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Three-dimensional visualization of orbital forcing and climatic reponse: interactively exploring the pacemaker of the ice ages

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Abstract Recent developments in continuous core-logging techniques now permit us to recover the high-resolution time series necessary for the detailed spectral analyses of paleoclimatic proxy records. When applied to long records recovered by scientific drilling (5–10 Ma) they enable us to look at the long-term history and evolution of the ocean's response to orbital forcing. A serious limitation in these studies is the need to display the complex, multidimensional spatial and temporal interactions of the ocean-climate system in an easily comprehensible manner. We have addressed this issue by developing a series 3D visualization tools which permit visualization of the role of the orbital parameters in determining the latitudinal variation of insolation as well as the interactive exploration of multidimensional data sets. The ORBITS tool allows us to visualize the effect of orbital eccentricity, precession, and tilt on the latitudinal distribution of insolation on the earth at the solstices and the equinoxes for any time over the past 5 Ma (for Berger's orbital model) or 10 Ma (for Laskar's orbital model). The effect of the orbital parameters on insolation can be viewed individually, in pairs, or all three together. By moving the model steadily through time, the rate at which orbitally induced changes in insolation occur can also be visualized. To look at the ocean's response to orbital forcing we take the long time series generated from our paleoclimatic proxies and calculate their spectrum over a fixed, but sliding, time window. To view the complex multidimensional relationships found in these evolutionary spectral analyses, we use another interactive 3D data exploration tool developed at the University of New Brunswick (Canada). This tool (FLEDERMAUS) uses a six-degrees-of-freedom input device (BAT) and a series of software modules for color coding, shading, and rendering complex data sets, to allow the user to interactively "fly" through the multidimensional data. Through the use of color, texture, and 3D position, as many as six or seven variables can be explored in a simple and intuitive manner. With special liquid-crystal-display glasses, the scene can be viewed in true "stereo." We use these tools to explore the relationship between orbital forcing and the response of the benthic isotope and calcium carbonate record at ODP Site 846 (90°W and 5°S) This analysis shows an equatorial Pacific carbonate record which has a large component of linear response to tilt, but little linear response to precession. There is a major shift in response, from a carbonate-dominated response to an isotope (ice volume)-dominated response at approximately 4.5 Ma, and as expected, there is a large nonlinear response at the lower frequencies (400 and 100 kyr) during the past 800 kyr to 1 Ma

Key words Paleoclimate · 3D visualization · Milankovitch cycles · Orbital models · Equatorial Pacific · Paleoceanography

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Introduction

In 1920 Mulitan Milankovitch presented an astronomical theory which attempted to explain the periodic waxing and waning of the ice ages in terms of periodic changes in the earth's orbit with respect to the sun (Milankovitch 1920). Milankovitch proposed that changes in the eccentricity of the earth's orbit around the sun [varying with periods of approximately 100000 years

(=100 kyr) and 400 kyr], the obliquity, or tilt, of the earth's rotational axis with respect to the orbital plane (with periods of 41 kyr), and changes in the precession of the equinoxes (with periods of 19 and 23 kyr) would combine to result in periodic, long-term changes in the insolation (amount of solar radiation reaching the surface of the earth) in sensitive northern latitudes. These changes in insolation would in turn have a cumulative effect on the buildup or melting of ice sheets and thus lead to the periodic progression between glacial and interglacial times.

In the early 1970s improvements in sampling techniques, analytical procedures, and stratigraphic resolution finally allowed Milankovitch's hypothesis to be tested against the paleoclimatic record contained in deep-sea cores (Broecker and van Donk 1970; Hays et al. 1976) These tests demonstrated that the orbital periodicities of 19, 23, 41, and 100 kyr predicted by Milankovitch were indeed present in the deep-sea records of a range of paleoclimatic proxies (e.g., oxygen isotopes to represent ice volume or assemblage distributions to represent sea-surface temperature) and illustrated the potential of using these deep-sea records to study the response of the climate system to a known external forcing function.

