SOUNDSCAPE CHARACTERIZATION AND THE IMPACT OF ENVIRONMENTAL FACTORS IN THE CENTRAL PART OF THE FRAM STRAIT

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1 INTRODUCTION

The Arctic is still a mostly pristine marine acoustic environment. Ambient sound levels in the interior Arctic are generally low and characterized by episodic sound generating mechanisms, such as ridging, break up of sea ice, and thermal cracking[1]. In the Marginal Ice Zone (MIZ) the primary natural sound-generating mechanisms are due to ocean processes impacting the sea ice dynamics, such as ocean waves propagating into the ice pack, and ice edge eddies. The temporal variations in sound generation are significant in the Fram Strait MIZ, primarily driven by the direction of wind and waves relative to the ice edge[2,3]. However it has been documented that the soundscape of the MIZ of the Fram Strait is influenced by various anthropogenic factors[4,5]. Studies show that low frequency seismic airgun noise produced at the coast of Norway propagates more than 1000 kilometres into the Fram Strait MIZ[6], and dominates the low frequency potion of the soundscape most of the year[4]. Another occasionally important contribution to the soundscape is icebreakers breaking heavy ice[5].

Yearlong time series of passive acoustic data (25-500 Hz) recorded by vertical acoustic arrays at two different locations – one in the central part of the Fram Strait and one in the West Spitsbergen Current are analyzed. Many of the recordings include seismic airgun and mechanical noise, and the natural ambient noise data are made by excluding these recordings. In total 18 variables from satellite images, direct measurements and reanalysis from a wave model are obtained as the predictors which might cause the variability of the natural ambient noise. This paper proposes use of an objective approach for significant variable selection. The natural ambient noise data are analyzed using the selected variables as explanatory variables with multiple linear regression analysis[7] (MLR). The results show the relation between the natural noise variability and major explanatory variables.

In section 2 we present the time series passive acoustic data recorded under the ACOBAR experiment[8] and external factors which might cause the variability of the ambient noise. In section 3 the statistical approaches to be used are presented. The results of the analysis for the natural ambient noise are shown in Section 4.

2 DATA ACQUISITION

2.1 Passive acoustic data

A multipurpose acoustic system was deployed and operated as part of the ACOBAR project. The system comprised three transceiver moorings (A, B and C) and one acoustic receiver mooring (D). The mooring configuration is shown in Figure.1. Further details are given in Sagen et al.[9]. The three sources (A, B and C) sent a signal for 60 s every 3 hours with a time difference and the receivers were programmed to wake up to record the signal from each of the sources. The signal from the source in mooring C was lost after a couple of weeks of the deployment. Therefore, the recordings at A, B, and D expecting the signal from mooring C do not contain the tomographic signal. Furthermore, the recordings in mooring B were mostly dominated by cable strumming. Thus, the passive acoustic recordings from the receiver array in moorings A and D are used for the analysis in this paper. The acoustic recordings were 100 s long including 20 s before and after the expected transmission time. The analysis in this paper covers the time period from 24 September 2011 to 31 July 2012.

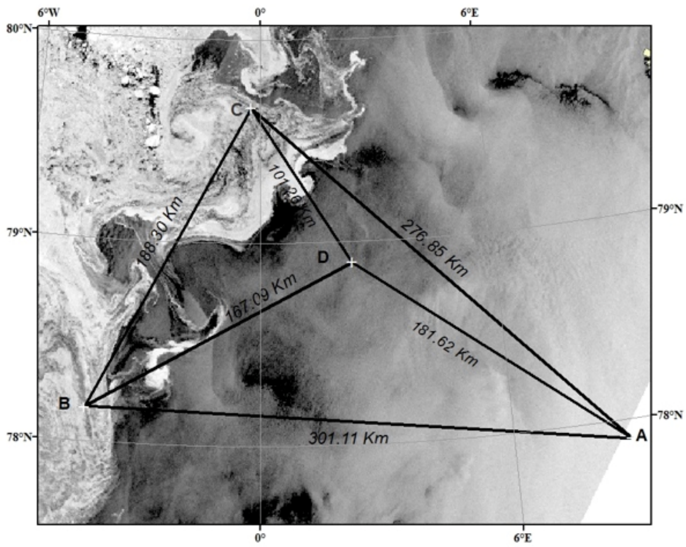


Figure 1. Positions of three transceivers, A, B and C and one receiver mooring D in the ACOBAR experiment. The moorings A and D, discussed in this study, were located at 77°53.60'N, 008°44.49'E and 78°53.42'N, 002°19.42'E respectively.

