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Classification of acoustically stable areas using empirical orthogonal functions – examination of stability methods

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English summary

Overview and control of the oceanographic and acoustic variations are very important in underwater warfare. We have developed a method for dividing an area into smaller subareas that can be represented by a single vertical sound speed profile. This is useful in an operational context since it can be used during sonar operations to determine how often, geographically and temporally, the sound speed should be measured, but also during rapid environmental assessment (REA) missions where it can be used to determine the distribution of REA assets. It can also be used tactically by submarines to find areas with variable oceanography where they are harder to detect. The method is based on a forcast from an ocean model containing salinity and temperature gridded in space and time.

The proposed procedure divides an area into smaller acoustically stable subareas. Acoustically stable areas are defined as areas where the majority of sound speed profiles from the area result in approximately the same modeled sonar performance. The procedure employs empirical orthogonal functions to characterize groups of sound speed profiles. The sound speed profiles are then grouped according to these characteristics using a cost function. Two methods using different cost functions are introduced. The first method is based on acoustic modeling using the acoustic raytracer Lybin, while the second method examines the sound speed variance directly. The first method is more accurate but has a higher computational cost than the second methode. We regard the first method as the benchmark.

The main goal of this study is to determine if the second method may be used without significant loss of accuracy. The methods were applied on three different data sets from an ocean model that covers the area outside Bergen. The data sets were provided by the Norwegian Meteorological Office. The largest data set contains 66 successive weeks of data. Our main find was that the second method is not sufficiently accurate for summer conditions. Acceptable results were observed for the remainder of the year, but data sets from other times and/or places should be investigated before any conclusion regarding the second methods validity for non-summer seasons may be drawn. We therefore recommend using the first method. It may be slower, but for most applications accuracy should be prioritized.

A suggestion for further work and a possible improvement of the faster second method is to use the variance of the vertical sound speed gradient instead of the variance of the sound speed. The sound speed gradient has more influence on acoustic propagation than the value of the sound speed.

Sammendrag

Oversikt og kontroll over oseanografiske og akustiske variasjoner er svært viktig i undervannskrigføring. Vi har utviklet en metode for å dele et havområde opp i mindre underområder hvor disse underområdene kan representeres med én vertikal lydhastighetsprofil. Dette er svært nyttig i undervannsoperasjoner hvor det kan brukes til å avgjøre hvor ofte, både geografisk og i tid man bør gjøre lydhastighetsmålinger, eller det kan brukes taktisk av ubåter til å plassere seg i områder med varierende oseanografi. Også for Rapid Environmental Assesment-(REA) operasjoner vil dette være nyttig da det kan brukes til å bestemme hvor man bør ha fokus på datainnsamlingen. Utgangspunktet for metoden er varsel fra en havmodell som inneholder salt og temperatur griddet i rom og tid. Målet er at metoden kan anvendes i et varslingsprodukt.

Prosedyren som presenteres deler et område i mindre, akustisk stabile underområder. Akustisk stabile områder er definert som områder der majoriteten av lydhastighetsprofilene i området gir omtrent samme modellerte sonarytelse. Prosedyren bruker empirisk ortogonale funksjoner for å gruppere lydhastighetsprofilene og en kostfunksjon brukes til å avgjøre om gruppen med lydhastighetsprofiler er stabil eller ikke. To metoder som bruker ulike kostfunksjoner er testet. Den første metoden er basert på akustisk modellering ved hjelp av strålegangsmodellen Lybin, mens den andre metoden bruker variansen til lydhastighetsprofilene. Den første metoden er mer nøyaktig, men mye mer beregningskrevende enn den andre metoden. Den første metoden anses som referansemetode.

Hovedmålet med arbeidet er å dokumentere om den andre metoden kan brukes uten at det går på bekostning av nøyaktigheten. Metodene ble anvendt på tre ulike datasett fra en havmodell som dekker området utenfor Bergen. Det største datasettet inkluderer 66 suksessive uker med data. Dataene ble levert av Meteorologisk institutt (met.no). Det viktigste funnet var at den andre metoden ikke var tilstrekkelig god nok i sommerperioden. Metoden ga tilfredsstillende resultater resten av året, men den må anvendes på datasett fra flere år før vi med sikkerhet kan si at den andre metoden er gyldig tre fjerdedeler av året. Derfor anbefaler vi å bruke den første metoden basert på akustisk modellering. Den er tregere, men for de fleste tilfeller bør nøyaktighet prioriteres.

Et forslag til videre arbeid og forbedring av den raskere andre metoden er å bruke variansen til lydhastighetsgradienten istedenfor variansen til lydhastigheten. Lydhastighetsgradienten har større påvirkning på akustikken enn absoluttverdien til lydhastigheten.

Contents

1 Introduction

Overview and control of the oceanographic and acoustic variations are very important in underwater warfare. Normally it is difficult to separate areas with one characteristic from another; areas where one single sound speed profile is valid. An algorithm for dividing an ocean area into groups is developed and two methods to check the stability of the groups are developed and tested. The dividing algorithm uses empiric orthogonal function (EOF) analysis of the sound speed profiles (SSPs) to determine the groups. The first stability method uses the sum of variance of the EOF coefficients and is a very simple and fast method. The second stability method determines the acoustic stability on basis of calculated signal excess for a group. The latter method is more accurate and therefore considered as the benchmark solution, but has a high computational cost. The methods have earlier been tested with good results on data sets with short time range (within 33 hours) [1]. In this study the methods are tested for longer time ranges to look at seasonal variations.

The study is part of a work for developing an oceanographic/acoustic forecast product. This product is a decision aid that helps the user decide how often the sound speed profile should be measured in different areas.. This will make it easier to plan and carry out Rapid Environmental Assesment (REA) missions and sonar operations.

The result of this study will decide which stability method should be used in an operational product which forecasts acoustically stable areas.

2 Method

The proposed method divides a group of SSPs into a set of smaller, but acoustically stable groups of SSPs. The SSPs are typically taken from an ocean model and each SSP represents an area. The size of the area depends on the resolution of the ocean model data. The ocean model data is presented in chapter 3. An acoustically stable group of SSPs therefore represents an area, henceforth called an acoustically stable area.

The flowchart in Figure 2.1 illustrates the method. A group is considered stable if it passes two criteria; the size criterion and the stability criterion. The size criterion requires that the group contains more than *K* SSPs. Since each SSP represents a unique area, *K* represents the minimum geographical extent of a group of SSPs and is selected by the user. The stability criterion is passed if the group cost is below a selected threshold. Two different methods are used; one acoustic method and one using the sum of the variance to the EOF eigenvalues . Both methods are described in section 2.3. A group of SSPs which not passes the stability criterion is divided into two smaller groups. This division is based on the EOF coefficients of SSPs in the split group, see section 2.2.

