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ORIGINAL PAPER

Azores High and Hawaiian High: correlations, trends and shifts (1948–2018)

Malgorzata Falarz[1]

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Abstract

The paper focuses on investigation of 'twin' subtropical oceanic highs of the Northern Hemisphere, i.e. the Azores High (AH) and the Hawaiian High (HH) in January and July based on gridded 2.5° × 2.5° data of Reanalysis Project of the National Center for Atmospheric Research for the period 1948–2018. The aim is to answer three questions: (1) Are there any connections between AH and HH (both within and between the systems)? (2) What is the long-term variability and trends of the basic characteristics of AH and HH? (3) Do the AH and HH move, and if so, in what directions? The most important results are as follows: (1) the long-term trend of sea level air pressure in the AH centre in January is positive, statistically significant with the increase of 0.63 hPa/10 years, (2) pressure in both centres significantly relates with the latitude of each system; variables characterising the HH in January explain 11% of variation of the variables of the AH in July, (3) the NE-SW/SW-NE index proves the shifting of the AH in January from the south-west to the north-east from the 1990s of the twentieth century and again to the south-west in the twenty-first century, (4) the HH in January and July moved generally from the north-east to the south-west until the end of the twentieth century and shifted again to north-east during the twenty-first century, (5) the AH in July was characterised by complicated displacement system with the prevalence of the shifting from the north-east to the south-west with the exception for the period 1980–1990. In winter, the AH moves towards the land area of Europe in the second half of the twentieth century, while the HH moves towards the open Pacific. The statistically significant increase of pressure in the centre of the AH in January is closely related to the shifting of the system to the north-east. The positive pressure trend in the centre of the AH in January combined with the zero trend in July is the cause of diminishing difference between summer and winter air pressure value of the high. Due to increased sea surface temperature of the Atlantic, the AH does not lose its strength in winter as it used to a few decades ago.

1 Introduction

Climate change research carried out in recent decades led in many cases to the conclusion that the cause of these changes are changes and variability in the macro- and mesoscale atmospheric circulation (e.g. Konrad 1998; Clark et al. 1999; Marsz 1999; Slonosky et al. 2001; Falarz 2007, 2013; Rasmus et al. 2015). Hence, at the same time, there was a surge of interest in cyclic and non-cyclic changes in circulation (e.g. Slonosky et al. 2000; Thompson and Wallace 2000; Thompson et al. 2000), temporal trends and correlations between circulation indices (e.g. Rogers 1984) as well as their relations with the temperature of the ocean surface (e.g. Hasanean 2004). The field of research into changes in circulation also includes investigation of fluctuation and interaction of atmospheric centres of action (ACAs) over the globe. This paper contributes to this line of research.

The term 'centre of action', originally used by L. Teissenenc de Bort in 1881, was applied to the maxima and minima of pressure on daily charts (Glossary of Meteorology 2018). H.H. Hildebrandson (1897) defined centres of action as high and low pressure systems occurring on the Earth all year around (permanent centres of action) or for at least one season (quasi-permanent centres of action). Similarly, a more precise definition can be found in modern meteorology glossaries, namely (1) atmospheric centre of action (centre of atmospheric activity) is an area of high or low pressure on the globe with a more or less permanent location, remaining for long periods (Niedźwiedź 2003) and (2) any one of the semi-permanent highs and lows that appear on mean charts of sea level pressure (Glossary of Meteorology 2018). The formation of atmospheric centres of action is related to the varied rate of

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absorbing and releasing heat by the surfaces of continents and oceans.

ACAs have already been the subject of numerous studies. The first detailed studies concerning atmospheric centres of action had already been achieved in the early 1970s (Perry 1971; Angell and Korshover 1974) while large scale research into the centres were initiated in the 1990s (Sahsamanoglou 1990; Sahsamanoglou et al. 1991; Zhang et al. 1995; Christoforou and Hameed 1997; Serreze et al. 1997; Kapala et al. 1998; Mächel et al. 1998).

Within the research into ACAs conducted thus far, there are at least five fields that can be distinguished:

1) investigation of changes in location and intensity of the centres; (Quadrelli and Wallace 2004; Chang and Lu 2012; Qu et al. 2015; Shatilina et al. 2016; Zheleznova and Gushchina 2016); some results are as follows:

- the statistically significant tendency of northward moving of Icelandic Low and Azores High (Zhang et al. 1995; Mächel et al. 1998; Falarz 2009),
- the eastward shift of the NAO centres of action of interannual variability during the period after 1980, probably due to an increase in the strength of the zonal mean westerly winds in the North Atlantic region (Luo and Gong 2006),
- the strengthening of the Azores High over the past 20 years resulting in the positive trend of the North Atlantic Oscillation index (Hasanean 2004),
- Icelandic and Aleutian Lows are deeper in the months of abnormally high air temperature in the Northern Hemisphere (Quadrelli and Wallace 2004),
- the weakness of Siberian High in the second half of the twentieth century (Sahsamanoglou et al. 1991, Gong and Ho 2002, Panagiotopoulos et al. 2005, Hasanean et al. 2013) and recovering of it from the 1990s (Jeong et al. 2011),
- the affecting of Siberian High by the Hadley circulation cell (Hasanean et al. 2013),
- northward shift and strengthening of the Aleutian Low (Park et al. 2012);

2) investigation of interactions between the centres (Wallace and Thompson 2002; Honda et al. 2005b; Tubi and Dayan 2013; Sun et al. 2017); some results are as follows:

- strong correlation of Icelandic Low latitude and air pressure in the centre of Azores High in winter (Mächel et al. 1998),
- the simultaneous occurrence of strong positive NAO and the negative trend of Aleutian Low (Raible et al. 2005),
- relation of centres of action over the Atlantic Ocean to the position and features of ITCZ (Souza and Cavalcanti 2009),
- the inversely proportional relationship (seesaw) of air pressure in the centres of Icelandic and Aleutian Lows (Honda and Nakamura 2001; Honda et al. 2001; Sun and Benkui 2013),
- The Aleutian–Icelandic Low seesaw was weak in the mid-1950s through the mid-1960s, while it was particularly strong during the preceding period from the 1920s to the 1940s (Honda et al. 2005b),
- enhanced cyclogenetic conditions over the eastern flank of the Icelandic Low are associated with a milder Siberian High (Tubi and Dayan 2013);

3) investigation of the impact of the centres of activity on climatic conditions of land areas (Kapala et al. 1998; Iqbal et al. 2013; Iqbal and Ilyas 2013; Sfîcă et al. 2015); some results are as follows:

- the East Asian winter monsoon is in relation to the Siberian High (Chang and Lu 2012),
- precipitation totals of Eurasia are in relationship with Northern Hemisphere centres of action (Murav'ev and Kulikova 2011),
- there is an inversely proportional relation between long-term variability of winter precipitation in the Middle East and Azores High pressure (Iqbal et al. 2013); a significantly great portions of interannual variance of winter precipitation over Indo-Pak Region (Northeast Pakistan and Northwest India) can be explained by including the contributions of the Icelandic Low pressure in addition to ENSO and AO (Iqbal and Ilyas 2013),
- the higher than average long-term difference between Azores High and Icelandic Low is associated with warming of the winter in northern and central Europe (Kapala et al. 1998),
- there exists inversely proportional relation between temperature and precipitation of high latitude of Asia (30°–70°N) with the intensity of winter Siberian High (Gong and Ho 2002),
- changes in the sea level pressure in Icelandic Low and latitude of Azores High in January (taken into account as a complex of features) explain about 40% of air temperature variability in central Europe (Falarz 2009),
- the average air temperature of winter in Poland is correlated inversely proportionally with the pressure in the centre of the Azores High and with the difference between this high and the Icelandic Low; positive trend of these two characteristics is a good explanation of significant warming of winters in Poland (Falarz 2009);

4) investigations of associations of centres of action with the sea surface temperature (Hasanean 2004; Park et al. 2012); some results are as follows:

– the Azores High in winter is influenced by the sea surface temperature in tropical part of the Northern Atlantic (Hasanean 2004),
– the Aleutian Low activity impacts on the main thermocline depth in the Kuroshio recirculation region (Sugimoto and Hanawa 2010),
– the positive sea surface temperature trend in the western North Pacific is the result of the weakening of the East Asian winter monsoon due to the decline of the Siberian High (Park et al. 2012);

5) investigations of associations of centres of action with the atmospheric pressure in the higher levels of the atmosphere (Zarrin et al. 2010); the result is as follows:

– there is a clear difference in the location of the summer subtropical highs over Asia and Africa in the lower, middle and upper troposphere (Zarrin et al. 2010).

