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Article

Icelandic Climate and North Atlantic Cyclones in ERA-40 Reanalyses

ANDREA SCHNEIDEREIT, RICHARD BLENDER, KLAUS FRAEDRICH, AND FRANK LUNKEIT

Meteorologisches Institut, Universität Hamburg, Bundesstrasse 55, D-20146 Hamburg, Germany

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Abstract

The frequency of winter cyclones in the North Atlantic is determined for 1957-2002 in the ERA-40 European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis data set. The cyclone frequency shows distinct maxima for the intensity and the variability between southeastern Greenland and Iceland. The numbers of cyclones near Iceland (50 – 60N, 30 – 10W) and their intensity show an increase consistent with the North Atlantic Oscillation (NAO) and decreasing surface pressure in Iceland during 1961 – 2001 (station Reykjavík). Noteworthy is the decrease in near surface temperature (previously found) and 10m wind speed. Positive correlations are observed for the numbers of Icelandic cyclones with the NAO-index, the Icelandic surface pressure, and wind speed, while near surface temperature is not correlated. For precipitation the correlation with the cyclones is higher than with the NAO-index.

Zusammenfassung

Das Isländische Klima und nordatlantische Zyklonen in ERA-40 Reanalysen

Die Häufigkeit der Zyklonen im Nordatlantik wird für die Winter von 1957-2002 in den Reanalysen des European Centre for Medium-Range Weather Forecasts (ERA-40) bestimmt. Die Zyklonenhäufigkeit zeigt eindeutige Maxima in der Intensität und Variabilität im Bereich Südgrönland/Island. Die Anzahl der Tiefdruckgebiete nahe Island (50 – 60N, 30 – 10W) und deren Intensität weisen eine Zunahme auf, welche mit der Nordatlantischen Oszillation (NAO) und einem beobachteten Absinken des Bodendruckes in Island während 1961 – 2001 verbunden ist (Station Reykjavík). Bemerkenswert ist das bereits zuvor festgestellte Absinken der bodennahen Temperatur und der 10m-Windgeschwindigkeit. Weiterhin werden positive Korrelationen für die Anzahl der Zyklonen mit dem NAO-Index, dem isländischen Bodendruck, sowie der 10m-Windgeschwindigkeit gefunden, während die bodennahe Temperatur mit der Anzahl der Zyklonen nicht korreliert ist. Die Korrelation des Niederschlags mit den Zyklonen ist höher als die mit dem NAO-Index.

1 Introduction

Weather and climate of Iceland are under the dominant influence of the North Atlantic cyclones. Northern Atlantic depressions and their relationship with large scale teleconnection patterns and the European climate have been analysed in a number of studies. BRÜMMER et al. (2000) determine the Arctic cyclone statistics in ECMWF ERA reanalysis in 1986-91 and find large monthly variabilities. For climatological analyses it is relevant that weak cyclones may still be insufficiently observed, assimilated and predicted in operational weather forecasts (for example in the Fram Strait, BRÜMMER et al. (2001)) and, hence, in the ERA-40 reanalyses (CONDRON et al., 2006). According to BRÜMMER et al. (2001) these cyclones are correlated with the ice export (correlation coefficient 0.4 – 0.66 during 1978 – 1993) which is itself relevant for the temperature in northern Iceland (HANNA et al., 2004).

In a detailed climatological study, HANNA et al. (2004) analyse trends of several climatic variables in Iceland including air pressure, temperature, precipitation and sunshine data during the 20th century to assess a possible climate change. The authors find trends in certain time intervals, however, without a general trend during the century that could be related to global warming. There are station dependent correlations with the North Atlantic Oscillation (NAO) index: $r \approx -0.26 \ldots 0.09$, for seasonal temperatures, and significant values, $r = 0.29 \ldots 0.45$, for annual precipitation.

The cyclones in the vicinity of Iceland are in part caused dynamically by the Greenland massive (SERREZE et al., 1997). To determine this influence DETHLOFF et al. (2004) and JUNGE et al. (2005) analysed high resolution simulations with removed Greenland orography. The comparison with a control simulation shows that the cyclonic activity between Greenland and Iceland is reduced to one half if the orography is eliminated.