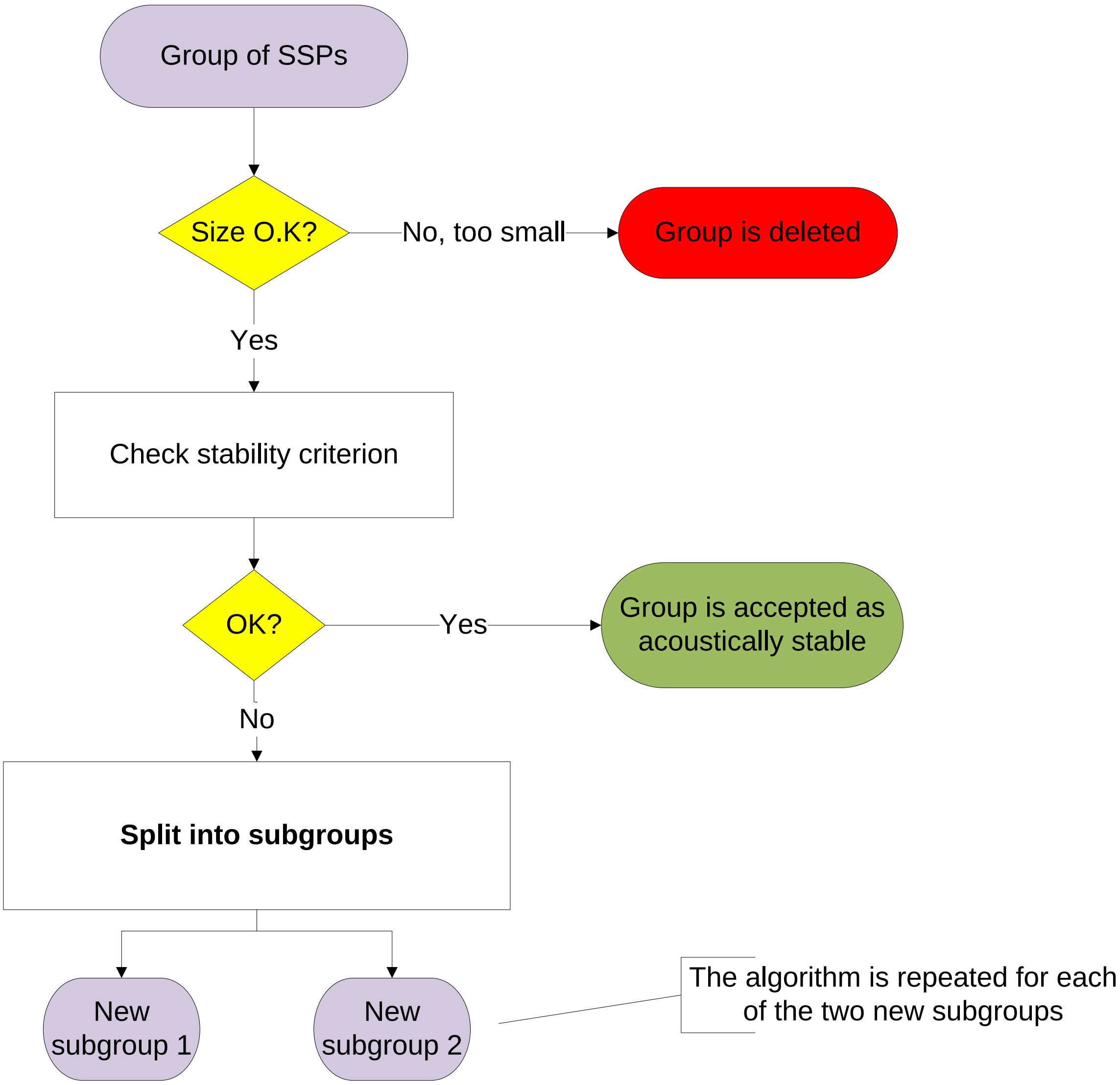

Figure 2.1 Flow chart that illustrates the method used to divide a group of SSPs into smaller, acoustically stable groups.

2.1 Empirical orthogonal functions

A detailed account on how EOFs are derived from a data set is found in [2]. The following gives a short synopsis of the method.

Consider a data matrix $\widehat{\mathbf{C}}$, where each row contains a single mean subtracted SSP, $\hat{\mathbf{c}}(\mathbf{x},t)^T$ with an associated position, ***x***, and time, *t*. The mean subtracted SSP is given by:

$$\hat{\mathbf{c}} = \mathbf{c} - \bar{\mathbf{c}} \qquad (1)$$

where $\boldsymbol{c}$ is a SSP and

$$\bar{\mathbf{c}} = \frac{1}{M} \sum_{m=1}^{M} \mathbf{c_m} \tag{2}$$

where $\boldsymbol{c_m}$ is the mth SSP.
The correlation matrix, $\boldsymbol{R_c}$, is given by:

$$\mathbf{R_C} = \frac{1}{M} \widehat{\mathbf{C}}^T \widehat{\mathbf{C}} \tag{3}$$

where M is the number of SSPs in the data matrix. The SSPs may then be represented by the following expression:

$$\mathbf{c} = \bar{\mathbf{c}} + \sum_{k=1}^{N} \kappa_k \mathbf{u_k} \tag{4}$$

where $\boldsymbol{u_k}$ are EOFs and may be derived by solving the following eigenvector problem:

$$\mathbf{R_C} \mathbf{u_k} = \lambda_k \mathbf{u_k} \tag{5}$$

where λ_k is the eigenvalue corresponding to $\boldsymbol{u_k}$. There are N EOFs, where N is the number of depth steps in the SSPs. The EOF corresponding to the highest eigenvalue is commonly called the leading coefficient. The coefficients, κ_k, representing a specific SSP, $\widehat{c}$, are found as follows:

$$\kappa_k = \mathbf{u_k}^T \widehat{\mathbf{c}}. \tag{6}$$

According to [2], the variance of the coefficients equals the eigenvalues:

$$\mathrm{E}(\kappa_k^2) = \lambda_k \tag{7}$$

2.2 Grouping by EOF

The grouping method used is called the coefficient sign test (CST). The method applies an EOF analysis on the input group of SSPs. The SSPs are subsequently split in two groups; one where the leading coefficient is positive and one where the leading coefficient is negative. Note that due to the iterative main algorithm, both the EOF analysis and the subsequent splitting are done on progressively smaller subsets of the original data set. The method is described in detail in [1]. It is also compared to a conventional method using cluster analysis and shown to give satisfactory results.

2.3 Stability criterion

The following sections describes two different methods for determining if a group of SSPs is considered acoustically stable or not, one acoustic method called the CA method, and one using the sum of all eigenvalues, called the CEOF method.

