Dependence of sea level variability in the Nordic Seas on the NAO - results from a pan-Arctic coupled ice-ocean model

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1. *Introduction*

The Nordic Seas (e.g., Hurdle, 1986) is a common name for the Greenland, Iceland and Norwegian Seas. The Nordic Seas are a key exchange region between the Arctic and Atlantic oceans.
The North Atlantic Oscillation (NAO) dominates atmospheric variability over the Northern Hemisphere and significantly effects the variability (changes) of climate of the North Atlantic and Europe (e.g., Hurrell, 1995; Hurrell and Deser, 2010). Periods that correspond to high positive phase of the NAO generally characterized by strong prevailing westerly winds over northern Europe, while negative phase generally give rise to weaker westerly winds with more episodes of continental (easterly) winds.
The NAO is quantified by so-called NAO index, defined as the difference between normalized sea level pressure SLP) over the Azores (the Azores High) and Iceland (the Icelandic Low) (Hurrell, 1995; Jones et al., 1997; Hurrell and Deser, 2010). The winter -mean NAO index (average of monthly mean value of index from December to March) is more useful NAO parameter (Osborn et al., 1999), since it shows the strongest low frequency variabilty of SLP and the strongest influence of the NAO on surface (and ocean) climate.
One of the parameters useful for monitoring large-scale climate variability in the ocean is sea level. It reflects changes and integrates virtually all static and dynamic processes in the hydrosphere and atmosphere. Connection between the NAO and sea level variabilty have been investigated in several paper for different parts of the Atlantic:, e.g., sea surface height (SSH) from satellite altimeters in the North Atlantic (Esselborn and Eden, 2001), sea level in the North Sea (Wakelin et al., 2003; Tsimplis et al., 2005; 2006), in the Baltic (Andersson, 2002), steric height variability in the Nordic Seas (Siegismund et al., 2007).
Here we study the effect of the NAO on variability of the modeled SSH over the Nordic Seas. The region of interest (*Figure 1*) includes the northern part of the Atlantic Ocean and the Nordic Seas and the western part of the Barents Sea. Monthly mean sea level output from a 3D pan-Arctic coupled ice-ocean model (Maslowski et al., 2004) is used to investigate the connection between the NAO and sea level variability in the Nordic Seas for the period of 1979-2004.
The main aim of this presentation is to estimate correlations of the modeled SSH as well as its sensitivity to the NAO index on winter time scale. The results are validated by comparison with statistics obtained from tide gauge observations.