Atmospheric centres of action are of crucial importance in the overall atmospheric circulation. Each change in the location of any of them, even a slight one, may have an impact on changes in circulation and climatic conditions over large areas of the globe. Therefore, this paper focuses primarily on investigation into the movements of 'twin' subtropical oceanic highs of the Northern Hemisphere, i.e. the Azores High (AH) and the Hawaiian High (HH). The existing papers on the movements of atmospheric centres of action are focussed studying the movements of atmospheric centres of action in the main directions (W-E/E-W, S-N/N-S; e.g. Luo and Gong 2006, Park et al. 2012). However, it seems important to investigate the movements in the intermediate directions as well. The AH and HH have been explored in this study using a consistent method with regard to their interactions, trends and directions of shift. An advantage of the study is the fact that it was based on an accurate location of the centre of the system read from the maps of mean monthly sea level pressure instead of regional mean of sea level pressure averaged over the area of ACA location which is most frequently used (e.g. by Hasanean 2004, Panagiotopoulos et al. 2005).

The aim of the paper is to answer the following questions: (1) Are there any connections between AH and HH characteristics (both within and between the systems)? (2) What are the long-term variability and trends of the basic characteristics of these atmospheric centres of action of the Northern Hemisphere? (3) Do the atmospheric centres of action of the Northern Hemisphere move, and if so, in what directions? Exploration of the variability and interactions of the AH and HH may contribute to detecting the circulatory mechanisms that influence climatic conditions of land and sea areas. This in turn will be helpful in explaining more fully the changes and variability of the climate and even in attempts to provide long-term estimation of these changes.

2 Data and methods

The geographical coordinates (longitude—x (°), latitude—y (°)) and the atmospheric pressure value (z; hPa) in the centre of both the AH and the HH were read from maps of mean monthly sea level pressure based on gridded 2.5° × 2.5° data of Reanalysis Project of the National Center for Atmospheric Research (Kalnay et al. 1996) for the period 1948–2018 (71 years). When two systems of closed isobars were observed within an area of medium occurrence of a given centre, the oceanic system with higher pressure in the centre was considered. The centre of each high was found by interpolation using maps with isobars of 1 hPa interval. Long-term correlations of AH and HH features in January and July were analysed considering both correlations within 1 month in one centre and relations between two centres and between the characteristics of the systems in winter and in summer (lag correlations). In order to examine relations between centres of action described simultaneously by a set of several characteristics (i.e. x, y, z), the method of canonical analysis was used. Values and statistical significance were determined for the largest coefficient of the canonical correlation that describes the connection between the characteristics of the AH and HH, and the total redundancy of the connections between the systems was analysed. Total redundancy is the mean percentage of variation explained in one set of variables, given another set of variables (Stanisz 2007).

Long-term trends for the features of the centres of both highs were examined by ascertaining their statistical significance. Most attention was devoted to examining the shifts of the systems during the analysed period. The movements of the centres in January and July were examined using several methods:

1) regression analysis of x and y for both centres in the analysed period; this only enabled assessment of the latitudinal and longitudinal shifts of the highs; statistical significance of the trends of x and y was evaluated; additionally, a 10-year consecutive average was used to smooth the series;
2) 10-year mean locations of each ACA in the following rigidly fixed periods: (1) 1951–1960, (2) 1961–1970, (3) 1971–1980, (4) 1981–1990, (5) 1991–2000, (6) 2001–2010, (7) 2011–2018.
3) cluster analysis which made it possible to separate period characteristic for the locations of both highs in January and July within the long-term period; for the clustering, standardised values of x and y separately for each of the

centres were taken; the method of *k*-averages was applied; the results were not completely clear; however, on the basis of the dominant cluster, the analysed period was divided into three sub-periods of different locations for the AH in January and July and for the HH in July as well as two sub-periods of a HH location in January;

4) indices taking into account the shifts of the centres in eight rhumbs of the compass, i.e. E, W, N, S, SW, NE, NW and SE. The indices were created as follows:

– index of E-W/W-E shift: *A1-B1*, where:

A1 is 10-year moving sum of $a1 = x - x\text{avg}$, for $x > x\text{avg}$ (i.e. for the location in the first and the fourth quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the East to the average),

B1 is 10-year moving sum of $b1 = x\text{avg} - x$, for $x < x\text{avg}$ (i.e. for the location in the second and third quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the West to the average),

x—longitude of the centre of action in a year; *x*avg—average longitude of the ACA for 1948–2018;

E-W/W-E index > 0 indicates predominance of the E location over the W one, while E-W/W-E index < 0 indicates predominance of the W location over the E one;

— index of N-S/S-N shift,: *A2-B2*, where:

A2 is 10-year moving sum of $a2 = y - y\text{avg}$, for $y > y\text{avg}$ (i.e. for the location in the first and the second quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the North to the average),

B2 is 10-year moving sum of $b2 = y\text{avg} - y$, for $y < y\text{avg}$ (i.e. for the location in the third and fourth quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the South to the average),

y latitude of the centre of action in a year, yavg average latitude of the centre of the ACA for 1948–2018;

N-S/S-N index > 0 indicates predominance of the N location over the S one, while N-S/S-N index < 0 indicates predominance of the S location over the N one;

— index of NE-SW/SW-NE shift: *A3-B3*, where:

A3 is 10-year moving sum of $a3 = (x - xavg) + (y - y\text{avg})$, for $x > x\text{avg}$ and $y > y\text{avg}$, (i.e. for the location in the first quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the North-East to the average),

B3 is 10-year moving sum of $b3 = (x\text{avg} - x) + (y\text{avg} - y)$, for $x < x\text{avg}$ and $y < y\text{avg}$ (i.e. for the location in the third quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the South-West to the average);

NE-SW/SW-NE index > 0 indicates predominance of the NE location over the SW one, while NE-SW/SW-NE index < 0 indicates predominance of the SW location over the NE one;

— index of NW-SE/SE-NW shift: *A4-B4*, where:

A4 is 10-year moving sum of $a4 = (x\text{avg} - x) + (y - y\text{avg})$, for $x < x\text{avg}$ and $y > y\text{avg}$ (i.e. for the location in the second quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the North-West to the average),

B4 is 10-year moving sum of $b4 = (x - x\text{avg}) + (y\text{avg} - y)$, for $x > x\text{avg}$, and $y < y\text{avg}$ (i.e. for the location in the fourth quarter of the coordinate system with a zero point of the average long-term location of each ACA; location of the centre on the South-East to the average).

NW-SE/SE-NW index > 0 indicates predominance of the NW location over the SE one, while NW-SE/SE-NW index < 0 indicates predominance of the SE location over the NW one.

The analysis consider only the centre points of each high. The extent of ACAs is neglected here.

3 Results

3.1 Main characteristics, trends and correlations of the AH and HH in January and July

In the period 1948–2018, the average pressure in the centre of the AH is similar in January and July (1025 and 1026 hPa, respectively; Table 1). The HH is stronger in July than in January; the average pressure is higher in July by 4 hPa (1023 and 1027 hPa, respectively). For the AH, the difference in pressure in the centre of the system in January and in July is only 1 hPa. The AH in July is shifted to the west relative to the average long-term January location, while the HH is to the northwest.