The acoustic recordings in the ACOBAR system were made by use of the Simple Tomographic Acoustic Receiver (STAR) technology[8], which was developed by Scripps Institution of Oceanography. Each STAR had a four-element receiving array with 9.0 m (~1.5 wavelengths at 250 Hz) spacing between the hydrophones. They were tagged as 1, 2, 3 and 4 from the closest hydrophone to the controller unit in a STAR. For the analysis of mooring A, the recordings from the shallowest hydrophone (A-1 at 373.0 m depth) in the STAR are used. The water depth at location A was 1431 m. Mooring D included two STARs. The upper and lower STARs were labeled Da and Db respectively. The four hydrophones were installed below the controller in STAR Da, namely Da-1 was the shallowest hydrophone in mooring D. STAR Db was furnished upside-down; thus, Db-1 was the deepest hydrophone in mooring D. The reference depths of Da-1 and Db-1 hydrophones, discussed in this paper, were 263.9 m and 954.0 m respectively. The water depth at mooring D location was 2439 m.

The hydrophone signals were amplified, bandpass filtered, and sampled using 16-bit delta-sigma converters at a 1000 Hz rate. Power spectral density (PSD) of each signal is calculated using 50 % overlapping Hanning window with a window length of 1024 samples. The mean of the sound level at each frequency is computed (frequency spectrum) and the time series mean frequency spectrum based on the recordings from hydrophones A-1 and Da-1 from 24 September 2011 to 31 July 2012 are shown as background color plot used in the panels in Figure 2 (spectrogram).

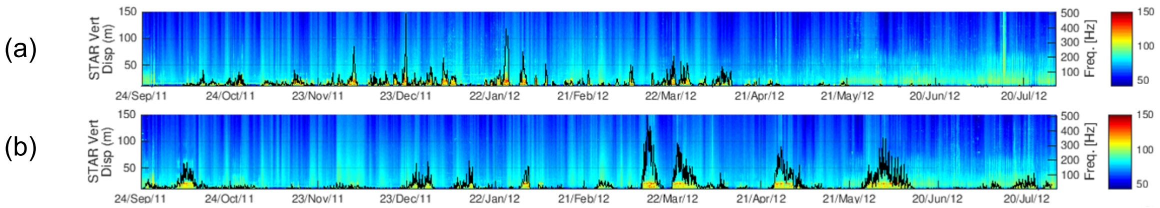


Figure 2. Plots of vertical displacement of the shallowest hydrophone in STARs A (A-1) and Da (Da-1) from the top respectively. The background color is the time series mean noise level of the corresponding recordings from 24 Sep 2011 to 31 July 2012. The colorbar unit is dB re 1μPa^2 Hz^{-1}

2.2. External variables

The following time-series data are obtained as external factors which might cause the variability in the recordings:

Distance to ice edge from the moorings is an important factor, since the strength of acoustic energy by individual floes in the ice field will indirectly depend on the relative distance from the ice edge. Mooring A was always located in open-ocean. While mooring D was located into the ice pack for 7.1 % of the experiment period. Satellite images from ENVISAT ASAR and ice chart produced by Norwegian Metrological institute (MET Norway) were used to measure the distance between location D and the nearest ice edge.

Mean ocean temperature is derived by inverting acoustic travel times (thermometry) during the experiment. The accuracy of the mean ocean temperature is around 70 millidegrees Celsius. Ocean temperature is important for bio-production and therefore also for marine life in the area.

Sea state, resulting from waves generated by local and distant wind systems, is important for estimating acoustic noise levels in open water. However, there are no in-situ measurements of sea state, wind or waves in this region, and therefore we use reanalysis of wind and waves from the NORA10 [10] in our analysis. NORA10 is a downscaling with the atmosphere model High Resolution Limited Area Model (HIRLAM) of ERA40 and analyses (after 2002) from the European Center for Medium Range Weather Forecasts (ECMWF), forcing the Wave Model (WAM) on a 10-11 km grid. The model analyses provide a large number of parameters such as *wind speed, wind north-southerly and east-westerly directions, mean sea level pressure, air temperature, relative humidity, precipitation, significant heights of wind sea wave and swell, peak periods of wind sea wave and swell, and north-southerly and east-westerly directions of peak wind sea wave and swell*. For this study, NORA10 provides time series modeled meteorological data at 77°87N, 08°70E and 78°86N, 02°72E as the external factors corresponding to moorings A and D respectively.