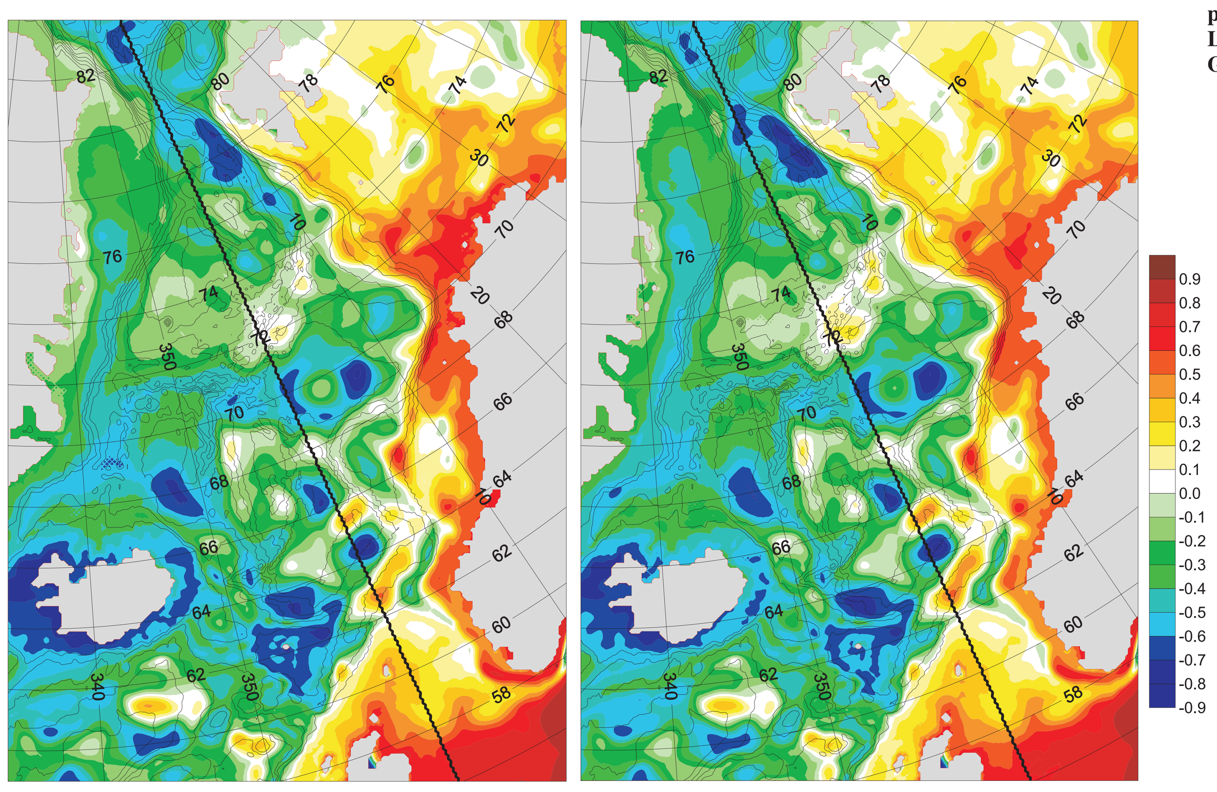

Figure 3. Correlation coefficient between winter-mean NAO index and winter-mean sea surface height - averaged over period of 1980 - 2004 (25 years, 25 winter periods). The bathymetry is overlaid with a contour-level interval (CI) of 500 m.
(a) left figure - estimated based on the NAO index data from (Jones et al., 1997);
(b) right figure - estimated based on the NAO index data from (Hurrell, 1995).

