Teaching Earth Signals Analysis Using the Java-DSP Earth Systems Edition: Modern and Past Climate Change

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ABSTRACT

Modern data collection in the Earth Sciences has propelled the need for understanding signal processing and time-series analysis techniques. However, there is an educational disconnect in the lack of instruction of time-series analysis techniques in many Earth Science academic departments. Furthermore, there are no platform-independent freeware tools available for teaching Earth signals analysis. In order to address these issues, we developed the *Java-Digital Signal Processing/Earth Systems Edition (J-DSP/ESE)*, a platform-independent software tool that can be integrated with the Earth Science university curriculum for signal processing and analysis instruction. This tool has an intuitive block-based programming environment, and students do not need be familiar with any programming language to use it. In order to demonstrate the utility of this software in an instructional environment, we developed three tutorials related to basic signal processing, and signal analysis of modern and past climate change. The tutorials use published data to examine the relationship between 20th century atmospheric CO_2 and global temperature, and the relationship between ocean temperature and solar radiation over the past 300,000 y. The tutorials were administered in two workshops with different communities of students in Earth Science and electrical engineering. Our technical assessments show that the students were able to comprehend basic signal processing and analysis of climate signals using *J-DSP/ESE*. In the subjective assessments, a vast majority of students stated that the software was easy to learn and use, and that it significantly improved their understanding of climate change. © *2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-025.1]

Key words: signal processing, time-series analysis, global temperature, sea-level change, carbon dioxide concentration, free software

INTRODUCTION

Time-series data have become prevalent in the Earth Sciences with the rise in monitoring and reconstruction of signals from multiple Earth system processes. These "Earth signals" fall into two broad categories: "near-time" and "deep-time." Near-time Earth signals relate to processes that are happening now or that occurred in the recent past, with the independent variable referred to time (seconds, days, years, etc.), e.g., air temperature recorded by weather station instruments. Deep-time Earth signals represent past Earth system behavior, with the independent variable referred to a proxy scale that is spatial (depth or length), e.g., geochemical ratios in temperature-sensitive phytoplankton remains that are preserved in deep-sea sedimentary deposits.

Earth signals analysis involves data preprocessing, spectrum estimation, time-frequency analysis, modeling, and prediction (e.g., Ghil et al., 2002). Preprocessing prepares the signal for spectrum estimation and can include trend removal ("prewhitening"), interpolation, resampling, and filtering. For deep-time signals, tuning is often performed to convert the proxy scale of the independent variable into a time scale. Coherency and cross-phase spectral analysis measures the correlation of two time series as a function of frequency and is used to model causation–response processes. Spectral estimators usually assume *stationarity*; i.e., the signal statistics do not change over time, a condition that is generally not valid for Earth signals. Thus, time-frequency methods such as spectrograms or wavelet analysis (e.g., Percival and Walden, 2000) are also used to study time-varying spectral properties of Earth signals.

While study of time-dependent processes is commonplace in the Earth Sciences, basic training in time-series analysis is not part of the Earth Science curriculum. This educational disconnect exists in many Earth Science departments and is problematic for a science community increasingly focused on problems with time dimensionality. For example, the advent of sensor network monitoring of Earth systems and participation of a new generation of students in sensor-based research place a premium on training in the processing, analysis, and interpretation of recorded digital signals. In climate change science, time-series data play a central role in understanding climate system mechanisms, thresholds, interactions, and feedbacks (e.g., Mudelsee, 2010). Study of earthquakes, physics of Earth's interior, and Earth surface processes in general all rely on understanding time series (e.g., Gubbins, 2004).

Working with time-series analysis algorithms requires knowledge of the mathematics of the algorithms, and programming skills in a high-level language, such as C, C++, FORTRAN, or MATLAB. Earth scientists can and do become well versed with programming and the necessary mathematical details, but the same cannot be expected from students being introduced for the first time to the concept of an Earth signal.

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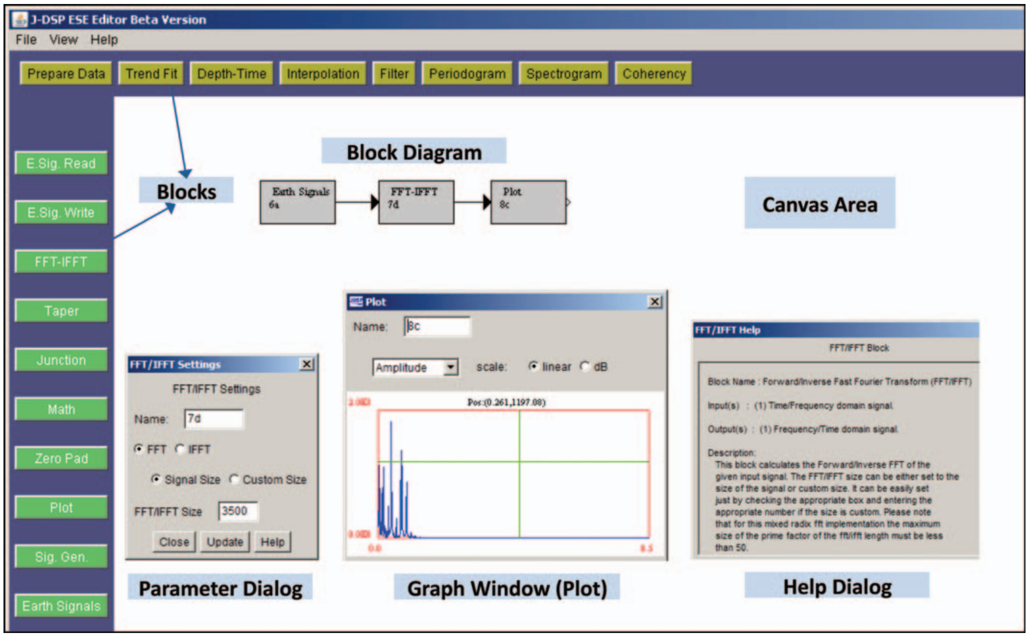

FIGURE 1: The *J-DSP/ESE* environment with a sample block diagram, dialogs, and graph. Please note that this environment reflects the *J-DSP/ESE* stand-alone application, which can be accessed at the URL: http://jdsp.engineering.asu.edu/jdsp_earth/jdsp_ese_application.html.