Table 1 Average and extremes of longitude (*x*, °), latitude (*y*, °) and sea level air pressure in the centre (*z*, hPa) of AH and HH (1948–2018)

Month	Feature	Azores High			Hawaiian High		
		x	*y*	*z*	*x*	*y*	*z*
January	Average	−25	34	1025	−134	32	1023
	Maximum	13	48	1035	−123	48	1030
	Minimum	−66	25	1017	−177	25	1017
July	Average	−37	36	1026	−152	38	1027
	Maximum	−25	45	1030	−138	45	1032
	Minimum	−53	30	1023	−170	33	1024

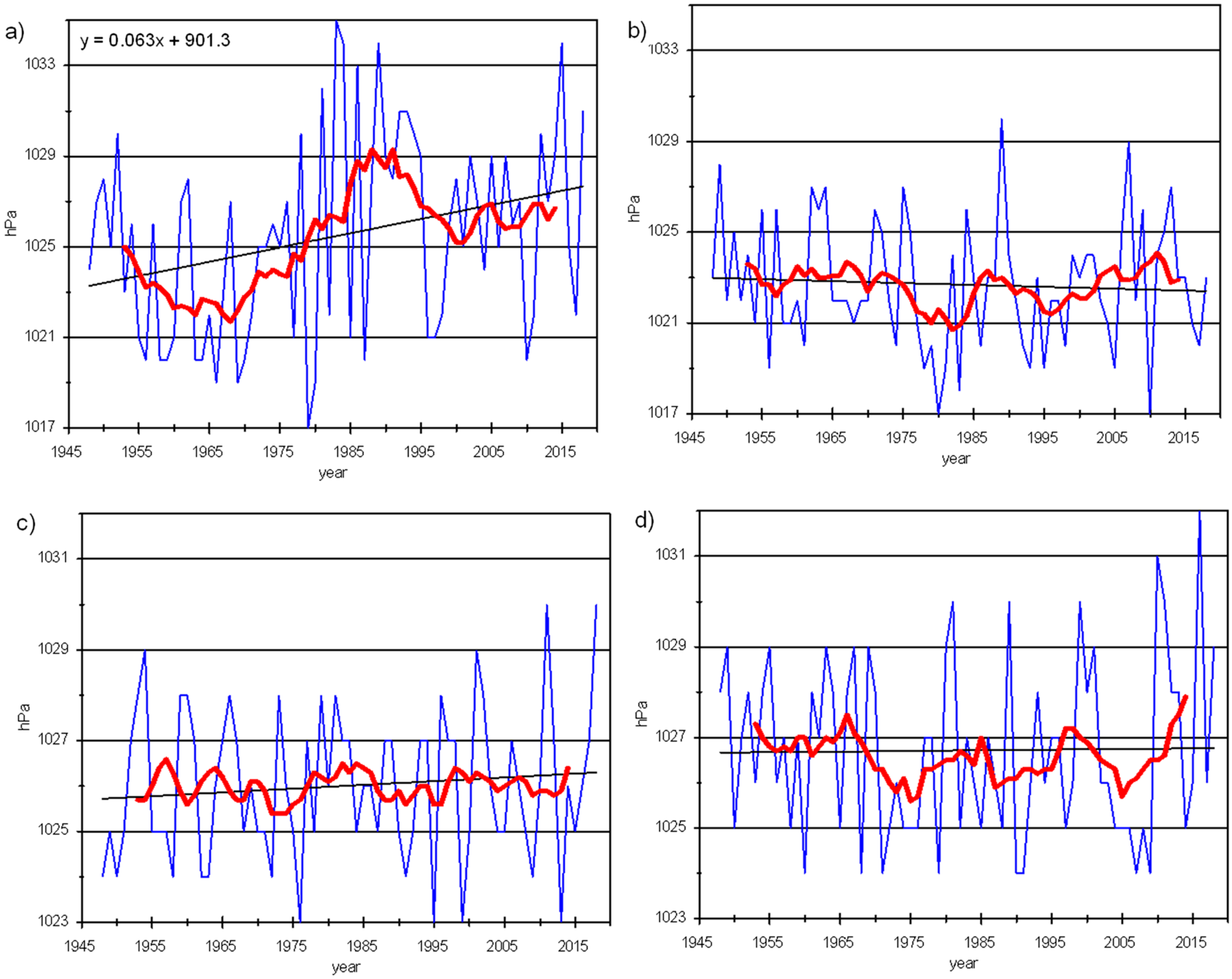
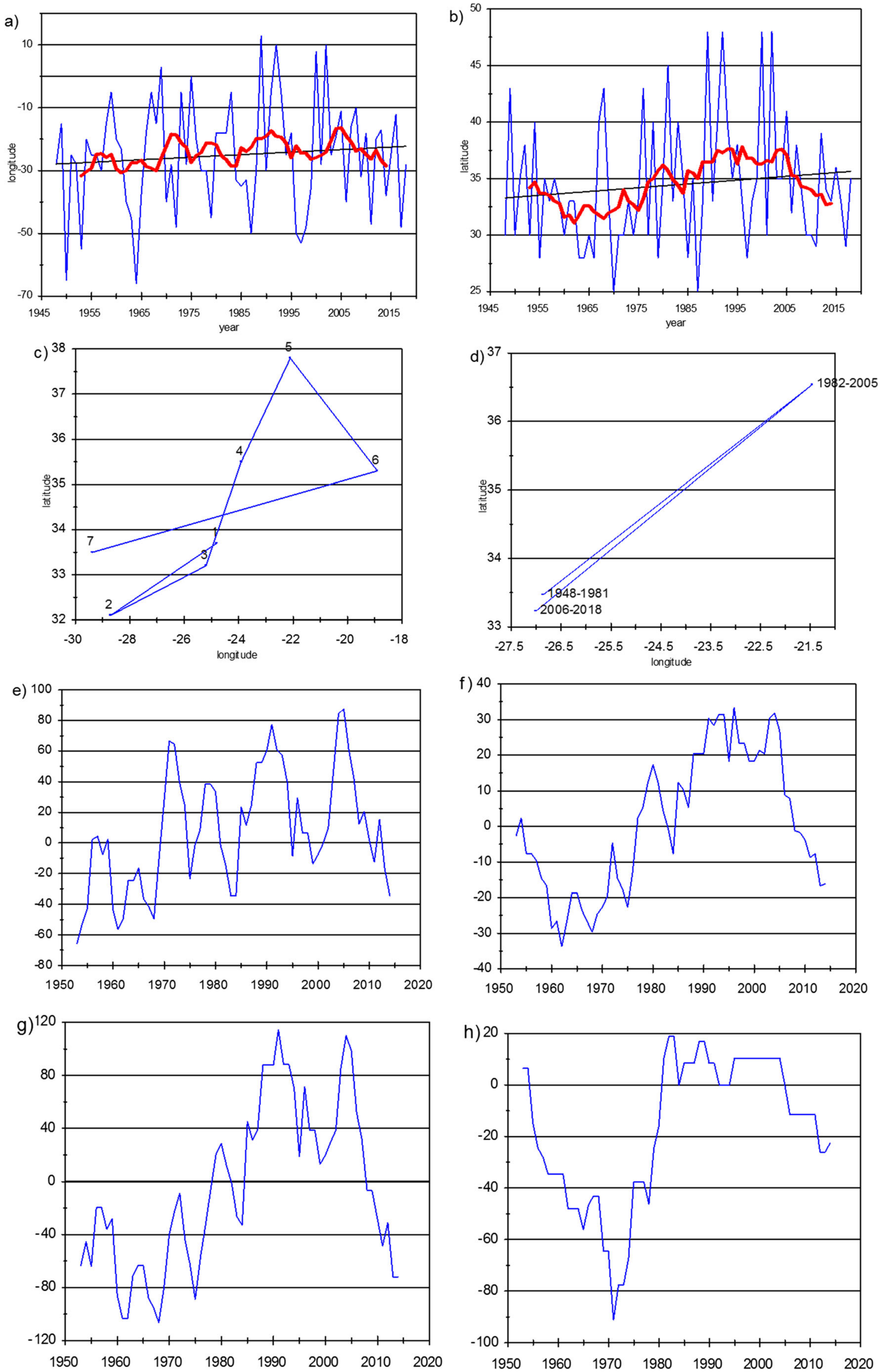


Fig. 1 Sea level air pressure (hPa) in the centre of AH (left) and HH (right) in January (upper) and July (bottom; 1948–2018). Ten-year consecutive average and trend lines were added. For statistically significant trend, the regression equation was shown

The long-term trend of sea level air pressure in the AH centre in the period 1948–2018 is positive, statistically significant in January and almost zero (slight positive, not significant) in July (Fig. 1a, c). The average increase in pressure in the centre of the AH in January is 0.63 hPa over 10 years (i.e. 4.5 hPa in the whole period). The HH does not reveal a statistically significant trend of pressure in the centre neither in January nor in July (Fig. 1b, d). Year to year, pressure

Table 2 Correlation coefficients for AH and HH *x*, *y*, *z* in January (Jan) and July (Jul; 1948–2018). Only the statistically significant (0.05) coefficients were shown (abbreviated table)