Seismic airgun has periodic signature for frequencies between 25 and 400Hz, especially the strong pattern is observed below 200 Hz. All the recordings influenced by seismic airgun noise was tagged through manual detection, see Figure 3. Notice that strong seismic signals are observed from the middle of April to the middle of November at both locations, while weak constant seismic signals are detected from December to March. During the winter time, seismic noise was more frequently observed at mooring A than at D. Most of seismic surveys during the experiment was carried out at the west coast of middle Norway and the border between Norwegian Sea and Barents Sea. The distances between mooring A and the locations of the seismic surveys were shorter than to mooring D. This and differences in propagation conditions might cause the difference between the two moorings on seismic detection during the winter[11].

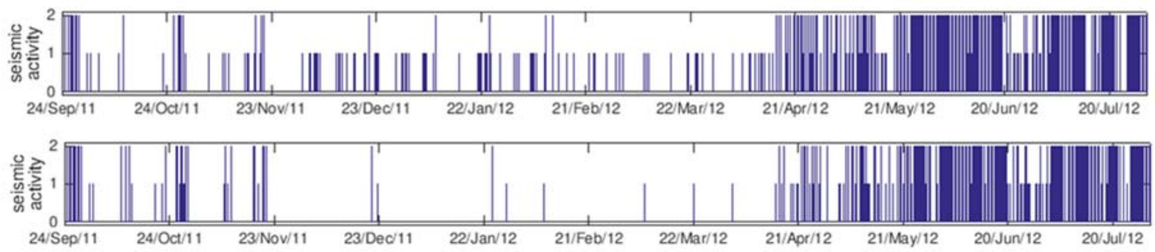


Figure 3. Manual seismic signal characterization for the yearlong recordings at locations A and D from the top respectively.

Mechanical noise, caused by the vertical displacement of the hydrophone, contaminates the recordings below 60 Hz as shown in Figure 2. The strong effects of mechanical noise are observed when the recordings obtained at times with vertical displacements of the hydrophones larger than

5.0, 2.5 and 1.5 meters for A-1, Da-1 and Db-1 respectively. Numbers of the recordings with the displacement lower than the thresholds are 1730 (A-1), 1233 (Da-1) and 597 (Db-1).

3 ANALYSIS METHODOLOGY

Statistical approaches are applied for explaining the acoustic variability with environmental factors as predictors in this study. In many cases, several significant predictors for statistical approaches are empirically chosen for getting the meaningful trends of data.

However, it is subjective and the results might be different by ways of how the variables are selected. Moreover, significant predictors might differ for datasets obtained from different instruments. This paper proposes use of specific criteria to objectively select the significant explanatory variables for each dataset. The recordings are analyzed with two steps of statistical approach. Firstly, the significant explanatory variables for the analysis are objectively selected, and the relation between the noise variability and selected variables are then clarified in the second step.

Multiple linear regression analysis[7] (MLR) is a statistical technique to assess the association between two or more explanatory variables and a single response variable. Linear statistical models such as MLR are relatively easily interpreted, because it provides results with a simple linear combination of the explanatory variables. However, the results depend on the selection of explanatory variables. For this study, in total 18 variables are available as the predictors; distance to the nearest ice edge, ocean temperature, 15 sea statue variables and the 18th variable is the vertical displacement of the STAR instrument as mentioned in section 2.2. This large number of variables might cause some problems as multicollinearity and overfitting if all the variables are used as the explanatory variables for MLR. In this study, several significant explanatory variables for MLR are objectively chosen through two statistical methods to be defined below.

Multicollinearity increases the variance of the regression coefficients, making them unstable and difficult to interpret. Our approach computes the variance inflation factor (VIF) to get rid of variables which have a high correlation between predictor variables. A VIF for a single predictor variable is obtained using the r-squared value of the regression of that variable against all other predictor variables:

$$VIF_i = 1 / (1-R_i^2) \qquad (1)$$

where $i = 1, \cdots, m$, m is a number of the predictors. The VIF is calculated for each predictor variable and those with high values are removed. In this analysis, a value of 5 is used as the threshold for the VIF.

Forward stepwise selection[7] (FSS) is then applied to avoid overfitting problem, which causes lack of degree of freedom. FSS starts with no variables in the model and adds and removes variables one step at a time until no more can be added or removed according to the stepwise criteria. F-statistics, a ratio of variances of two variables, are computed for all the combinations between the model and variables which are not included in the model yet. At each step, the variable that has the smallest p-value less than the specified threshold is added. At the same time, any variables in the model with a p-value greater than the specified threshold are removed. The thresholds are 0.05 and 0.10 for adding a new variable and removing variables in the model, respectively.