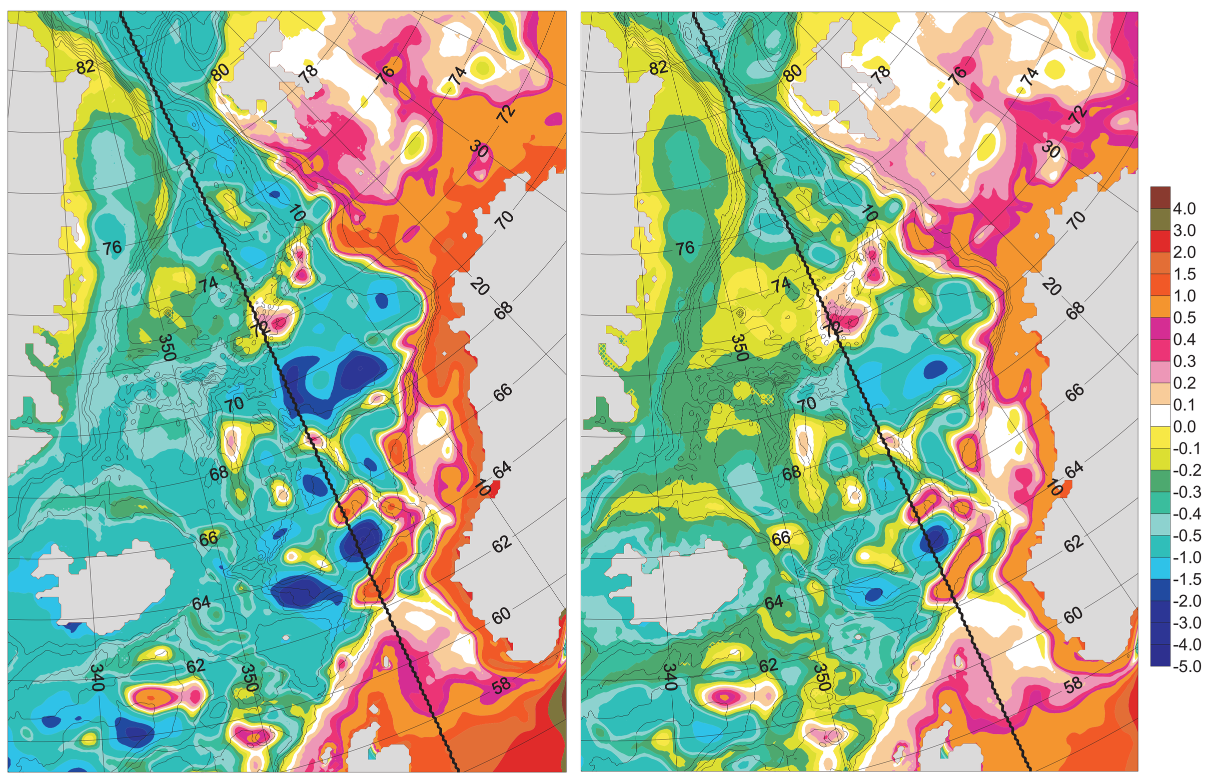

Figure 4. Sensitivity of the winter-mean ssh to the winter-mean NAO index in cm/ (unit NAO index). Linear trend (regression coefficient) [cm/year] - averaged over period of 1980 - 2004 (25 years, 25 winter periods, seasons). The bathymetry is overlaid with a contour-level interval (CI) of 500 m. The bathymetry is overlaid with a contour-level interval (CI) of 500 m.
(a) left figure - estimated based on the NAO index data from (Jones et al., 1997);
(b) right figure - estimated based on the NAO index data from (Hurrell, 1995).