Whereas the magnitude and phasing of changes in paleoclimatic indicators which occur at 19, 23, and 41 kyr can be explained as linear responses to insolation caused by variations in precession and tilt (see Imbrie et al. 1992 for a detailed discussion of this relationship), there is also a very large response at a period of 100 kyr. The 100-kyr response is far too great in magnitude to be explained as a linear response to changes in eccentricity (which result in changes in insolation of only a few tenths of a percent at the largest changes in eccentricity; Berger et al. 1993). Numerous nonlinear mechanisms have been called upon to explain the magnitude of the 100-kyr cycle (see Imbrie et al. 1993 for an overview of many of these mechanisms). Most recently, Liu (1995) has proposed that dynamical instabilities in the glaciation and deglaciation of the ice sheets can be triggered by pulsations in the rate of change of the orbital parameters, and particularly by the rate of change in the obliquity. A key element of each of these studies is the identification of changes in the orbital parameters as a measurable signal against which to examine the nature of climatic response.

Recognizing the importance of orbital forcing in climate studies, and taking advantage of improvements in the field of celestial mechanics, Berger and Loutre (1991) and Berger et al. (1993) have produced models which allow the calculation of changes in insolation as a function of the orbital parameters. These studies allow us to determine the latitudinal distribution of radiation on the surface of the earth back to approximately 10 Ma. More recently, Laskar et al. (1993) have produced a modified model of the orbital interactions which permits the calculation of insolation as a function of latitude as far back as 20 Ma. Although these authors have calculated insolation back to 10 and 20 Ma, respectively, the uncertainties grow as they are calculated back in time and we have therefore chosen to run our visualizations only back to 5 Ma for Berger's model and 10 Ma for Laskar's.

To help us better understand the complex interactions among orbital eccentricity, obliquity, and precession, as well as the influence of these parameters on the latitudinal distribution of insolation through time, the Ocean Mapping Group of the University of New Brunswick (Canada) has constructed an interactive computer tool (ORBITS) which allows visualization of the role of the orbital parameters in controlling insolation. In addition, the Ocean Mapping Group has developed a suite of interactive 3D data exploration tools (FLEDERMAUS) which allow interactive exploration of the complex interrelationships of paleoclimatic proxy data. This paper describes briefly both of these interactive tools and then presents an example of their use to look at the response of the eastern equatorial Pacific to orbital forcing.

The ORBITS tool

The ORBITS program uses the equations of either Berger et al. (1993) or Laskar et al. (1994) to model the relative position of the earth with respect to the sun as the earth–sun orbit varies in its eccentricity, obliquity, and precession. To show the interaction of these parameters we present a 3D image of the rotating earth (with continents) at four positions in the annual seasonal cycle: winter solstice; summer solstice; spring equinox, and autumn equinox (Fig. 1a). For any time over the past 5 myr (for Berger's model) or 10 myr (for Laskar's) the program shows the earth at each of these seasonal positions with its eccentricity (earth–sun distance – multiplied by ten so that it can be visualized), tilt with respect to the orbital plane (controlling the latitudinal distribution of radiation), and earth–sun distance with respect to the precession of the equinoxes. A color-coded time series depicting the amplitude of variation for each of the orbital parameters is also presented above the images of the earth.

For a given time, the latitudinal distribution of insolation (daily average, Berger et al. 1993) is calculated and displayed on the 3D earth as a function of color. Red colors indicate high values of insolation, whereas blues and greens indicate low values of insolation (Fig. 1a). The ORBITS tool allows us to explore the influence of any one of the orbital parameters individually or in combination. A simple selection on any one of the time-series curves will fix that parameter to its mean value; if two of the parameters are selected, the effect of only the remaining parameter can be explored, or if one parameters is selected, the interaction of the two remaining parameters together can be examined. Finally, if none are selected, the combined effect of eccentriciy, obliquity, and precession can be visualized.

