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Detection of Anthropogenic Climate Change in the World's Oceans

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Large-scale increases in the heat content of the world's oceans have been observed to occur over the last 45 years. The horizontal and temporal character of these changes has been closely replicated by the state-of-the-art Parallel Climate Model (PCM) forced by observed and estimated anthropogenic gases. Application of optimal detection methodology shows that the model-produced signals are indistinguishable from the observations at the 0.05 confidence level. Further, the chances of either the anthropogenic or observed signals being produced by the PCM as a result of natural, internal forcing alone are less than 5%. This suggests that the observed ocean heat-content changes are consistent with those expected from anthropogenic forcing, which broadens the basis for claims that an anthropogenic signal has been detected in the global climate system. Additionally, the requirement that modeled ocean heat uptakes match observations puts a strong, new constraint on anthropogenically forced climate models. It is unknown if the current generation of climate models, other than the PCM, meet this constraint.

Almost all rigorous studies attempting to find the impact of anthropogenic forcing in today's climate system have used air-temperature observations as the data set of choice for the detection study (1). These studies most often use near-surface air temperature [e.g., (2–6)]. Changes in sea ice (7) and the vertical temperature structure of the atmosphere obtained from radiosonde data (8–11) have also been investigated for evidence of an anthropogenic signal.

Climate models predict that there will be substantial anthropogenic changes in variables only weakly related to near-surface air temperature. For example, model-predicted signals have been detected in the magnitude of the annual cycle and wintertime diurnal temperature ranges (12), but there are few

such studies at present. It seems imperative that statements about the detection and attribution of model-predicted anthropogenic climate change, such as made in the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment (13), be placed on a stronger foundation by quantitatively identifying such signals in other elements of the climate system.

A major component of the global climate system is the oceans; covering roughly 72% of the planet's surface, they have the thermal inertia and heat capacity to help maintain and ameliorate climate variability. Although the surface temperature of the oceans has been used in detection and attribution studies, apparently no attempt has been made to use changes in temperature at depth. A recent observational study (14) has shown that the heat content of the upper ocean has been increasing over the last 45 years in all the world's oceans, although the warming rate varies considerably among different ocean basins. We show in this

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study that at least one global climate model, forced by a combination of observed and estimated anthropogenic gases, has reproduced the observed changes in ocean heat content with surprising accuracy.

The decadal changes over the last 45 years in the heat content of the upper 3000 m of the water column estimated from observations are shown in Fig. 1 (14). Only the very low frequency component of the signal is of interest here, so we chose to work relative to this depth and use decadal averages to filter out noise associated with eddies and interannual or decadal natural variability. A similar set of heat-content changes, relative to a 300-year control run climate, was computed from five different realizations of the Parallel Climate Model (PCM) forced by observed and estimated concentrations of greenhouse gases and the direct effect of sulfate aerosols on the atmosphere (15). This state-of-the-art global climate model, which uses no flux-correction scheme, is a cooperative effort between a number of universities and government laboratories in the United States (16). A brief summary of the model components, forcing scenarios, and current results are given in (17–19), while a more detailed description can be found at www.cgd.ucar.edu/pcm.

Figure 1 shows an unexpectedly close correspondence between the observed heat-content change and the average of the same quantity from the five model realizations. These results were obtained by subsampling the model data at the same locations and times where observations existed (20). When the scatter between the multiple model runs is included (shaded regions on Fig. 1), it becomes apparent that there is little or no significant difference between model and observations, even though the heat-content changes vary among ocean basins. The main exception occurs in the 1970s, when the observations show a decadal anomaly that the model runs do not reproduce. We speculate that the anomaly is associated with the apparent regime-like shift in the North Pacific Oscillation and other regional climate modes that occurred at that time (21–24). It is not possible, given the manner in which it was forced, that the model could have captured this specific decadal signal. However, the model does produce, in both its anthropogenically forced runs and control run, decadal fluctuations that have the same magnitude and time scale as those associated with the observed anomaly of the 1970s. In any event, the anomaly does not alter the close correspondence between model and observations.