	AH *x* (Jan)	AH *y* (Jan)	HH *y* (Jan)	HH *z* (Jan)	AH *x* (Jul)	AH *y* (Jul)	HH *x* (Jul)	HH *y* (Jul)
AH *y* (Jan)	0.69							
AH *z* (Jan)	0.32	0.64						
HH *z* (Jan)			0.62					
AH *x* (Jul)				−0.24				
AH *y* (Jul)				−0.23	0.66			
AH *z* (Jul)			−0.31		0.32	0.59		
HH *y* (Jul)							0.34	
HH *z* (Jul)						0.29		0.63


a)
longitude
year
b)
latitude
year
c)
latitude
longitude
1
2
3
4
5
6
7
d)
latitude
longitude
1982-2005
1948-1981
2006-2018
e)
f)
g)
h)

◀ **Fig. 2** Azores High in January. **a** Longitude (°), **b** latitude (°), **c** 10-year mean locations (periods are as follows: (1) 1951–1960, (2) 1961–1970, (3) 1971–1980, (4) 1981–1990, (5) 1991–2000, (6) 2001–2010, (7) 2011–2018), **d** cluster analysis periods, **e** E-W/W-E index, **f** N-S/S-N index, **g** NE-SW/SW-NE index, **h** NW-SE/SE-NW index

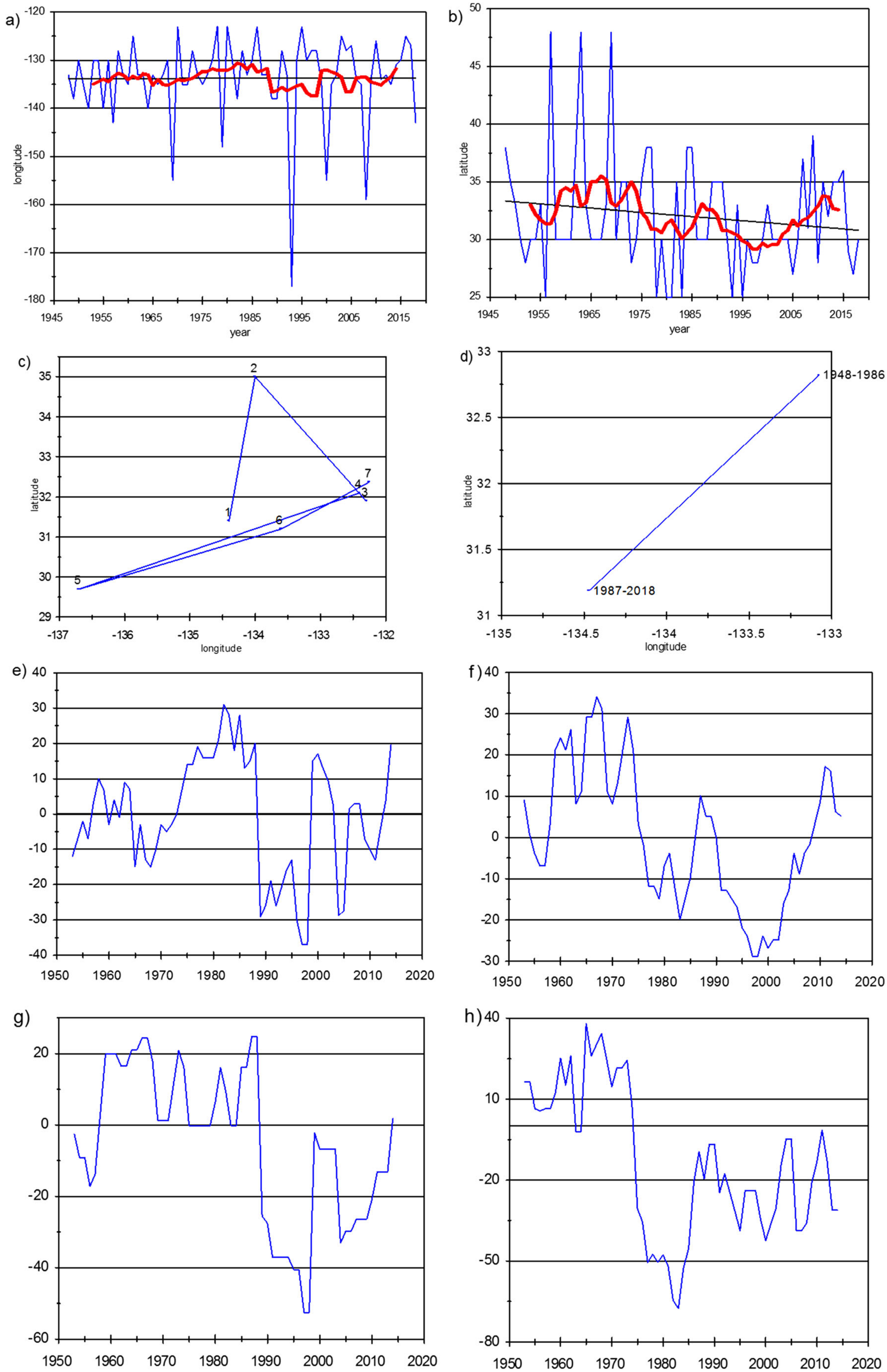
variability in January is considerably smaller in the HH than in the AH.

The systems concerned display the closest statistically significant correlations within one system in the same month (Table 2). These are directly proportional relations between the latitude and longitude for the AH (correlation coefficient r is 0.69 in January and 0.66 in July). Pressure in both centres, both in January and in July, relates to the latitude of each of these systems in the particular month ($r = 0.64$ for the AH and 0.62 for the HH in January, $r = 0.59$ for the AH and 0.63 for the HH in July). The systems are the stronger, the more their centres are located to the north. There are also statistically significant, but not too strong, correlations between the AH and the HH in the same month: latitude of the AH in July is positively correlated with the pressure in the centre of the HH in this month ($r = 0.29$). Furthermore, there is an inversely proportional relation between the latitude of the HH in January and air pressure in the centre of the AH in July (−0.31) and between pressure in HH in January and longitude and latitude of AH in July ($r = -0.24$ and -0.23 respectively). These correlations are however not close enough to enable forecasting features of the AH in July based on the HH location and latitude in January. The canonical correlation coefficient applied in order to examine the relation between the AH and the HH understood as a set of simultaneous acting features (x, y, z) is the highest for the above described relation and is 0.38. Total redundancy is 11%, which means that the variables (features) of the HH in January explain 11% of the variation of the variables of AH in July in the same year.

3.2 Shifts of locations of the AH and the HH in January

The Azores High in January shows in the studied period a slight, statistically insignificant increase in both the longitude and the latitude, which denotes a shift of the system to the east and the north (Fig. 2a, b). Both 10-year tracks and cluster analysis periods generally show a movement of the system to the north-east until 2005 (2010; Fig. 2c, d). The values of the E-W/W-E index confirm the shift of the AH in January to the east in the second half of the twentieth century while the values of the N-S/S-N index confirm a shift to the north in the period 1962–2000 (Fig. 2e, f). The NE-SW/SW-NE index proves a shift of the system from the south-west to the north-east until 1991 (the year of maximum value of the index; Fig. 2g). The values of the NW-SE/SE-NW index are negative for most of the study period and reach their minimum in 1971 (Fig. 2h). This is at the same time the year which saw the end of the downward trend of the latitude of the AH in January and the beginning of a positive trend signifying a shift of the system to the north. The highest value of that index was observed in 1982, i.e. in the first year of the second period separated by cluster analysis. The first and the second maximum peak of the values of both the indices E-W/W-E and NE-SW/SW-NE occurred in the same years (1991 or 2005). In 1961–1962, the minimum of the values of two indices occurred, i.e. of the N-S/S-N index and the NE-SW/SW-NE one, signifying a change in the direction of the system movement. This change is also well visualised in Fig. 2c). In the twenty-first century, a significant change in the direction of shift of AH in January was observed: both the longitude and latitude of the high began to decline, which denotes a shift of AH to the west and the south. The mean location for 2011–2018 differed significantly from the previous ones (Fig. 2c). The cluster analysis separated the period 2006–2018 when the AH in January was again close to the mean location of the period 1948–1981. The rapid change of movement direction since 2004–2005 shows also courses of E-W/W-E, N-S/S-N, NE-SW/SW-NE indices. However, for the whole analysed period, all the above mentioned indices reveal a positive statistically significant trend. Moreover, the E-W/W-E index shows a periodicity of about 15 years.

