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Technical Report

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USE OF SHORT TIME SERIES FOR EARLY GLOBAL WARMING TREND DETECTION FOR OCEAN ACOUSTIC TRAVEL TIMES

Gary D. McCartor
William R. Wortman
Steven Bottone

September 1996

Submitted by: MISSION RESEARCH CORPORATION
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13. ABSTRACT *(Maximum 200 words)*

Previous work indicated that for expected variability of ocean acoustic propagation times and the level of anticipated warming trends, it may take at least two decades of observation to establish, with an adequate level of confidence, that warming does or does not exist. In the current report, we have attempted to establish the extent to which the use of data from a shorter period may allow at least better definition of the period needed to establish these warming trends. Truncated simulated data sets, generally 5 or 10 years, from the MASIG model of acoustic propagation time variability over decades have been used to establish the extent to which the statistical trend extraction techniques give stable results using these shorter series to define the noise background. It is found that the use of these shorter series provides an apparent reduction of time required to detect trends; This unfortunately indicates that meaningful estimates of warming trends cannot be made with use of a lengthy data set approaching the full 20 year interval. Generally it is found that once the length of the background data is less than half of the full set, the estimates of times needed to detect trends are, falsely, reduced. This indicates that the variability which tends to mask trends is long period and that shorter observation intervals do not allow characterization of this variability. In another portion of this study, we find that the substantial short term variability seen in the first six months of the ATOC experiment is comparable with that seen by Spiesberger but that this variability plays almost no role for the long term trend detection problem, which is dominated by multiyear periods.

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TABLE OF CONTENTS

SECTION **PAGE**

LIST OF FIGURES

LIST OF TABLES

TABLE **PAGE**

1. INTRODUCTION

A possible indication of the existence of induced global climate warming is a decreasing trend for the travel times of acoustic pulses along a fixed long path, or paths, in the ocean over a period of many years. A warmer ocean implies, on average, an increased speed of sound which in turn implies a decrease in this travel time. The use of long acoustic paths substantially reduces the variability of temperature from local ocean weather, potentially allowing the detection of underlying climate trends [Munk and Forbes, 1989]. If taken over a long enough period of time, these data may provide an indication that global warming is occurring. The Acoustic Monitoring of Global Ocean Climate (AMGOC) experiment is measuring acoustic travel times over a number ocean paths with the coupled goals of improvement of ocean models and detection of any existing warming signature.

In two previous reports, we have developed statistical methods specifically for determining the presence of a long term trend for ocean warming from a temporal sequence of measurements of ocean acoustic propagation times [Bottone et al., 1995, Bottone et al., 1996]. Techniques for determining statistical models which best fit the data and means for testing for warming trends in these models suggested that, based on the best available simulations of acoustic propagation time variability, for the desired high levels of significance and for the expected levels of warming, a few decades will be needed to detect warming trends by AMGOC measurements. However, these results are dependent on the assumption that the noise background against which the trend must be detected is well described by the ocean model simulations.

Preliminary data from the ATOC (Acoustic Thermometry of Ocean Climate) segment of AMGOC may provide an experimental basis for the noise background models, thereby allowing more realistic projections of the time needed to detect a warming trend. In this report, we explore methods and limitations for the use of short term noise background information to refine estimates of times needed to detect trends.

In our two prior reports, a method of analyzing ocean acoustic propagation time series data to test for a trend were presented. That is, a method for testing the hypothesis that b is nonzero in the assumed relation:

$$X_t = a + b\,t + E_t \qquad (1)$$

where X_t is the acoustic travel time at time t, a and b are constants, and E_t is correlated noise from a statistical model established to match either real or simulated data. The method discussed in the second report controls the false alarm rate, under certain assumptions about the character of the noise, and thus allows a meaningful test of hypothesis to be constructed.

The method attempts to distinguish between a situation where natural variability of stationary noise provides an interval of apparent trend and the situation where a trend is actually present. The most important assumption regarding the noise is that properties of the noise that are most responsible for obscuring the difference between a trend and no trend are captured in an Auto Regressive (AR) model. Given that assumption, it was shown that the method gives quite good control over the false alarm rate in that for random AR processes the method will find a trend when none is actually present at the desired rate. If one has an AR model for the noise one can find the power of the test for a specified value of b by simulation.

