterns can be responsible for the completely different weather in Iceland that consequently influences the vegetation dynamics in the area. Especially the range and strength of Siberia High pressure should be monitored, as it affects greatly the vegetation dynamics of Iceland. For the same reasons also the range of Azores High Pressure should be monitored.

Acknowledgments

Iman Rousta is deeply grateful to his supervisor (Haraldur Olafsson, Professor of Atmospheric Sciences, Institute for Atmospheric Sciences-Weather and Climate, and Department of Physics, University of Iceland, and Icelandic Meteorological Office (IMO)), for his great
support, kind guidance, and encouragement. NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

Author Contributions

H.O. and I.R. proposed the topic, commanded the data processing, analysis, and wrote the manuscript.

Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Vedurfelagid, Rannis and Rannsoknastofa i vedurfraed.

ORCID

Haraldur Olafsson http://orcid.org/0000-0002-4181-0988
Iman Rousta http://orcid.org/0000-0002-3694-6936

Data availability statement:

The data available after contacting Iman Rousta at irous.ta@yazd.ac.ir, https://pws.yazd.ac.ir/irousta/en/

References

Alcaraz-Segura, D., Chuvieco, E., Epstein, H. E., Kasischke, E. S., & Trishchenko, A. (2010). Debating the greening vs. browning of the North American boreal forest: Differences between satellite datasets. Global Change Biology, 16(2), 760–770. https://doi.org/10.1111/j.1365-2486.2009.01956.x
Arnalds, Ó. (2008). Soils of Iceland. Jökull, 58, 409–421. https://doi.org/10.1007/978-94-017-9621-7
Arnalds, O., Hallmark, C., & Wilding, L. (1995). Andisols from four different regions of Iceland. Soil Science Society of America Journal, 59(1), 161–169. https://doi.org/10.2136/sssaj1995.03615995005900010025x
Bjerke, J. W., Karlson, S. R., Hogda, K. A., Malnes, E., Jepsen, J. U., Lovbond, S., Vikhamar-Schuler, D., & Temmervik, H. (2014). Record-low primary productivity and high plant damage in the Nordic Arctic region in 2012 caused by multiple weather events and pest outbreaks. Environmental Research Letters, 9(8), 084006. https://doi.org/10.1088/1748-9326/9/8/084006
Bokhorst, S. F., Bjerke, J. W., Temmervik, H., Callaghan, T. V., & Phoenix, G. K. (2009). Winter warming events damage sub-Arctic vegetation: Consistent evidence from an experimental manipulation and a natural event. Journal of Ecology, 97(6), 1408–1415. https://doi.org/10.1111/j.1365-2745.2009.01554.x
Chen, X., & Yang, Y. (2020). Observed earliest start of the growing season from middle to high latitudes across the Northern Hemisphere snow-covered landmass for the period 2001–2014. Environmental Research Letters, 15(3), 034042. https://doi.org/10.1088/1748-9326/ab6d39
Chmielewski, F.-M., & Rötzer, T. (2001). Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology, 108(2), 101–112. https://doi.org/10.1016/S0168-1923(01)00233-7
Cui, L., Shi, J., Yang, Y., & Fan, W. (2009). Ten-day response of vegetation NDVI to the variations of temperature and precipitation in eastern China. Acta Geographica Sinica, 71(1), 011. https://en.cnki.com.cn/Article_en/CJFDTotal-DLXB200907011.htm
Dabrowska-Zielinska, K., Kogan, F., Ciolkosz, A., Gruszczynska, M., & Kowalik, W. (2002). Modelling of crop growth conditions and crop yield in Poland using AVHRR-based indices. International Journal of Remote Sensing, 23(6), 1109–1123. https://doi.org/10.1080/01431160110070744
De Beurs, K. M., & Henebry, G. M. (2008). Northern annual mode effects on the land surface phenologies of northern Eurasia. Journal of Climate, 21(17), 4257–4279. https://doi.org/10.1175/2008JCLI2074.1
De Beurs, K. M., & Henebry, G. M. (2010). A land surface phenology assessment of the northern polar regions using MODIS reflectance time series. Canadian Journal of Remote Sensing, 36(sup1), S87–S910. https://doi.org/10.5589/m10-021
Didan, K. (2015). MOD13Q1 MODIS/Terra vegetation indices 16-day L3 global 250m SIN grid V006. In NASA EOSDIS Land Processes DAAC. doi:10.5067/MODIS/MOD13Q1.006
Dugmore, A. J., Gisladóttir, G., Simpson, I. A., & Newton, A. (2009). Conceptual models of 1200 years of Icelandic soil erosion reconstructed using tephrochronology. Journal of the North Atlantic, 2(1), 1–19. https://doi.org/10.3721/0371.002:0103
Dutta, D., Kundu, A., Patel, N., Saha, S., & Siddiqui, A. (2015). Assessment of agricultural drought in Rajasthan (India) using remote sensing derived Vegetation Condition Index (VCI) and Standardized Precipitation Index (SPI). The Egyptian Journal of Remote Sensing and Space Science, 18(1), 53–63. https://doi.org/10.1016/j.ejrs.2015.03.006
Einarnsson, M. A. (1984). Climate of Iceland. World survey of climatology, 15, 673–697. https://www.vedur.is/media/lofslag/myndasafn/frodleikur/Einarsson.pdf
Elmdendorf, S. C., Henry, G. H., Hollister, R. D., Björk, R. G., Boulanger-Lapointe, N., Cooper, E. J., Cornelissen, J. H., Day, T. A., Dorrepaal, E., Elumeeva, T. G., Gill, M., Gould, W. A., Harte, J., Hik, D. S., Hofgaard, A., Johnson, D. R., Johnstone, J. F., Jónsdóttir, I. S., Jorgenson, J. C., Klanderud, K., & Wipf, S. (2012). Plot-scale evidence of timberline vegetation change and links to recent summer warming. Nature Climate Change, 2(6), 453–457. https://doi.org/10.1038/nclimate1465
Foley, J. A., Levis, S., Costa, M. H., Cramer, W., & Pollard, D. (2000). Incorporating dynamic vegetation cover within global climate models. Ecological Applications, 10(6), 1620–1632. https://doi.org/10.1890/1051-0761(2000)010[1620:IDVCGW]2.0.CO;2
Forbes, B. C., Fauria, M. M., & Zetterberg, P. (2010). Russian Arctic warming and ‘greening’ are closely tracked by tundra shrub willows. Global Change Biology, 16(5), 1542–1554. https://doi.org/10.1111/j.1365-2486.2009.02047.x
Gandhi, G. M., Parthiban, S., Thummalu, N., & Christy, A. (2015). NDVI: Vegetation change detection using remote sensing and GIS—a case study of Vellore District. Procedia Computer Science, 57(1), 1199–1210. https://doi.org/10.1016/j.procs.2015.07.415
Geerken, R., Zaitchik, B., & Evans, J. (2005). Classifying rangeland vegetation type and coverage from NDVI time series using Fourier Filtered Cycle Similarity.