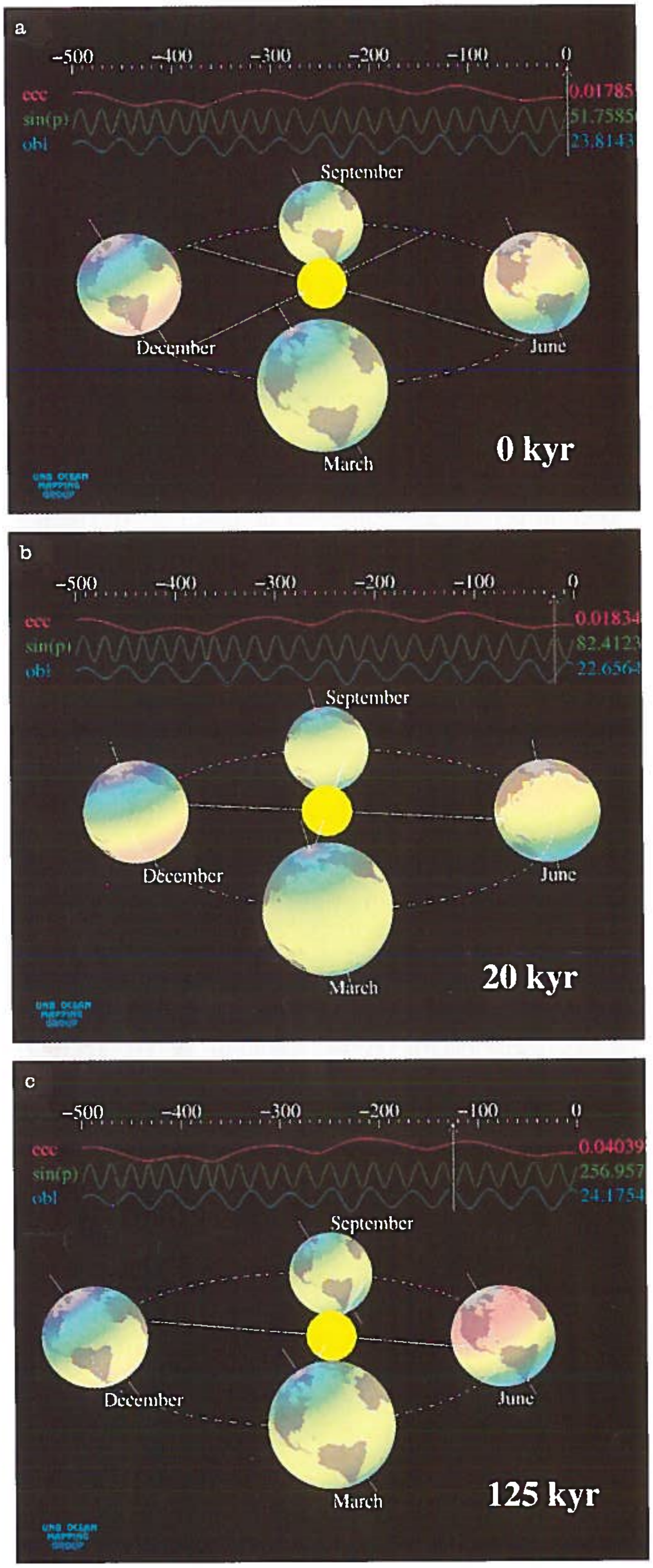

Fig. 1 a–c Screen captures of display of the ORBITS program. Presented are the relative earth–sun positions at summer and winter solstices and autumn and spring equinoxes. The earth is tilted at its obliquity with respect to the orbital plane and is in its proper position relative to eccentricity and precession of the equinoxes. The *three color-coded time series* at the top of each panel represent the values of eccentricity, precession, and tilt as a function of time in thousands of years before the present. **a** The present configuration; **b** the configuration at 20 kyr BP; **c** the configuration at 125 kyr BP

With the mouse the user can select any point on the time series to see the effect of the orbital parameters at that time or, by using the left and right arrow keys, the user can slide through time watching the earth change its eccentricity, precession, and tilt, and see a graphic depiction of the effect of these parameters on the latitudinal distribution of insolation. A second set of arrow keys allow the user to zoom into the view of the earth (for the summer solstice earth position) and a third set of keys allow the user to vary the observational perspective of the orbit (e.g., from the side or above).

Figure 1a depicts the position of the earth with respect to the sun for modern times and demonstrates the causes of seasonal variations in insolation on today's earth. Note that in its present configuration the eccentricity of the earth's orbit with respect to the sun is very small (we now have a nearly circular orbit), but the earth–sun distance as determined by the precession of the equinoxes is nevertheless larger for the position of the earth during the northern hemisphere summer than it is for the northern hemisphere winter. Whereas the sun may appear smaller in summers in the northern hemisphere than during winters, it is sufficiently high above the horizon as a result of the obliquity of the earths's orbit with respect to the ecliptic during northern hemisphere summers to provide the familiar seasonal contrast (Fig. 1a). Thus, for the seasons, it is tilt (obliquity) which provides the dominant effect on the distribution of insolation.