In winter cyclone frequency increases in high-latitudes and decreases in mid-latitudes in NCEP reanalyses (MCCABE et al., 2001). The northward shift of the cyclone intensity is also observed in ERA-15 ECMWF reanalyses (SICKMÖLLER et al., 2000). A similar north-

*Corresponding author: Richard Blender, Meteorologisches Institut, Universität Hamburg, Bundesstrasse 55, D-20146 Hamburg, Germany, email: blender@dkrz.de

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east shift is detected in increasing greenhouse gas scenario simulations (e. g. SCHUBERT et al. (1998)).

Between southeastern Greenland and Iceland a climatological low pressure centre prevails caused by stationary waves and transient synoptic systems (LÖPTIEN and RUPRECHT, 2005). This centre of action, commonly denoted as Icelandic low, contributes to the NAO (HURRELL, 1995) which is highly correlated with the climate in the North Atlantic and Europe. In this area a large number of relatively weak and quasi-stationary cyclones are found which show higher correlations with the NAO-index ($r \approx 0.5$) than the cyclones propagating across the North Atlantic (SICKMÖLLER et al., 2000).

In a rotated principal component analysis of the storm track, defined by the 2-8-day band pass filtered daily sea level pressure (SLP) variability, ROGERS (1997) derives no link to the NAO in 1900-1992. SERREZE et al. (1997) analyse the seasonal cycle, trends, and extremes of cyclones in the NMC (National Meteorological Center) twice daily sea level pressure data set of 1966-1993 with moderate resolution (47×51 octagonal gridpoints). A poleward shift of the cyclones is found which is related to the NAO. However, despite the increase of the NAO-index during the observation period, an increase of the number of cyclones is not detected.

A Pacific-Atlantic teleconnection is provided by relationships between the El Niño/Southern Oscillation (ENSO) and the climate in Europe and the North Atlantic (FRAEDRICH et al., 1992) with negative pressure anomalies in Iceland during ENSO cold events.

The aim of this paper is to relate winter (DJF) climate means in Iceland to the cyclonic activity in a surrounding area ($60 - 70$ N, $30 - 10$W). Cyclone frequencies, their inter-annual variability and decadal change are determined by tracking individual cyclones in ERA-40 reanalyses. As a representative station for the climate in Iceland the station Reykjavík is chosen. It includes the variables near surface temperature, precipitation, surface pressure, and 10m wind speed with a negligible number of missing data.

In Section 2 the data sets and the analysis techniques are described. Section 3 includes the results on the cyclone frequency, their variability, long term changes and the relationships with the NAO and ENSO. In Section 4 the correlations of the winter Icelandic climate with the cyclones in the vicinity of Iceland are derived. The final Section 5 presents a summary and discussion.

2 Data and analysis techniques

Data: The cyclones are determined in the reanalysed observations of the ECMWF (European Center for Medium- Range Weather Forecasts) for the winters 1957/58−2001/02. The resolution is T106 ($\approx 1^\circ \times 1^\circ$) and the time interval is 6 hours. This high resolution is of major relevance for the present study since we are interested in weak cyclones and in a detailed regional analysis. To allow a comparison with the majority of studies we concentrate on the DJF winter season which reveals the most intense cyclones. The cyclones in NCEP reanalysis data have been analysed by GULEV et al. (2001) and a comparison of cyclone tracks in NCEP and ERA-15 reanalyses is found in HODGES et al. (2003).

The monthly mean station data of Reykjavík (Icelandic Meteorological Office) are available since 1961. We use near surface temperature (2m), precipitation, surface pressure, and wind speed (10m) measured at this station until 2001.

The relationship between the cyclone density and the large scale circulation is analysed with respect to the NAO and ENSO. The NAO-index is given by the difference of the standardised pressure time series of the Azores and Iceland (Climate Research Unit, http://www.cru.uea.ac.uk/cru/, HURRELL (1995)). The ENSO index time series is defined by the Nino3 sea surface temperature anomalies (NCEP/NOAA, http://www.cpc.noaa.gov/data/indices/).