Variables selected by the above methods are used as explanatory variables for MLR. Suppose n combinations with p explanatory and a response variables, $(x_{i1}, x_{i2}, \cdots, x_{ip}, y_i)$, $i=1, \cdots, n$, are given. Here n represents a number of samples. A model of MLR is defined by

$$y_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \cdots + b_p x_{ip} \qquad (2)$$

where b_0 and $b_1, \cdots, b_p$ are a constant term and partial regression coefficients (PRC) respectively. The objective of MLR is to compute a combination of $b_0, b_1, \cdots, b_p$ so as to minimize the sum of the square errors between observations (y_i) and expected values($\hat{y}_i$) as:

$$Min. \sum_{i=1}^{n} (y_i - \widehat{y_i})^2 \tag{3}$$

The 18 predictor variables are standardized so as to be the standard deviation of 1 and mean of 0 before the analysis.

4 RESULTS

The recordings from the three hydrophones, A-1, Da-1 and Db-1 with 373.0m, 263.9m and 954.0m depths respectively, are analysed using the statistical methods in section 3 and the results are compared. Two different frequency domains are considered: below 200 Hz and 200 - 500 Hz. In this section, the natural components of the soundscape are studied. Seismic airgun noise and mechanical noise influence the noise level below 200 Hz for all the hydrophones. Consequently the effects of airgun noise and mechanical noise are taken out from the analyses, by manual inspection and setting a threshold of the vertical displacement of the hydrophone, respectively. The recordings from A-1 were sometimes influenced by seismic airgun noise also between 200 and 500 Hz. These recordings were excluded from the analysis. All the recordings were used for the Da-1 and Db-1 analyses at 200 - 500 Hz. In each case, 5 - 7 out of the 18 variables were selected by VIF and FSS. Those were used as the explanatory variables in MLR.

4.1. Contributors to the variability of the natural ambient noise

Multiple linear regression analysis (MLR) was applied for the two frequency domains separately for each instrument. From the analysis, it was found out that the characteristics of the noise variability below 100 Hz are different from 100 - 200 Hz at mooring A. This difference is most likely propagation effects but not yet understood. Therefore, mean noise level between 100 and 200 Hz was used as the response variable for the A-1 analysis at the low frequency level. While, mean noise levels at 25 - 200 Hz were analysed for Da-1 and Db-1. For the high frequency domain, mean noise levels between 200 and 500 Hz were used for all the analyses.

The results are presented for each instrument and frequency domain in Table 1. The third column gives the number of recordings with only natural noise included in our analyses. b_0 is an expected mean noise level at the frequency domain when all the external factors take their mean values. The details about the three most significant explanatory variables for each model (Eq.(2)) are also shown in Table 1. The partial regression coefficients (PRCs) give the coefficients for the three variables in the model. The PRC indicates how much the noise level will increase/decrease when changing the explanatory variable by one standard deviation (STD). A negative value of PRC means that the noise level drops by increasing that variable, e.g. it is found from the results at 100 - 200 Hz for A-1, that the noise level (0.769 dB) decrease as mean sea level pressure (MSLP, 12.55 hPA) increases. The MCCs (Multiple Correlation Coefficients) show correlation coefficients between the observed mean noise level and expected mean noise level from the linear model, as the three most significant explanatory variables are introduced one by one.

Comparing the mean noise levels for the two frequency domains, it is found that the mean noise levels at the low frequency band are higher than within the higher frequency band for any instruments. When comparing the mean noise levels at two different depths (Da-1 and Db-1), the mean noise levels at the deep location are higher than the shallow one for both frequency domains.

Furthermore Table 1 shows that wind speed (WS) is the most significant explanatory variable for the noise variability, for all the frequency levels and instruments. MSLP is also one of the most significant parameters for all the hydrophones. Wind sea significant wave height (wsHs) is a significant factor especially below 200 Hz. The vertical displacement of the hydrophone was selected as the third significant factor at 200 - 500 Hz, but only for Da-1. Thus, the vertical displacement of the hydrophone causes more noise at the upper location in mooring D than at the other hydrophones. This is reasonable because the vertical displacement is stronger at mooring D than A as shown in Figure 2.