To explore the effect of the individual orbital parameters on climate we have run our model for each of the orbital parameters while holding the other two fixed. Space limitations do not permit us to illustrate each of these pertubations of the model here (a videotape of this is available from the authors), but from this exercise it is clear that it is changes in the precession of the equinox (with periodicities of 19 and 23000 years) which have the dominant effect on the net insolation. Changes in the eccentricity are manifested as changes in the earth–sun distance, and thus the effect on insolation is dominant in the low latitudes. Tilt, on the other hand, which changes between 22.4 and 24.4° over a 41000-year cycle, has its dominant effect on the higher latitudes near the region of polar night. The uneven distribution of land masses on the earth also results in an asymmetrical distribution of heat between the northern and southern hemispheres.

To illustrate the complex interactions of the orbital parameters and their role in controlling the latitudinal distribution of insolation on the surface of the earth, Figs. 1b and c show the relative positon of the earth with respect to the sun near the last major interglacial (125 ka) and near the last glacial maximum (20 ka). It is seen clearly that at the 20 ka (Fig. 1b) the tilt was low and the eccentricity and precessional effect were high resulting in a relatively large earth–sun distance during northern hemisphere summers, and thus low insolation, which was more concentrated on the equatorial regions than the high latitudes. The net result of this combination of factors was cold high-latitude northern hemisphere summers which prevented the melting of the ice and snow which accumulated during the winters. It was the buildup of ice during this period of cold northern hemisphere summers which led to the glacial maximum at approximately 18 ka.

At 125 ka (Fig. 1c) the eccentricity and precessional effects are low (resulting in shortened earth–sun distances during northern hemisphere summers) and the tilt is near a maximum (resulting in increased summer insolation in the high northern latitudes). The net effect of this combination is relatively warm summers in the high northern latitudes, extensive melting of snow and ice, and thus, an interglacial time. The ORBITS tool allows us to explore interactively the relative position of the earth with respect to the orbital parameters and the resulting distribution of insolation for any time back to 10 Ma (using the Laskar model). In addition, the ability to visualize the changes continuously as a function of time (e.g., sliding through a range of times) allows us to visualize the rate at which insolation varied, a parameter which may be as important as the absolute value and distribution of insolation in determining climate. (The ORBITS program will run on any Silicon Graphics workstation and is available via FTP from the corresponding author).

Visualizing the oceanographic response to orbital forcing

Orbitally induced changes in insolation provide a critical, relatively well-known, forcing function for climate. The key to utilizing this information to better understand how the ocean-climate system works lies in our ability to understand the response of the ocean-climate system to this forcing. In order to do this, we have focused our attention on long, nearly continuous records of paleoclimatic proxies which represent various components of the ocean-climate system. We take these long records and calculate the spectral response of each proxy through time; we then take advantage of another 3D interactive visualization tool developed at the University of New Brunswick (FLEDERMAUS) to interactively explore these complex multivariate data sets.

Evolutionary spectra

Recent advances in analytical techniques have made practical (but still very time-consuming) isotopic analyses (e.g., $\partial^{18}O$, $\partial^{13}C$) on deep-sea cores at sample intervals of 5 cm or less. Depending on sedimentation rates, these analyses can produce paleoclimatic proxy records with temporal sampling intervals of the order of a few hundred years or less (e.g., Labeyrie et al. 1995). In addition, a number of workers have demonstrated that the near-continuous, high-resolution records collected by laboratory core loggers (e.g., Gamma Ray Attenuation Porosity Evaluator – GRAPE or magnetic susceptibility) can be transformed into, or interpreted in, terms of paleoclimatic proxies. These core logging records have the potential to rapidly produce very high-resolution records of various components of the ocean-climate system. For example, Mayer (1991), and Herbert and Mayer (1991), demonstrated that in certain depositional environments, the GRAPE record can be transformed into a very accurate representation of the carbonate content record. Bloemendal and DeMenocal (1989) showed that the magnetic susceptibility record in certain environments is indicative of the aolian content of marine sediments. Herein we apply the approach described by Mayer (1991) to both GRAPE and oxygen isotope records from ODP Site 846 (Leg 138) in the eastern equatorial Pacific (Mayer et al. 1992; Pisias et al. 1995) to generate "evolutionary spectra" of the ocean's response to orbital forcing.