Cyclone Tracking: The cyclone track analysis is designed to detect weak cyclones with high spatial resolution (the algorithm used in the present analysis is described in BLENDER et al. (1997) and SICKMÖLLER et al. (2000)). Further cyclone tracking algorithms have been applied by GULEV et al. (2001) and HODGES et al. (2003). Lows are defined by minima of the 1000hPa geopotential height and additionally, a 1000hPa geopotential height gradient of at least 50gpm/1000km. The cyclone tracks are determined by connecting nearby cyclones at subsequent time steps with a maximum distance (speed) condition. To avoid spurious detections, we demand a minimum lifetime of 1 day (more precisely at least 5 subsequent time steps in the 6h data). Note that an increase of the minimum lifetime by one day (for example from 1 to 2 days or 2 to 3 days) reduces the number of detected cyclones to roughly 60%. This condition acts as an additional filter to sort out erroneous cyclones.

The cyclones are tracked in the North Atlantic and the adjacent regions (90W−40E, $20 - 90$N), besides southern Europe (east of 0E, south of 50N). This wide area is chosen to detect all cyclones which may impact the core region of the study. Regions with orography higher than 1000m are excluded (see Fig. 1 for the ERA-40 orography in this area north of 40N). A cyclone density is determined by the numbers of cyclones for each grid point and a normalisation by its area and the number of time steps. The density represents the probability (in percent) to detect a cyclone with the required minimum life time within an area of 10^6km^2 (roughly a 5° latitude circle). These densities are determined for the individual 45 winters to derive inter-annual variability and long term changes. To determine the impact of cy-

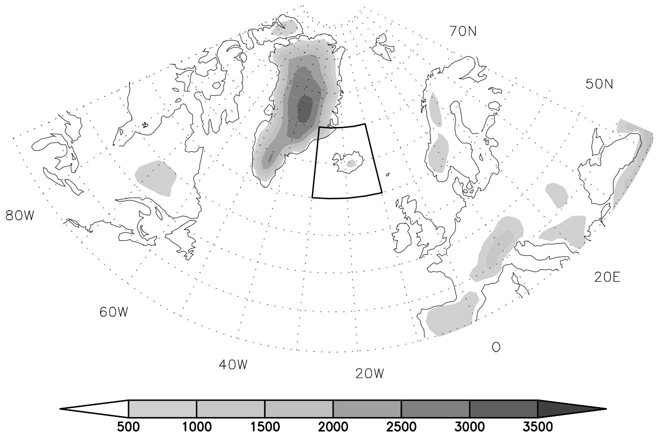

Figure 1: Orography in ERA-40 and the marked region, 60 – 70N, 30 – 10W, where the cyclones with impact on Iceland are extracted. The contour interval is 500m.

clones on the Icelandic climate, we consider the individual cyclones at each time step, if they occur in the region 60 – 70N, 30 – 10W surrounding Iceland (see the marked region in Fig. 1). These cyclones have a minimum life time of one day. In the following the cyclones in this region are used in a trend and a correlation analysis with the Icelandic climate.

3 Cyclone track variability

A sample of cyclone tracks is presented for the winter 1959/60 in Fig. 2. The restriction to orography below 1000m excludes mainly the central part of Greenland. The cyclone tracks spread across the whole North Atlantic with distinct preference for the west coast of Greenland. Lysis along Western Europe is clearly visible. Since the cyclone occurrences are negligible in the south of the analysed region, the following analyses are restricted to north of 40N.

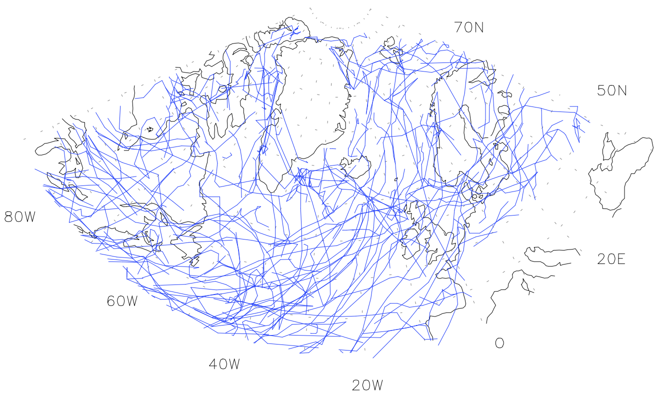

Figure 2: Sample cyclone tracks during winter 1959/60.

The cyclone density and its variability have been analysed in high resolution (T106) ERA-15 reanalyses (SICKMÖLLER et al., 2000) for the winter season. A major result of this study was the high density between Greenland and Iceland which was correlated with the NAO-index while the cyclones propagating across the North Atlantic are less correlated with the NAO-index.