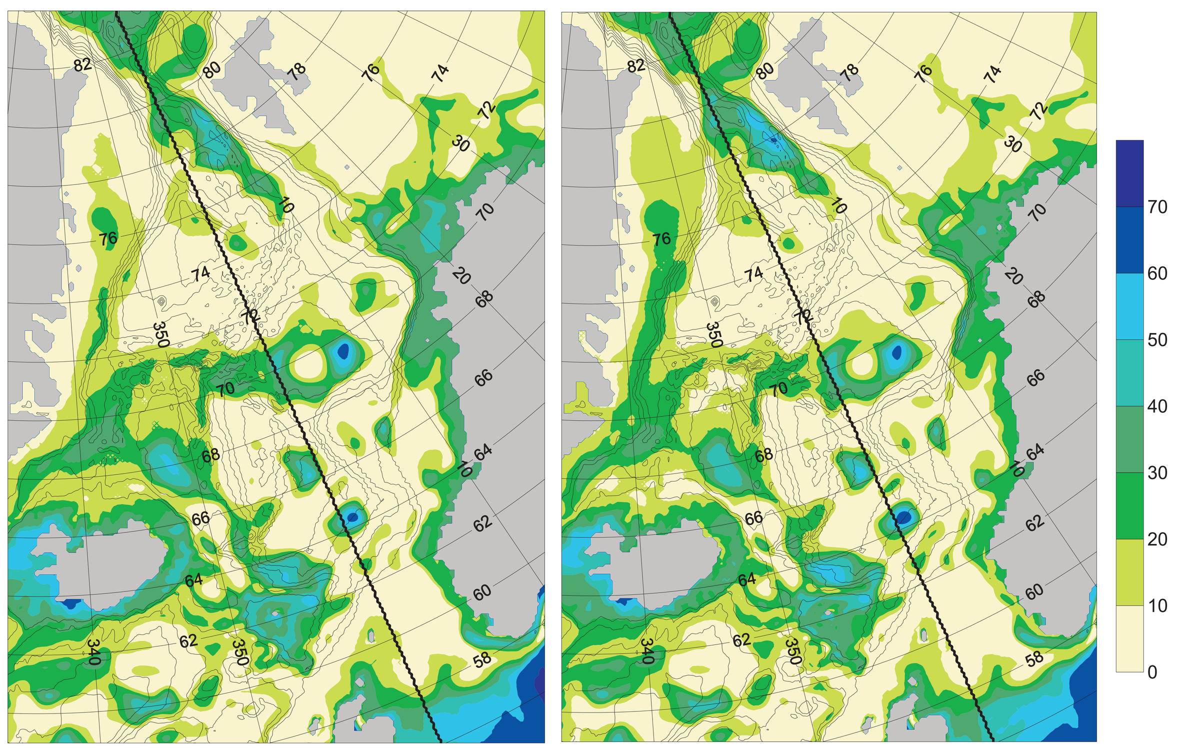

Figure 5. Spatial distribution of total winter-mean ssh variation explained (squarred correlation coefficient) [%] by the linear function of the NAO winter-mean index - averaged over period of 1980 - 2004 (25 years, 25 winter periods). The bathymetry is overlaid with a contour-level interval (CI) of 500 m.
(a) left figure - estimated based on the NAO index data from (Jones et al., 1997);
(b) right figure - estimated based on the NAO index data from (Hurrell, 1995).

Table 2 Statistical characteristics of mean winter-season (DJFM) sea level over period 1980-2004 used for model validation results: std_s, a_s std_m, a_m - standard deviation and linear trend (regression) of the observed and simulated data, respectively; cor, rmse - correlation coefficient and root mean square difference between the modeled and the observed data,

No	Station symbol	std_s [cm]	std_m [cm]	cor [-]	a_s [cm/yr]	a_m [cm/yr]	rmse [cm]
1	n_15r	8.58	2.18	0.77	-0.16	-0.05	7.0
2	n_31r	9.48	3.11	0.69	0.21	0.15	7.7
3	n_61r	9.00	2.61	0.73	0.07	0.09	7.3
4	n_91r	8.78	3.37	0.59	-0.12	0.18	7.3
5	n_136r	8.68	3.51	0.73	0.07	0.20	6.5
6	n_142r	7.01	2.98	0.85	-0.23	-0.20	4.7
7	i_10r	5.55	1.47	-0.04	-0.003	-0.01	5.8
8	i_15r	5.24	1.48	-0.37	0.42	-0.02	5.9
9	i_25r	7.99	1.27	0.16	-0.40	0.02	7.9

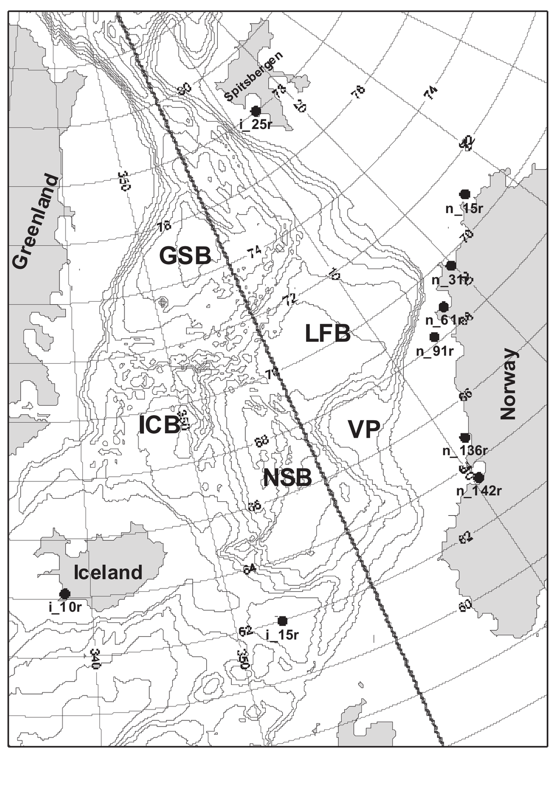

Figure 1. Model bathymetry of the Nordic Seas (contour-level interval (CI) of 500 m) and location of tide gauge stations (see also *Table 1*). The prominent bathymetry features and major basins are shown: the Lofoten Basin (LFB), Voring Plateau (VP), Norwegian Sea Basin (NSB), Greenland Sea Basin (GSB), and Iceland Sea Basin (ISB).