2.3.1 CA method

The CA method computes the averaged percentage, CA, of target ranges, r, and depths, z, considered where the bias, b is below a set threshold, T_b. r ranges from 0 to 10 km and z ranges from 0 to 200 m.The averaging is over all SSPs in that group. T_b is set to 5 dB in this study. The bias for a single SSP is defined as:

$$b(r,z) \quad = \quad |SE_j(r,z) - SE_m(r,z)| \qquad (8)$$

where $SE_j(r,z)$ is the modelled signal excess [3] at $[r,z]$ using the jth SSP in the acoustic model. The mean signal excess, $SE_m(r,z)$, is given by:

$$SE_m(r,z) \quad = \quad 10\log_{10}\frac{1}{N}\sum_{j=1}^{N} 10^{SE_j(r,z)/10} \qquad (9)$$

where N is the number of SSPs in the considered group. Groups where the computed percentage (CA) exeeds a selected threshold TA are assumed to have stable sonar conditions. TA is set to 0.85 in this study, which means 85 % of the b(r,z) in a group must be below T_b for the group to be considered stable. TA should depend on the applications, e. g. some applications require higher CA than others for a group to be considered as stable.

2.3.2 CEOF method

The CEOF method uses the sum of all eigenvalues, CEOF, to decide if a group is stable:

$$CEOF = \sum_{k=1}^{N} \lambda_k \qquad (10)$$

This corresponds to the summed variance of the SSPs in the group:

$$CEOF \quad = \quad \sum_{j=1}^{N} \mathrm{E}\left(\hat{c}_j^{\,2}\right) \qquad (11)$$

where the E() operator is the expectation.

The above equation is easily proved:

$$CEOF = \sum_{j=1}^{N} \mathrm{E}\left(\left(\sum_{k=1}^{N} \kappa_k u_{jk}\right)^2\right) \tag{12}$$

u_{jk} is the jth element of the kth EOF.

$$CEOF = \mathrm{E}\left(\sum_{j=1}^{N}\left(\sum_{k=1}^{N} \kappa_k u_{jk}\right)^2\right) \tag{13}$$

Since the EOFs are orthonormal, then:

$$\sum_{j=1}^{N} u_{jk} u_{jl} = \begin{cases} 1, & k = l \\ 0, & k \neq l \end{cases} \tag{14}$$

This yields:

$$CEOF = \sum_{k=1}^{N} \mathrm{E}\left(\kappa_k^2\right) \tag{15}$$

Which, according to (7) becomes:

$$CEOF = \sum_{k=1}^{N} \lambda_k \tag{16}$$

A group of SSPs is assumed stable if:

$$C_{EOF} \leq T_{EOF} \tag{17}$$

It is well known that the acoustic field, particularly at mid-frequencies, is very sensitive to sound speed variability [4]. However, the extent of the sensitivity depends on the sonar parameters and the sonar – target geometry [5]. This means that acoustic stability is connected to the summed sound speed variance, but that this connection is not linear, and must be determined for each sonar and environment considered. We therefore propose that the threshold TEOF is calibrated for a specific sonar and environment before use. This calibration is detailed in the following section.

2.3.3 Calibration of the CEOF method

We calibrate the CEOF method by determining which TEOF corresponds to the given TA, 0.85 in our case, see section 2.3.1. This is done by generating groups of artificial SSPs similar to the original data set. The CEOF and CA of each group are plotted and the CEOF that corresponds to CA = TA is selected as TEOF, see the illustration in Figure 2.2.

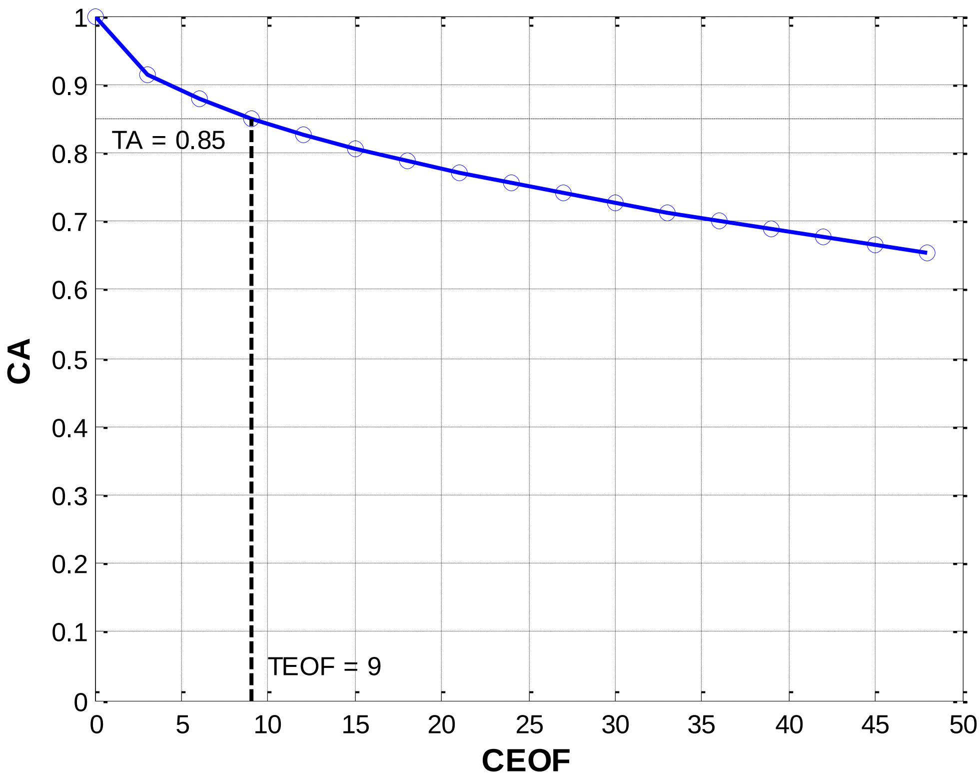

Figure 2.2 CA-CEOF curve based on 17 different randomly generated groups of SSPs. The CA and CEOF values for each of 17 groups are indicated using circles. The horizontal dashed line indicates the threshold TA, while the vertical one indicates the TEOF that corres.

The SSPs used are generated using (4), but the standard deviations, μ_k, of the coefficients are changed using the following formula:

$$\mu_k = \sqrt{\frac{\lambda_k CEOF}{\sum_{k=1}^{N} \lambda_k}} \qquad (18)$$

Where λ_k is the eigenvalues of the original data set and CEOF is varied from 0 to 50 as shown in Figure 2.2 This ensures that CEOF remains the sum of all coefficient variances:

$$CEOF = \sum_{k=1}^{N} \mu_k^2 \qquad (19)$$

The CEOF method has a far lower computational cost than the CA method. While it takes about one hour to compute the groups and check the stability for one time step with the CA method, it takes about 30 seconds with the CEOF method.

3 Data

The SSPs used in this study are based on three dimensional forecasts of temperature and salinity from the high resolution numerical ocean model Westcoast200m. This ocean model is a version of Princeton Ocean Model (POM) called MI-POM, run operationally by the Norwegian Meteorological Institute [6]. The model domain covers an area of approximately 16.000 km^2 from 59.N 4E to 61N 5.75E with a horizontal resolution of 200 m. e 3 shows the general oceanography and extent of the considered area. The forecast period is 33 hours with 11 time steps at 3 hour intervals. The data are subsampled to a horizontal resolution of approximately 1~km, 11 time steps (3 hours), and 9 depth levels ranging from 0 to 200~m. Most data from fjords and inlets are removed.