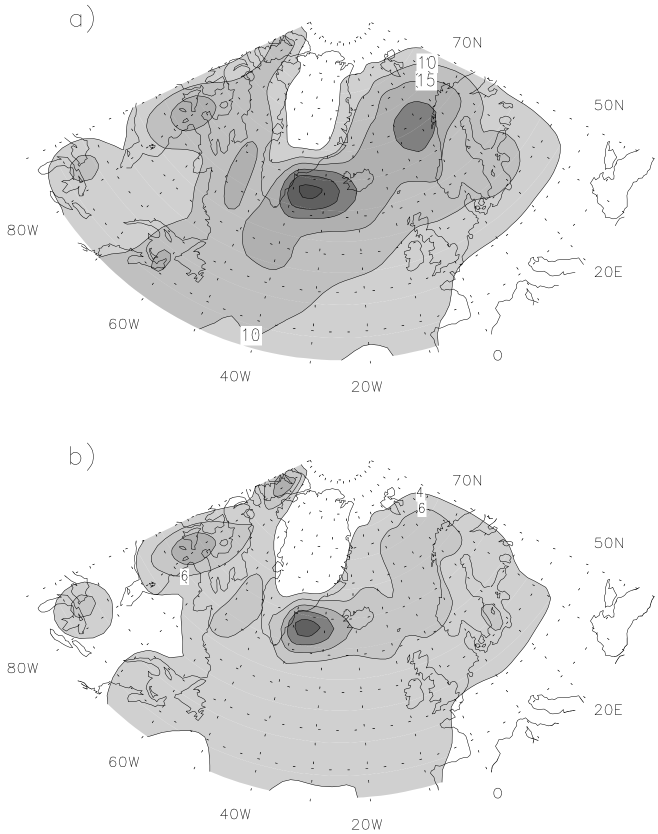

Figure 3: Cyclone density: (a) mean and (b) standard deviation in ERA-40. The map indicates the presence of a cyclone in a 10^6km^2 area (in %). Contour intervals are (a) 5%, (b) 2%, above 4%.

Climate: The mean cyclone density (Fig. 3a in 1957 – 2002) shows the occupation of an area of 10^6km^2 with a cyclone (in %). Hence a value of 10 denotes a chance of 10% to find a cyclone within this area at any time. This representation is independent of the resolution of the data and the time step of the analysis. The patterns are smoothed to 1000km to represent means in 10^6km^2. The cyclone tracks are concentrated along the North Atlantic with a clear maximum between South Greenland and Iceland. On the T106 grid up to two cyclones per grid point and winter occur in the region between South Greenland and Iceland.

The season-to-season variability of the 45 winter mean cyclone density maps (Fig. 3b) extends across the North Atlantic and shows a huge value in the area with high density south of Greenland/Iceland. Hence, Iceland is not only under the impact of large numbers of cyclones during winter, these number vary even more than in the remainder of the North Atlantic. Note, however, that the ratio of the standard deviations and the means is of comparable magnitude in most parts of the analysed region.

Long term change: The long term change of the cyclone density is determined by the difference of the means in 1980 – 2001 and 1958 – 1979 (winter years are defined by the January). Fig. 4 shows that the cyclone density in the North Atlantic is shifted northward with a particular increase between South Greenland and Iceland.

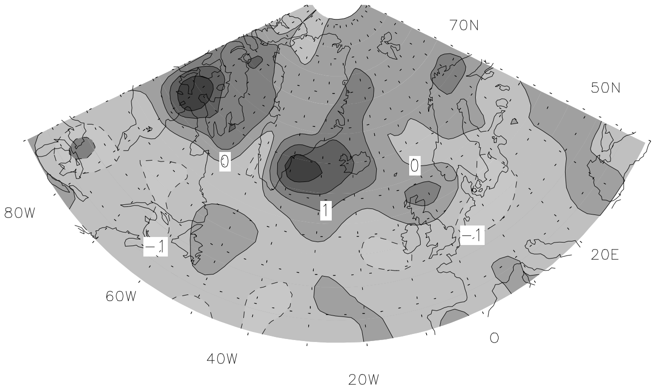

Figure 4: Decadal change of winter mean cyclone density determined by the difference of the means in 1980-2001 and 1958-1979 (% in 10^6km^2 area).