The longitude of the HH in January was stable during the period of the study with the exception of a few years (1969, 1979, 1993, 2000, 2008) when the highest pressure was noted further to the west for the average long-term location of the system (Fig. 3a). The latitude of the HH in January was characterised by a slight decreasing trend, which denotes a shift of the system towards the equator (Fig. 3b). The 10-year shifts show a great dynamic in the changes of the location of the HH albeit over a not very large area (Fig. 3c). During the first decade of the analysis period, a shifting of the system to the north took place. In the period 1961–1980, the HH moved to the south-east and remained in a stable location until the end of the 1990s. In the last decade of the twentieth century, the system moved significantly to the south-west and in the twenty-first century shifted again to the north-east. The cluster analysis provided grounds for separating two periods of the HH location in January, i.e. 1948–1986 and 1987–2018 (Fig. 3d). This implied a general conclusion on the shift of the high from the north-east to the south-west. The breakthrough year 1987, noticed in the cluster analysis, is also visible in the course of the NE-SW/SW-NE index for which the maximum value is observed just in this year (Fig. 3g). Following that particular year, the index produced negative values (indicating predominance of the SW location over the NE one) until the end of the analysed period. Another breakthrough year in the location of the system is 1997 (1998). This is the year in which as many as three indices, E-*W*/W-E, N-S/S-N and NE-SW/SW-NE reached their minimum value (Fig. 3e–g). The N-S/S-N index shows a slow shift in the system to the north at the


a)
longitude
year
b)
latitude
year
c)
1
2
3
4
5
6
7
latitude
longitude
d)
1948-1986
1987-2018
latitude
longitude
e)
f)
g)
h)

◀ **Fig. 3** Hawaiian High in January. **a** Longitude (°), **b** latitude (°), **c** 10-year mean locations (periods are as follows: (1) 1951–1960, (2) 1961–1970, (3) 1971–1980, (4) 1981–1990, (5) 1991–2000, (6) 2001–2010, (7) 2011–2018), **d** cluster analysis periods, **e** E-W/W-E index, **f** N-S/S-N index, **g** NE-SW/SW-NE index, **h** NW-SE/SE-NW index

beginning of the period, then to the south from the 1960s and again northwards from the beginning of the twenty-first century. The NW-SE/SE-NW index indicates the advantage of the NW location over the SE in January until 1975 and then a significant reverse trend (Fig. 3h). This is however not the dominant change in the HH location in January.

3.3 Shifts of location of the AH and the HH in July

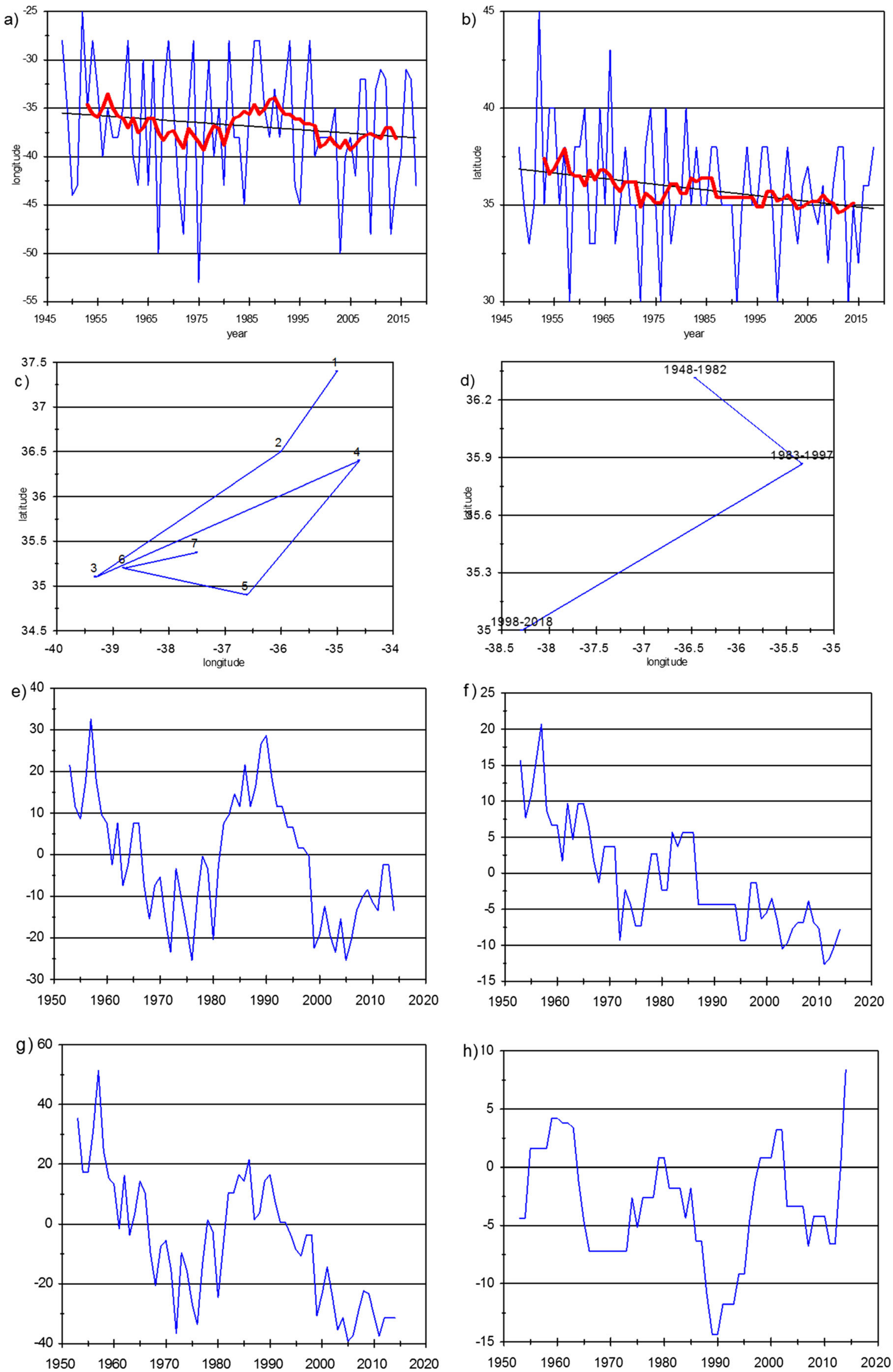
The AH in July displays a slight statistically insignificant downward trend concerning both the longitude and the latitude, which denotes a slight shift of the system to the west and to the south in the whole of the analysed period (Fig. 4a, b). The 10-year average locations show a rather complicated system of AH locations with the prevailing shifting of the high from the north-east to the south-west (Fig. 4c). The cluster analysis enabled grouping the locations of the system within three periods, i.e. 1948–1982, 1983–1997 and 1998–2018 (Fig. 4d). Between the first and the second period, a short distance shifting of the system to the south-east took place, and in the last two decades, a shift to the south-west was observed. The E-W/W-E index indicates a rather significant shifting of the AH in July to the west with the exception of the period 1980–1990 in which the system was moving eastwards (Fig. 4e). In a course of that index, one can notice three periods corresponding to those separated in cluster analysis. The N-S/S-N index shows the high shifting southwards at an almost uniform rate. The NE-SW/SW-NE index shows again an exceptional period 1980–1990 in which the steady shifting of the AH in July from the north-east to the south-west was disrupted (Fig. 4f). That index reveals a statistically significant decreasing trend for the whole studied period. The NW-SE/SE-NW component reaches very small values and is not significant in the analysis of the AH shifting in July (Fig. 4g).

The longitude of HH in July in the period 1948–2018 displayed a slight negative statistically insignificant trend, while the trend of the latitude is almost zero (Fig. 5a, b). The 10-year tracks show the predominant direction of the system shifting from the east to the west and south until 2010 and quite rapid movement to the NE in the last years (Fig. 5c). The cluster analysis enabled to distinguish three periods in the following location: north-east to the mean long-term location (1948–1969), south-west to the mean long-term location (1970–1980) and north-west to the mean location (1981–2018; Fig. 5d). In the third period, the system was relocated north-eastwards relative to the former one. Index E-W/W-E reveals a decreasing statistically significant trend meaning in general a westward shift. Two indices (E-W/W-E and NE-SW/SW-NE) reached their maximum values in the same year, i.e. 1957 (Fig. 5e, g). This was the year of the maximum displacement of the system to the E and the NE relative to the average location in the long-term period. The NW-SE/SE-NW index values are quite small and have a rather chaotic profile (Fig. 5h). The shift of the system to the NW-SE/SE-NW was thus barely significant. Three indices, the E-W/W-E, N-S/S-N and NE-SW/SW-NE for the HH in July reached their first or second minimum peak in the same year, 1972 (1973); Fig. 5e–g). It was thus one of the breakthrough years in the location of this system. These three indices show a periodicity of about 31–35 years. In the twenty-first century, all these three indices revealed an increase in values indicating changes of direction of high to the east, north and north-east respectively.