Three periods are studied, March 7-20 2011, August 23 to September 6 2010, and a 66 week period starting January 13 2010 and ending April 4 2011. The two fourteen day periods are chosen to study short time variations at different times of year. Only the first eight time steps of each model run is used since time steps 9-11 overlap the first three time steps in the following model run. In the period in August-September two model runs, August 24 and 27, are missing due to lack of data. In the 66 week period we want to look at seasonal variations and how they affect the method. In the 66 week period only one time step per week is used.

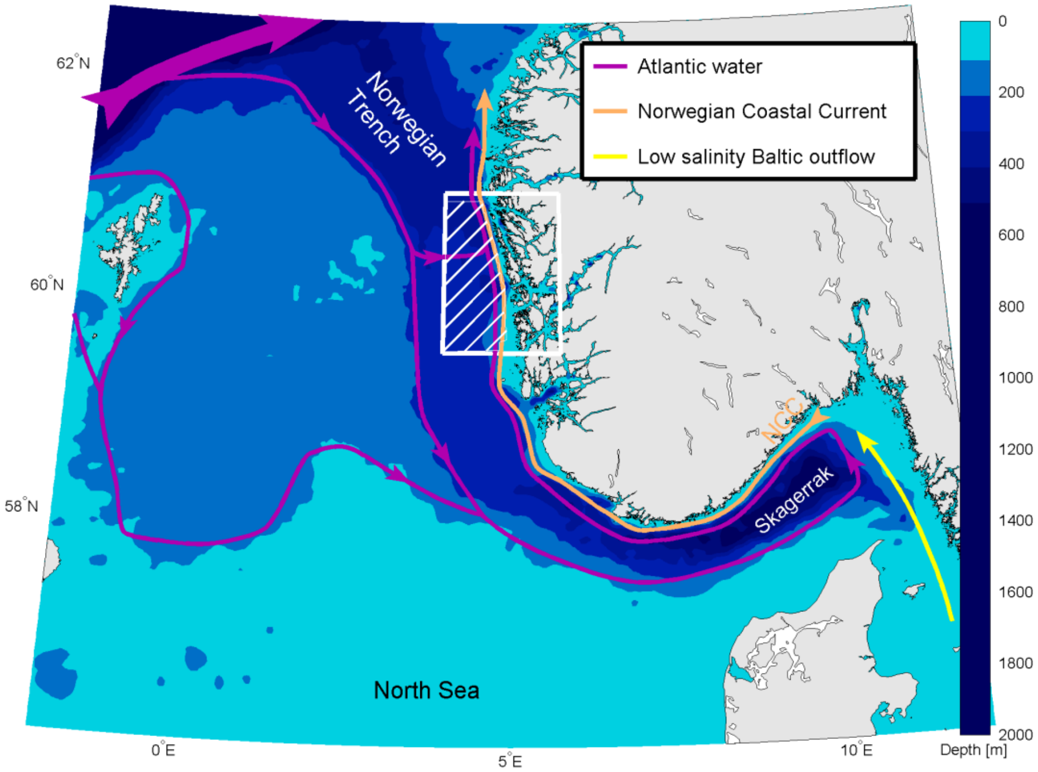

Figure 3.1 An overview of the oceanography of the relevant area. The white box indicates the area the oceanographic data is taken from

4 Results

Because of the computational cost of the CA method we are eager to find out if we can use the CEOF method as stability criterion instead. We try two hypotheses:

1. A global threshold TEOF exists that results in a group distribution similar to the distribution found when using the CA method. This global threshold is found by calibrating the CEOF method once per week or rarer.
2. A local threshold on TEOF exists that results in a group distribution similar to the distribution found when using the CA method. In order to find this threshold we calibrate the CEOF metod regularly, e. g. daily.

Each hypothesis is tested using the three data sets discussed in section 3. Two different sonar depths are examined; 50 m and 100 m depth.
For each TA we find a corresponding TEOF by generating a group of sound speed profiles with a chosen TEOF and then determining the corresponding TA. The values used for TEOF is 1, 2, 3, 5, 7, 9, 10, 15, 20, 25, 30, 35, 40, 45, and 50.

4.1 Summer season August 23 – September 2010

4.1.1 Sonar depth at 50 m

Figure 4.1 shows CEOF plotted against CA for August 23 to September 06. CA is calculated with a sonar at 50 m. The plot shows that high CEOF corresponds to a low CA and vice versa. To reach the threshold TA = 0.85, the threshold TEOF must be lower than three. Note also that CA varies by 0.25 in the CEOF interval. Figure 4.2 displays the variation of TEOF corresponding to TA = 0.85 during the fourteen day period. TEOF varies almost from one time step to the next in the first four days. From August 29 to September 4 TEOF is 5 except for three time steps. The last day TEOF drops to 3. While TEOF is relatively stable in the second part of the 14 day period, it indicates that a single value for the whole period cannot be used, thus hypothesis 1 fails for this case. This is also reflected in the number of groups produced by the CA and CEOF methods for this situation, see Figure 4.3. The number of groups produced by the CA method varies less than number of groups produced by the CEOF method. If we look at the size and distribution of the groups the difference between the two methods is highlighted even more (Figure 4.4 and Figure 4.5. The CA method tends to produce one to three large contiguous groups for every time step, while the CEOF method tends to calculate smaller and scattered groups and a large amount of groups containing less than 100 SSPs. The cyan colored group in the two first panels in Figure 4.5 exists from August 25 at 06:00 to September 01 at 12:00. The CEOF method has no indications of the same group in space and time. Thus hypothesis 2 also fails for this case.

The large number of small groups generated by the CEOF method draws a chaotic picture, even when we calibrate TEOF for every time step. Running the method with a constant TEOF instead of the calibrated TEOF would not give the same distribution of groups, but it would still give the same information of an unstable situation and still differ from the CA method. The method was run with TEOF = 5, which is the median of the TEOF during the 14 day period. This shows that the CEOF method is not feasible, at least for this data set, but it would not make a big difference if we use calibrated or constant TEOF.

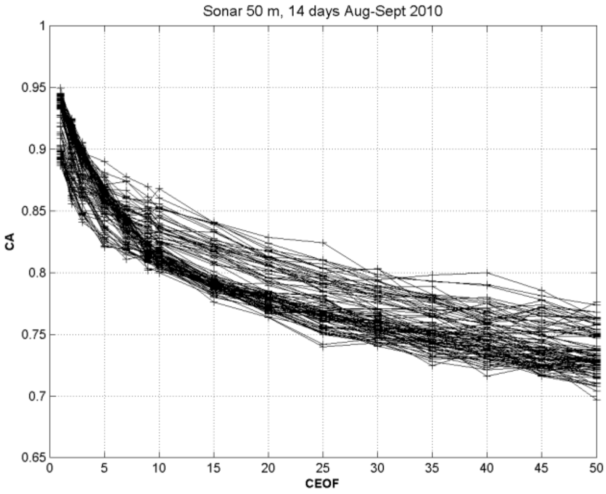

Figure 4.1 CEOF vs. CA for a sonar at 50 meter in the period August 23 - September 05 2010. Each line represents one time step.