The ODP's Leg 138 drilled 11 sites in the eastern equatorial Pacific in order to provide detailed information on the ocean's response to global change during the Neogene. In order to ensure the continuous recovery of the sedimentary section, all sites drilled on ODP Leg 138 were cored at least three times. Both onboard and postcruise processing were applied to the core and downhole logs in order to the remove the coring gaps which occur inevitably at core breaks (approximately every 9 m). Spliced records were produced, which represented continuous 6-m.y. records of sedimentation in the equatorial Pacific (Hagelberg et al. 1992; Hagelberg et al. 1995). A detailed stratigraphic framework was applied to these records, initially using microfossil records and magnetic polarity reversals and then using the continuous GRAPE record to tune the timescale to variations in the orbital parameters as described by Berger and Loutre (1991). The result of this effort was a set of internally consistent high-resolution age models which provide an absolute timescale for the equatorial Pacific for the past 6 m.y. (Shackleton et al. 1995a). It is the combination of a very precise timescale and near continuous high-resolution proxy records which allows us to apply our tools to visualize the nature of the ocean's response to orbital forcing.

Figure 2a shows a continuous 6-m.y. carbonate record from ODP Site 846 (90°W and 5°S) generated by applying a series of transfer functions to the GRAPE density record. These transfer functions correct for sediment rebound and compaction and then use empirically established relationships between saturated bulk density and carbonate content to predict carbonate from the GRAPE record (Mayer 1991; Hagelberg et al. 1995b). The resulting carbonate record has a 1- to 2-cm sample interval. When the high-resolution stratigraphy

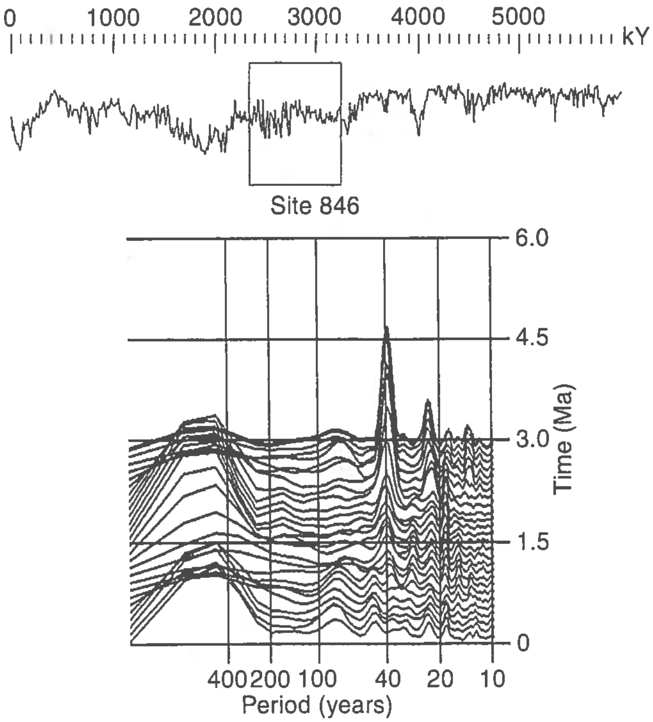

Fig. 2 Generation of evolutionary spectra. The spectrum over a 900-kyr window of a long, continuous paleoclimatic record is calculated and plotted on a 3D plot of frequency, time, and variance. The window is then offset by 10% (90 kyr) and another spectrum is calculated. This is continued until the end of the time series is reached

of Shackleton et al. (1995a) is applied to these data, the resulting temporal resolution is approximately 1000 years (given the sedimentation rates at Site 846).

In order to explore the evolving nature of variations in the carbonate system and their relationship to the orbital forcing signal, an evolutionary spectral calculation is made by taking a 900000-year window of the time series and calculating its spectrum using the lagged autocovariance method of Jenkins and Watts (1968). The high-resolution sampling interval provided by the GRAPE allows for subsampling at a 2000-year sample interval with minimal interpolation. When interpolation is necessary a linear interpolation is used. Autocovariance and cross-covariance functions for the 900000-year time-series segments (N=450 points) are tapered using a 150 point (N/M=3) Tukey window (Jenkins and Watts 1968) before the spectral and cross spectral functions are calculated. The resulting bandwidth of the spectra is 0.0044 cycles/ka with eight degrees of freedom. These window lengths were chosen so as to resolve the separation between the 19- and 23-kyr spectral peaks while still allowing for the calculation of variance in the long period (100 and 400 kyr) bands.