Moreover, Table 1 shows that the vertical displacement of the hydrophone makes more noise variability at the shallow place than the deep one. By comparing the MCCs obtained for each hydrophone it is seen that WS explains about 75 % of the variability of the natural ambient noise at 200 - 500 Hz, while it explains 60 - 70 % below 200 Hz.

Table 1. Relation between natural ambient noise and three most significant explanatory variables for two frequency domains: below 200 and 200 – 500 Hz. Numbers of the available complete dataset for A-1, Da-1 and Db-1 are 2457, 2462 and 2458 respectively.

	Freq. (Hz)	# of data	b_0	variable	PRC	STD	MCC
A-1	100-200	921	74.54	wind speed	1.581	4.35 m/s	0.602
				wind sea sig wave Ht.	1.003	1.65 m	0.606
				MSLP	-0.769	12.55 hPA	0.633
Da-1	25-200	822	78.38	wind speed	1.456	4.05 m/s	0.673
				wind sea sig wave Ht.	1.271	1.56 m	0.708
				MSLP	-0.747	12.29 hPA	0.743
Db-1		411	83.58	wind speed	1.426	3.91 m/s	0.696
				wind sea sig wave Ht.	1.035	1.53 m	0.731
				MSLP	-0.745	12.27 hPA	0.775
A-1	200-500	1334	66.78	wind speed	2.698	4.45 m/s	0.730
				MSLP	-0.557	12.93 hPA	0.742
				ocean temperature	0.498	0.24 °C	0.748
Da-1		2462	67.62	wind speed	2.206	4.16 m/s	0.743
				MSLP	-0.829	11.94 hPA	0.761
				VDH *	0.838	13.42 m	0.799
Db-1		2457	72.73	wind speed	2.253	4.16 m/s	0.756
				MSLP	-0.854	11.95 hPA	0.794
				wind sea sig wave Ht.	0.695	1.46 m	0.800

* vertical displacement of hydrophone

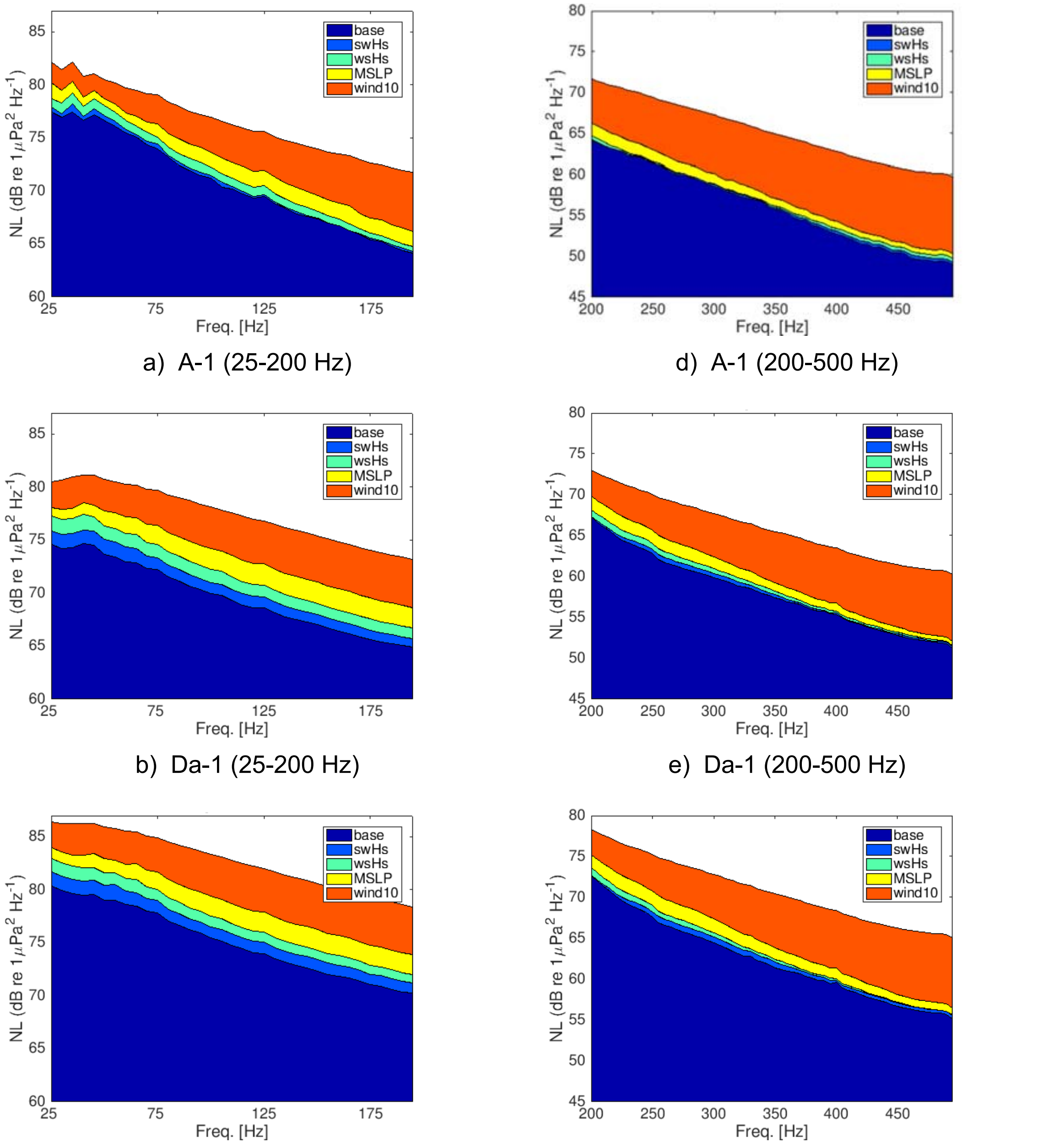
4.2. The impacts of major environmental factors and noise baseline