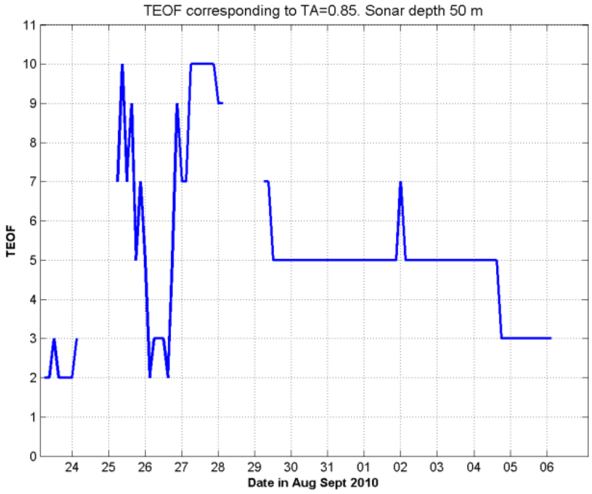

Figure 4.2 Values of TEOF corresponding to TA = 0.85 in the period August 23 - September 05 2010 for a sonar at 50 meter

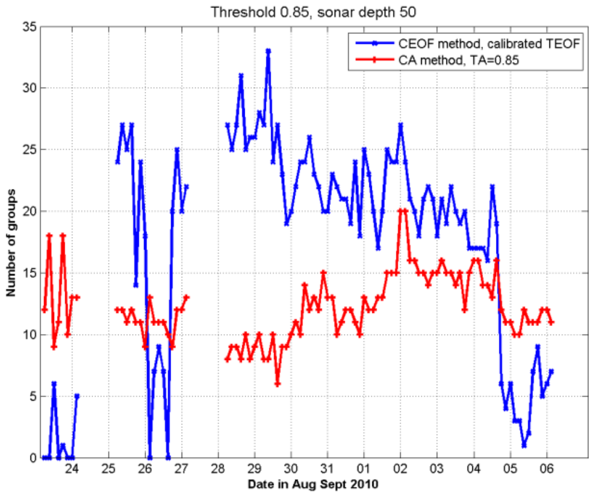

Figure 4.3 *Number of groups produced by the CA and CEOF method August 25 - September 06 2010 with a sonar at 50 m .*

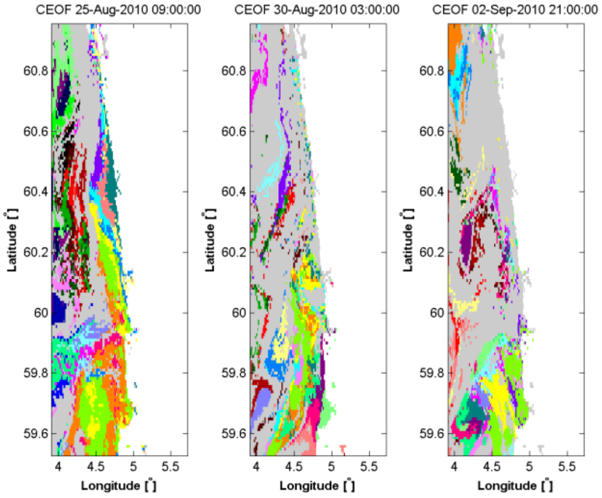

Figure 4.4 *Geographical distribution of groups generated with the CEOF method for three different time steps in August/September 2010. Each group is represented by a single colour. The grey group is a collection of groups that did not pass the size criterium, TA =0.85 and sonar depth is 50 m*

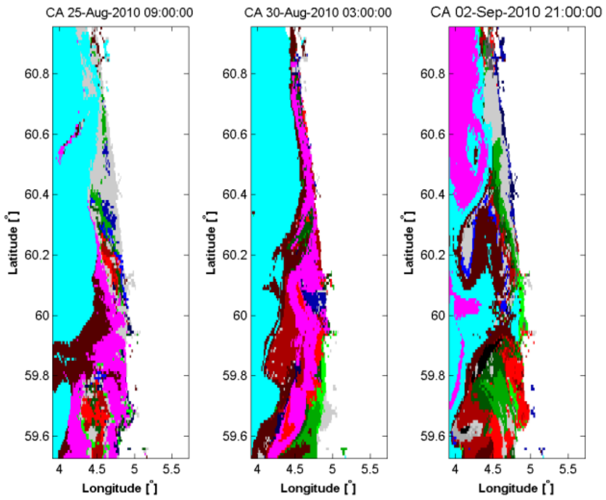

Figure 4.5 Geographical distribution of groups generated with the CA method for three different time steps in August/September 2010. Each group is represented by a single colour, TA =0.85 and sonar depth is 50 m

4.1.2 Sonar depth at 100 m

For a sonar at 100 m the situation is different and CA is above 0.85 for all CEOFs, which means that TEOF is 50 for all time steps. The number of groups produced for the two methods are shown in Figure 4.7. The two methods generate the same number of groups except for three time steps, where the CA method has a higher number of groups than the CEOF method. For this case the two methods give the same result and no calibration of the TEOF during the 14 day period is needed. For the summer case (see chapter 4.1) variable sonar depth will affect the number of groups generated by the two methods. In this case hypothesis 1 gives adequate results.

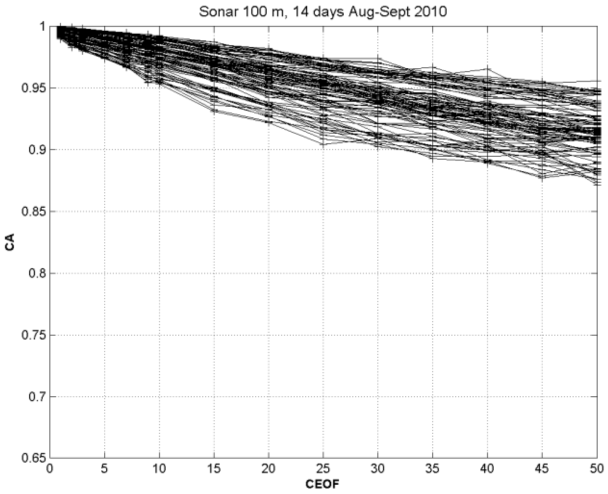

Figure 4.6 CEOF vs. CA for sonar at 100 meter in the period August 23 - September 05 2010. Each line represents one time step