With the completion of a spectral calculation for each 900000-year window, the window is then shifted by 10% (90 kyr) and another spectrum is calculated and plotted (Fig. 2a and b). Spectra are thus calculated for 0–900, 90–990, 180–1080 ka, etc., to the end of the time series at approximately 6 Ma. Similar calculations are also made for the record of insolation at 65°N (Berger and Loutre 1991) and for a high-resolution benthic oxygen isotope record for the site (Shackleton et al. 1995b; Mix et al. 1995. In addition, cross-spectra are calculated between the carbonate record and insolaton as well as the isotope record and insolation. Each cross-spectral calculation produces a 2D array (time and frequency) of four variables: 1 and 2, variance for each time series; 3, coherency between the time series; and 4, relative phase between the time series. Thus, for a single site we have four or five variables whose relationships interest us. To facilitate the exploration of these complex interactions we have taken advantage of the FLEDERMAUS Toolkit which allows the interactive exploration of multidimensional data sets in a simple and intuitive manner.

The FLEDERMAUS Toolkit

Originally developed by researchers at the University of New Brunswick for 3D exploration of the massive data sets generated by modern multibeam sonar systems, the Fledermaus Toolkit consists of a six-degree-of-freedom input device (BAT) and interface software (Ware et al. 1990) which allows the postion and motion of the BAT to be transmitted into the 3D scene to be explored. The BAT is a handheld device which uses either electromagnetic or ultrasonic sensors to detect its position and relative motion through space. Simple hand movements are transmitted instantly to the scene: If the observer moves his hand to the right, the scene shifts as if the observer had moved to the right; a downward motion shifts the scene as if the observer had moved downward; a twisting motion causes the scene to spiral, and so on. The rate at which the observer moves his hand controls the acceleration through the scene. With the use of specially designed liquid-crystal-display (LCD) glasses, the observer can also view the scene in true "stereo".

The Fledermaus software package also provides interactive tools for taking any multidimensional data set and rendering it in 3D. These include tools which allow for the interactive generation of color maps and false sun-illumination (shading). For the case of the evolutionary spectra we have chosen to display spectral frequency on the *x*–axis and geological time on the *y*-axis; the 3D relief of the display is the variance in each frequency band (Fig. 3a). For the plot of the evolutionary spectrum of insolation (Fig. 3a), the color map also represents the amplitude of the variance in frequency band. For each of the other plots (Figs. 3b, c and d), however, the color red is used to illustrate where significant (greater than 80% confidence limit) coherence is found between the two time series beirig analyzed. Thus, we can very simply diplay and analyze four di-