4 Conclusions and discussion

The most important results of the research can be summarised in the following statements:

- the long-term trend of sea level air pressure in the AH centre during 1948–2018 in January is positive and statistically significant; the average increase of pressure in the centre of the AH in January is 0.63 hPa over 10 years. The AH in July and the HH in January and in July do not display statistically significant changes in pressure in the centre of the system in the studied period;
- pressure in both centres, both in January and in July, is significantly correlated with the latitude of each of these systems in the particular month ($r = 0.64$ for the AH and 0.62 for the HH in January, 0.59 for the AH and 0.63 for the HH in July). The AH and HH are the stronger, the more their centres are located to the north; the variables characterising the HH in January (x, y, z) explain 11% of variation of the variables characterising the AH (x, y, z) in July in the same year;
- the NE-SW/SW-NE index proves the shifting of the AH in January from the south-west to the north-east until 1991 and again to the south-west in the twenty-first century.
- the HH in January moved generally from the north-east to the south-west until the end of the twentieth century and shifted again to north-east in twenty-first century;
- the AH in July was characterised by quite a complicated displacement system with the prevalence of the shifting of the high from the north-east to the south-west with the exception of the period 1980–1990 in which the system moved eastwards;
- the HH in July shows the predominant direction of movement from the east to the west and south until 2010 and a quite rapid shift to NE in the last years. The breakthrough years for the location of the system were 1957, when the



a)
longitude
year
b)
latitude
year
c)
1
2
3
4
5
6
7
latitude
longitude
d)
1948-1982
1983-1997
1998-2018
latitude
longitude
e)
f)
g)
h)

◀ **Fig. 4** Azores High in July. **a** Longitude (°), **b** latitude (°), **c** 10-year mean locations (periods are as follows: (1) 1951–1960, (2) 1961–1970, (3) 1971–1980, (4) 1981–1990, (5) 1991–2000, (6) 2001–2010, (7) 2011–2018), **d** cluster analysis periods, **e** E-W/W-E index, **f** N-S/S-N index, **g** NE-SW/SW-NE index, **h** NW-SE/SE-NW index

system was shifted extremely to the E and the NE relative to the average location in the long-term period and 1972 (1973) when three indices, the E-W/W-E, N-S/S-N and NE-SW/SW-NE reached their first or second minimum peak; these indices show a periodicity of about 31–35 years for the HH in July;

- the shifts of both systems are more significant in January. In July, both highs display a higher stability in their locations;
- particularly prominent in the shifting of the systems analysed are the breakthrough years common for at least two analysed cases, which denote changes in the directions of movement of the systems i.e. 1970 (1969–1973) for the AH in January and HH in July, 1981 (1980–1982) for all analysed cases (AH and HH in January and in July), 1990 (1991) for the AH in January and in July as well as 1997 (1998) for HH in January and AH in July.

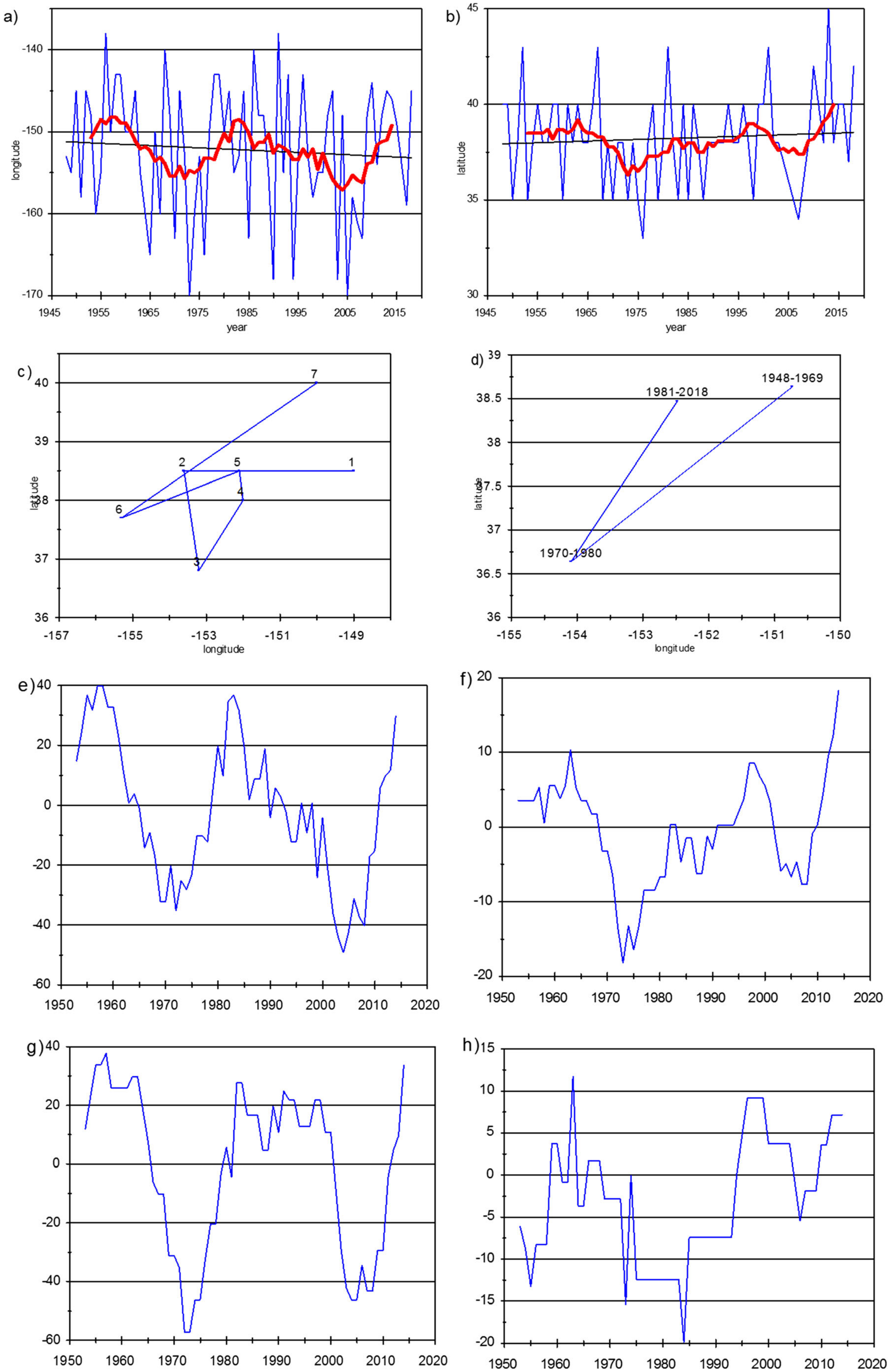
In winter, the systems analysed moved until the end of the twentieth century in different directions: the AH towards the land area of Europe and the HH towards the open Pacific. This may significantly affect the changes in the climatic conditions of both continents. In the first case, it implies an increase in the impact of the system on Europe, mainly by increased intensity of the air flow from the North Atlantic to Europe. In the second case, it implies decreased significance of the system for the North American continent. In summer, both systems display a not too clear tendency towards moving away from the shores of Europe (AH) and North America (HH).

The strengthening of the Azores High observed in the last 20 years of the last century by Hasanean (2004) appeared to be a significant feature of that centre in January manifesting itself in positive trend over the entire period of 71 years considered herein. A statistically significant increase in pressure in the centre of the AH in January is closely correlated with the shifting of the system to the north-east in the analysis period. This is due to a close correlation between pressure in the centre of the AH and its latitude and a less close one between pressure in the AH and its longitude. Thus, the observed increase in the latitude and longitude of the system in January until the end of the twentieth century is accompanied by an increase of air pressure in its centre.