A few freeware applications are available for Earth signals analysis, but none is platform-independent. *Analyseries* (Paillard et al., 1996) and *Arand* (Howell et al., 2006) operate in Macintosh, *SSA-MTM Toolkit* (Ghil et al., 2002) operates in Macintosh and Unix, and *SPECTRUM* and *REDFIT* operate in Windows (Schulz and Stategger, 1997; Schulz and Mudelsee, 2002). The *SSA-MTM Toolkit* (Ghil et al., 2002) offers a variety of approaches for spectrum estimation. It can handle multivariate data and compute spectral noise models. *SPECTRUM* (Schulz and Stategger, 1997) is based on the Lomb-Scargle Fourier transform and performs univariate and multivariate spectral analysis with noise modeling. Links to these applications are provided in the Supplemental Materials (which can be found online at http://dx.doi.org/10.5408/13-025s1). Finally, there is a large but uncoordinated internet population of free codes and scripts in different languages (MATLAB, R, FORTRAN, C, etc.) donated by helpful researchers.

Despite these tools and their demonstrated utility in scientific research, they are limited from a pedagogical perspective. There is no intuitive tool that can work across multiple platforms with all functionalities. Some of the tools are rapidly aging. To address these shortfalls, we have bundled useful functionalities from existing freeware applications into a Java applet, *Java-Digital Signal Processing/Earth Systems Edition (J-DSP/ESE)* (Ramamurthy et al., 2008), which can be used online for instruction in Earth signals analysis to entry-level Earth Science students. We have also developed a stand-alone Java application (Hinnov et al., 2011, 2012, 2013) that augments the functionality of this applet, along with the capability to import/export large data sets. The user interface of the application and the applet is the same, and there is no difference in the user experience except for additional functionality incorporated in the stand-alone application.

JAVA-DIGITAL SIGNAL PROCESSING/EARTH SYSTEMS EDITION SOFTWARE

J-DSP/ESE is platform independent and based on the intuitive block-based programming environment that was developed in the parent *Java-Digital Signal Processing (J-DSP)* software (Spanias and Atti, 2005), and it was developed for the purpose of processing Earth systems signals. The software provides an intuitive block-based programming environment to perform Earth signals analysis for students and practitioners. Block diagrams are created by dragging and dropping the blocks (*drag-n-drop*), setting the parameters in the blocks, and establishing connections between the blocks. Users do not need to have knowledge of conventional programming languages, but they do need to understand the concept of a time series. Since no text-based programming is required, students can spend their time analyzing signals rather than struggling to learn and implement mathematical and programming algorithms. *J-DSP/ESE* provides functions for data preparation, spectrum estimation, time-frequency analysis, filtering, and coherency analysis to extract useful information from Earth signals. Past assessments indicate that the majority of users become familiar with the *J-DSP* environment in less than an hour (Spanias and Atti, 2005).

The software is freely available on the internet as an applet, as well as a downloadable application (http://jdsp.engineering.asu.edu/jdsp_earth/index.html).

J-DSP/ESE Environment

The *J-DSP/ESE* environment is illustrated in Fig. 1. The main window is the *J-DSP/ESE* editor, which opens as soon as the applet/application is started. The blocks that are used for establishing the block diagram are presented in two panels, across the top and down the left side. The white area is the *Canvas*, where the blocks are placed and simulations are established. Blocks are placed onto the *Canvas* by

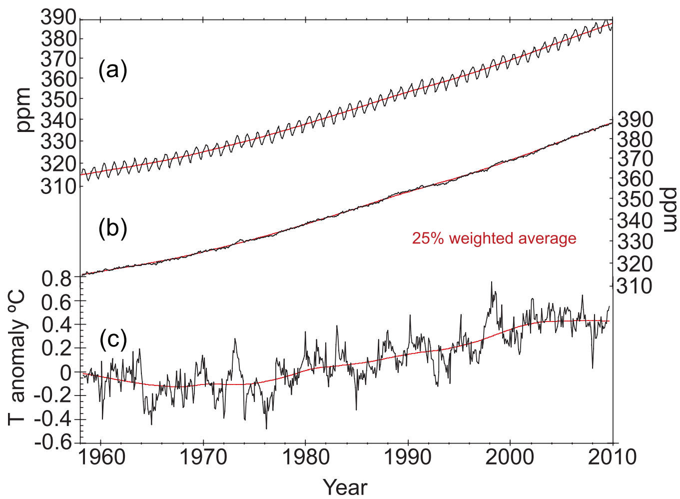

FIGURE 2: Monthly mean values of atmospheric CO_2 concentration (ppm) derived from in situ air measurements (Keeling et al., 2001) at Mauna Loa Observatory, HI, and monthly mean global temperature record averaged over a 5° × 5° global grid (Brohan et al., 2006), known as "HadCrut3," for the time interval April 1958–August 2009: (a) Original CO_2 time series. (b) CO_2 time series with seasonal components removed (see text). (c) HadCrut3 global temperature, reported as temperature anomaly relative to a 1961–1990 reference period; seasonal components were removed by the data provider. Red curves are 25% weighted LOESS averages (Cleveland, 1979).

clicking the desired button and releasing (by clicking) the button after moving the pointer onto the *Canvas*. Blocks are linked by "drawing a line" connecting the output of the block to the input of another block. The *Parameter Dialog* is opened by double-clicking a block in the *Canvas*. After setting the parameters, the actual parameters are activated when the *Update* button is clicked. The *Help Dialog* for each block is opened by clicking the *Help* button, and it contains information about the functionality of a block. Some blocks such as *Plot* also include a *Graph Window* that displays the data. The *Graph Window* in this case contains a cross-hair cursor, which can be used to accurately identify points within a curve. A description of the *J-DSP/ESE* functions is given in the Supplemental Materials.

J-DSP/ESE Tutorials

To address fundamental problems in climate change science, we have developed three tutorials. We envision that Earth Science students are the main target of these tutorials, which can be administered in a laboratory setting as part of a university general geoscience course, or introductory climatology or climate dynamics course. The learning objectives are to examine and understand the time-series data used by experts to study fundamental aspects of the climate system. The tools for achieving those objectives involve signal processing and analysis methods that are available in *J-DSP/ESE*. Tutorial 1 introduces basic concepts of digital signal processing and leads the student through a series of tasks in the *J-DSP* environment. Tutorial 2 applies these concepts in an examination of global warming during the 20th century and analyzes the correlation between atmospheric carbon dioxide (CO_2) and the global temperature record. Tutorial 3 investigates climate change over the past 300,000 y through analysis of the biogeochemistry and abundance of fossil phytoplankton in the deep-sea sediment record.