Unfortunately, there does not currently exist a data set for long term, long range, acoustic propagation time variation to allow precise modeling of the background noise. Thus estimates of the probability that the AMGOC program will detect a specified trend after a given number of years must be based on noise models have been derived from simulations. There is no general agreement regarding the veracity of the models in predicting that noise.

For these reasons it is attractive to consider the possibility that data taken over a short length of time might be used to improve or verify the predictions of the power of the AMGOC program to detect a given trend over a longer period of time. There are at least two ways that this idea might be implemented: use the data taken over the short term to test, and possibly improve the noise models which are given by the simulations; use the data taken over the short term by itself to fit a noise model. It is this second possibility on which we focus in the present report, although some discussion of the first is also provided.

2. APPROACH

In order to test the utility of the use of data taken over the short term to fit a noise model, we have run a sequence of trend detection examples using simulated data from the MASIG [Mesoscale Air-Sea Interface Group] model provided by Professor O'Brien at Florida State. These calculations are used to provide propagation times for ten Pacific acoustic paths, from Hawaii to the West Coast, over a simulated twenty year period [Pares-Sierra and O'Brien, 1989]. A comparison of the results for the full interval with that for shorter intervals gives the basis for our analysis.

By following this approach, we will determine to what extent it is possible to use shorter intervals of simulated data to project the detection of trends. The implications of the results for real data will remain to be determined. However, it would seem unlikely that the use of real data would lead to more rapid trend detection since we anticipate that simulated data will not have contributions from all sources of background variability.

The details of our **Suggested Procedure** (**SP**), as used in the remainder this report, are then as follows:

1. Take data for n years.

2. Test for trend using our methods from the TRENDS methodology of Bottone et al. [1996].

3. Assuming no trend is found, as is likely, assume the data are mostly mean plus noise.

4. Fit an AR model to the data.

5. Use that noise model to test the power of the AMGOC program to detect a given hypothesized warming trend in N years, where N can be any value of interest.

It seem likely that the **SP** can overestimate the power of the test, at least if N is too much greater than n: Those aspects of the noise which will be most readily confused with a trend will involve primarily the longer period components of the noise. Periods short compared with N years will mostly be averaged out in the data but periods comparable to or greater than N years will readily be confused with a trend. Since the data taken over n years will contain relatively little information about the longer periods, we may expect that if we use the **SP** to make predictions for too great a value of N, the result will be a serious over prediction of the true power: the noise model will simply not contain the most important information about the noise. In this report we shall try to quantify these remarks to at least some degree.

We do not yet possess the analytic skills to analyze the problem in closed form; there are a lot of variables and the expressions are quite complex. We shall therefore study specific examples by use of simulation. For these simulations, we shall make use of simulated data from MASIG giving traveltime series on the ten paths connecting Hawaii to the West Coast of the United States. The original data set consists of values every 5 days giving six values for every nominal 30 day month. We have reduced the size of the data set by averaging each group of six values giving a monthly value for twenty years on each path or 240 equally spaced (in time) measurements for each path. There is very little short term variation over a months worth of these data so nothing is lost by this averaging. Examples of the MASIG data sets for 240 points on each of three paths are shown in Figure 1.