Teleconnections (NAO and ENSO): The mean position of the cyclone density is correlated with the mean large scale circulation dominated by the state of the NAO (see e. g. LÖPTIEN and RUPRECHT (2005) for a discussion on the causal relationships). Winter mean composites of the cyclone density are derived for the NAO-index above and below one standard deviation (Fig. 5). The NAO-index time series is further considered below (see Fig. 7). The correlation coefficients of the NAO-index with the winter mean cyclone density (not shown) reach $r \approx 0.5$ in the region of maximum cyclone density between South Greenland and Iceland, negative extrema ($r \approx -0.4$) are found in the south of the analysed region. To indicate areas with significant relationship between NAO-index and cyclone density, the correlation coefficients $|r| > 0.3$ are shaded in Fig. 5 ($>$ 95% significance).

The North Atlantic storm track shifts southward during ENSO warm phases (SICKMÖLLER et al., 2000) in ERA-15 reanalyses. This corresponds to reduced surface pressure in the northern part of the North Atlantic (FRAEDRICH et al., 1992). Fig. 6 presents the composite pattern of the cyclone density for warm minus cold El Niño events. Areas with significant correlations ($>$ 90%) between the ENSO-index and the cyclone density are shaded. A high-resolution (T106) GCM simulation (MERKEL and LATIF, 2002) reveals the same southward shift of winter cyclones during El Niño events.

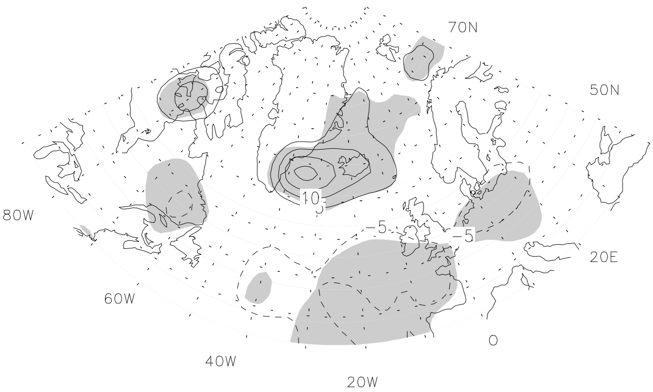

Figure 5: Difference of the cyclone density composites for winters with NAO-index above σ versus below $-\sigma$ (% in 10^6km^2 area). Contour interval is 5%, significant values shaded ($>$ 95%).

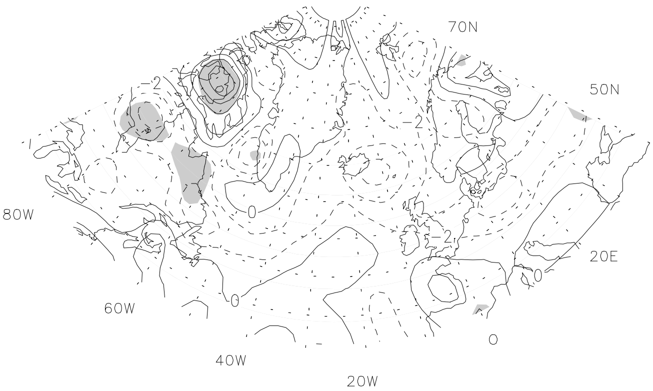

Figure 6: Composites of the cyclone density for winters with ENSO warm minus cold events defined by the Nino3 temperature above σ versus below $-\sigma$ (% in 10^6km^2 area), contour interval is 2%; significant ENSO-cyclone density correlations shaded ($>$ 90%).

4 Cyclones and the Icelandic climate

To assess the relationships between cyclones and the Iceland climate we extract the cyclones in the vicinity of Iceland (60 – 70N, 30 – 10W, see box in Fig. 1) The number of cyclones is characterised by the number of lows N_{lows} (which constitute the cyclones, but counted at every time step), the central 1000hPa geopotential height CZ, and its gradient GZ, within a surrounding area of 10^6km^2. The Icelandic climate is represented by the winter means at the station Reykjavík: near surface temperature T (2m), precipitation R, surface pressure p, and wind speed U (10m). The cyclone and the climate data are compared with the North Atlantic Oscillation (NAO) index time series. To determine the long term relationships and a possible climate change, the trends within the last decades are considered. The inter-annual relationships are derived by the detrended correlations.

