Comparison of Interannual Intrinsic Modes in Hemispheric Sea Ice Covers and Other Geophysical Parameters

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***Abstract*—Recent papers have described 18-year trends and interannual oscillations in the Arctic and Antarctic sea ice extents, areas, and enclosed open water areas based on newly formulated 18.2-year ice concentration time series. They were obtained by fine-tuning the sea ice algorithm tie points individually for each of the four sensors used to acquire the data. In this paper, these analyses are extended to an examination of the intrinsic modes of these time series, obtained by means of empirical mode decomposition, which handles both nonstationary and nonlinear data as found in these time series, unlike filtering techniques based on Fourier analysis. Our analysis centers on periodicities greater than one year. Quasi-biennial and quasi-quadrennial oscillations similar to those observed earlier with a multitaper-filtered Fourier analysis technique were also observed here. The intrinsic modes described here feature frequency as well as amplitude modulation within their respective frequency bands. The slowest varying mode in the Antarctic sea ice cover has slightly less than a full period during this 18.2-year time period, but the change in sign of its curvature hints at a modal period of about 19 years, with important implications for the trend analyses published earlier.**

***Index Terms*—Geophysical measurements, microwave measurements, remote sensing, sea, sea ice.**

I. Introduction

THE AMOUNT of sea ice in the hemispheric canopies has frequently been described as an indicator of climate change [1]. In order to assess recent climate changes, a seamless 18.2-year dataset of sea ice concentrations over the time span of 1978–1996 has been recently produced [2], [3]. The observations were made with four different instruments: the Scanning Multichannel Microwave Radiometer (SMMR) onboard the National Aeronautics and Space Administration Nimbus 7 satellite and three Special Sensor Microwave/Imagers (SSMIs) onboard the F8, F11, and F13 Defense Meteorological Satellite Program orbiters. In order to discern short-term climate changes, these data were used to determine overall and seasonal trends for the Arctic sea ice canopy as a whole and for nine subregions [4]. Also, the spatial distributions of the trends and of the seasonality in the ice packs were analyzed for both hemispheres [5]. The trends were determined in two different ways: 1) an ordinary least squares multiple-linear-regression method was used in which the intercept, slope, and coefficients for five harmonics of the annual cycle (12 coefficients in all) were determined simultaneously [6]; 2) a band-limited regression (BLR) method was used in which the data are filtered with a multiple-window bandpass filter that eliminates oscillations with periods shorter than 1/4 of the data span [7]. The reported BLR trends all have statistical confidence levels of 99% or better, but could also be affected by long-term oscillations with periods of 4.5 years or greater.

In earlier studies of climate variability [4]–[12], most of the long-term geophysical data have been assumed to be either periodic or stationary; the detailed nature of the processes has never been explored. For example, quasi-quadrennial oscillations were observed in shorter time series consisting solely of SMMR data using a Fourier spectral analysis technique [10]–[12] that included multiple-window filtering [13]–[18]. While not conclusive because of the brevity of the time-series, there was also an indication of longer-period oscillations in these earlier data. However, that spectral analysis technique is not appropriate for nonstationary phenomena nor is it capable of detecting nonlinearity, a likely property of natural phenomena. We propose a different view of an expanded version of these data to examine not just the spectrum but also the specific time series and its phase.

In this paper, we introduce a new method for nonlinear, nonstationary data analysis and apply it to a combined SMMR/SSMI dataset. The new method is a recently developed empirical mode decomposition (EMD) [19]–[22] applicable to nonstationary phenomena, followed by the calculation of instantaneous periodicities through the use of an Hilbert transform. We also compare on an instantaneous basis the ice canopy oscillations with those in the length-of-day (LOD) [23], [24] and North Atlantic oscillation (NAO) parameters in the same time interval. These comparisons are contrasted with earlier ones [4]–[12] based on the average oscillatory properties obtained by ordinary or multiple-window Fourier analysis. Common to these earlier studies was the inference that southern oscillation index (SOI) or LOD information was telecommunicated somehow to the ice canopies by virtue of their similar spectra. We report here that these inferences are not supported by detailed comparison of the amplitude, time scales, as well as phase of the corresponding individual intrinsic modes obtained by EMD of the various phenomena. However, recombinations of the respective intrinsic modes of

Manuscript received September 5, 2002; revised January 13, 2003. This work was supported in part by the National Aeronautics and Space Administration (NASA) Office of Earth Science Research Division and in part by the Cryospheric Sciences Research Program at NASA. N. Huang was also supported by an Office of Naval Research grant from the Processes and Prediction program.

