A Methodology for Defining an Operational Synoptic Temporal Oceanic Sampling System. II. Nonstationary Conditions

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ABSTRACT

Using oceanic wind data, effects of nonstationary events on the spectral computation of wind speed and wind direction were estimated by analyzing stationary records before and after superimposing spike and shift nonstationarities. The differences of the results show that the inclusion of nonstationarities in environmental sampling can produce large errors in the data and their analysis. It is concluded that specialized observational techniques are required for nonstationary time series for any efficient environmental sampling system.

A hypothetical sampling system is proposed which provides for filtering the stationary environment as described in Part I and continuous checking for the occurrence of nonstationarities. Significant nonstationarities are reported separately and not included in stationary processing. As an example of a nonstationary detector, a simple automated method to detect and report wind shift nonstationarities was developed.

It is concluded that not only does the proposed sampling system improve the synoptic observation value, but it also satisfies the special observation requirement for weather transmissions. It is further stated how such a system allows an increase of the minimum spacing between observation stations, thus increasing the cost-effectiveness of the observational network.

1. Introduction

To determine representative temporal environmental synoptic values, all fluctuations having periods smaller than twice the synoptic sampling interval must be removed. These unwanted fluctuations have been separated into nonstationary and stationary components. Sampling under stationary conditions is discussed in Part I of this article (Baer and Withee, 1971). Special events, restrictive types of nonstationarities which either change the statistical properties in frequency regions of interest or are important in themselves, are considered in this second part. Specific types of nonstationarities are described, their effects on stationary representativeness calculated, methods of their detection developed, and methods for their removal suggested.

Nonstationarity, in general, is that quality of an ensemble of continuous time or space functions which shows changing statistical properties under a translation of the origin. For the purpose of this paper we ignore the possible interactions between the stationary and nonstationary components and are not concerned with the randomness of the time of occurrence of the nonstationarity. When considering data sampling problems the important nonstationarities are specific events of time scales shorter than twice the sampling interval (Nyquist) which occur so seldom that they are essen-

tially nonrepetitive within many sampling intervals. When considering spectral computations, the entire frequency range for such specific events is included.

Since finite records are analyzed, partially represented low frequencies (or trends) are nonstationary, even though they may be stationary in longer time frames. Such a trend or slowly varying mean will be called a first-order nonstationarity and the infrequent events will be termed second-order nonstationarities. A first-order nonstationarity can be easily removed for time series computations by high-pass filtering such as prewhitening, which is substituting a difference for the original record. A record containing second-order nonstationarities, resulting from occasional regions of large high-frequency (larger than Nyquist) fluctuations, may also be made quasi-stationary by filtering. For example, a continuous wind speed record of 24 hr in length is not stationary when turbulence occurs only in the afternoon. A low-pass filter, which eliminates the turbulent frequencies, removes this type of nonstationarity. When the nonstationarity is too large in amplitude or occurs with an equivalent period which approaches the Nyquist period, it is more difficult to remove by filtering since portions of the desired fluctuations will also be filtered. Evaluation of the effects of these large second-order nonstationarities is the purpose of this paper. Specifically, two classes of second-order nonstationarities will be considered, namely,

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spikes and shifts, since these represent the only significant forms in the natural environment.

Physical examples of important second-order nonstationary functions would include a time or space series of wind direction (including shifts), wind speed (including gusts), and surface pressure or temperature (including sharp classical frontal passages). Examples of some second-order nonstationarities illustrated by wind spikes and shifts are shown in Fig. 1. It should be noted that many nonstationarities are not easy to see on a typical, fast-response, continuous strip chart recording. Only after proper scaling and filtering do they appear as sharply in Fig. 1.

2. Nonstationary effects

To investigate the effects of second-order nonstationarities, simulated shifts and spikes of various characteristics were introduced into apparently typical observed stationary time series of wind direction and speed. For each nonstationary time series, spectra were calculated and compared with spectra of the corresponding stationary time series. This technique permits an evaluation of the importance of nonstationary effects on stationary representativeness and a projection of the implication on sampling. Example results for spike and shift cases are shown in Figs. 2 and 3.

a. Spikes

Spikes commonly occur as gusts in wind speed and as pressure checks accompanying frontal passages. A number of spikes, N , having an amplitude A and duration D were randomly superimposed on a stationary

FIG. 1. Examples of second-order nonstationarities occurring in actual records after being smoothed with a 10-min running mean. Refer to Table 1 of Part I for information on referenced wind recorder.