These tutorials were presented in a workshop at the Northeastern/Southeastern Geological Society of America (GSA) Meeting in March 2010, held in Baltimore, MD. The attendees were geology students (undergraduate and graduate) and Earth Science professionals. A preliminary evaluation of the assessment results was presented in Ramamurthy et al. (2011). All three tutorials described in this paper were administered in a second workshop held at Arizona State University (ASU) in January 2012, in which the attendees were electrical engineering graduate students and professionals. In the Baltimore workshop, the attendees used the *J-DSP/ESE* applet, whereas in the ASU workshop, the participants performed the exercises using the stand-alone application. Assessment results indicate that in both workshops, the attendees understood the introduced concepts and rapidly became comfortable performing Earth signals analysis using *J-DSP/ESE*.

CLIMATE CHANGE SCIENCE

The climate change tutorials presented here instruct students on modern-day and past climate ("paleoclimate") change with hands-on data manipulation and interpretation. We begin with remarks on our scientific approach to these topics before introducing the tutorials. These topics have been identified specifically as important to sustainability education (Theis and Tomkin, 2012).

20th Century Climate Change

The analysis of climate change is a vast scientific effort, commonly with the goal to predict near-future climate change for the benefit of society. Detailed space + time modeling of global climate conditions, and comparison with meteorological observations have been remarkably successful in elucidating 20th century climate (Randall et al., 2007).

Among the myriad studies of climate change, a little-pursued yet highly insightful approach is the evaluation of the frequency-dependent relationship between atmospheric CO_2 and global temperature (Kuo et al., 1990; Park, 2009, 2011). In Tutorial 2, we replicate this approach through study of monthly mean atmospheric CO_2 and global-average temperature data for the years 1958–2010. Through analysis of the frequency-dependent correlation between these two variables, it is possible to understand feedbacks and delays in specific segments of the global carbon cycle.

Atmospheric CO_2 Record

Monthly mean values of atmospheric CO_2 concentration (ppm) from in situ air measurements at Mauna Loa Observatory, HI, are a good representation of the global CO_2 (partial pressure of CO_2) of the atmosphere (Keeling et al., 2001). This CO_2 record is shown for the time interval 1958–2009 along with the 25% weighted average in Fig. 2a. It has a strong annual cycle due to seasonal variations in ocean temperature and terrestrial vegetation (phenology). The seasonal cycle was removed from the data by subtracting a 4-harmonic fit with a linear gain factor (Bacastow et al., 1985) (Fig. 2b). A long-term trend is still

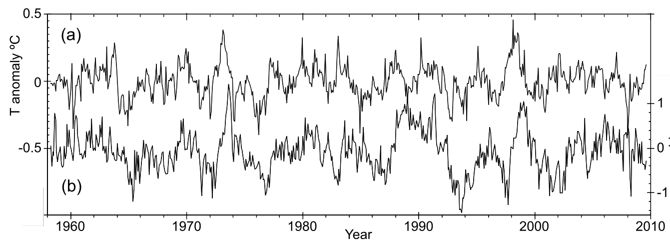

FIGURE 3: (a) Nonseasonal HadCrut3 global temperature and (b) nonseasonal Mauna Loa CO_2 records for the time interval April 1958–August 2009; 25% weighted averages (see Fig. 2) have been removed from the records.

visible in the data, which must be subtracted for the analysis in Tutorial 2; otherwise, it will manifest high power in ultralow-frequency components of the spectrum and mask other low-frequency components of interest.

Global Temperature Record

The global temperature record consists of monthly mean temperature data that are averaged over 5° × 5° (longitude, latitude) grids from more than 3000 stations. Most of the stations are land-based, and all are unevenly distributed around the globe. The data are preprocessed to remove the seasonal cycle, biases from stations at different elevations, and different averaging formulae. The "HadCrut3" record (Brohan et al., 2006) for the interval 1958–2009 is used in Tutorial 2 (Fig. 2c).

Relationship between Atmospheric CO_2 and Global Temperature

The increasing trends in CO_2 and global temperature depicted in the 25% weighted average curves (Fig. 2) are significant, yet they cannot be interpreted or interrelated directly. Rigorous climate modeling is required to establish causality between the rising atmospheric CO_2 and global temperature (Hegerl et al., 2007). A statistical causal relationship can only be understood by measuring correlation between variable frequencies, for example, a consistent lag between variables at a specific frequency. Obviously, this cannot be determined from a linear trend, but it might be determinable from study of fluctuations in the trend.

We turn to interannual variations in global temperature and their relationship to those in the atmospheric CO_2 (Fig. 3) to assess feedbacks and delays in the global carbon cycle. As reported by Park (2009, 2011), coherency analysis of CO_2 and global temperature records from 1958 to 1988 indicates that CO_2 change is correlated to global temperature change with a delay of at least 6 mo. A similar analysis performed from 1979 to 2008 indicates that this response time lengthened from 6 to more than 14 mo over the past 30 y. The suggested cause for this increased delay is saturation of the oceanic carbon sink. This is the topic of Tutorial 2, administered using *J-DSP/ESE* with analysis performed on the time intervals 1958–1988 and 1981–2009.