In section 4.1, it was revealed that the significant factors which cause the noise variability are wind speed (WS), mean sea level pressure (MSLP) and wind sea significant wave height (wsHs). A fourth important variable was swell wave height (sHs). In this section, the impacts of these four significant variables are clarified and noise baseline is defined.

Mean noise level was computed from the recordings for each 5 Hz in the range of 25 - 500 Hz for each hydrophone. Multiple linear regression analysis (MLR) was applied using the mean noise level as the response variable and the four major factors as the explanatory variables. We define baseline of the noise by subtracting the total impact of the four significant variables from the expected mean noise level obtained by the MLR. The noise baseline and impacts of the four major factors are plotted for each hydrophone and the two frequency domains in Figure 4. The figure is interpreted so that the impacts of swHs (blue), wsHs (green), MSLP (yellow) and WS (orange) are respectively added to the noise baseline (dark blue). The top line is the expected mean noise level at each frequency.

From Figure 4, the mean noise levels and noise baselines decrease as the frequency increases for any locations and depths. Comparing hydrophones at the two mooring locations (A-1 and D-1) the mean noise levels are similar. The most significant factor is WS at all the frequencies and at all hydrophones. The impact of the other three factors are smaller and decreases with frequency.

Details in the figure show that the contribution from the noise components are different in all the frequency bands. For example, wsHs contributes to the noise variability below 200 Hz, the contribution is very small above 200 Hz at both locations. The impact of MSLP relative to the WS for Da-1 is higher than A-1. Furthermore, comparing the two different depths at D, all the components of the noise variability are similar, while the mean noise levels are different since the noise baseline at the deep location is 5 – 6 dB higher than the shallow one.



a) A-1 (25-200 Hz)

d) A-1 (200-500 Hz)

b) Da-1 (25-200 Hz)

e) Da-1 (200-500 Hz)

c) Db-1 (25-200 Hz)

f) Db-1 (200-500 Hz)

Figure 4. Baseline of natural ambient noise and four major noise components at 25-200 Hz (a-c) and 200-500 Hz (d-f). From the top, the results of the recordings from hydrophones A-1, Da-1 and Db-1 are displayed respectively. Note that the frequency range is 60 – 87 Hz in a, b and c, and 45 – 80 Hz in d, e, and f.

5 CONCLUSIONS

Yearlong time series of passive acoustic data (25 - 500 Hz) and 18 external variables were obtained for understanding soundscape and impacts of environmental factors in the central and eastern part of the Fram Strait. The variability of the natural ambient noise was analyzed with objectively selected explanatory variables using multiple linear regression analysis for two different locations and depths.

The results give the noise baseline and its variability show the contributions from the major environmental factors: wind speed, mean sea level pressure, wind sea significant wave height, and swell significant wave height. In this study, the wind speed was the most significant factor of the noise variability at all frequencies. As both moorings were most of the time in open water this result is in agreement with common knowledge for open water ambient noise. The observed and expected mean noise levels in eastern part of the Fram Strait are not so much different from the middle of the Fram Strait. However, the contributions from the major factors were different, see Figure 4.

6 ACKNOWLEDGEMENT

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