In summary, the PCM, forced by anthropogenic constituents, produced changes in heat content in each of the major oceans over the last 45 years that are highly similar to those observed.

The vertical development of the oceanic

warming signal in the PCM for the world's oceans is shown in Fig. 2. Here we show the time evolution, from the start of the integrations (1870) through the year 2000, for the average of the five-member ensemble. The scatter among the five realizations allowed us to estimate a standard deviation that was used to filter the

results so that temperature anomalies exceeding a 90% confidence limit are indicated by the gray shaded areas.

The nature of the warming in the various oceans is markedly different. The Atlantic, particularly the South Atlantic, shows strong vertical convection taking the signal to depth

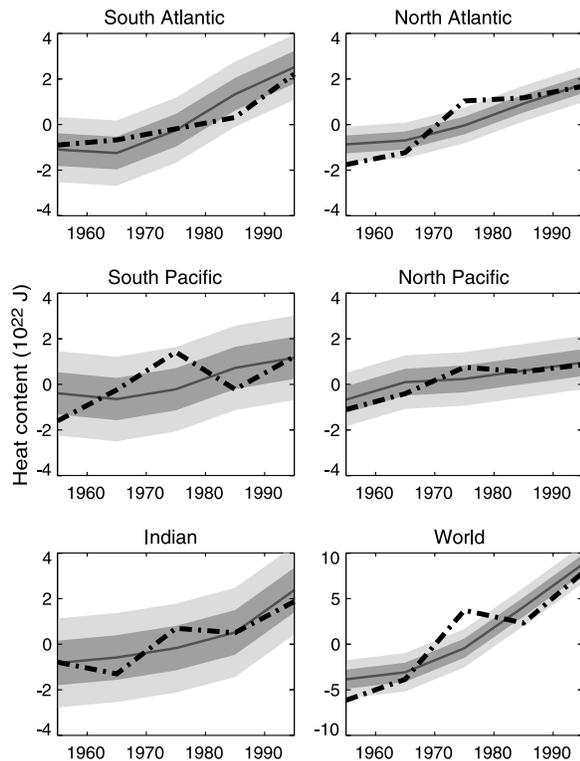


Fig. 1. Decadal values of anomalous heat content (10^{22} J) in various ocean basins. The heavy dashed line is from observations (14), and the solid line is the average from five realizations of the PCM (16–19) forced by observed and estimated anthropogenic forcing. Both curves show significant warming in all basins since the 1950s. The shaded bands denote one (heavy shading) and two (light shading) standard deviations about the model mean signal estimated from the standard deviation in the scatter of the five-member ensemble. The heat content is computed over the upper 3000 m of the water column. The space/time sampling was identical for both model and observations. Basin averages for the northern oceans are defined between 60°N and the equator. The southern ocean averages are between the equator and 77°S .