Paleoclimate Change

Study of paleoclimate change involves the analysis of deep-time time series. Tutorial 3 examines ocean tempera-

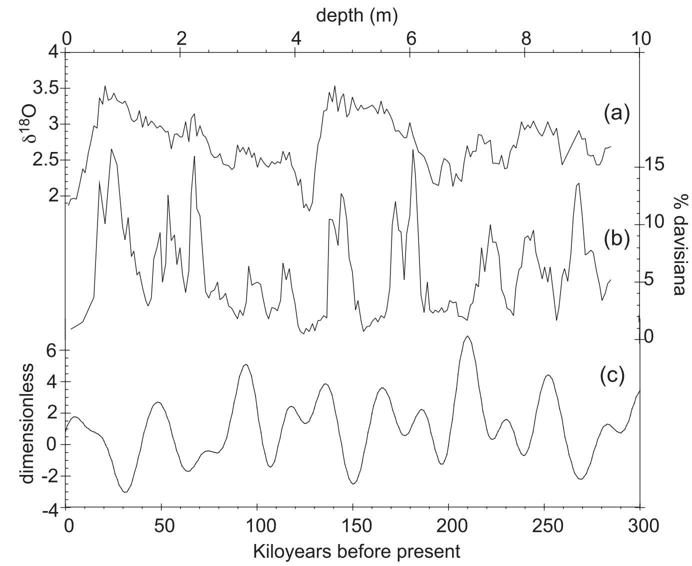

FIGURE 4: Core RC11-120, drilled through 953 cm of sediment in the Indian Ocean (43°31′S, 79°52′E) from a water depth of 3193 m, and sampled at 5 cm intervals. (a) *G. bulloides* $\delta^{18}O$; (b) *C. davisiana* abundance with core depth (top horizontal axis). The two data sets do not share the same depth points. (c) ETP signal over 0–300,000 y before present (bottom horizontal axis, according to the La2004 model computed with *Analyseries*; link in Supplemental Materials).

ture records from 0 to 278,700 y ago. The proxy data are the oxygen isotope composition ($\delta^{18}O$) of the calcitic shells ("tests") of the surface-ocean foraminifer *Globigerina bulloides*, and the abundance of the middepth oceanic radiolarian *Cycladophora davisiana* (Hays et al., 1976). These data were obtained from Core RC11-120, one of the five original ocean cores used to construct the classic "SPECMAP Stack" that led to the wide acceptance of the theory of astronomically forced paleoclimate (Imbrie et al., 1984).

The *G. bulloides* $\delta^{18}O$ and *C. davisiana* abundance data sets that were collected from Core RC11-120 are displayed in Fig. 4. *G. bulloides* occurs abundantly in high northern and high southern latitudes and low-latitude upwelling regions. The $\delta^{18}O$ of *G. bulloides* carbonate tests varies as a function of the temperature of seawater in which the forams live, as well as the volume of continental ice sheets (Shackleton and Opdyke, 1973). That is, when it is cold, ^{16}O is preferentially distilled from the oceans and sequestered in ice sheets, thereby enriching the oceans in ^{18}O; at the same time, colder seawater favors ^{18}O during $CaCO_3$ precipitation by marine fauna. Thus, $\delta^{18}O$ is a paleoclimatic proxy signal for which more positive values are associated with colder climates, and more negative values are associated with warmer climates. *C. davisiana* is characteristic of cold, high-latitude water masses; its intrusion from high latitudes into low-latitude sites represents injection of deep cold water of high-latitude origin. Thus, relatively high abundances of *C. davisiana* are associated with colder climates.

The paleoclimate proxy signals show that pronounced oscillations in temperature occurred at the midlatitude oceanic location of Core RC11-120. To estimate the time represented by the signals, geochronologic data were

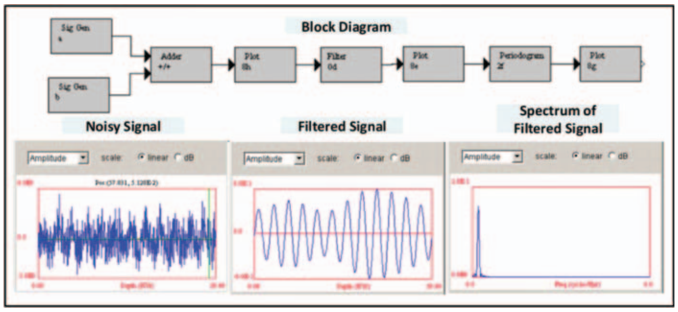

FIGURE 5: *J-DSP/ESE* block diagram and plots for *Tutorial 1: Basic Signal Processing*.

developed along the core: an age of zero (i.e., the present day) at the top of the core, a radiocarbon age of 9.4 ka (thousands of years before present) at 39 cm core depth, and an age of 127 ka for the boundary between isotope stages 5 and 6, at 440 cm (Hays et al., 1976). This chronology, when extrapolated to the bottom of the sampled core, suggests that these paleoclimatic signals encompass 0 to 278.7 ka. Thus, the large $\delta^{18}O$ oscillations have a 100-ky-scale periodicity, whereas the % *C. davisiana* cycles are much shorter and have multiple frequencies, some echoed in muted cycling in the $\delta^{18}O$ signal.

This evidence for 10^4 to 10^5 y timescales for these paleoclimatic variations led researchers to hypothesize that Milankovitch cycles played a major role in their genesis (Hays et al., 1976). Milankovitch cycles describe variations in solar radiation due to Earth's astronomical parameters, with three basic origins: Earth's orbital eccentricity E (cycle periods of 400,000 and ~100,000 y), axial tilt T (cycle period at 41,000 y; also known as the "obliquity"), and precession P (principal cycle periods of 23,000 and 19,000 y). The three effects may be represented as a single "ETP" (eccentricity-tilt-precession) model signal, in which the three astronomical parameters are standardized and summed together (Imbrie et al., 1984). The ETP signal (Fig. 4c) represents all of the astronomical variations of incoming solar radiation (insolation) with respect to time, but not the relative contributions of the astronomical parameters. Astronomically forced insolation is the hypothesized cause for paleoclimatic change in the RC11-120 core data sets, and we expect that coherency between these data sets and ETP will be high at the main ETP periodicities. This analysis is undertaken in Tutorial 3.

THREE TUTORIALS: TEACHING CLIMATE CHANGE USING *J-DSP/ESE*

The objectives of the three tutorials presented here are twofold. First, we introduce basic signal processing concepts. No skills in conventional programming languages are required in order to use the *drag-n-drop* environment of *J-DSP/ESE*. Hence, the student can focus on learning concepts related to basic signal processing in a hands-on manner rather than spending time learning to program. This objective is fulfilled by Tutorial 1, which serves as a springboard for the users to analyze more complex Earth signals in the succeeding tutorials. Second, we demonstrate the utility of *J-DSP/ESE* to handle "near-time" and "deep-time" Earth systems signals. Tutorials 2 and 3 address this objective by focusing on problems in 20th century climate change and paleoclimate change, focusing on time-series analysis tools that are useful for handling many other Earth signals.