FIG. 2. Example spectra from a record containing artificial spikes having the specified amplitudes A and total durations T .

wind speed time series of record length L . Each spike is a triangle with an amplitude A and a base D . The relative total spike duration, $T=ND/L$, must be small to represent a realistic nonstationary process. Since the mean of the record will not change significantly by the addition of these spikes, the change in total variance is a function of the squared amplitude of the spikes and the length of time over which they occur. Specifically, the variance change is proportional to T and A^2 for each spike. Spectrally, the spike is interpreted as a fluctuation with a frequency of approximately $1/D$. The distribution of the variances into frequency bands, as illustrated in Fig. 2, is controlled by the ratio of the amplitude to the duration. The efficiency of a filter in

FIG. 3. Example spectra from a record containing an artificial shift having the specified amplitudes A and total durations T .

FIG. 4. Maximum standard deviation of errors resulting from spikes introduced into a stationary wind speed record.

removing spikes depends on the frequency characteristics of both the spike and the filter itself; however, it is obvious from the spectral differences shown in Fig. 2 that it would take a filter application time of a few hours to appreciably delete most nonstationary effects.

As a presentation of errors, the total change in variance, for all computed frequencies between stationary and spike spectra, has been plotted in Fig. 4. This variance difference can be interpreted as the maximum squared deviation from a stationary or representative value that would occur as a result of sampling with no filtering. It is also the total spectral variance error to be expected when determining stationary error without considering spikes. The plots presented in Fig. 4 show the standard deviation of error due to a number of spikes having different amplitudes and different durations. It would make little difference in this plot whether the total duration results from one or a number of spikes, although it would make a difference in spectral shapes as shown in Fig. 2.

As an example interpretation of this plot, consider a record with 6-hr sampling containing a number of spikes of 20-kt amplitude with durations totaling 5.4% of an observation sampling time. This would cause an error having a standard deviation from a representative stationary value of 2.8 kt.

b. Shifts

Shifts commonly occur in wind direction and other parameters such as temperature and dew point, as the result of frontal passages. Typical amplitudes and durations are well known. To examine the effects of shifts on spectra, one shift of amplitude A and duration D was superimposed on a wind direction time series. The mean of a record of length L will be changed by a shift, but the amplitude squared will be the dominating effect in changing the variance of the record. To keep the time of the shift occurrence from affecting the variance, the record was prewhitened. Thus, the total duration, $T = D/L$, of the shift was proportional to the

variance as a function of frequency. The shift affects only those spectral periods $\gtrsim D$. These effects are shown by typical shift spectra overlaid on the stationary spectra shown in Fig. 3. Results show that the shift causes a low-frequency spectral distortion as compared to the higher frequency spectral effect of spikes. For this reason the distortion due to fronts cannot be filtered without harming the low-frequency synoptic information. This distortion is great enough to allow differentiation between spectra of real wind direction records containing and not containing shifts as shown by Fig. 5.

Fig. 6 represents the total standard deviation of misrepresentation error caused by shifts of different durations and amplitudes. As expected, the duration effect is not significant. Note that these errors were computed from time series that were filtered with a high-pass filter which takes out trends. Thus, these significant errors are realistic, if not low, estimates for the calculated frequency region. Also note, with real data, that consistent statistical properties should not be expected across a shift. Thus, normal data processing, such as filtering, should not be applied across a shift.

In summary, consideration of the effects on sampling of the second-order nonstationarities is crucial. Spikes should be detected and recorded, and care taken that the filtering is adequate to suppress their effects. Shifts should be detected and reported, but under no circumstances should any filter be applied across the shift.

3. Hypothetical sampling systems

Significant synoptic sampling errors result from the effects of nonstationarities being improperly filtered as was shown in Figs. 4 and 6 for nonstationary spike and

FIG. 5. Separation of wind direction spectra caused by naturally occurring shifts.

FIG. 6. Maximum standard deviation of errors resulting from shifts introduced into a stationary wind direction record.

shift errors. Without special processing they cause errors in synoptic representativeness at least as large as the minimum errors resulting from filtered sampling of the stationary process as presented in Part I. Thus, any system in which there is an attempt to improve its representativeness and accuracy by filtering should also include a special allowance for the nonstationarities. Actually, nonstationary problems have been long recognized and traditionally solved in meteorology by use of "special observations", reporting such special phenomena as frontal passages, thunderstorms and gustiness.