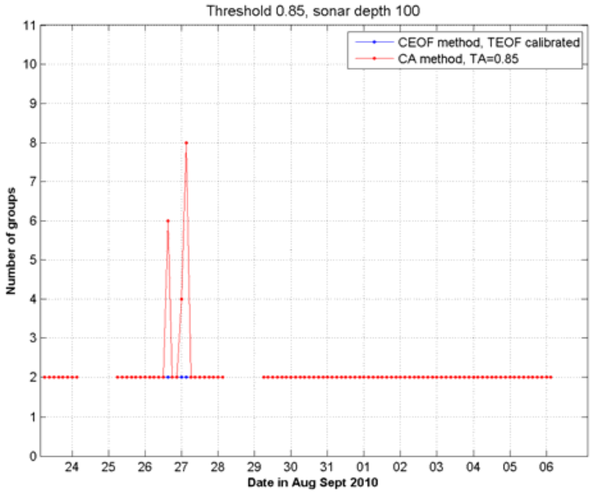

Figure 4.7 The number of groups generated by the CEOF and CA methods for the period August 23 - September 05 2010

4.2 Winter season March 7 – 22 2011

4.2.1 Sonar depth at 50 m

For the winter case the situation is quite different compared to the summer situation. CA varies little and is above 0.85 through the CEOF interval (Figure 4.8). For the winter situation TEOF will be 50 for all time steps, so no calibration will be needed during the 14 day period. The number of groups is also the same for the two methods except for five time steps at March 11. In this case hypothesis 1 gives adequate results.

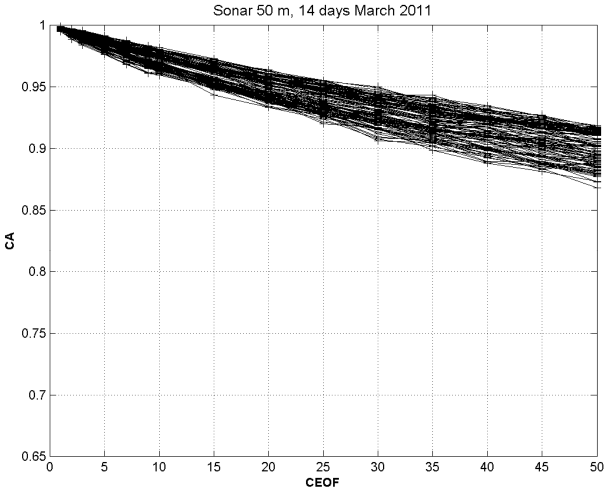

Figure 4.8 CEOF vs. CA for sonar at 50 meter in the period March 7-22 2011. Each line represents one time step.

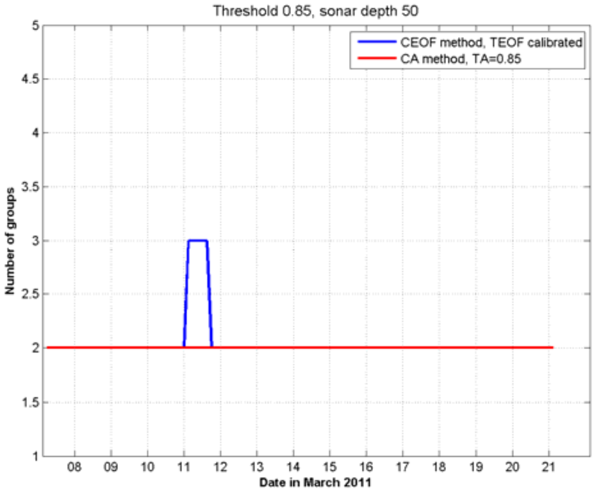

Figure 4.9 Number of groups generated by the CA and CEOF methods Sonar depth at 100 m

When the sonar is placed at 100 m the situation is much the same as for 50 m. There is slightly more variation in CA through the 14 day period and for four time steps CA drops below 0.85, but only by 0.01. For these time steps CEOF decreases below 50 to 45. If we use TEOF = 50 for all time steps, the number of groups generated with the CEOF method is the same as for calibrated TEOF. The amount of groups generated is also the same as for the 50 m case (Figure 4.9). That concludes that the dataset and CA method is not influenced by variable sonar depth for the winter case studied here and a constant value of TEOF = 50 could be used,which means that hypothesis 1 gives adequate results.

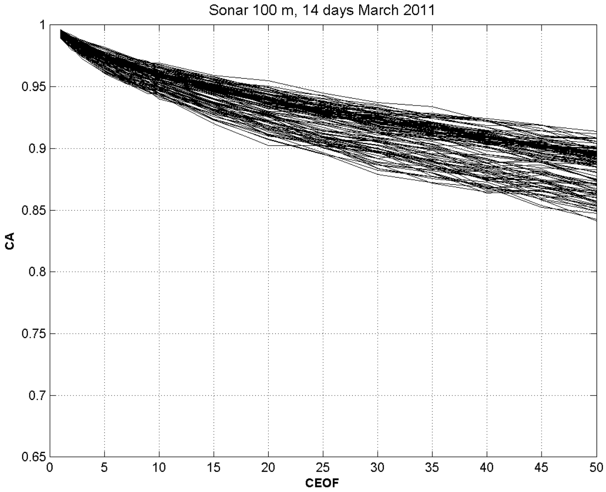

Figure 4.10 CEOF vs. CA for sonar at 100 meter in the period March 7 - 22 2011. Each line represents one time step .

4.3 January 2010 – April 2011

The reason for studying this period is to look at long term variations. The 14 day periods showed that CEOF method can be used with one calibration during the winter case (hypothesis 1), while in the summer situation the CEOF method differed from the CA method. It showed that calibration had to be done often (hypothesis 2), but even then the CEOF method generated more groups and smaller groups than the CA method. For the majority of the time steps in the period August 23-September 06 the CA method mostly generated one to three large contiguous groups that could be considered stable.

4.3.1 Sonar depth 50 meter

Figure 4.11 CA as function of CEOF through the 66 weeks period from January 2010 to April 2011. Blue represents low values of CA and red high values of CA. shows the variation of CA as a function of CEOF. It is clear that CA is lower and fluctuates more in the summer/fall (week 28 to 41) than in the rest of the year, which supports the conclusion from the summer season data set. This corresponds fairly well with the number of groups generated from the two methods (Figure 4.12). In the "stable" period, week 1-25 and week 42-66 the methods produce the same number of groups for 42 of the 50 weeks. For 6 of the 9 remaining groups the CEOF method produce 3 groups while CA method generates 2 groups, see Figure 4.13.

For the weeks 28 to 41 the results for the two methods do not match. For most of those weeks both methods generate more than 10 groups, which gives the whole model domain an unstable characteristic. Even if the size, number, and placement of the groups match, the two methods state that the area is unstable, see Figure 4.14.

The variations observed in CEOF in Figure 4.11 clearly show that a global, all year TEOF cannot be determined. A calibration is required regularly. Also, the variations seen from week to week indicate that a calibration is needed more often than on a weekly basis. This rules out hypothesis 1.