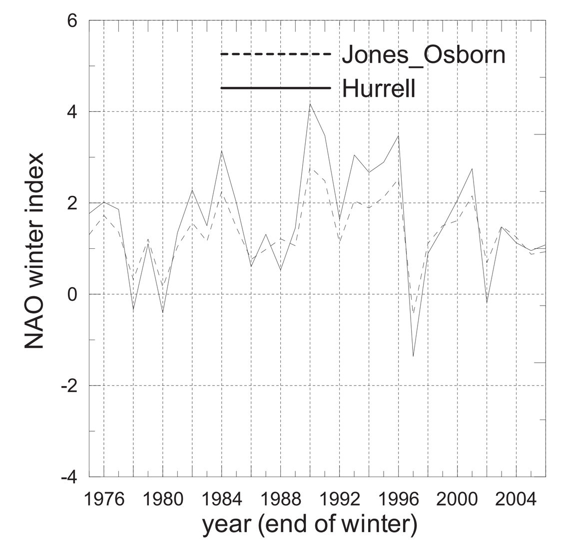

Figure 2. Winter-mean NAO index (DJFM) over period of 1975 - 2005: Jones_Osborn - based on data from (Jones et al.., 1997) and Hurrell one - based on data from (Hurrell, 1995).

Table 1 Stations with sea level data (monthly mean tide gauge data from PSMSL) used for model validation results

No	Station symbol	PSMSL tide gauge station longitude	PSMSL tide gauge station latitude	Model point longitude	Model point latitude	Station name	Period [years]	Number of winters
1	n_15r	25.9833	70.9833	25.9700	70.9500	Honningsvag	1986-2004	18
2	n_31r	18.9667	69.6500	18.8200	69.8999	Tromso	1979-2004	25
3	n_61r	16.5500	68.8000	16.5300	68.8400	Harstad	1981-2004	23
4	n_91r	14.4833	68.2167	14.4900	68.1700	Kabelvag	1979-2004	25
5	n_136r	11.2500	64.8667	11.2700	64.8900	Rorvik	1979-2004	25
6	n_142r	10.4333	63.4333	10.3900	63.4400	Trondheim	1990-2004	14
7	i_10r	-21.9333	64.1500	-21.9770	64.1500	Reykjavik	1979-2004	25
8	i_15r	-06.7667	62.0167	-06.7700	61.9800	Torshavn	1979-2003	23
9	i_25r	14.2500	78.0667	14.2200	78.0100	Barentsburg	1979-2004	25

Table 3a Statistical characteristics of relationships between the winter-mean (DJFM) simulted and observed sea level, and winter-mean NAO index (Jones_Osborn index): std_s, std_m, std_n - standard deviation of the observed, simulated and NAO index data, respectively; cor_s, cor_m - correlation coefficient between ssh and the NAO index of the observed and simulated data, respectively; sen_s, sen_m - sensitivity of the SSH to the NAO index of the observed and simulated data, respectively; expvar_s, expvar_m - explained variance (squarred correlation coefficient cor_s, cor_m, respectively.

No	Station symbol	std_s [cm]	std_m [cm]	std_n [unit]	cor_s [-]	expvar_s [%]	sen_s [cm/unit]	cor_m [-]	expvar_m [%]	sen_m [cm/unit]
1	n_15r	8.58	2.18	1.22	0.72	52	5.09	0.68	46	1.21
2	n_31r	9.48	3.11	1.11	0.78	61	6.62	0.58	33	1.61
3	n_61r	9.00	2.61	1.15	0.80	64	6.23	0.62	38	1.41
4	n_91r	8.78	3.37	1.11	0.81	66	6.37	0.58	34	1.75
5	n_136r	8.68	3.51	1.11	0.83	69	6.50	0.59	34	1.85
6	n_142r	7.01	2.98	1.17	0.77	59	4.64	0.74	55	1.89
7	i_10r	5.55	1.47	1.11	0.30	9	1.48	-0.69	48	-0.91
8	i_15r	5.24	1.48	1.14	0.55	30	2.53	-0.67	45	-0.87
9	i_25r	7.99	1.27	1.11	0.60	36	4.33	0.05	0.2	0.06

Table 3b Statistical characteristics of relationships between the winter-mean (DJFM) simulted and observed sea level, and winter-mean NAO index (Hurrell index): std_s, std_m, std_n - standard deviation of the observed, simulated and NAO index data, respectively; cor_s, cor_m - correlation coefficient between SSH and the NAO index of the observed and simulated data, respectively; sen_s, sen_m - sensitivity of the ssh to the NAO index of the observed and simulated data, respectively; expvar_s, expvar_m - explained variance (squarred correlation coefficient cor_s, cor_m, respectively.