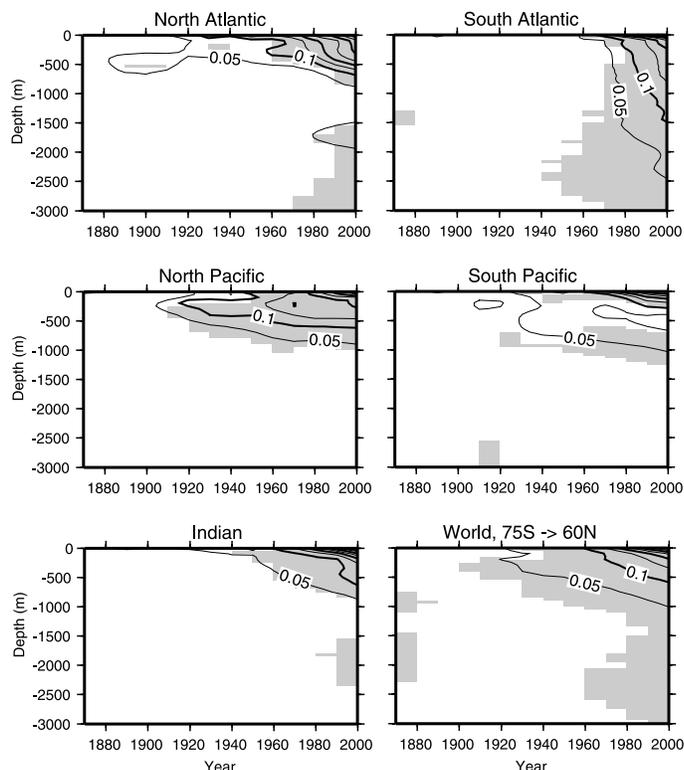


Fig. 2. Decadal temperature anomalies ($^{\circ}\text{C}$) in various ocean basins since 1870 from the PCM. Gray-shaded regions indicate signals statistically distinguishable from zero. The timing of the warming, as well as its vertical structure, varies substantially among the basins. The deep changes in the “World” oceans are seen to be derived solely from changes in the Atlantic. The contour interval is 0.05°C .

quite rapidly. The South Atlantic regional average includes portions of the model's deep-water formation region in the Weddell Sea, so the rapid penetration to depth is expected. The signal is larger in the North Atlantic, but does not appear to penetrate as rapidly, possibly because the regional averaging area in that ocean is large relative to the space scales of deep vertical mixing. In the other oceans, the signal is more consistent with what one would expect from a purely diffusive process. It is important to note that there is little deep water formed in the South Pacific regional average, which otherwise would be expected to resemble the South Atlantic regional average. At any rate, it is apparent that the signal in the deep ocean labeled "world" oceans comes from the Atlantic in the model simulations.

The temporal evolution of the model's vertical temperature structure is compared with observations in Fig. 3, for the North Pacific and North Atlantic Oceans. These are oceans where the data density is highest. In this case, we have concentrated on temperature changes in the upper 2000 m to emphasize the region of maximal signal strength and applied the model-derived significance factors used in Fig. 2 to filter noise from the data.

In the North Atlantic, the observations show a near-surface warming since about 1980, whereas the model begins warming at about 1950. This result may be partially due to the presence of a single, noisy observation set compared with the smoother, ensemble average. However, the penetration of warming with time and depth is otherwise similar between the model and observations. The more-or-less diffusive penetration in the North Pacific is captured in the model, al-

though the very near-surface structure is again somewhat different. These discrepancies in near-surface behavior may be due to the large interannual and decadal variability that the model, running with no real-world input, cannot be expected to capture (unless it were to be forced by the observed fluxes of heat, momentum, and moisture). The model also contains no natural external forcings such as solar or volcanic mechanisms (25). The key point is that the substantial differences in the way the observed warming has penetrated to depth in the two oceans is reasonably well captured by the PCM, albeit with the caveats noted above.

We examined whether the model-produced changes in ocean heat content are different from those expected by chance, e.g., different from those expected in a long control run of the PCM. This indicates whether a significant climate change has been observed in the forced model runs. We further examined whether the model-produced changes are statistically consistent with the observations. The first question addresses the detection of climate change, whereas the second examines whether anthropogenic forcing could be responsible for the observed changes.

The detection and attribution method that we use here is termed "optimal detection" and is well documented (3, 26–28). The basic idea is to compute the space/time pattern of change predicted by the model—the anthropogenic fingerprint—and its strength. Normalization of the data before estimating these signals by the natural variability or noise, determined from one of two PCM control runs (300 years long), is necessary for "optimal" detection (29, 30). The space/time distribution of the observations are projected

onto this "fingerprint," and the observed pattern strength estimated. We then used the second PCM control run (270 years long) to estimate the level of expected natural variability under conditions where no anthropogenic forcing exists. This latter information allows us to estimate a confidence level on the observations and thus make significance statements about difference between the observed signal strength and the model-predicted signal strength (31)

The analysis showed that a single space/time pattern or fingerprint captured the model's anthropogenic signal well enough that both the optimal and nonoptimal detection analyses gave basically the same result. From here on, we use a nonoptimal analysis so that both control runs can be used to estimate levels of natural variability. The signal strength of this pattern from each of the five realizations and their mean value are shown in Fig. 4. Also shown is the signal strength for the observations projected onto the model fingerprint. The projection of the control run data onto this fingerprint allows a noise estimate for computing significance. These latter values were expressed as 95% confidence intervals and centered on the mean model value to facilitate discussion (stippled region).