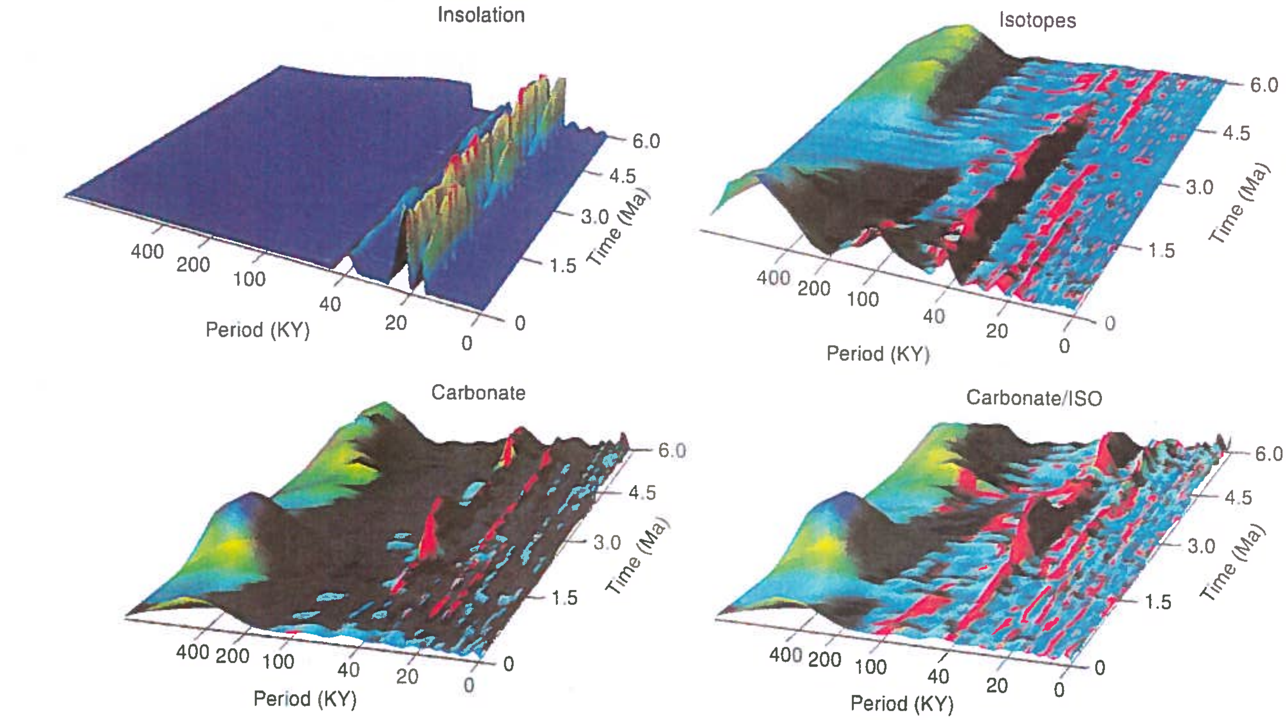

Fig. 3a–d Screen captures from interactive 3D exploration using the FLEDERMAUS Toolkit, of evolutionary spectra from site 846 in the eastern equatorial Pacific. **a** A 3D plot of the evolutionary spectra of insolation over the past 6 Ma. In this plot the color map is related to the variance in each band. **b** A 3D plot of the evolutionary spectrum of the benthic isotope record from site 846. In this plot the *red colors* represent areas which have significant (>80%) coherence with orbital forcing. **c** The evolutionary spectrum of the calcium carbonate record (determined from GRAPE data) from site 846. Again the *red* indicates coherence with orbital forcing. **d** The same evolutionary spectrum as that in **c** (carbonate), but in this plot the coherence is mapped with the isotope record, rather than the insolation record

mensions of data. Fledermaus also permits us to simultaneously input and explore multiple data sets and to arrange them in a true geo-referenced coordinate scheme. Thus, if we were exploring multiple drill holes, we could view their evolutionary spectra in their relative geographic postion and even positioned at their relative depth in 3D space. Finally, we can also use texture to represent an additional variable allowing us to easily and intuitively explore the interaction of as many as seven variables at a time.

With simple hand movements the observer can interactively "fly" around the data set, exploring it from all angles and perspectives. The observer can also move to any point in the multidimensional space and with a mouse button, query any data point for all of its attributes. Tools are also available for the quantitative comparison of one surface to another providing a quick and quantitative means at looking at regional and temporal differences. (Although we can only present a static image of this type of exploration herein (Fig. 3), a video animation of an interactive flight through the evolutionary spectra discussed herein is availale from the corresponding author and example flights can be found on the World Wide Web at: www.omg.unb.ca.)

A 3D evolutionary spectra from the eastern equatorial Pacific

To demonstrate the usefulness of this approach we present a series of color-coded evolutionary spectra from ODP Site 846 (Leg 138; Mayer et al. 1992; Pisias et al. 1995). We start by looking at the climatic forcing function – summer insolation at 65°N (Fig. 3a). The perspective view shows clearly that the record of insolation is dominated by the precessional frequencies (19 and 23 kyr), and that while the 23 kyr component has remained fairly constant over the past 6 myr, the 19 kyr component has had major (periodic) fluctuations with peaks in 19 kyr precessional energy occurring at approximately 1.3 and 4.2 Ma. The 41 kyr component is much weaker and, as discussed previously, there is virtually no power in the 100 kyr band for insolation.

The evolutionary spectrum of the benthic isotope record from Site 846 is shown in Fig. 3b, in which we add another dimension to the data by coloring high coherency with insolation in red. The evolutionary spectrum shows very little variance or coherence in the isotope record prior to approximately 4.5 Ma. From approximately 4.5 Ma to the present we see the growing influence of the tilt component which is highly coherent with insolation. This change in oceanic response at 4.5 Ma is coincident with a number of other major oceanographic changes at this time. We also see clearly the nonlinear response of the system (no coherence with insolation) at 400 and 100 kyr. In the 400 kyr band there is a large amount of variance prior to 4.6 Ma and after 3.2 Ma, and in the 100 kyr band we see growing variance over the past 1 myr.