No	Station symbol	std_s [cm]	std_m [cm]	std_n [unit]	cor_s [-]	expvar_s [%]	sen_s [cm/unit]	cor_m [-]	expvar_m [%]	sen_m [cm/unit]
1	n_15r	8.58	2.18	2.19	0.74	55	2.89	0.68	46	0.67
2	n_31r	9.48	3.11	1.96	0.74	55	3.59	0.53	28	0.84
3	n_61r	9.00	2.61	2.04	0.79	62	3.49	0.59	35	0.77
4	n_91r	8.78	3.37	1.96	0.80	64	3.57	0.53	28	0.90
5	n_136r	8.68	3.51	1.96	0.79	62	3.49	0.54	29	0.96
6	n_142r	7.01	2.98	2.06	0.73	55	2.48	0.74	55	1.07
7	i_10r	5.55	1.47	1.96	0.25	6	0.69	-0.66	44	-0.50
8	i_15r	5.24	1.48	2.01	0.46	21	1.18	-0.64	41	-0.47
9	i_25r	7.99	1.27	1.96	0.70	49	2.87	0.04	0.2	0.03

5. *Final remarks*

The modeled fields of SSH showed strong correlation with winter-mean (DJFM) NAO index. The clear spatial pattern observed in the correlations between sea level and the NAO on a winter-mean timescale is related to specific topographic features of the Nordic Seas. The sensitivity of the sea level to the NAO ranges from ~ -5 cm per unit NAO index to ~ 4 cm per unit NAO.

Negative extreme values are in deepwater regions (Lofoten Basin, Norwegian Sea Basin). Positive extreme values can be observed in coastal zone along the Norway coasts.
The estimates of the connection between the SSH variability and the winter-mean NAO have been performed using two data source for NAO indices, one from Hurrell (1995, updated) and other from Jones et al. (1997, updated). The results of the calculations show some differences in values of calculated parametres as well as in their spatial distribution.

The modeled sea level characteristics and the obtained relationships have been validated using observed data recorded at the 9 selected coastal tide gauge stations (PSMSL Service data). Comparison of the simulated and in situ data shows that model reproduces the sea level variability in relatively good accordance with the recorded sea level data at the tide gauges located along the Norway coasts, where correlation coefficients between the modeled and the in situ data are higher than 0.58. The agreement of model-observations comparison is not so good in the case of tide gauge stations located at the coasts of Spitsbergen (i_25r), the Iceland (i_10r) and Faroes Is. (i_15r). These disagreement in the case of the last two tide gauges may be explained by their locations, not far from the closed lateral boundary of the model domain.

The correlations, explained variations and the sensitivities of the modeled SSH related to the winter-mean NAO index agree well with the relationships estimated based on the tide gauge time series from the 6 stations located at the Norwegian coast. In the case of the other 3 stations (i_25r, i_10r, i_15r) disagreement is seen and is related in the case of the last two, mainly, to their locations in the model domain.

Some distinctions may be seen in the values of the statistical characteristcs estimate calculated using different data set of the NAO index. These differences may be explained by the differences in the standard deviations, std_n, calculated for both NAO index data sets as well as by differences in the correlations between SSH and the NAO index. Over the period of 25 winter seasons estimates of standard deviations of the Jones_Osborn NAO index have been almost 2 times smaller than those of the Hurrell NAO index. Thus, so the standard deviation is a measure of the variability of the time series, the distinctions in our estimates may be explained by difference in internal variability of both time series of the NAO index used herein.

The agreement between the estimates of statistics for the model relationship with the NAO index and those of the tide gauge data gives confidence in the results over the whole model domain including away from the coasts. For 1979–2004 model results have reflected these correlations well, indicating that the long-term model forcings and model response to the atmospheric forcings have been correct.