The confidence limits do not include the origin (the "no signal" or no climate change

Fig. 3. Modeled and observed temporal and vertical changes in the temperature in the upper 2000 m of the data-rich North Pacific and North Atlantic Oceans. Near the surface, where interannual and decadal changes and external forcings strongly affect the thermal structure, any agreement is largely due to chance. Gray-shaded regions denote areas where changes are statistically different from zero. The model broadly reproduces the main features of the vertical structure and its temporal evolution over the last 40 years. The contour interval is 0.05°C.

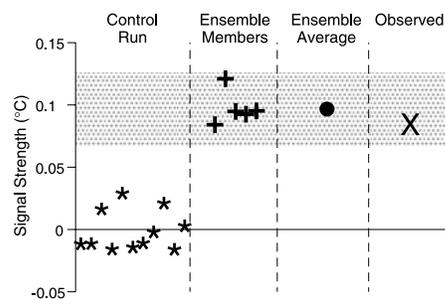
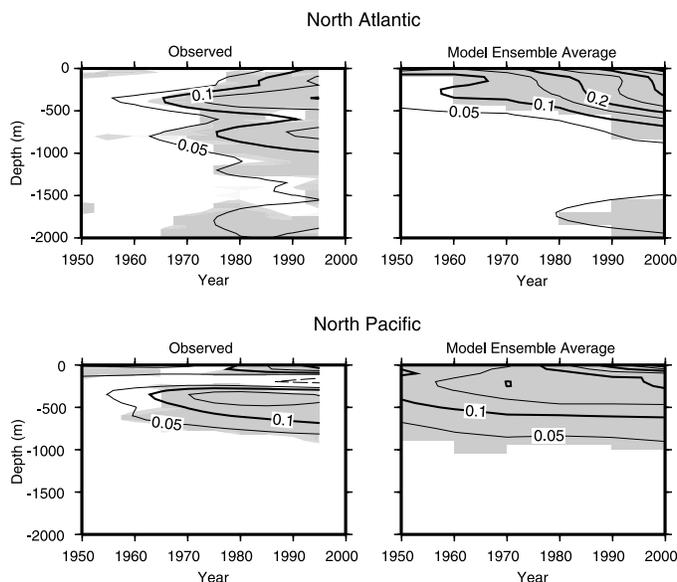


Fig. 4. Detection and attribution diagram. The strength of the anthropogenic pattern of model-predicted changes in depth-averaged ocean temperatures (°C) is shown for each of the five realizations (+) and their ensemble average (●). Also shown is the strength of the model-predicted signal in the observations (X). The lightly stippled region corresponds to the 95% confidence region, centered on the ensemble average, associated with natural variability as estimated from the PCM control runs [see (31)]. The individual signal-strength estimates for independent 45-year chunks of the control run are indicated (*). All forced runs, their mean, and the observations fall within the 95% confidence region and so are indistinguishable from each other, i.e., the model-produced signal and the observations are "consistent" with each other. The uncertainty region does not include the origin, so that natural variability, as estimated by the model, cannot explain the signal in the observations. The results are for the nonoptimal detection method, but do not differ appreciably from that for the full optimal approach.

case), and so the mean of the anthropogenic runs is highly significant and detection of a climate change signal in the model has occurred, i.e., the mean is not expected to occur by chance in the control run. Further, the differences between the various model runs and the observed state all fall within the confidence limits, so that we cannot distinguish between any of the five realizations or the observations. They are all identical from a statistical point of view. Hence, we say that the observations are consistent with the anthropogenically forced model results. This suggests, with confidence exceeding 95%, that one may accept anthropogenic forcing as one possible explanation for the observed changes in heat content of the global oceans. There may be other possible explanations that were not included in the model simulations—hence the word “consistent” used above.