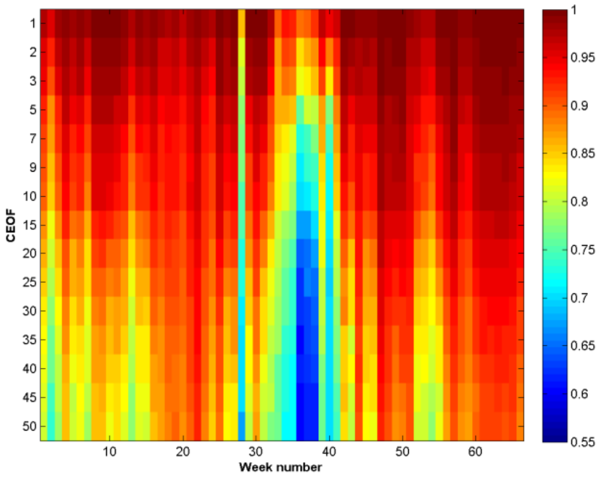

Figure 4.11 *CA as function of CEOF through the 66 weeks period from January 2010 to April 2011. Blue represents low values of CA and red high values of CA. .*

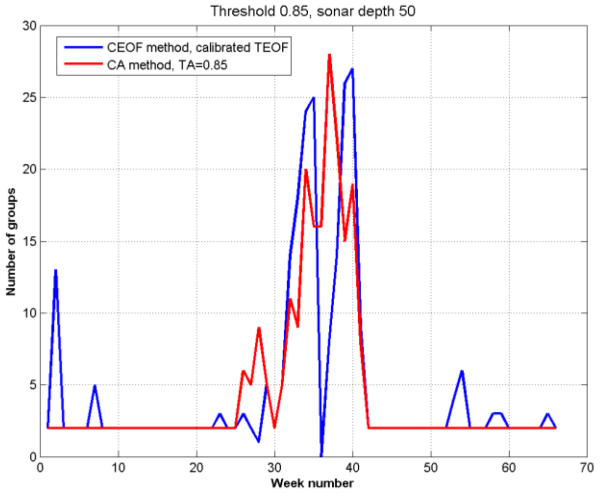

Figure 4.12 *Number of groups generated for the CA and CEOF method for the 66 week period. Sonar depth is 50 meter*

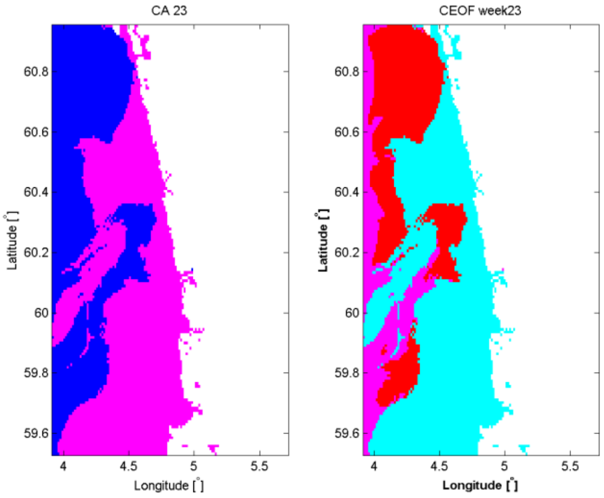

Figure 4.13 *Geographical distributions of groups in week 23 generated by the CA method (left panel) and CEOF method (right panel). Each group is represented by a single colour. Note that the pink group for the CA method equals the cyan group for the CEOF method, while the blue group for the CA method is splitted into 2 groups with the CEOF method.*

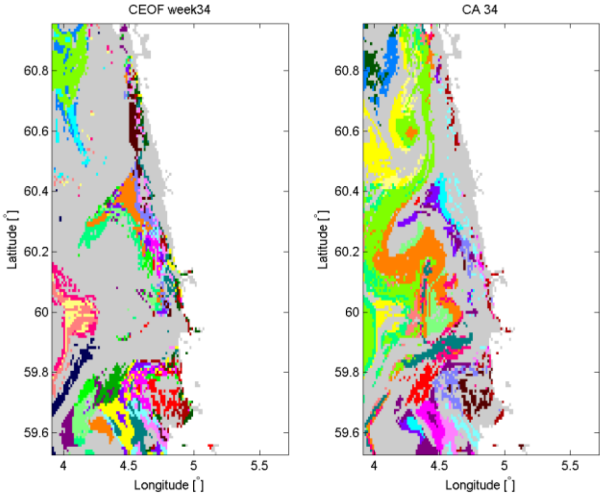

Figure 4.14 *Geographical distributions of groups in week 34 generated by the CA method (left panel) and CEOF method (right panel). Each group is represented by a single colour. The grey group is a collection of groups that did not pass the size criterium. The colors in the CEOF and CA plots are individual for each plot, i.e. green group when using the CEOF method does not have the same characteristics as the green group when using the CA method.*

4.3.2 Sonar depth 100 meter

Compared to sonar at 50 meter (Figure 4.11), the TEOF requires lower values in week 1-15 to reach the threshold TA = 0.85 (Figure 4.15). On the other hand higher values of TEOF is sufficient to reach the threshold TA = 0.85 in the weeks 28-41 than for sonar at 50 m. This is also reflected in the number of groups produced by the two methods. The CEOF method produces fewer groups in the weeks 28-41 when the sonar is placed at 100 m compared to 50 m, while it is opposite in the first and last 15 weeks (Figure 4.16). The CA method (Figure 4.17) generates fewer groups in the weeks 26-41 when the sonar is placed at 100 m compared to 50 m, while the CA method is not influenced by varying sonar depth the rest of the weeks (except for week 2, 24, 53, and 54 where a sonar placed at 100 m produces more groups than a sonar at 50 m). Together with the results from section 4.2.1 it seems like variable sonar depth will not affect the CA method in the winter season.

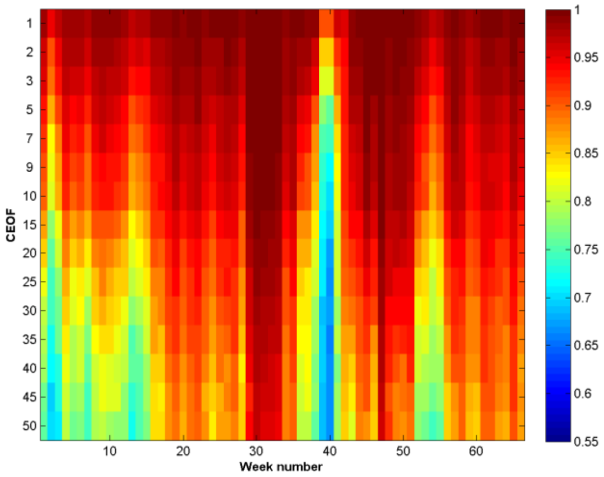

Figure 4.15 *CA as function of CEOF through the 66 weeks period from January 2010 to April 2011 with sonar at 100 meter. Blue represents low values of CA and red high values of CA.*