2. *Data*

Model data

The model data consist of 26 years of output data from a three-dimensional pan-Arctic coupled ice-ocean model (Maslowski et al., 2004). The model domain includes the Sea of Japan, the Sea of Okhotsk, the sub-Arctic North Pacific and North Atlantic Oceans, the Arctic Ocean, the Canadian Arctic Archipelago (CAA) and the Nordic Seas. The model lateral boundaries are closed at 30° N in the North Pacific and at 40-45° N in the North Atlantic, and an artificial channel through Canada is introduced to balance the net northward transport through the Bering Strait. The model is configured on a rotated spherical coordinate grid with horizontal grid spacing of 1/12° (or ca. 9 km) and has 45 vertical depth layers with eight levels in the upper 50m. The model was forced with daily averaged atmospheric reanalysis data derived from European Centre for Medium-range Weather Forecast (ECMWF). More model details and results of the simulations are given in Maslowski et al. (2004).

NAO index data

Two data sets for the winter-mean (DJFM) NAO index have been used:
- one, Jones index (herein named as Jones_Osborn), defined as the difference between the normalized sea level pressures (nSLP) over Gibraltar and southwest Iceland (Jones et al., 1997), has been taken from the Climatic Research Unit, University of East Anglia (web site: http://www.cru.uea.ac.uk/cru/data/nao.htm),
- second, Hurrell index, based on the difference of the nSLP between Lisbon (Portugal) and Stykkisholmur/Reykjavik, Iceland (Hurrell, 1995, obtained from the Climate and Global Dynamic division of NCAR (web site: http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html/#naostatdjfm).

Time series of both winter-mean NAO indices for period of 1975-2005 are shown in *Figure 2.* Some differences in the values as well as in course in time of both indices may be clearly seen.

In situ data

The observed data were taken from the archive of the Permanent Service for Mean Sea Level (PSMSL) (Woodworth and Player, 2003, updated up 2004 (2009)), where monthly means derived from most of the globally available tide gauge records have been compiled. For model validation and comparison, only subset of so-called "Revised Local Reference" (rlr) have been used. This subset consists of monthly-mean sea levels for 9 tide gauge stations along the coasts of the Norway (6 stations) and three ones located at the coast of the Iceland (1), the Faroes Is. (1) and Spitsbergen (1). *Figure 1* displays their location in the model domain of the Nordic Seas. *Table 1* presents technical information for the selected tide gauge stations, length of observation period, number of winter season as well as coordinates of the closest model point to each of them. Small gaps in the recorded time series of SSH, not greater then three months, were fulfiled by linear interpolation.

3. *Results*

Correlation

Based on the output model of monthly mean SSH fields of the winter-mean sea levels for 25 winter seasons were calculated and next, for each model grid point, correlation with the winter-mean NAO index have been estimated using both data sets for the NAO index. *Figures 3a,b* display their spatial distributions in the model domain of the Nordic Seas.
The values greater (smaller) than 0.4 (-0.4) are significant at the 95% level for the record length of 25 winter seasons (effective degrees of freedom estimated as in Emery and Thompson, (1998)). Modeled fields of SSH reveal strong correlation with winter-mean NAO index. The estimated correlation coefficients in some regions (along the Iceland and the Norway coasts and in open deepwater in the Lofoten Basin, the Norwegian and Greenland seas, and in the North Sea) are greater than ± 0.6-0.7 (*Figure 3a,b*). Significant positive correlation are observed in the eastern regions along the of coasts of Norway. Negative significant correlations are observed along the coasts of Iceland and in selected deepest regions of the Greenland, Iceland and Norwegian Seas. A clear spatial pattern in the correlation between SSH and the NAO on a winter-mean timescale may be observed in *Figure 3a,b*. It is related to main specific topographic features of the model domain of the Nordic Seas (*Figure 1*).