The student learning goals of the three tutorials are:

1. Introduce concepts of time series, frequency, filtering, and power spectrum.
2. Demonstrate how signal information is recovered with spectrum estimation.
3. Illustrate the benefits of preprocessing Earth signals.
4. Identify useful preprocessing steps based on type of Earth signal.
5. Perform spectral analysis and identify significant frequencies.
6. Perform coherency analysis between two signals and understand cross-phase.
7. Analyze and interpret the relationship between CO_2 and global temperature.
8. Analyze and interpret the relationship between paleoclimate and insolation.

Climate change is an urgent societal issue. These tutorials can be used by Earth Science students and non–Earth Science students to equal benefit. Instructional guides for the tutorials are provided with the *J-DSP/ESE* application at URL: http://jdsp.engineering.asu.edu/jdsp_earth/index.html.

Tutorial 1: Basic Signal Processing

In this tutorial, the student learns how to separate signal from noise using a filter, and how to compute a power spectrum (also known as a "periodogram"). The student creates a time series with time units in years, and with a single frequency sinusoid sampled at time intervals of 0.08333 y (i.e., monthly, 1/12 y). The signal length is 60 y, and Gaussian noise with a zero mean and unit variance is added to the signal values. The student examines the time and frequency domain representations of this noisy signal, then filters the signal using an appropriately designed *Filter*, and then plots the filtered signal and its spectrum. The *J-DSP/ESE* block diagram for this tutorial is illustrated in Fig. 5.

Tutorial 2: 20th Century Climate Change

Tutorial 2 is instrumental in teaching basic and advanced spectrum estimation while analyzing "near-time" Earth signals of great societal importance. This tutorial analyzes the coherency between the CO_2 and global temperature data. The seasonal components have been removed for both data sets (Fig. 3). The signals are restricted to the timescale of interest using the *Prepare Data* block, and a 25% weighted average trend is removed using the *Trend Fit* function. The data can be obtained from the *Earth Signals* library (see Supplemental Materials) or, alternatively, read from an external file with the *Earth Signals Read* function.

Two time intervals, 1958.2–1988 and 1981–2009, are analyzed separately, following the strategy of Park (2009, 2011) to investigate changes in frequency and phase of the time series. The data are detrended and resampled to 20 samples/y, to ensure that their abscissae are matched. The spectra of the preprocessed signals are estimated using *Periodogram* to examine the distribution of signal variance as a function of frequency. *Coherency* between global temperature and CO_2 is carried out, and output coherency and cross-

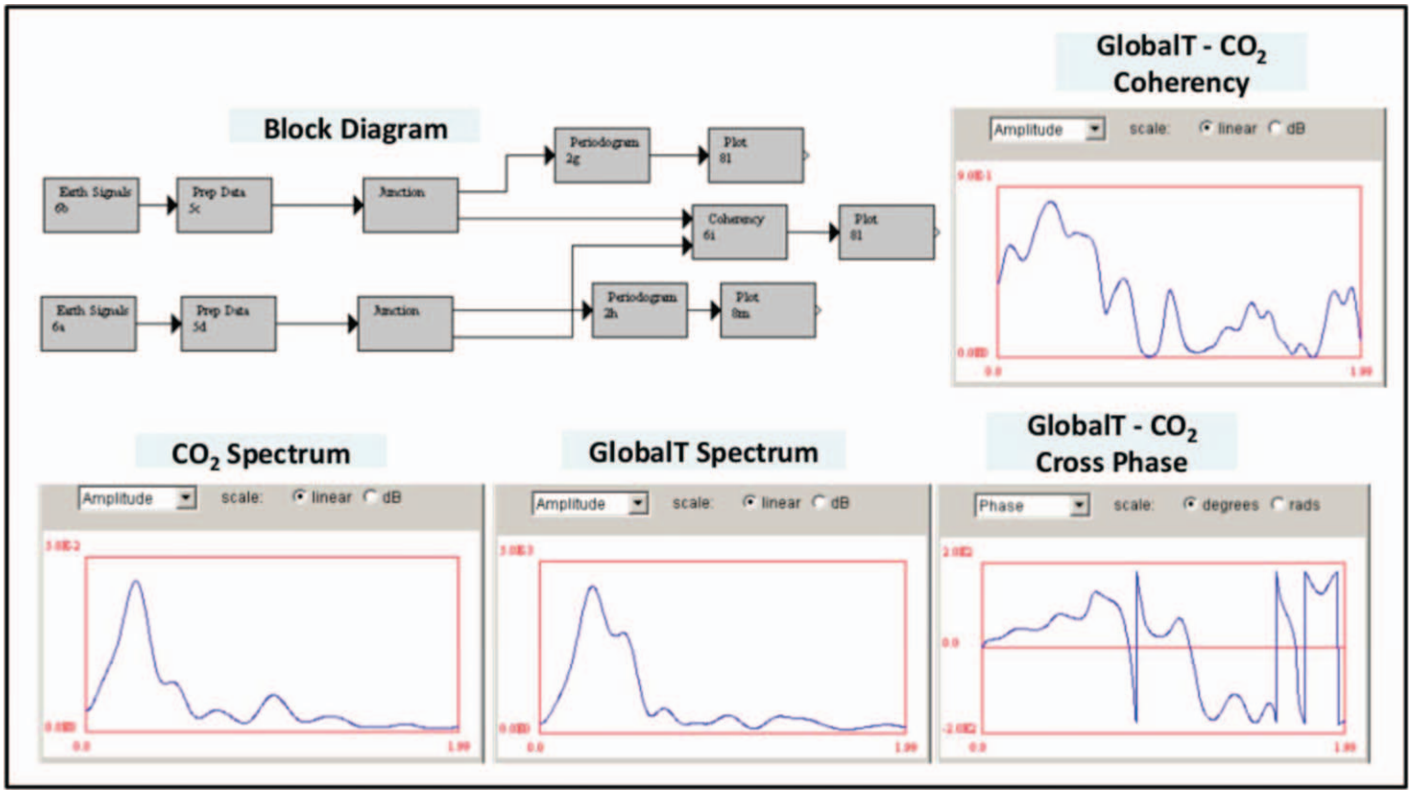

FIGURE 6: ***J-DSP/ESE*** **block diagram and plots for** ***Tutorial 2: 20th Century Climate Change—Atmospheric*** CO_2 ***vs. Global Temperature*****.**

phase spectra are displayed and interpreted. The output coherency spectrum records the Pearson cross-correlation coefficient between two input time series as a function of frequency; the cross-phase spectrum measures the phase between the two time series as a function of frequency, where positive phase indicates that the first input time series lags the second input time series (see Supplemental Materials).