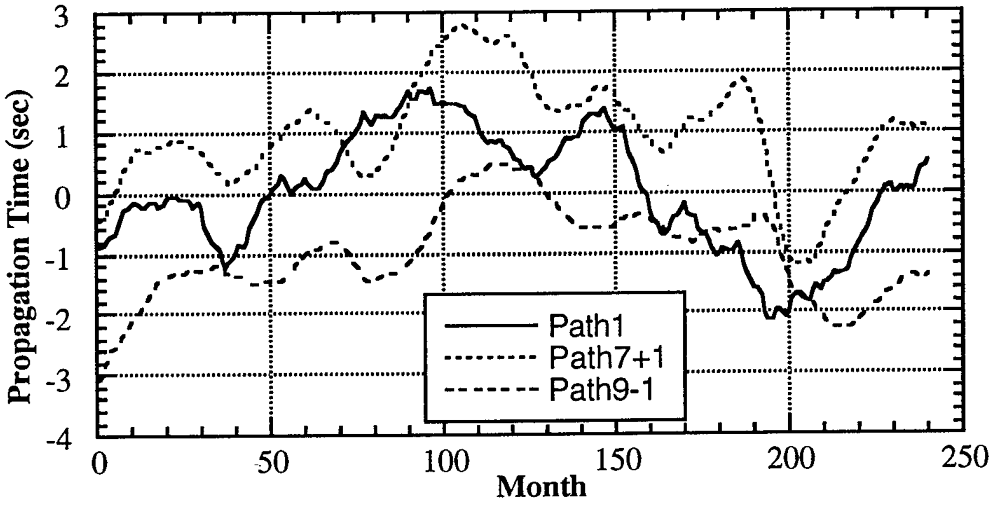

Figure 1. Relative propagation times for three MASIG paths, with one second offset.

2.1 First Attempt and a Warning

The general procedure we shall use to perform the analysis is to invoke the **SP** using the MASIG simulated data. As a concrete example, we might estimate the power of the test of TRENDS to find a nominal warming trend of 0.01 degrees Celsius per year [Manabe et al., 1991, Mikolajewicz et al., 1990], which corresponds to a propagation time change of approximately -0.1 seconds/year on these paths, in the presence of the MASIG noise on path 1 of the MASIG simulations over the full twenty year period for which we have results (we choose N to be twenty). We then use two years of this same simulated data (we choose n to be two) to fit an AR noise model. We then use that noise model to create a number of AR realizations of twenty-year records of noise and estimate the power of the test to detect a trend of -0.1 seconds/year in the presence of that noise. We then compare the results of each of those calculations with the estimated power of the test we obtained using the full twenty year MASIG record. This procedure is seen to be a detailed simulation of **SP**, asking the question " if the MASIG data were actual data for twenty years, how well would hypothetical researchers have done using **SP** at the end of two years to estimate the power they would have after twenty years." We can repeat the entire calculation for other paths and for other two-year segments of path 1 to study the reliability of **SP** for the particular values: n=2; N=20. For these values of n and N, we have 10 independent sets of values with which to work. As n increases – we cannot increase N – the number of independent sets drops. For n=10 we have only 2 independent sets.

Our initial plan was to remove this limitation by creating "MASIG-like" data sets of our own. The idea was to fit a AR model to each path then use that fit to create additional realizations giving twenty-year "data" sets. Since a fundamental assumption of the procedure of TRENDS is that such a fit should capture the important features of the noise, we hoped that the "MASIG-like" "data" sets would serve our needs. As a control, we used the new twenty-year data sets to estimate the power after twenty years assuming that we would get values near the estimated power for the MASIG path on which the set was based. That is not what we observed. The results varies wildly with a strong bias to be larger than the estimate for the original MASIG "data". These results may cast doubt on the applicability of the procedure of TRENDS to the ocean acoustic problem or they may not. The question is complex and we will not pursue it further here. We will recommend further study before the procedure is applied to AMGOC data and the results used for policy issues.

Here we will study the question we originally set regarding the potential utility of **SP** under the assumptions that the TRENDS procedure is valid. Because of the results we have just discussed, we shall not create our own "MASIG-like" data sets but rather restrict ourselves to the simulated data obtained from the MASIG calculations. While a study of the "MASIG-like" data sets we could create would still be a valid study of **SP** as it might apply to them, the "MASIG-like" sets differ from the actual MASIG sets in a way we do not understand but which we know to be important to the power of the test of hypothesis. Since the MASIG calculations are based on the physics of the ocean acoustic problem and make use of real geophysical data as drivers, we prefer not to contaminate our results with the uncontrolled additional numbers. In light of the results we shall present in the next section we do not believe that the limited amount of simulated data available to us is a serious limitation in that the qualitative conclusions we shall reach – the only type of conclusion useful to the AMGOC program on this issue – would be very unlikely to change if we had further MASIG simulated data sets.