The work reported here yields strong results, but some caveats are necessary. The observational data are sparse in the southern oceans before the 1980s, which should be kept in mind when comparing the observations with the model and when using model and observed data from these regions in a detection methodology. However, our subsampling method of using model data only where comparable observations occurred should largely overcome this problem for detection purposes. Finally, the estimates of natural variability used in the detection work were derived from simulations—not observations, which do not exist in sufficient quantity for this purpose.

A very low frequency variability, perhaps drift, can be seen in the model control run that varied in magnitude and sign from ocean to ocean. The time scale of this variability was on the order of hundreds of years, much longer than the 45-year time slices used in this study. Sensitivity studies suggest that it has not affected our analysis. We suggest that the control run be extended to an order of 1000 years in future studies, as has been done by other centers, to better evaluate natural variability in the model and the role of ultralow-frequency change. In addition, the forced runs we used for detection did not include indirect sulfate, ozone, so-called black aerosols, and other anthropogenic factors, nor did they include external forcing due to solar variability and volcanic activity [e.g., (25)]. Most of the excluded factors introduce a cooling that might negate the fact that the model is a little too warm.

The detection and attribution study used regional and vertical averages. A more complete analysis should consider the full three-dimensional structure of the signal and noise fields. Such an analysis is currently in progress, although we do not expect it to change the major conclusions presented here. Further confirmation of our results comes

from a similar analysis of anthropogenically forced runs at the Max Planck Institute in Hamburg, Germany (32).

Perhaps the most important aspect of this work is that it establishes a strong constraint on the performance and veracity of anthropogenically forced climate models. For example, a climate model that reproduces the observed change in global air temperature over the last 50 years, but fails to quantitatively reproduce the observed change in ocean heat content, cannot be correct. The PCM has a relatively low sensitivity (less anthropogenic impact on climate) and captures both the ocean- and air-temperature changes. It seems likely that models with higher sensitivity, those predicting the most drastic anthropogenic climate changes in the future, may have difficulty satisfying the ocean constraint. To our knowledge, the PCM is the only model currently able to do this and still accurately reflect the changes in surface air temperature over the last 50 years. Future studies should take into account the ocean constraint when deciding which future climate summaries are most reliable.

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15. The five anthropogenic runs were started from different points in the control run separated by 10 years. The forcing was prescribed according to observed and projected estimates of the concentration of greenhouse gases and the direct effect of sulfate aerosols. See (17) for details of these runs and their forcing. Each run lasted from 1870 to 2000. We subtracted from each run the corresponding 130-year section of the control run. This effectively created anomalies and removed ultralow-frequency variability and/or consistent model drift from the subsequent analysis.
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19. The atmospheric component of the PCM is the CCM3 atmospheric general circulation model (AGCM) developed at the National Center for Atmospheric Research (NCAR) and is used at T42 resolution (about 280 km by 280 km grid). The CCM3 includes a land surface model that accounts for soil moisture, vegetation types, and so forth. The University of Texas (Austin) parallel river transport model is a new component of the PCM and is designed to match the resolution of the atmospheric model. The ocean component of PCM is the Parallel Ocean Program (POP) model developed jointly by Los Alamos National Laboratory, Naval Postgraduate

School (NPS), and NCAR. This model has unusually high spatial resolution for an anthropogenic scenario integration, with grid spacing of about 0.67° latitude/longitude except near the equator, where the grid interval is 0.5°. The final major model component of PCM is a sea-ice model developed by Y. Zhang at NPS, which has a 27-km resolution and uses an elastic-viscous-plastic formulation. The sea-ice formulation treatment is especially important for reproducing a realistic feedback mechanism between sea-ice processes and climate-change forcings. The model uses no flux corrections. Full references and further details of the model can be found at www.cgd.ucar.edu/pcm.