The evolutionary spectrum of the GRAPE-derived carbonate record is also dominated by tilt, but for this component the largest variance is between 6 and 5 Ma and 3 and 1.9 Ma. This is in contrast to the isotope record, which shows no coherence with insolation from 6 to 4.5 Ma. The carbonate record loses coherence with tilt in the younger part of the record where the isotope record shows high coherence. The carbonate record is also coherent with precession prior to approximately 1.5 Ma. Finally, in Fig. 3d we look at the evolutionary spectrum of the carbonate record again, but this time the coherence we display is the coherence with the isotope record. Here we can see that carbonate loses coherence with isotopes after approximately 1.5 Ma indicating that prior to the Pleistocene there was much more coupling between ice volume and deep water and implying a change in the processes controlling ice volume.

Summary and conclusions

We have developed a series of tools which allow us to more fully explore the nature of the complex interactions between orbital forcing and the response of the ocean-climate system. The ORBITS tool allows us to visualize the effect of orbital eccentricity, precession and tilt on the latitudinal distribution of insolation on the earth at the solstices and the equinoxes for any time over the past 5 Ma (for Berger's orbital model) or 10 Ma (for Laskar's orbital model). The effect of the orbital parameters on insolation can be viewed individually, in pairs, or all three together. By allowing the model to move steadily through time, the rate at which orbitally induced changes in insolation occur can also be visualized. The ORBITS program provides an excellent tool for teaching about Milankovitch cycles as well as providing the researcher with a an unambiguous representation of the orbitally induced distribution of temperature at any time over the past 10 Ma.

To explore the impact of these changes in insolation on the response of the ocean-climate system, we have taken advantage of recent advances in analytical and stratigraphic techniques which now permit us to produce long, extremely high-resolution records of various paleoclimatic proxies which represent different components of the ocean-climate system (e.g., $\partial^{18}O$, magnetic susceptibility or percent carbonate derived from gamma-ray-attenuation logging). After a careful stratigraphy has been worked out for these records, we take the long time series and calculate the spectrum of the time series over a 900 kyr window. The window is then shifted 10% (90 kyr) and another spectrum is calculated. The result is a 3D matrix of time, frequency, and variance of the paleoclimatic response. We also calculate cross spectra between each paleoclimatic time series and the orbital forcing function (insolation). This results in a four-dimensional array (time, frequency, variance of each time series and coherence between the two time series) which is a quantitative representation of the evolution through time of the response of the paleoclimatic proxy to orbital forcing.

To view the complex multidimensional relationships found in the evolutionary spectral analyses, we use another interactive 3D data exploration tool developed at the University of New Brunswick. This tool (FLEDERMAUS) uses a six-degree-of-freedom input device (BAT) and a series of software modules for color coding, shading, and rendering complex data sets, to allow the user to interactively "fly" through the multidimensional data. Through the use of color, texture, and 3D position, as many as six or seven variables can be explored in a simple and intuitive manner. With special LCD glasses the scene can be viewed in true "stereo".

As an example of the use of these tools, we explore the evolutionary spectra of a high-resolution benthic oxygen isotope record and near continuous gamma-ray-derived calcium carbonate record from ODP Site 846 in the eastern equatorial Pacific (90°W and 5°S). This analysis shows an equatorial Pacific carbonate record which has a large component of linear response to tilt, but little linear response to precession. There is a major shift in response, from a carbonate-dominated response to an isotope (ice volume)-dominated response at approximately 4.5 Ma and as expected, there is a large nonlinear response at the lower frequencies (400 and 100 kyr) during the past 800 kyr to 1 Ma.

We have only just begun to use these tools, but already they have proven to be invaluable in permitting us to rapidly visualize complex multidimensional relationships which would be difficult to discern. We hope to extend the ORBITS tool to include the build up and melting of ice sheets, and eventually, controls on the alkalinity of the ocean. To do this we face the more formidable task of exploring in more detail the nature of the nonlinear responses to orbital forcing.

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