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Digital Object Identifier 10.1109/TGRS.2003.811814

the various parameters with periods longer than the seasonal cycle, forming in effect a lowpass filter, show some similarities between them.

II. EMD

We shall utilize the EMD method developed by Huang and others [19]–[22] to analyze the oscillatory behavior of the hemispheric ice covers during the time span of October 26, 1978 to December 31, 1996. The EMD method is necessary to deal with both nonstationary and nonlinear data. Contrary to almost all the previous methods, this new approach is intuitive, and the way the basis of the expansion is generated is direct, a posteriori, and adaptive, with the basis of the decomposition based on and derived from the data. The decomposition is based on the simple assumption that all data consist of different simple intrinsic modes of oscillations. An intrinsic mode function (IMF) with the following definitions represents each of these oscillatory modes.

1) In the whole dataset, the number of extrema and the number of zero-crossings must either equal or differ at most by one.
2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

An IMF represents a simple oscillatory mode as a counterpart of the simple harmonic function, but it allows amplitude and frequency modulation; therefore, it is much more general. With the definition, one can decompose any function as follows. Identify all the local extrema then connect all the local maxima by a cubic spline line as the upper envelope. Repeat the procedure for the local minima to produce the lower envelope. The upper and lower envelopes should include all the data between them. Their mean is designated as m_1, and the difference between the data and m_1 is the first component (h_1), i.e.,

$$X(t) - m_1(t) = h_1(t). \tag{1}$$

The procedure is illustrated in [21].

Ideally, h_1 should be an IMF, for the construction of h_1 described above should have made it satisfy all the requirements of IMF. In Fig. 1, we illustrate (1) by applying it to a signal, Arctic sea ice extents (Fig. 2), described more fully later. Part of the signal $X(t)$ is shown in Fig. 1(a). The mean of the upper and lower cubic spline fits to the signal maxima and minima, respectively, (m_1) is shown in Fig. 1(b). The trial IMF (h_1) is shown in Fig. 1(c). We note that h_1 does not meet the definitions of a true IMF, i.e., there are small-scale oscillations superimposed on some higher amplitude ones that do not cross zero, as required by the definition of an IMF. To correct this, the sifting process has to be repeated as many times as is required to reduce the extracted signal as an IMF. In the subsequent sifting process, h_1 is treated as the data. Then

$$h_1(t) - m_{11}(t) = h_{11}(t). \tag{2}$$

After the second sift, the mean $m_1 1$ and the subsequent trial IMF $h_1 1$ are shown in Fig. 1(d) and (e). We note that $h_1 1$ is a vast improvement over h_1, but also that a few oscillations without zero crossings remain. We correct this by repeating the sifting process as many times as necessary. After repeated sifting, say, up to k (e.g., $k = 7$) times, h_{1k} becomes a true IMF, i.e.,

$$h_{1(k-1)}(t) - m_{1k}(t) = h_{1k}(t). \tag{3}$$

Then it is designated as

$$c_1(t) = h_{1k}(t) \tag{4}$$

the first IMF component of the data, shown in Fig. 1(f), and also as Mode 1 in Fig. 2.

Overall, c_1 should contain the finest scale or the shortest period component of the signal. We subtract c_1 from the signal to obtain a residue r_1

$$X(t) - c_1(t) = r_1(t). \tag{5}$$

V. Discussion

In earlier papers [8]–[12], the various authors suggested by inference a connection between the ENSO and sea ice variations in certain regions of both hemispheres. The inference depended upon the similarity of their average periodograms. In order for the comparison of periodograms of this sort to be valid, the phenomena under investigation must be stationary. In this paper, we have shown that the phenomena reported earlier are, in fact, nonstationary, and hence the earlier average periodograms were perhaps overinterpreted. EMD presents an efficient means for removing the seasonal cycle and shorter periodicities from the oscillations of the various phenomena, and we have demonstrated that data so filtered for purposes of comparison shows promise of identifying coupled phenomena.

Knowing that sea ice is driven by, among other things, a combination of atmospheric events (e.g., near-surface winds and sea-level pressures) and sea surface temperatures, we plan in the future to apply EMD to those gridded fields of observational data near the ice edge and to the gridded sea ice concentrations, in search of similar oscillatory structures and a viable correlation on a more localized basis. While we have no model to support this hypothesis, it may be that the ice canopies have some inherent natural resonance frequencies that can be excited by impulsive input. We already know that the Antarctic Circumpolar Wave is present in some atmospheric fields [34] and in the sea ice [34], [35], and that it is but loosely connected to the ENSO. We shall report on these subsequent activities in a later paper.