3. RESULTS

In Table 1 we show estimates of the power of the test of hypothesis to detect a trend of -0.1 seconds/year after twenty years for each of the MASIG paths using n=N=20. The results for powers of the tests range from 0.17 for Path 1 to 0.64 for Path 6. Here, power means the probability of detecting this trend at a nominal 5% level of significance. It is a rather happy accident, from our point of view, that this is an interesting range to study since a trend of -0.1 seconds/year is approximately that predicted in some global warming estimates. To make these calculations we used 100 realizations each of which used 399 bootstrap calculations (see Bottone et al. [1996] for details of the meaning of these parameters); that should give us results reliable to within a few percent.

Table 1. Power of test of hypothesis to detect a trend of -0.1 seconds/year after twenty years for MASIG simulated data, n=N=20.

Path #	Power
1	.17
2	.21
3	.24
4	.28
5	.46
6	.64
7	.24
8	.22
9	.37
10	.41

In this same spirit, we then chose n=2 years and made estimates of the power after twenty years (N=20) using **SP** for the total of twenty independent two-year segments from paths 1 and 6. For these and all the later calculations we again used 100 realizations and 399 bootstraps. For each of these twenty calculations the projected power was 0.97 or higher. It is clear that for data of which the MASIG simulations are characteristic, the expectation discussed in the Introduction, that the lack of low frequency information will lead to a serious overestimation of the power, is strongly realized for n=2 years and N=20 years, and that making such an extrapolation is a meaningless exercise. That is, use of two years worth of noise data is not a sensible approximation to the use of twenty years worth for the purpose of estimating the presence of trends.

This effort was repeated for five years worth of simulated noise data. In Table 2 we show the results of this choice of n=5 years to show the extrapolated power for each of the forty independent 5 year intervals available to us. Here again we see that the tendency of **SP** to overestimate the power is realized. Out of the forty cases only one – path 10 for the interval 121-180 – has the extrapolated power less than the power estimated using the full twenty year interval; and that by an insignificant amount. Many of the extrapolated powers are 1.0 or very near. While the results are improved over the case of n=2 years, in that not all the extrapolations give results indistinguishable from 1.0, we do not see that there is any suggestion in our results that using **SP** to extrapolate from five years to twenty years for data of which the MASIG simulations are a fair representative is a useful thing to do.

Table 2. Power of test of hypothesis to detect a trend of -0.1 seconds/year after twenty years using 5 years of MASIG simulated data, n=5, N=20, for four 5 year segments for each path. n=N=20 shown in last column.

	Interval of Months					
Path #	**1-60**	**61-120**	**121-180**	**181-240**	**Ave.**	***20/20***
1	1.0	.98	.51	.36	.71	*.17*
2	1.0	.70	1.0	1.0	.92	*.21*
3	1.0	1.0	.91	.96	.97	*.24*
4	1.0	.75	1.0	.99	.94	*.28*
5	1.0	.74	1.0	1.0	.94	*.46*
6	1.0	.60	1.0	.98	.90	*.64*
7	1.0	.56	.96	.74	.82	*.24*
8	1.0	.70	1.0	1.0	.93	*.22*
9	.89	.74	.87	.77	.82	*.37*
10	.79	.80	.36	1.0	.74	*.41*

The corresponding case for n=10 year is shown in Table 3. Here the results are much more promising in their similarity to the n=20 case. The average of the two extrapolated powers for each path overestimates the power obtained by using the full twenty years of "data" by only 0.03 when averaged over the ten paths. The sample standard deviation for that quantity is 0.08. Furthermore there is a strong tendency for the paths which have higher power as estimated using all twenty years to have higher extrapolated powers; the correlation coefficient is 0.85. Thus we see here that for data of which the MASIG simulations are characteristic, extrapolation from ten years to twenty years using **SP** would give a useful indication of the degree of success to be expected.

Table 3. Power of test of hypothesis to detect a trend of -0.1 seconds/year after twenty years using 10 years of MASIG simulated data, n=10, N=20, for two 10 year segments for each path. n=N=20 shown in last column.