The AH is exposed to the impact of the temperature of the tropical part of the North Atlantic in the winter (Hasanean 2004). The positive pressure trend in the centre of the AH in January combined at the same time with the almost zero trend in July is the cause of diminishing differences between summer and winter air pressure value in the centre of the high. The average long-term pressure of this system in January is almost equal to that in July. This is an unusual situation. The sea surface temperature (SST) of the North Atlantic in winter should not create such favourable conditions for maintaining the air pressure value in the centre of the AH at a level almost equal to the summer one. Such a situation is caused by the simultaneous impact of two features of the SST trend of the North Atlantic Ocean: (1) the increase in the SST of the North Atlantic and (2) the negative trend of the seasonal range in SST (both characteristics of the SST of the Atlantic were described by Taboada and Anadón 2012). At present, the Atlantic Ocean does not cool down in winter as before and therefore, the AH does not lose its strength (does not weaken) as much in this season relative to the summer season as it used to be a few decades ago. The third cause of the described phenomenon may be the decrease in the difference in temperature in January between the SST of the North Atlantic and the air temperature over the European continent. This would lead to attenuation of air settling over Europe and attenuating the flow of air between the land and the ocean. The above thesis requires further investigation but the proven reduction of the duration of snow cover in Europe (Rasmus et al. 2015; Ye and Lau 2017), which results in reduced winter albedo of the continent, leads indisputably to increased absorption of solar radiation and an increase in the winter air temperature in Europe (Scaife et al. 2008). In summer, air pressure in the centre of the AH has only a slight, statistically insignificant positive trend. This is the result of weak relations between the AH and the SST over the tropical Atlantic in summer as described by Hasanean (2004). Thus, the summer AH does not respond significantly to the changes in the SST of the North Atlantic.

The situation is different in the case of the HH where pressure in the centre remains higher by 4 hPa in July than in January, which is a normal situation. The slight, statistically insignificant negative trend of the sea level air pressure in the centre of the HH in January in the second half of the twentieth century is related to the weak movement of the system to the south and the south-west during that period, i.e. with the decreasing latitude of the system.

One of the breakthrough years, 1970 (1969–1973) coincides with the beginning of the third circulation epoch of the twentieth century, characterised by increased intensity of zonal circulation (Makrogiannis


a)
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1948-1969
1981-2018
1970-1980
latitude
longitude
e)
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◀ **Fig. 5** Hawaiian High in July. **a** Longitude (°), **b** latitude (°), **c** 10-year mean locations (periods are as follows: (1) 1951–1960, (2) 1961–1970, (3) 1971–1980, (4) 1981–1990, (5) 1991–2000, (6) 2001–2010, (7) 2011–2018), **d** cluster analysis periods, **e** E-W/W-E index, **f** N-S/S-N index, **g** NE-SW/SW-NE index, **h** NW-SE/SE-NW index

et al. 1991; Degirmendzic et al. 2000; Sidorenkov and Orlov 2008). In that year, the following were observed:

- one of the two minima of the AH latitude in January;
- a minimum value of the NW-SE/SE-NW index for the AH in January;
- one of three maximum of the latitude of HH in January;
- a second minimum peak of the NE-SW/SW-NE index for the AH in July;
- the beginning of the second sub-period separated by cluster analysis for the HH in July;
- the first or second minimum peak of the three indices, E-W/W-E, N-S/S-N and NE-SW/SW-NE for the HH in July; the system was displaced extremely to the south and west in that year.

A large accumulation of extreme values during that year confirms its significance in separating epochs of circulation changes. The beginning of the intensification of zonal advection was only clearly marked in the case of the AH in January when it manifested itself by accelerating the system shifting and pushing it plainly to the north-east. This caused a reduction in the distance between the AH and the centre of the Icelandic Low and consequently, an increase in the intensity of zonal advection in moderate latitudes expressed by, inter alia, the above-mentioned thermal changes in winter over Europe.

The explanation of relations between HH in January and AH in July demonstrated by canonical correlation requires further research. This relation is both distant in space and lagged in time (by 6 months). However, connections between oceanic lows of the Northern Hemisphere (Icelandic and Aleutian) had been proved and called a seesaw by Honda and Nakamura (2001), Honda et al. (2001), Honda et al. (2005a), so the relations between the AH and the HH are also highly probable.

The application of cluster analysis made it possible to divide the analysed period into sub-periods of different locations of the AH and HH. Even better results were obtained by using the indices showing the movements of the ACAs in the main (E-W/W-E, N-S/S-N) and intermediate (NE-SW/SW-NE, NW-SE/SE-NW) directions. This enabled clarification of existing knowledge on the directions of movements of the ACAs. The statements by Zhang et al. (1995), Mächel and co-authors (Mächel et al. 1998) and Falarz (2009), who point to a northward movement of the AH, as well as the conclusions drawn by Luo and Gong (2006), who talk of an eastward movement of the NAO centres of action after 1980, were probably not entirely precise. The utilisation of additional tools led to the conclusion on the north-east moving of AH in the second half of the twentieth century.

Further research will focus on (1) a detailed explanation of the reasons for the increased intensity of the AH in January, (2) searching for correlations and examining the shifts of other ACAs in the Northern Hemisphere, (3) investigating the impact of the changes in the intensity of the atmospheric centres of action and their shift on climatic conditions of Europe and North America.

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References

Angell JK, Korshover J (1974) Quasi-biennial and long-term fluctuations in the centres of action. Mon Weather Rev 102:669–678

Chang C-P, Lu M-M (2012) Intraseasonal predictability of Siberian High and East Asian winter monsoon and its interdecadal variability. J Clim 25:1773–1778

Christoforou P, Hameed S (1997) Solar cycle and the Pacific 'centers of action'. Geophys Res Lett 24(3):293–296. https://doi.org/10.1029/97GL00017

Clark MP, Serreze MC, Robinson DA (1999) Atmospheric controls on Eurasian snow extent. Int J Climatol 19:27–40

Degirmendzic J, Kożuchowski K, Wibig J (2000) Epoki cyrkulacyjne XX wieku i zmienność typów cyrkulacji atmosferycznej w Polsce. Przegl Geof 45(3–4):221–238

Falarz M (2007) Snow cover variability in Poland in relation to the macro- and mesoscale atmospheric circulation in the 20th century. Int J Climatol 27:2069–2081

Falarz M (2009) Variability of Icelandic Low and Azores High in winter and their influence on climatic conditions in Poland. Bull Geogr – Phys Geogr Ser 2:9–23

Falarz M (2013) Seasonal stability of snow cover in Poland in relation to the atmospheric circulation. Theor Appl Climatol 111(1–2):21–28. https://doi.org/10.1007/s00704-012-0642-x

Glossary of Meteorology (2018) American Meteorological Society, http://glossary.ametsoc.org/wiki/Center_of_action. Accessed 20 June 2018.

Gong DI, Ho CH (2002) The Siberian High and climate change over middle to high latitude Asia. Theor Appl Climatol 72:1–9

Hasanean HM (2004) Variability of the North Atlantic subtropical high and associations with tropical sea surface temperature. Int J Climatol 24(8):945–957

Hasanean HM, Almazroui M, Jones PD, Alamoudi AA (2013) Siberian High variability and its teleconnections with tropical circulations and surface air temperature over Saudi Arabia. Clim Dyn **41**(7–8):2003–2018

Hildebrandson HH (1897) Quelquers recherches sur les centres d'action del' atmosphere. K Svenska Vetens. – Akad. Handl.