This analysis uses the cyclones with a minimum life time of one day. For every winter, the number of cyclones is determined every 6h detection time step. In the mean there are 152 cyclones in this area during a winter, about 16 cyclones develop and the same number of cyclones decays, while 5 cyclones remain here during their full life cycle. (Comparison with Figure 3 has to consider that this map is smoothed using the cyclone counts

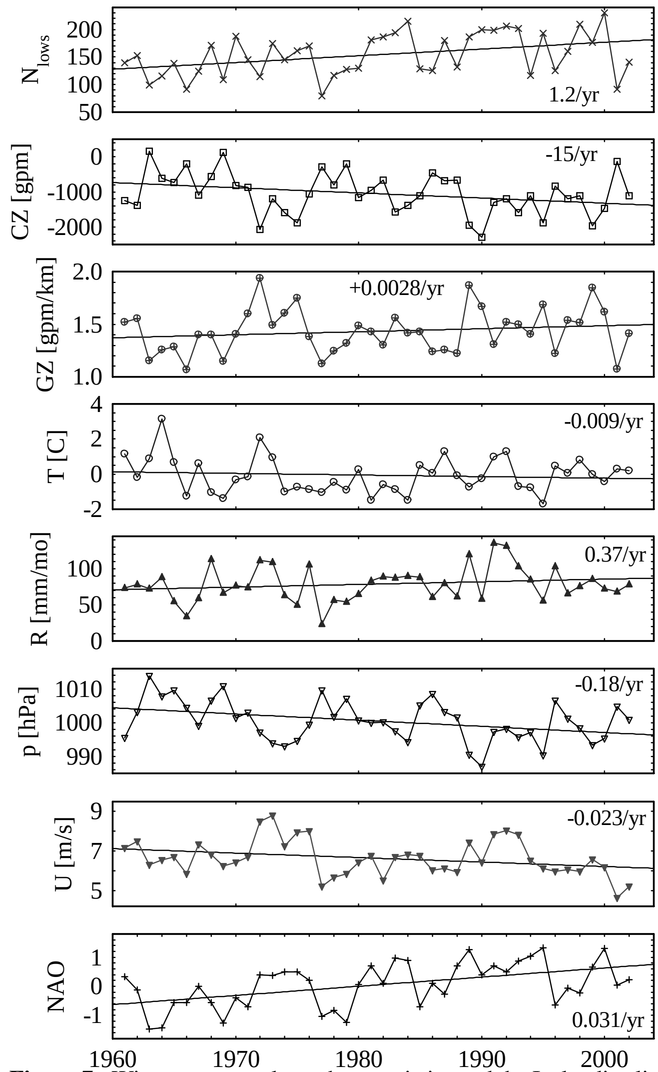

Figure 7: Winter mean cyclone characteristics and the Icelandic climate (Reykjavík): number of lows N_{lows}, mean central geopotential height CZ [gpm] and its gradient GZ [gpm/km], near surface (2m) temperature T [C], precipitation R [mm/month], surface pressure p [hPa], wind speed (10m) U [m/s], and North Atlantic Oscillation (NAO) index. Linear trends per year are included (dimension of variable).

per grid point and winter (360 observation times) in the region marked in Fig. 1 (190 grid points), see Section 3.)

The cyclone and climate time series, including the linear trends from 1961 to 2002, are shown in Fig. 7. The trends of N_{lows}, CZ, p, U, and the NAO-index are significant above 90%. Near surface temperature T decreases by 0.009C/yr in agreement with HANNA et al. (2004). Precipitation R increases, however, accompanied with a large inter-annual variability. The dynamic variables show consistent long term changes: The pressure p as well as the mean central geopotential heights (CZ) decrease, while the number of lows N_{lows}, the mean geopotential height gradient (GZ) and the NAO-index increase.

The correlations of the winter climate in Iceland, as described by near surface temperature T (2m), precipitation R, surface pressure p, and wind speed U (10m) with the cyclone characteristics N_{lows}, CZ, GZ, and the NAO-index are shown in Table 1. For the correlation analysis, the time series are detrended. The threshold for the correlation coefficient is $r \approx 0.25$ for rejecting the hypothesis of no correlation with a significance level of 90% in 41 years. The main aspects of the correlations with the winter to winter varying numbers of cyclones and their intensities are:

(1) The near surface temperature is not correlated; a possible reason is the opposite effect of cyclones in the west and in the east of Iceland.