	Interval of Months			
Path #	**1-120**	**121-240**	**Ave.**	***20/20***
1	.25	.22	**.24**	***.17***
2	.24	.35	**.30**	***.21***
3	.22	.28	**.26**	***.24***
4	.29	.45	**.37**	***.28***
5	.33	.82	**.58**	***.46***
6	.35	.83	**.59**	***.64***
7	.19	.19	**.19**	***.24***
8	.25	.28	**.27**	***.22***
9	.48	.33	**.41**	***.37***
10	.29	.26	**.28**	***.41***

These results suggest that if the noise background data are taken from a sequence of length within a factor of two of the length of the full set, comparable trend detection will be available. As a small test of whether these results could be taken to indicate such a "factor-of-two" rule, we raised the assumed slope by a factor of four, to -0.4 seconds/year (to allow more rapid detection), and took N to be ten years and n to be five years. These results are shown in Table 4. A glance at the table shows that there is a very distinct difference between using the first sixty months and using the second sixty months as the short "data" sample. It has been observed before that the early part of the MASIG simulation seems to have a somewhat different statistical character from the later part [Gray, 1995]. One could, of course, not expect **SP** to work if the entire character of the noise changes after the end of the short data sample. Thus we are not quite sure how to interpret the results shown in Table 4. If only the second 5 year period is used we again obtain useful estimates by extrapolation with **SP**, relative to the use of the 10 years of simulated noise data.

Table 4. Power of test of hypothesis to detect a trend of -0.4 seconds/year after ten years using 5 years of MASIG simulated data, n=5, N=10, for two 5 year segments for each path. n=N=10 shown in last column.

	Interval of Months		
Path #	**1-60**	**61-120**	***10/10***
1	.98	.77	***.40***
2	.99	.78	***.33***
3	1.0	.85	***.20***
4	1.0	.45	***.33***
5	1.0	.50	***.42***
6	.99	.39	***.30***
7	.94	.45	***.33***
8	.77	.24	***.47***
9	.83	.41	***.39***
10	.55	.44	***.33***

3.1 Higher Frequencies

Realistic ocean acoustic data will presumably include some additional higher frequency variability components that cannot be simulated with the limited time and spatial scales available for the MASIG, or other, global circulation model. The arguments given in the introduction suggest that such higher frequencies probably will have little effect the results we have presented. However, this depends on the magnitude of any such additional variability. As a limited test of our assumptions of such effects, we have made use of some long range acoustic propagation data provided to us by Professor John Spiesberger. These data were taken from the "Kaneohe Source" experiments [Spiesberger et al., 1992] with a source off Oahu and seven receivers near the West Coast. The data from receiver R3, which was almost daily data over about 1/3 of a year are shown in Figure 2. Note that the overall magnitude and rate of variation is quite comparable with that seen in Figure 1 for the

MASIG simulation when view over the same time interval. We have taken these data, fit an AR model to them and tested the power which would result from that noise if data were taken for twenty years. As might be expected the power is 1.0 – the high frequency component, which is the dominant feature, presents essentially no impediment to finding a trend in twenty years since there are no long term variations in this noise model.

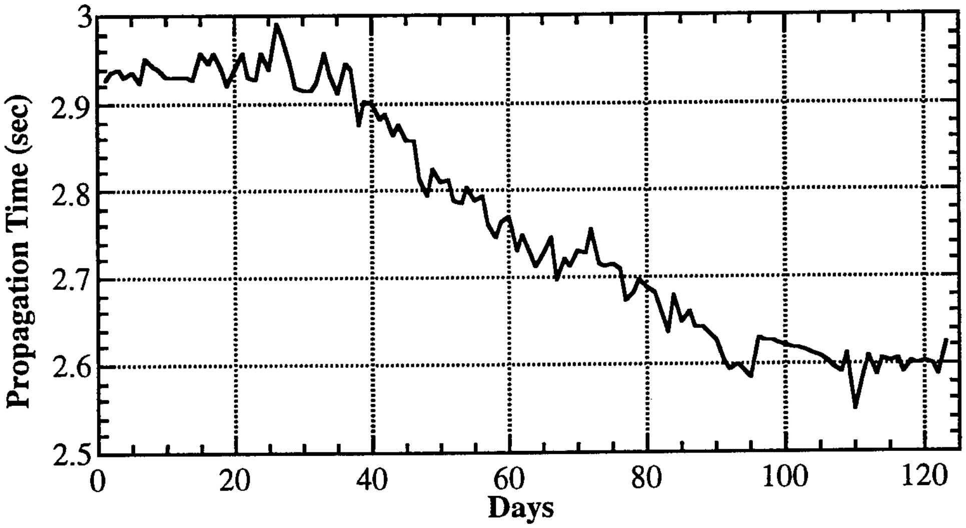

Figure 2. Kaneohe Source receiver R3 data.