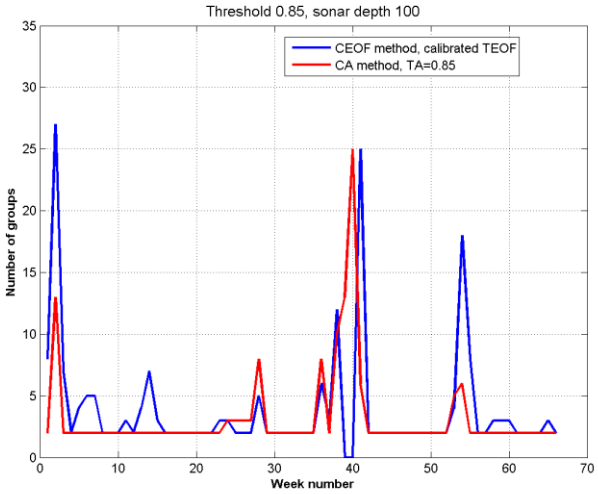

Figure 4.16 *Number of groups generated for the CA and CEOF method for the 66 week period. Sonar depth is 100 m.*

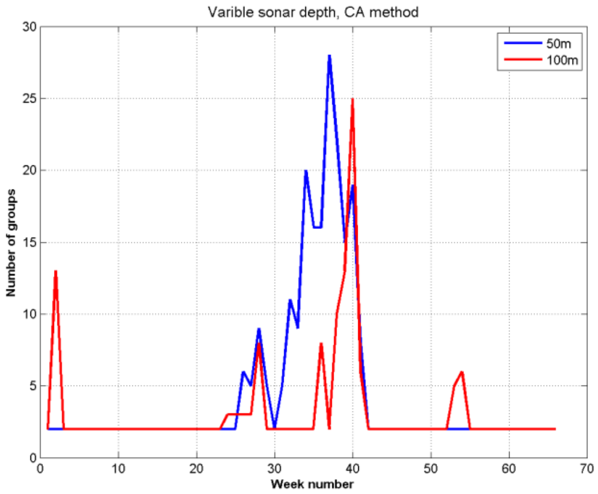

Figure 4.17 Number of groups generated by the CA method for sonar depth at 50 m and 100 m Concluding remarks

In chapter 4.2 we showed that we can use a constant TEOF = 50 (hypothesis 1) for both sonar depths for the period in March and get the same number and geographical distribution of the groups and a good agreement between the CEOF and CA methods. For the summer situation (chapter 4.1) this was not the case. Constant and calibrated TEOF gave the same chaotic picture of the group distribution, but neither matched the result from the CA method, meaning that hypothesis 2 also failed for this case.

For the 66 week data set, CEOF varies throughout the period with higher values in winter than summer. A constant TEOF = 50 (hypothesis 1) for all 66 weeks (Figure 4.18) will give a good match for the stable weeks (1-25 and 42-66), but fail in the unstable period (week 26-41). A calibrated TEOF (hypothesis 2) yields approximately the same number of groups as the CA method throughout the whole year, but the detailed analysis of the summer season given in section 4.1 shows that this method is not always sufficiently accurate either.

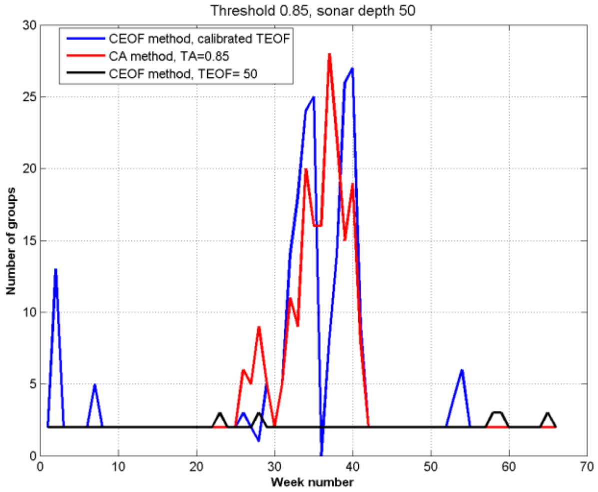

Figure 4.18 Number of groups generated for the CA and CEOF method for the 66 week period. CEOF method is run with calibrated (blue) and constant (black) TEOF. Sonar depth is 50 m.

5 Summary

We have developed a method for finding acoustically stable areas. Empirical orthogonal functions are employed on an ocean model data set and areas containing sound speed profiles with similar EOF coefficients are grouped. Two different methods for determining if such groups are acoustically stable are developed and tested. The first method models the signal excess using the acoustic model Lybin to determine if a group is acoustically stable. The second method determines the stability by studying the sound speed variance directly. The second method is faster, but less accurate than the first method. The main goal is to determine if the second method may be used without significant loss of accuracy.

It is clear that there are seasonal variations in the amount of groups generated by the CA and CEOF method. The period March 7-22 shows no variation in TEOF in that period for sonar placed at 50 m and only small variations when the sonar was placed at 100 m. But for both cases the number of groups generated is the same for both sonar depths.

One of the goals was to see if we could use one single value for TEOF throughout the year. It is obviously that this is not the case. Especially in the summer season the calibration shows that TEOF varies too much. The difference in TEOF from the more stable winter situation to the more unstable summer situation is too big that we can use one single TEOF value which satisfies both seasons. For the weeks 1-25 and 42-66 we could use TEOF = 50, but for the weeks 26-41 that would not be the case. Another problem is to find out when the constant TEOF is no longer valid. For weeks 26-41 and in the period August 23 – September 06 2010 we also see that the CEOF method do not agree with the CA method when it comes to the size and distribution of the groups.

This was clearly seen in the August-September period when the CA method produced one large group which was never seen in the CEOF method for the period August 25 – September 02. A complaint about the CA method is the dependence on sonar parameters. Values for tilt, sonar depth, beam width etc will affect the results. The method was run for two sonar depths, and it was discovered that the results are affected by the sonar depth at some extent in the weeks 24-41, but not as much as expected. Sensitivity on sonar depth is strongly connected to where the sonar is placed according to the vertical SSP gradients. If the sonar is placed at depths where the gradient varies, so will the results.

Another question that rises is about the threshold TA=0.85. Is this not strong enough? A higher threshold would generate more groups all over and may cause that a constant TEOF could not be used in the winter period either.

Based on this study the CEOF method is overall not good enough because of the mismatch with the CA method in parts of the year, which means that it is safer to use the CA method. Since the CA method has a high computational cost compared to the CEOF method, some compromises have to be done. With the code running today it will take about 8 hours to calculate the groups for 24 hours. One compromise could be to only use two time steps or use a lower spatial resolution of the data set.

6 Future work

A possible improvement of the CEOF method is to compute the variance of the vertical sound speed gradients and use that value for determining whether a group of sound speed profiles is acoustically stable or not. It is well known that the sound speed gradient has a strong influence on acoustic propagation.

The main drawback with the CA method is its high computational cost. This could be reduced through optimizing or parallelization techniques.

Acronyms

CA	Acoustical stability measure
CEOF	EOF stability measure
CST	Coefficient sign test
EOF	Empirical orthogonal function
SE	Signal excess
SSP	Sound speed profile
TA	Threshold on acoustical cost function
TEOF	Threshold on EOF cost function

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