Figure 6 shows the *J-DSP/ESE* block diagram for this tutorial, with plots of the results for 1958.2 to 1988. In this time interval, coherence is high in the low-frequency region, and cross-phase is approximately linear. The cross-phase at a frequency of 0.595 cycles/y is 107.5°, from which the time lag of CO_2 to global temperature is computed as [(107.5°/360°)/(0.595 cycles/y)] × (12 mo/y), or 6 mo, which agrees with the value reported by Park (2009, 2011). This gives the impression that temperature is driving CO_2, whereas we have been informed by climate science that the opposite is true. However, this frequency tracks a dynamical exchange between the ocean and atmosphere: A global surface temperature increase results in decreased CO_2 uptake by the surface ocean, and a (temporary) rise of CO_2 in the atmosphere. This exchange occurs over a range of frequencies, i.e., all frequencies registering high coherency, which are closely associated with the El Niño–Southern Oscillation (ENSO) phenomenon. Similar analysis performed for 1981–2009 (not shown) reveals an approximately linear cross-phase in the low-frequency region with a steeper slope, indicating a CO_2 to global temperature lag of 14.2 mo. This also agrees with Park (2009, 2011) and supports the idea that the oceanic carbon sink may have become saturated.

Tutorial 3: Paleoclimate Change

Analysis of "deep-time" proxy signals of paleoclimate change is the subject of this tutorial. The student analyzes the coherency of *G. bulloides* $\delta^{18}O$, and % *C. davisiana* abundance series from the RC11-120 deep-sea core and an astronomical forcing (ETP) signal. All three signals are in the *Earth Signals* library (see Supplemental Materials). These records are "deep-time" Earth signals, in which core depth is a time proxy. Therefore, conversion from depth to time is necessary, and it is achieved using an age model and resampling to a uniform sample rate of 7.06 samples/ky prior to coherency analysis. A depth-to-time scale conversion is made with an age model, i.e., a table that maps depth to time at specific points along the core. Several age models are available for the RC-11-120 core and are built into the *Earth Signals* library. Time is linearly interpolated between the specified points for each sampled depth along the record.

Figure 7 shows the *J-DSP/ESE* block diagram and coherency plots for % *C. davisiana* versus ETP. The parameters used for the coherency analysis are also displayed. The age model used is the SPECMAP model from Imbrie et al. (1984). Similar behavior is observed in the analysis of *G. bulloides* $\delta^{18}O$ versus ETP. The students observe frequencies with peak coherency values at 0.00946 cycles/ky and 0.025 cycles/ky, which are close to the eccentricity (*E*) frequency of 0.01 cycles/ky (1/100 ky) and tilt (*T*) frequency of 0.0243 cycles/ky (1/41 ky). The cross phase at the *E* frequency indicates a phase lead of 180° for the % *C. davisiana* with respect to ETP; at the *T* frequency, phase leads by 90°. This indicates a time lag of (180°/360°) × [1/(0.01 cycles/ky)] = 50 ky at the *E* frequency, and (90°/360°) × [1/(0.0243 cycles/ky)] = 10 ky at the *T* frequency. Glaciation models include a

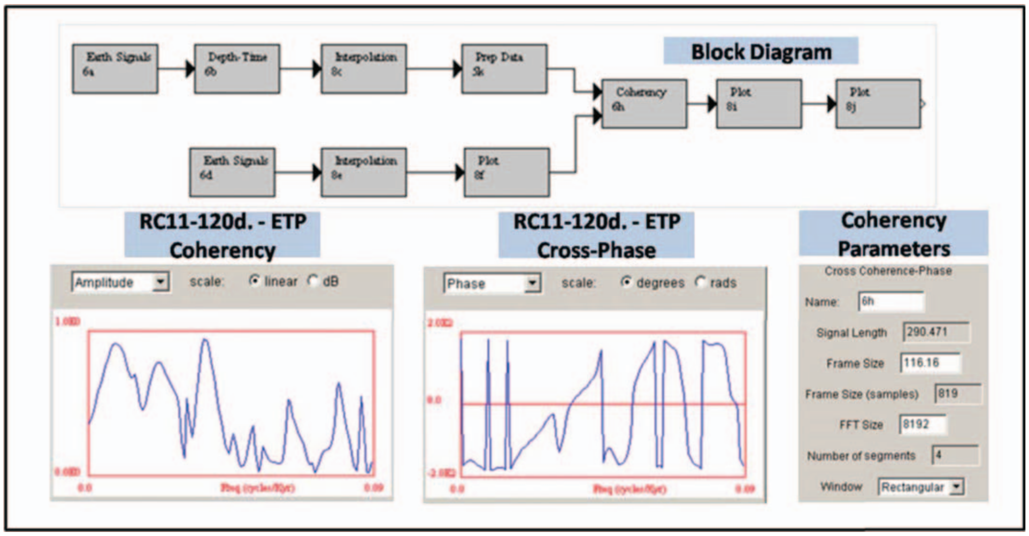

FIGURE 7: *J-DSP/ESE* block diagram and plots for *Tutorial 3: Paleoclimate Change*.

lagged response of ice sheets to astronomical forcing, which explains the *T* time lag (Imbrie and Imbrie, 1980), but not the *E* time lag, which remains debated to this day (Imbrie et al., 1993; Lisiecki, 2010).

ASSESSMENT PROCESS AND RESULTS

We administered the tutorials in two workshops with different audiences. The first workshop was tailored for students in Earth Sciences and consisted of Tutorials 1, 2, and 3. The second workshop was aimed towards an electrical engineering audience and consisted of Tutorial 2 only. The three tutorials can be adapted for a 3-h-long "Earth climate signals" laboratory in a general undergraduate geosciences course.

The first workshop was held during the March 2010 Geological Society of America NE/SE meeting in Baltimore, MD. There were 10 participants in this workshop. Detailed assessments with technical questions on the introduced concepts (conceptual assessment), and general questions on perception of the pedagogy and software (subjective assessment) were prepared and administered after the tutorials. The technical assessment questions, along with the correct answers, and the subjective assessment questions are given in Tables I and II, respectively. For each question in the subjective assessment questionnaire, the participants could choose from the following responses: (a) strongly agree, (b) agree, (c) neutral, (d) disagree, and (e) strongly disagree.