To illustrate the sampling concepts discussed above, consider the characteristics of a possible hypothetical operational synoptic buoy system with environmental information being reported every 6 hr. A representative stationary sampled value of each parameter is obtained by use of optimized filters as described in Part I. The environment will be continuously monitored for nonstationarities. Any nonstationarities that occur in this 6-hr period are automatically detected and reported. If a front or discontinuity occurs during the filter application time, it is reported and the values into and out of the shift will be given. The best representative of the "before" value is probably the previous synoptic observation. The best estimate for the "after" value is that one which would be found from application of the longest possible filter beginning immediately

after the shift was completed. If a nonstationarity or possible nonstationarity occurs during a reporting period, the event will be flagged "in progress" and will be completely described in the next report. To determine the complete sampling requirements of this system, nonstationarity detection errors must be estimated. From these errors, complete error diagrams similar to those presented for stationary errors in Part I can be established by considering the possibility of nonstationarities occurring during a sampling interval. The complete error description can be the basis for setting optimum system design requirements.

As an alternate operational system, if an adequate nonstationarity detection program cannot be designed to absolutely detect a particular occurrence, a simpler program can be used to detect the possibility of the occurrence. Whenever there is the possibility of nonstationarities occurring, short-interval sampling and reporting must be used. From a research standpoint this would have great advantages, but for a large-scale synoptic network the extra data could clog communications. Oceanographically, this type of approach may be at least temporarily necessary because so few time series observations of oceanographic parameters have been measured that some significant phenomena might be occurring without adequate description.

Methods for the detection of nonstationarities needed for the proposed hypothetical operational system should be developed. These methods necessarily depend upon describing the characteristics of the nonstationarities. For an example of a detection method, a computer program has been written to detect wind direction shifts. The same program could be carried out aboard any data collection buoy. The detection of a typical shift is illustrated in Fig. 7 as an example to show the possible simplicity. To allow for a significant shift detection, the data are conditioned with a prior ramp filter (Baer and Withee, 1971) having a filter application time of K_1 . This may be the same filtering used to reduce aliasing for synoptic sampling. The filtered

FIG. 7. One-hour ramp-filtered wind direction record showing shift detection.

data are prewhitened or differenced over a time K_2 . If this difference (rate) is above a minimum K_3 (K_3 being different for each parameter and possibly for location and season), a flag is tripped to note the possible detection of a shift. If differences of this magnitude remain for a length of time K_4 (allowing for minor deflections less than a time K_5), a passage flag is tripped. The disturbance is then monitored until the first derivative is less than K_3 , indicating the shift has been completed. The time and amplitude of the occurrence are stored or reported after defiltering to locate the time of occurrence more accurately. The detection and passage flags are then reset to zero in preparation for the next passage. For wind shifts at Argus Island, the following values were found to be appropriate:

Filter application time:	$K_1 = 1$ hr
Differencing time:	$K_2 = \frac{1}{2}$ hr
Minimum significant rate of change for shift:	$K_3 = 20^\circ \text{ hr}^{-1}$
Minimum significant duration for shifts:	$K_4 = \frac{1}{2}$ hr
Allowable duration of minor deflections within shift:	$K_5 = \frac{1}{4}$ hr

Though the example of the shift in Fig. 7 is quite obvious, the above technique has detected very weak semi-stationary frontal passage wind shifts about as well as an experienced observer.

A similar scheme must be devised to detect spike-type nonstationarities. Since spikes have different characteristics than shifts, a separate program must be developed. Thus, two nonstationarity programs would be needed to monitor spikes and shifts simultaneously for the same parameter. Operationally, this program might be a combination of digital and analog processing, and would monitor the environmental signal continuously, but only record or telemeter a special report for any important nonstationary occurrences in the observation period.

4. Conclusions

Two important results from these preceding nonstationarity discussions are obvious. First, in trying to solve classical stationary sampling problems, any nonstationarities distort the spectra. This has long been known but too often ignored. Second, in actual reporting at sea, at every reporting time, large nonstationarities should not be included in the filtered representative value, but should be reported separately. Separation and reporting of the nonstationarities should result in more accurate and representative data, and thus better environmental analysis and forecasting, and more realistic sensor design requirements. These system improvements combined with accurate locations of important phenomena will allow a decrease in the number of observing stations needed.

It should be stressed that for every parameter the nonstationarities should be defined, their importance determined, and solutions developed as needed. Only then can the quality of automated measurements approach or exceed the capability of an experienced man observing continuously. Finally, it should be noted that these results should be applicable not only to automated systems but also should be included in the instructions for manual observations.

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