We have also combined the Spiesberger data (with the slower "seasonal" variation excised by subtraction of a polynomial fit) with the MASIG simulated data to make a more realistic data set containing the MASIG noise modified by the direct addition of high frequency component of Spiesberger data. The results of the power estimates using the augmented MASIG simulated data are indistinguishable from those using the MASIG simulated data alone.

3.2 Preliminary ATOC Data

Our original ambition for this current analysis was the potential use of preliminary data from the ATOC program to improve estimates of the time that will be required for projecting potential warming trends. In the previous subsection we reported on the use of portions of data from a prior experiment. There now exist some data for acoustic propagation times from periodic tests with the ATOC source located off the California coast at Pioneer Sea Mount at (-123.44513, 37.34254) degrees latitude and longitude. We have been provided with these data by Dr. Bruce Howe [1996] at the University of Washington. The data set made available to us is that providing propagation times from the ATOC source to two Navy receivers, labeled 'k' and 'o', at fictive locations (+170.982,42.007) and (-141.612,27.587), respectively. Each of these two sites have their distinctive set of up to twelve identifiable ray arrivals. Time series for these individual rays are provided in the data for the ATOC transmissions whenever detection is possible.

The current ATOC testing, which is controlled by studies of possible marine mammal effects of sound transmissions, consists of clustered transmissions which have been typically been every few weeks. During these transmission times of a few days, propagation data points are taken six times per day. Figure 3 shows propagation times for three rays seen at receiver 'k' for this year. The straight line segments between real data bursts correspond to times with no transmissions. Note that the 'seasonal' variation over this 200 day interval provides changes of approximately a half second which is similar to that seen in both the MASIG simulation and the Spiesberger data.

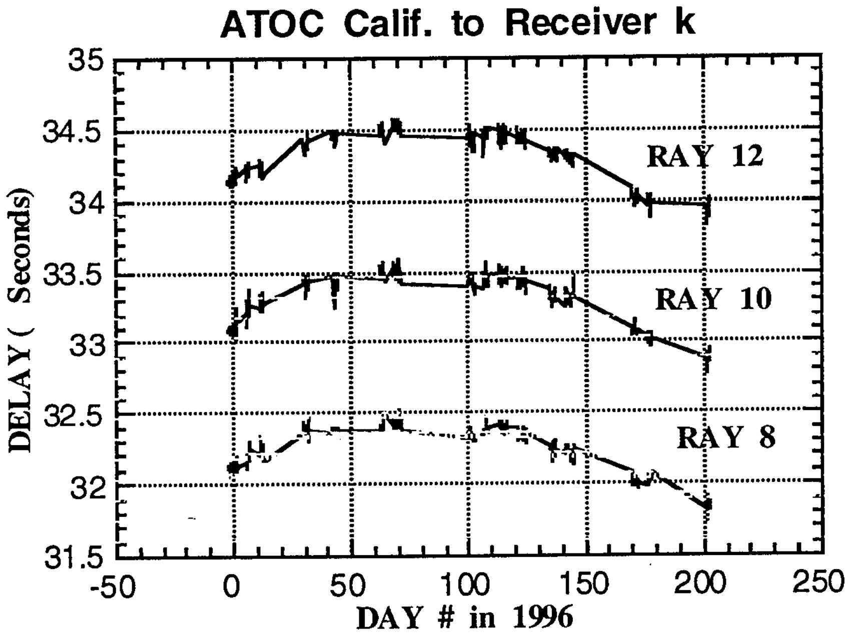

Figure 3. ATOC receiver k data for three rays.

The short term variability of the ATOC 'o' receiver ray 8 data is illustrated in Figure 4. The longest continuous sequence available, 23 points from nearly 4 days, was used to generate an AR model. A realization form this model, with six/day sample rate, was sampled once per day and the result compared with the high frequency daily data extracted from the Spiesberger experiment, after offset by 0.1 second.