The results of technical and subjective assessments (Fig. 8) indicate that 70% of the queries in the conceptual assessment were answered correctly. Considering the fact that the background of the attendees in signal processing was very limited, this is noteworthy. About 82% of the participants agreed that they were able to perform the tasks in the exercises with ease and that *J-DSP/ESE* improved their understanding of the concepts. This is because *J-DSP/ESE* is an intuitive tool, and the participants were not burdened with having to learn to program. This finding corroborates with the general student perception about *J-DSP* in electrical engineering courses (Spanias and Atti, 2005), and hence we can say that the block-based programming model used in *J-DSP* has high appeal with Earth Science students.

It is also instructive to compare questions that were always answered correctly and mostly answered incorrectly. The questions that were always answered correctly are 2, 4, and 6 (Fig. 8). These questions are related to the concepts with which the students were actually asked to experiment. Question 9 was mostly answered incorrectly, by 80% of the participants. The correct answer to this question is something that the students never experimented with because we never asked them to do so. In other words, the students learn best when they actually work by themselves and understand the concept. *J-DSP/ESE* provides a good platform for such experimentation because of its ease of use.

A second workshop was presented at ASU, Tempe, AZ, during January 2012, to an audience of 14 people predominantly consisting of electrical engineering graduate students with a background in signal processing, but unfamiliar with Earth Sciences. Therefore, we restricted the presentation to Tutorial 2 only, which deals with climate change in the 20th century and which can be easily related to by the nonspecialist audience. We also included a lecture in the beginning of the tutorials, to introduce the students to key concepts behind 20th century climate change.

A pretutorial quiz conceptual assessment that consisted of seven questions was administered to the audience before the start of the workshop. At the end of the workshop, the participants were asked to answer a post-tutorial quiz conceptual questionnaire that consisted of the same seven pretutorial quiz questions and an extra set of three questions, along with a subjective assessment questionnaire of four questions. 10 ten questions along with their correct answers are given in Table III. The questions in the subjective questionnaire, administered at the end of the workshop, are given in Table IV. Similar to the Baltimore workshop, there were five possible responses to the first three questions in the subjective questionnaire. For question 4, the four possible answers were: (a) less than 5 min, (b) less than 10 min, (c) less than 30 min, and (d) more than 30 min. The responses to the technical assessment and first three questions of the subjective assessment are summarized in Fig. 9.

TABLE I: Baltimore workshop conceptual assessment questions with the correct answers.

No.	Question	Type	Answer
1.	To recover a 5 y cycle in a climate time series, what cut-off frequencies should you choose?	Multiple choice	[0.1, 0.2, 0.3] cycles/y
2.	A filter can ALWAYS perfectly recover a signal from noise.	True/False	False
3.	How is the period of cycling related to the frequency?	Multiple choice	Inverse of the frequency
4.	Preprocessing the temperature and CO_2 time series by removing the mean and linear trend helps to get a clearer picture of the low-frequency components present.	True/False	True
5.	The value of a coherency spectrum magnitude is always:	Multiple choice	Positive
6.	A peak in the periodogram (power spectrum) indicates a _____ frequency component in the time series.	Multiple choice	Strong
7.	How many time series are needed to perform coherency analysis?	Multiple choice	Two
8.	What is the need for resampling a paleoclimate time series?	Multiple choice	To make the timescale uniform
9.	The following is NOT usually a preprocessing procedure for the time series:	Multiple choice	Computing a power spectrum

The average performance in the technical assessments improved from 40% to 69%, as evaluated from the pre- and post-tutorial quiz results, which points to a successful use of the tutorials and *J-DSP/ESE* in interdisciplinary education. Considering question 6, the fact that CO_2 lags temperature is a counterintuitive concept that is not clear to many nonspecialists. The performance of participants improved from 20% to 80% for this question, due to improved understanding obtained from the tutorial. As a contrasting example, consider the case of question 5, where the performance improved from 15% to 36%. The fact that global temperature rise has slowed in the past decade is so counterintuitive that even though we see a performance improvement, the reinforcement of this fact due to the tutorials was not as concrete as expected. Furthermore, from the subjective assessment results in Fig. 9, 85% of the participants agreed that *J-DSP/ESE* was easy to use and they were comfortable in understanding the concepts presented. Over 85% of the participants answered that they became comfortable using *J-DSP/ESE* in less than 10 min. From these assessment results, we conclude that these tutorials, along with the software, imparted valuable understanding about 20th century climate change to the nonspecialist audience.

TABLE II: Baltimore workshop subjective assessment questions.

No.	Question
1.	Contents of this exercise improved my understanding of the power spectrum. (Tutorial 1)
2.	I understand the concept of signal and noise more clearly after performing the exercise. (Tutorial 1)
3.	The use of filtering in separating out the signal and the noise was clearly demonstrated. (Tutorial 1)
4.	I understand the concept and use of coherency and cross-phase more clearly after performing the exercise. (Tutorial 2a)
5.	I understood the need for preprocessing the time series after performing this exercise. (Tutorial 2a)
6.	Converting the paleoclimate data from depth to time scale and resampling a time series are easier with J-DSP. (Tutorial 3)

CONCLUSIONS

The *J-DSP/ESE* software is an intuitive, block-based visual programming environment that can be used by students and practitioners in the Earth Sciences for time-series analysis. It can be used on any computer and is