Sensitivity

The sensitivity of the simulated winter-mean SSH to the winter-mean NAO index has been estimated. It is measured by the slope of the regression line formed by assuming that the sea surface height is a linear function of the winter-mean NAO index. As in case of the correlations the sensitivity has been calculated using both series of the NAO winter-mean index data. Spatial distribution of the calculated values of sensitivity is displayed in *Figures 4a,b*. Values of the sensitivity of the sea level to the NAO index ranges from ~ -5 cm per unit NAO index to ~ 4 cm per unit NAO. Negative extreme values are in deepwater regions (Lofoten Basin, Norwegian Sea Basin). Positive extreme values can be observed in coastal zone along the Norway coasts.

Variations explained

The total sea level variations explained, estimated as the squared correlation coefficient between ssh and the NAO index, displayed in *Figure 5a,b*, completes the picture of the spatial distribution of the relationships between the variability in the NAO and the sea elevation over the Nordic Seas. The areas over which the correlation is greater than ± 0.4 (*Figure 3a,b*) roughly correspond to regions where the total sea level variability explained by the linear function of the winter-mean NAO index exceeds 20%.

4. *Comparison with observations*

The simulated SSH and the obtained reationships have been validated using the observed data recorded at the 9 selected coastal tide gauge stations. See *Figure 1* on their location and *Table 1* for additional technical information for these selected tide gauge stations: length of observation period, number of winter season as well as coordinates of the closet model point to each of them. The length of the modeled time series of ssh has been reduced to the length of the observed time series for comparison purposes. For both data sets, observed and modeled, winter-mean (December to March) sea level elevations were calculated from the monthly means.

Validation - model-in situ data comparison

Table 2 presents statistical charcteristics estimated to validate winter-mean model results with the observed data. Length of the model data series were reduced to that of in situ data (station): 1 (n_15r), 2 (n_31r), 6 (n_142r), 7 (i_10r) and 8 (i_15r)). For tide gauges stations 1 to 6, located at the Norway coasts, correlation coefficients exceed 0.58 and are all significant at the 95% level. Standard deviations of the two sets of sea level data measure the variabilities of the time series. Their values for the observed SSH (std_s) are almost 2-4 times higher than those of the modeled sea level data (std_m) - see *Table 2*. Root mean square difference (rmse) between the simulated and and observed sea level data ranges from 4.7 cm to 7.9 cm.

Validation of dependence of SSH variability on the NAO

Tables 3a and *3b* present statistical characteristics estimated with application of both time series of the NAO index: Jones_Osborn index) (Table 3a) and Hurrell index (Table 3b). Besides the standard deviation calculated for the observed (std_s), modeled (std_m) and NAO index (std_n) time series, the correlation coefficient between the in situ data and NAO index (cor_s), and correlation coefficient between the simulated data and the NAO index (cor_m) as well as the sensitivity of the SSH to the NAO index of the observed (sen_s) and the modeled SSH data (sen_m) have been estimated. In addition, values of the explained variances (expvar_s, expvar_m) estimated as squarred correlation coefficient between SSH and the NAO index of the observed and simulated data, cor_s, cor_m, respectively, have been also put in *Table 3a,*b. The correlation coefficients, explained variances and sensitivities of the simulated data compare wel l with those of the in situ data for the first 6 tide gauge stations (located along the Norway coast - cf. *Figure 1*). For the stations 1 to 6 the signs of the correlation coefficients between the model data and the NAO index agree with those between the observations and NAO index (*Table 3a,b*) but the values of cor_s are higher than those for model results cor_m. In the case of the island coastal tide gauges, 7 to 9, the estimated correlation coefficients differ in sign (station 7 and 8) as well as in value (station 7 and 9) (*Table 3a,b*). Similar findings are found for the explained variances and sensitivities (*Table 3a,b*).

Some distinctions may be seen in the values of the estimates of the statistical characteristcs calculated using different data set of the NAO index (*Table 3a,b*). These differences are related to the differences in the standard deviations, std_n, calculated for both NAO index data sets as well as to differences in the correlations between SSH and the NAO index (*Table 3a,b*). The values of standard deviations of the Jones_Osborn NAO index (*Table 3a*) are almost 2 times smaller than those of the Hurrell NAO index (*Table 3b*). Since, the standard deviation is a measure of the variability of the time series, the distinctions in our estimates may be explained by difference in internal variability of both time series of the NAO index used herein.

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