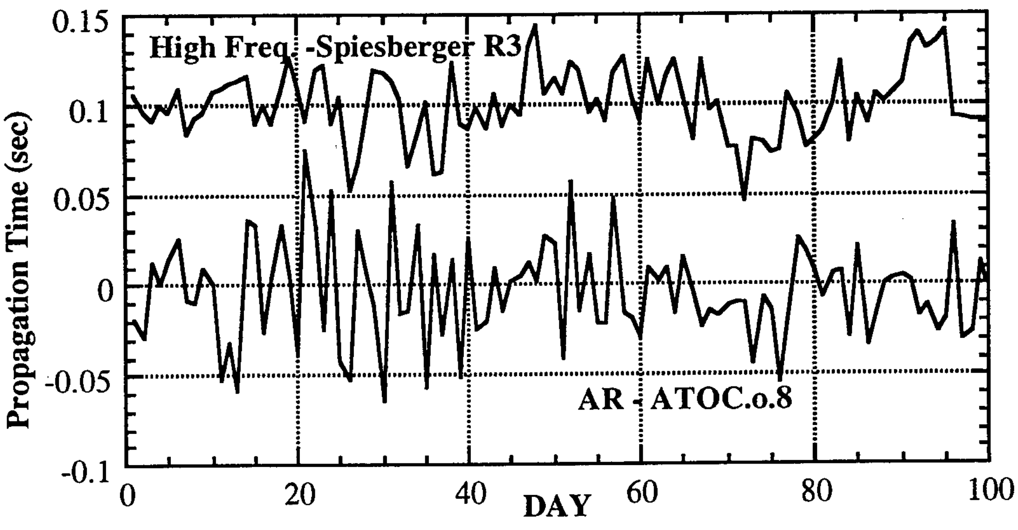

Figure 4. Short term noise from ATOC receiver o ray 8 and Spiesberger R3.

The daily sampled short term noise features from the two experiments are quite similar even though the paths are of different lengths and at different locations in the Pacific. This indicates that the results quoted earlier on the lack of effects of high frequency noise on trend extraction are not likely to be altered with the addition of more extensive ATOC data.

4. CONCLUSIONS

Our previous work [Bottone et al., 1996] indicated that for expected variability of ocean acoustic propagation times and the level of anticipated warming trends, it may take at least two decades of observation to establish, with an adequate level of confidence, that warming does or does not exist. For the current report, we have attempted to establish the extent to which the use of data from a shorter period may allow at least better definition of the period needed to establish these warming trends.

Truncated simulated data sets of 5 and 10 years from the MASIG model of acoustic propagation time variability over decades have been used to establish the extent to which the statistical trend extraction techniques give stable results using these shorter series to define the noise background. It is found that the use of the shorter series provides an apparent reduction of time required to detect trends; This unfortunately indicates that meaningful estimates of warming trends cannot be made with use of a lengthy data set approaching the full 20 year interval. Generally it is found that once the length of the background data is less than about half of the full set, the estimates of times needed to detect trends are, falsely, reduced. This indicates that the variability which tends to mask trends is long period and that shorter observation intervals do not allow characterization of this variability. It would be unwise to use this procedure with ATOC data to attempt to extrapolate a power estimate of a warming trend more that a factor of two in time into the future. If an extrapolation of a factor of two would be of interest we believe that the results of the procedure would be interesting but should be used with caution: we do not have a strong feeling for how well it works for an arbitrary process, only that it works fairly well for some processes which are thought to be related to the ocean acoustics problem.

The performance of the extrapolation procedure and indeed of the TRENDS methodology depend, to some extent, on the use of an AR model to fit the data. The same overall strategy could still be employed using a different fitting procedure. If a fitting procedure based more on the physics of the ocean acoustic problem could be developed and used, that might well lead to better performance of the extrapolation procedure, the TRENDS methodology or both. Such considerations are beyond the scope of the present report.

We also find that the substantial short term variability seen in the first six months of the ATOC [Howe, 1996] experiment is comparable with that seen by Spiesberger [1992] but that this variability plays almost no role for the long term trend detection problem, which is dominated by multiyear periods.

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