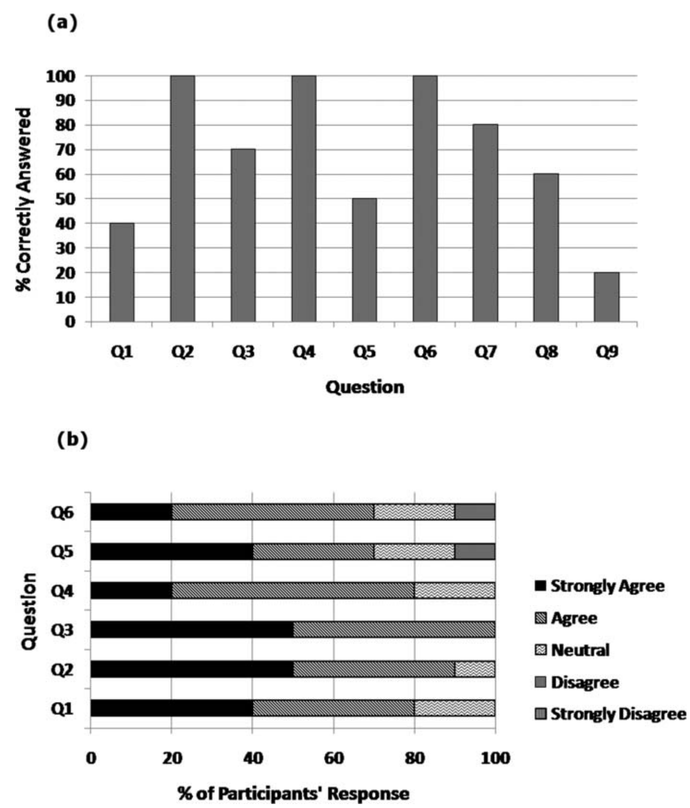

FIGURE 8: (a) Conceptual assessment results for the Baltimore workshop, with Earth Science participants. Questions and the correct answers are available in Table I. (b) Subjective assessment results for the Baltimore workshop. Questions are provided in Table II.

TABLE III: ASU workshop conceptual assessment questions with the correct answers. The first seven questions were a part of the pretutorial quiz assessment.

No.	Question	Type	Answer
1.	Consumption of energy by humans from a million years has increased:	Multiple choice	100-fold
2.	The primary energy source in the U.S. is:	Multiple choice	Fossil fuels
3.	The average human sitting burns:	Multiple choice	100 watts
4.	Interannual variations of atmospheric carbon dioxide are characterized by:	Multiple choice	Periodicities in the 3–5 y range
5.	Long-term trend in the global temperature is:	Multiple choice	Increasing but slowing in the past decade
6.	Global temperature variations have the following relationship with carbon dioxide variations:	Multiple choice	Carbon dioxide lags temperature
7.	Global sea-level variations have the following relationship with global temperature variations:	Multiple choice	Sea level lags temperature
8.	At a frequency of 1 cycle/y, if the cross-phase is 90 degrees, what is the lag between the two signals (global temperature and carbon dioxide)?	Multiple choice	3 mo
9.	Over the past 30 y, what change has happened in the phase relationship between the global temperature and carbon dioxide variations?	Multiple choice	The lag period has increased
10.	The phase relationships between the sea level and global temperature variations point to the possible following cause(s):	Multiple choice	Deglaciation

platform independent. Three tutorials were developed to introduce students and practitioners to Earth signals analysis with a focus on climate change. An introductory *Tutorial 1: Basic Signal Processing* introduces fundamentals of signal analysis; *Tutorial 2: 20th Century Climate Change* and *Tutorial 3: Paleoclimate Change* explore well-known problems in modern-day and past climate science.

These tutorials were presented in a workshop organized at the 2010 Northeast/Southeast Geological Society of America meeting in Baltimore, MD, and at another workshop in 2012 for electrical engineering graduate students at ASU, Tempe, AZ. Assessment results indicate that the attendees understood the presented concepts easily and gained a good working knowledge of the software. *J-DSP/ESE* provides a much-needed platform for easy and quick experimentation of complex concepts in order to accelerate the learning process. We anticipate that the universal availability and ease of use of *J-DSP/ESE* will positively impact university-level Earth Science education in terms of Earth signals analysis instruction. The software can serve as an interdisciplinary education tool in topical courses for nonspecialists, and in the near future, we plan to develop additional tutorials that address other notable

TABLE IV: ASU workshop subjective assessment questions.

No.	Question
1.	I understand the concept and use of coherency and cross-phase more clearly after performing the exercises.
2.	The user interface of *J-DSP/ESE* is intuitive and easy to use.
3.	I will be able to perform analysis of similar Earth systems data sets comfortably using the *J-DSP/ESE* version.
4.	How much time did you need to become comfortable in using the *J-DSP/ESE* version?

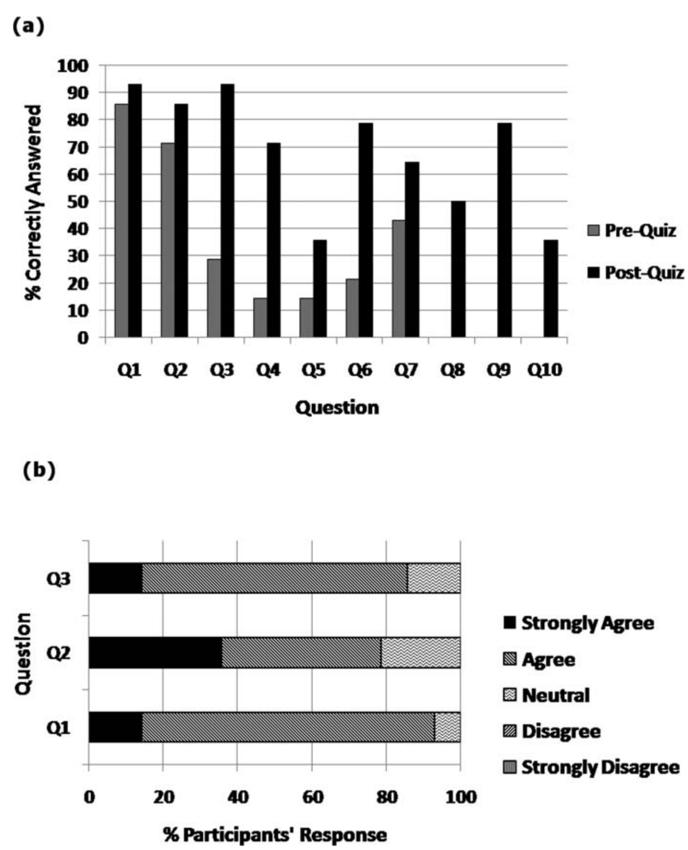

FIGURE 9: (a) Conceptual assessment results for the ASU workshop, with electrical engineering participants. Questions and the correct answers are available in Table III. (b) Subjective assessment results for the ASU workshop. Questions are provided in Table IV.

Earth Science problems in seismology, space geodesy, and environmental monitoring.

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