(2) Precipitation is predominantly correlated with the number of cyclones; the correlations with the NAO and with the intensity of the cyclones are distinctly lower. A possible interpretation is that even weak cyclones lead to considerable amounts of precipitation in Iceland.

(3) The surface pressure and the wind speed show high correlations with the number of cyclones and their intensities.

(4) The correlations between NAO-index and cyclones, as well as between the central geopotential height (CZ) and the geopotential height gradient (GZ) are as expected.

The correlations between the Icelandic near surface temperature and the NAO-index are determined by HANNA et al. (2004) for all seasons during the 20th century who find $r = -0.18$ for Reykjavík (while $r = -0.23$ is found for the present period).

To assess whether the station Reykjavík is representative for the climate in Iceland we consider the station Teigarhorn (where pressure is not available). This station shows similar correlations, besides the relationships of the wind speed with the other variables (for example, correlation with near surface temperature is negative). As discussed in BROMWICH et al. (2005) who conducted a high-resolution climate simulation over Iceland, the analysis of observational wind and precipitation data is frequently difficult due to the impact of the complex terrain. This leads to highly variable land-sea-breeze circulations and catabatic winds rendering the surface observations weakly representative.

5 Summary and Conclusions

This study associates North Atlantic cyclones in ERA-40 reanalyses with the Icelandic climate of 1961 – 2001. In winter the frequency of North Atlantic cyclones attains a maximum between the southeast of Greenland and Iceland. In the same region the variability of the cyclone frequency reveals a distinct maximum; a secondary maximum is found west of Norway at the end of the North Atlantic storm track. During the last decades the cyclone density increased near Iceland.

For a comparison of the trends and correlation analysis with the Icelandic climate, the cyclones with one day life time are determined in a region around Iceland, 50 – 60N, 30 – 10W. The numbers of these show a linear increase accompanied with increasing intensities which correspond to increasing NAO-index and decreasing pressure. In low resolution data this increase of the number of cyclones has not been detected (SERREZE et al., 1997).

The detrended anomaly time series of the numbers of cyclones, in particular their intensities, are highly correlated with the Icelandic surface pressure, wind speed, and the NAO-index. For precipitation the correlation with the cyclones is higher than the correlation with the NAO-index. The highly significant decrease in wind speed in Reykjavík, which contradicts the overall trend of the dynamical variables including the number of cyclones, is possibly due to considerable urban development.

The presence of trends opposite to the global trend during the last century is a challenge for climate variability analysis. Obviously, low frequency variability caused by long term memory processes in the ocean (FRAEDRICH and BLENDER, 2003) superimposes the trend during the 20th century (BLENDER and FRAEDRICH, 2003) which is attributed to anthropogenic impacts. The central role of the North Atlantic region south of Greenland shows up in a recent analysis of a coupled climate simulation which reveals that ultra low frequency climate variability on millennial time scales is uniquely found here (BLENDER et al., 2006). The result of this control simulation with constant external forcing agrees quantitatively with the findings in the Greenland ice core records.

Extensions of the present analysis may consider (i) inclusion of sea ice variability and its relationships with the cyclones (see for example BRÜMMER et al. (2001)), (ii) a more detailed analysis of the Icelandic climate and the extension of the winter season to November and March, and (iii) analysis of high resolution regional model simulations.

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r	N_{lows}	CZ	GZ
T	-0.12	-0.02	0.02
R	**0.44**	**-0.26**	**0.27**
p	**-0.59**	**0.87**	**-0.75**
U	**0.52**	**-0.68**	**0.63**
NAO	**0.53**	**-0.71**	**0.59**
CZ	**-0.53**		
GZ	**0.49**	**-0.90**	

Table 1: Correlation coefficient r between detrended winter means of T (2m temperature), R (precipitation), p (surface pressure), U (10m wind speed), NAO (North Atlantic Oscillation). N_{lows} (number of lows), CZ (central 1000 hPa geopotential height), and GZ (1000 hPa geopotential height gradient). Cyclones in 50 – 60N, 30 – 10W, and observations at Reykjavík; significant correlations are bold.