20. The model and Levitus (14) data set were interpolated onto a common grid. Each model grid point was sampled only if there was a nonzero value in the Levitus grid point fields (the “gp” set), indicating the influence of an observation; other locations were set to climatology. Thus, the observed and model-predicted heat-content changes were computed in exactly the same manner. Full sampling of the model grid indicated little change in the results, especially after 1970. In the northern oceans, there was no change due to the heavier sampling in those oceans. Indeed, the “gp” coverage after 1956 to a depth of 3000 m is typically 80 to 90% by volume in all basins, with the exception of the South Pacific, where it varies between 60 and 80% for the period 1975 to 1990, before returning to above 90%. The role of ocean eddies in this data set is one of uncorrelated, quasi-random noise. The spatiotemporal smoothing used in this study effectively eliminates eddy contamination.
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30. The noise was estimated from the control-run heat-content values after removing a quadratic fit to the 300 years of record for each basin. The changes in heat content on time scales of 50 years were not affected by removal of this ultralow-frequency variability. The detection analyses described in (31) were done with and without this filtering. In the case of no filtering, i.e., the low-frequency signal left in the data, the distribution of heat-change estimates was strongly biased negatively, i.e., toward ocean cooling. This analysis made the detection significance statements unrealistically strong in our view. Analysis with the low frequency removed resulted in detection statements that, although still strong, we believe are much more conservative than those made with the low-frequency changes left in the data. We also removed a simple trend fit, instead of the quadratic, and found that the results were not affected.
31. The detection data consisted of five decadal values of anomalous heat content for each of six ocean basins. These data were concatenated for each of the five realizations, giving a total of five series each 30 (=5 × 6) terms in length. These series include the space and time variations of the heat content for each realization as in (28). The data were both (i) weighted by the appropriate noise estimate derived from the control run for an optimal detection and (ii) left unweighted. The covariance of either of these data were computed by using true ensemble-averaging techniques. The leading empirical orthogonal function (EOF) of these covariance matrices accounted for 87% of the data set variance and is referred to in the text as the anthropogenic “signal.” The second and higher EOFs in either case were statistically degenerate and not considered further. The associated principal components give the strength of the model’s anthropogenic signal. The dot product of the observations, weighted (or unweighted) as noted above, and the signal gave the “observed” strength of

the signal. The significance of these estimates was tested against nonoverlapping 45-year-long slices of data derived from the control run, i.e., against the hypothesis that the heat-content changes in the anthropogenic runs could have occurred as a result of natural, internal variability in the absence of any anthropogenic forcing. Forty-five-year chunks of the control run data were processed just as the observations and five anthropogenic realizations were processed, and then projected onto the signal. The results show that the signal strengths of the five realizations and observations are quantitatively similar and nonzero relative to the uncertainty of the natural variability of the model, i.e., the model and observed

projections are statistically consistent and not expected to occur as a result of internal model variability. The confidence associated with this statement exceeds 95%. With no variance weighting, i.e., non-optimal detection, the results were essentially identical, if not a little stronger than in the optimal case.

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Climate Response to Orbital Forcing Across the Oligocene-Miocene Boundary

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Spectral analyses of an uninterrupted 5.5-million-year (My)-long chronology of late Oligocene-early Miocene climate and ocean carbon chemistry from two deep-sea cores recovered in the western equatorial Atlantic reveal variance concentrated at all Milankovitch frequencies. Exceptional spectral power in climate is recorded at the 406-thousand-year (ky) period eccentricity band over a 3.4-million-year period [20 to 23.4 My ago (Ma)] as well as in the 125- and 95-ky bands over a 1.3-million-year period (21.7 to 23.0 Ma) of suspected low greenhouse gas levels. Moreover, a major transient glaciation at the epoch boundary (~23 Ma), Mi-1, corresponds with a rare orbital congruence involving obliquity and eccentricity. The anomaly, which consists of low-amplitude variance in obliquity (a node) and a minimum in eccentricity, results in an extended period (~200 ky) of low seasonality orbits favorable to ice-sheet expansion on Antarctica.