Honda M, Nakamura H (2001) Interannual seesaw between the Aleutian and Icelandic lows. Part II: its significance in the interannual variability over the wintertime Northern Hemisphere. J Clim 14:4512–4529

Honda M, Nakamura H, Ukita J, Kousaka I, Takeuchi K (2001) Interannual seesaw between the Aleutian and Icelandic lows. Part I: seasonal dependence and life cycle. J Clim 14:1029–1042

Honda M, Kushnir Y, Nakamura H, Yamane S, Zebiak S (2005a) Formation, mechanisms, and predictability of the Aleutian–Icelandic Low seesaw in ensemble AGCM simulations. J Clim 18: 1423–1434

Honda M, Yamane S, Nakamura H (2005b) Impacts of the Aleutian–Icelandic Low seesaw on surface climate during the twentieth century. J Clim 18:2793–2802

Iqbal MJ, Ilyas K (2013) Influence of Icelandic Low pressure on winter precipitation variability over northern part of Indo-Pak Region. Arab J Geosci 6(2):543–548

Iqbal MJ, Hameed S, Khan F (2013) Influence of Azores High pressure on Middle Eastern rainfall. Theor Appl Climatol 111(1–2):211–221

Jeong J-H, Ou T, Linderholm HW, Kim B-M, Kim S-J, Kug J-S, Chen D (2011) Recent recovery of the Siberian High intensity. J Geophys Res 116:D23102. https://doi.org/10.1029/2011JD015904

Kalnay et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–470

Kapala A, Mächel H, Flohn H (1998) Behaviour of the centres of action above the Atlantic since 1881. Part II: associations with regional climate anomalies. Int J Climatol 18:23–36

Konrad CE (1998) Intramonthly indices of the Pacific/North American teleconnection pattern and temperature regimes over the United States. Theor Appl Climatol 60:11–19

Luo D, Gong T (2006) A possible mechanism for the eastward shift of interannual NAO action centers in last three decades. Geophys Res Lett *33*(*24*):L24815. https://doi.org/10.1029/2006GL027860

Mächel H, Kapala A, Flohn H (1998) Behaviour of the centres of action above the Atlantic since 1881. Part I: characteristics of seasonal and interannual variability. Int J Climatol 18:1–22

Makrogiannis TJ, Sahsammonoglou HS, Flocas AA, Blautsos AA (1991) Analysis of the monthly zonal index values and longterm changes of circulation over the North Atlantic and Europe. Int J Climatol 11: 493–503

Marsz AA (1999) Oscylacja Północnoatlantycka a reżim termiczny zim na obszarze północno-zachodniej Polski i polskim wybrzeżu Bałtyku. Przegl Geogr 71(3):225–245

Murav'ev AV, Kulikova IA (2011) Interrelation of total precipitation over Eurasia with atmospheric centers of action of the northern hemisphere and with major modes of the North Atlantic surface temperature variability. Russ Meteorol Hydrol 36(5):285–293

Niedźwiedź T (ed.) (2003) Słownik meteorologiczny. PTG, Institute of Meteorology and Water Management, Warszawa.

Panagiotopoulos F, Shahgedanova M, Hannachi A, Stephenson DB (2005) Observed trends and teleconnections of the Siberian High: a recently declining center of action. J Clim 18:1411–1422

Park Y-H, Yoon J-H, Youn Y-H, Vivier F (2012) Recent warming in the western North Pacific in relation to rapid changes in the atmospheric circulation of the Siberian High and Aleutian Low systems. J Clim 25:3476–3493. https://doi.org/10.1175/2011JCLI4142.1

Perry AH (1971) Changes in position and intensity of major Northern Hemisphere 'centres of action'. Weather 26(6):268–270. https://doi.org/10.1002/j.1477-8696.1971.tb04206.x

Qu X, Huang G, Hu K, Xie S-P, Du Y, Zheng X-T, Liu L (2015) Equatorward shift of the South Asian high in response to anthropogenic forcing. Theor Appl Climatol 119(1–2):113–122

Quadrelli R, Wallace JM (2004) A simplified linear framework for interpreting patterns of Northern Hemisphere wintertime climate variability. J Clim 17:3728–3744

Raible CC, Stocker TF, Yoshimori M, Renold M, Beyerle U, Casty C, Luterbacher J (2005) Northern Hemispheric trends of pressure indices and atmospheric circulation patterns in observations, reconstructions, and coupled GCM simulations. J Clim 18:3968–3982

Rasmus S, Boelhouwers J, Briede A, Brown IA, Falarz M, Ingvander S, Jaagus J, Kitaev L, Mercer A, Rimkus E (2015) Recent change - terrestrial cryosphere. In: The BACC II Author Team, Second Assessment of Climate Change for the Baltic Sea Basin, ser. Regional Climate Studies, Springer, London, pp. 117–129. DOI: https://doi.org/10.1007/978-3-319-16,006-1

Rogers JC (1984) The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. Mon Weather Rev 112:1999–2015

Sahsamanoglou HS (1990) A contribution to the study of action centres in the North Atlantic. Int J Climatol 10(3):247–261. https://doi.org/10.1002/joc.3370100303

Sahsamanoglou HS, Makrogiannis TJ, Kallimopoulos PP (1991) Some aspects of the basic characteristics of the Siberian anticyclone. Int J Climatol 11(8):827–839. https://doi.org/10.1002/joc.3370110803

Scaife AA, Folland CK, Alexander LV, Moberg A, Knight JR (2008) European climate extremes and the North Atlantic Oscillation. J Clim 21:72–83

Serreze MC, Carse F, Barry RG, Rogers J (1997) Icelandic Low cyclone activity: climatological features, linkages with the NAO, and relationships with recent changes in the Northern Hemisphere circulation. J Clim 10:453–464

Sficã L, Voiculescu M, Huth R (2015) The influence of solar activity on action centres of atmospheric circulation in North Atlantic. Ann Geophys 33:207–215

Shatilina TA, Tsitsiashvili GS, Radchenkova TV (2016) Estimating the trends and variability of atmospheric action centers over the Asian-Pacific Region in summer in 1950–1979 and 1980–2012. Russ Meteorol Hydrol 41(1):10–18

Sidorenkov NS, Orlov IA (2008) Atmospheric circulation epochs and climate changes. Russ Meteorol Hydrol 33(9):553–559

Slonosky VC, Jones PD, Davies TD (2000) Variability of the surface atmospheric circulation over Europe, 1774–1995. Int J Climatol 20:1875–1897

Slonosky VC, Jones PD, Davies TD (2001) Atmospheric circulation and surface temperature in Europe from the eighteenth century to 1995. Int J Climatol 21:63–75

Souza P, Cavalcanti IFA (2009) Atmospheric centres of action associated with the Atlantic ITCZ position. Int J Climatol 29(14):2091–2105. https://doi.org/10.1002/joc.1823

Stanisz A (2007) Przystępny kurs statystyki z zastosowaniem STATISTICA PL na przykładach z medycyny, vol. 3: Analizy wielowymiarowe, Statsoft Polska, Kraków.

Sugimoto S, Hanawa K (2010) Impact of Aleutian Low activity on the STMW formation in the Kuroshio recirculation gyre region. Geophys Res Lett 37:L03606. https://doi.org/10.1029/2009GL041795

Sun J, Benkui T (2013) Mechanism of the wintertime Aleutian Low–Icelandic Low seesaw. Geophys Res Lett 40(15):4103–4108. https://doi.org/10.1002/grl.50770

Sun XJ, Wang PX, Wang JXL (2017) An assessment of the atmospheric centers of action in the northern hemisphere winter. Clim Dyn 48: 1031–1047

Taboada FG, Anadón R (2012) Patterns of change in sea surface temperature in the North Atlantic during the last three decades: beyond mean trends. Clim Chang 115:419–431. https://doi.org/10.1007/s10584-012-0485-6

Thompson DJW, Wallace JM (2000) Annular modes in the extratropical circulation. Part I: month-to-month variability. J Clim 13(5):1000–1016

Thompson DJW, Wallace JM, Hegerl G (2000) Annular modes in the extratropical circulation. Part II: trends. J Clim 13(5):1018–1036

Tubi A, Dayan U (2013) The Siberian High: teleconnections, extremes and association with the Icelandic Low. Int J Climatol 33(6):1357–1366. https://doi.org/10.1002/joc.3517

Wallace JM, Thompson DWJ (2002) The Pacific center of action of the Northern Hemisphere annular mode: real or artifact? J Clim 15: 1987–1991

Ye K, Lau N-C (2017) Influences of surface air temperature and atmospheric circulation on winter snow cover variability over Europe. Int J Climatol 37:2606–2619

Zarrin A, Ghaemi H, Azadi M, Farajzadeh M (2010) The spatial pattern of summertime subtropical anticyclones over Asia and Africa: a climatological review. Int J Climatol 30(2):159–173. https://doi.org/10.1002/joc.1879

Zhang QY, Wang SW, Wang WCH (1995) Variations of the atmospheric centres of action in the Northern Hemisphere and their associations with the climate change in China; [in:] 6th International Meeting of Statistical Climatology. pp. 231–234.

Zheleznova V, Gushchina DY (2016) Circulation anomalies in the atmospheric centers of action during the Eastern Pacific and Central Pacific El Nino. Russ Meteorol Hydrol 41(11–12):760–769

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