Orbital dynamics are thought to have driven Quaternary climate change, but their effects in earlier times when climate boundary conditions differed have been difficult to resolve. Here, we examine the late Oligocene and early Miocene (~20.0 to 25.5 Ma), a time when Antarctica was either ice-free or only partially glaciated, using a 5.5-My-long high-fidelity benthic foraminiferal stable isotope record. This record is a composite constructed largely with newly collected data from Ocean Drilling Program (ODP) Site 926, Ceara Rise (3°43'N, 42°54'W), as well as data from Site 929. Sedimentation rates at Site 926, which is located at a depth of 3598 m where carbonate dissolution is reduced, are as much as 50% higher than at Site 929 and other deeper sites (1).

We use the age model of Shackleton and

colleagues (2) for our isotope records. They calibrated proxy records of Oligocene and Miocene lithologic cycles, including magnetic susceptibility (MS), in the Leg 154 cores (3) to an orbital curve (4) using modern values for tidal dissipation and dynamical ellipticity (5). They achieved an absolute calibration by pattern matching the 400-ky cycles of eccentricity-modulated precession in MS with similar cycles in the target curve. They then used individual obliquity maxima to establish the fine-scale tuning and verified this by comparing the 1.2-My amplitude modulation of obliquity in the data. The astronomical age derived for the Oligocene-Miocene (O/M) boundary, as recognized by the presence of *Sphenolithus delphix* and a positive carbon isotope anomaly of 0.65‰, is roughly 700 ky younger than that established in the radiometric calibrated time scale (6).

We developed high-resolution (~3.7 ky) carbon and oxygen isotope records for benthic foraminifera specimens collected from Hole 926B (7). Our records match those for Hole 929A (8) for each cycle down to the obliquity level over the interval of overlap (926B, 20.0 to 25.2 Ma; 929, 20.5 to 25.4 Ma) (Fig. 1A). The only no-

ticeable differences are the higher frequency oscillations present in the 926 record (e.g., precession) that are not resolved at Site 929 because of lower sedimentation rates (26 m/My for Hole 926B versus 19 m/My for Hole 929A across the O/M boundary). The ranges of isotope values are similar despite the nearly 1 km difference in water depth between sites. This similarity implies that the deep water in this part of the Atlantic was chemically homogeneous over much of this period and that a large portion of the variance in the isotopic record is signal.

The most prominent feature of the records is a positive excursion in $\delta^{18}\text{O}$ coupled with a positive shift in $\delta^{13}\text{C}$ values at 23.0 Ma, the Mi-1 excursion. This event, which can be distinguished in other deep-sea $\delta^{18}\text{O}$ records (9), is characterized by a series of obliquity period cycles beginning at 23.3 Ma over which $\delta^{18}\text{O}$ increase, to a peak at ~23.0 Ma. This peak is followed by a series of three declining cycles (deglaciations) over the next ~150,000 years. Thereafter, the cycles appear to be predominantly 100 ky. A second, but weaker, positive $\delta^{18}\text{O}$ excursion occurs at 21 Ma. The $\delta^{13}\text{C}$ values show low-frequency cycles that increase in amplitude and value, eventually peaking from 23.0 to 21.6 Ma, after which they decline.

To ascertain the nature of the high-frequency signals in the isotope records, we first built composite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ time series by splicing gaps in the Hole 926B records with grafts from the Hole 929A records [Web table 1 (10)]. We then applied band-pass gaussian filters to each isotope record as well as the orbital calculations and MS to extract oscillations associated with 400-, 100-, and 41-ky cycles [AnalySeries (11)] (Fig. 1B). In the 400-ky band, both the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ filters co-vary with the 400-ky filter of eccentricity, in that they appear phase-locked between 20 to 24 Ma. Also, the 400-ky eccentricity-related amplitude modulation of $\delta^{13}\text{C}$, and to a lesser extent $\delta^{18}\text{O}$, exhibits a pattern similar to that of the orbital modulation, including subtle peaks near ~21.4 and 23.0 Ma (Fig. 1B). The amplitude of the 400-ky filter of $\delta^{18}\text{O}$ increases only after 23.4 Ma, just below the O/M boundary. This is the

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