

Abstracts for the AGU Fall Meeting 10–14 December 2001

Union

U11A MC: 134 Monday 0830h

Milankovitch and Climate:

Twenty-five Years Later I (*joint with OS*)

Presiding: T J Crowley, Duke

University; W Prell, Brown University

U11A-01 0835h

Astronomical Solutions for Paleoclimates Studies

JACQUES LASKAR ((33) 1 40 51 21 14;
laskar@bdl.fr)

ASD/IMC, Observatoire de Paris, 77 av Denfert-Rochereau, PARIS 75014, France

The acceptance and development of Milankovitch astronomical paleoclimate theory resulted largely from accurate measurements of various geological indicators of the climate of the past, starting with the celebrated work of (Hays, Imbrie, and Shackleton, 1976), but also from the improvement of the computed past evolution of the orbital and rotational motion of the Earth, in continuation of the work of LeVerrier (1856) which was already used by Croll (1864) and Milankovitch (1930). In the past 25 years, there was also a steady improvement of these orbital or rotational solutions (Bretagnon, 1974, Berger, 1976, Laskar, 1988, Quinn et al, 1991, Laskar et al, 1993) which have followed the improvement of the quality of geological data.

In the recent years, there has been a large improvement in the quality of the geological data, as well as the time length on which they are collected as they now span more than 30 million years in continuous records.

This motivated the construction of an improved solution for the orbital and rotational motion of the Earth which will be presented here.

U11A-02 0850h INVITED

Some Novelties in the Astronomical Theory over the Last Decades

Andre L. BERGER¹ (32-10-47-33-03;
berger@astr.ucl.ac.be)

Marie-France LOUTRE¹ (32-10-47-32-99;
loutre@astr.ucl.ac.be)

Michel CRUCIFIX¹ (32-10-47-33-65;
crucifix@astr.ucl.ac.be)

¹Institut d'Astronomie et de Geophysique G. Lemaitre Universit catholique de Louvain, Chemin du Cyclotron, 2, Louvain-la-Neuve 1348, Belgium

The paper by Hays, Imbrie and Shackleton has triggered a lot of research over the last decades. These lead to new developments and to a generalisation of the Milankovitch theory. The Louvain-la-Neuve team has focussed mainly on the orbital parameters and the transient response of the climate system to the astronomically-induced insolation changes.

The orbital solution available in the late 70's has been shown accurate for 1.5 million years and is extended now over a few million years. The prediction made in 1982 that " a time will come when geologists will provide astronomers with estimates of periodicities ... and discuss with them which paleoastronomical effects should be added to the gravitational model " is realized. The origin of all the fundamental frequencies characterizing the long-term variations of the orbital parameters has been identified allowing to discuss their interrelationship and possible changes in times. Different sources for the 100-kyr astronomical cycle can be found in the orbital parameters and in the insolation itself. Instability of the 100-kyr eccentricity cycle has been shown related to its 400-kyr cycle. The amplitude and frequency modulations of the orbital parameters are also discussed.

The 2.5-D Climate model of LLN (one of the very first Earth models of intermediate complexity) has succeeded to simulate the entrance into glaciation 2.75 million years ago, the late Pliocene - early Pleistocene obliquity and precession cycles, the emergence of the 100-kyr cycle around 900 kyr BP, the glacial-interglacial cycles of the last 600 kyr, the stage 11-stage 1 analogy and the future climate at the astronomical time scale. Finally, the climate model points out that the length of the simulated MIS11 interglacial is very

sensitive to the interplay between insolation and CO₂, i.e. it depends strongly on the phasing between these two climate forcings. Although the present and near future insolation forcing is very similar to stage 11, the exceptionally long interglacial simulated for the future is much more robust.

An higher resolution version of this model (including 3 oceanic basins and the thermohaline circulation) allows to discuss the climate of isotopic stage 5, the late glacial, the last deglaciation, the Holocene, the last 1000 years and the last and next 100 years.

U11A-03 0905h INVITED

The 100 Kyr Ice Age Cycle: Inception and Demise

Richard W. Peltier (416-923-0829;
peltier@atmos.physics.utoronto.ca)

University of Toronto, Department of Physics,
Toronto, ON M5S-1A7, Canada

The quasi-periodic variation of continental ice volume that has been a dominant characteristic of low frequency climate variability since approximately 900 ka continues to defy detailed explanation. Although the linkage between this "ice-age cycle" and the Milankovitch variations of orbital insolation was essentially confirmed by the analyses of Hays, Imbrie and Shackleton (1976), their spectral analyses of deep-sea core oxygen isotopic concentrations provided no explanation of why the 100 kyr component of the ice volume response should be so dominant. Since the intensity of the forcing on the 100 kyr timescale is inconsequential, it seems clear that the explanation of this component is to be found in climate system nonlinearity. I will describe two different lines of analysis which provide insights into the detailed nonlinear mechanics of the 100 kyr cycle. It will first be established, through detailed AGCM analyses of the inception process, that the cycle is initiated entirely by the deficit in summer seasonal insolation which occurs under conditions of high eccentricity and low obliquity, just as Milankovitch suggested. Once nucleated, continental ice sheets thereafter expand as a consequence of ice albedo feedback and the diminishing level of atmospheric CO₂ concentration. Termination, on the other hand, appears to depend upon a collective interaction that involves both glacial isostasy and rising CO₂ levels, the latter playing an essential role.

U11A-04 0920h INVITED

Monsoons and Milankovitch

John E Kutzbach (608-262-2839;
jek@facstaff.wisc.edu)

University of Wisconsin-Madison, Center for Climatic Research
Atmosphere-Ocean Sciences, Madison, WI 53706, United States

Insolation changes associated with orbital changes alter the broad-scale land/ocean temperature contrasts and thereby cause variations in the strength of continent-scale monsoon circulations. Whereas Milankovitch concentrated on explaining the role of orbital changes in causing glacial cycles, he noted that orbital changes would influence tropical climates too. However, the connection between orbital changes and monsoons was largely ignored until the late 1970s-early 1980s, when accurate dating of wet/dry events in the tropics became available. The first quantitative studies of monsoon changes and orbital changes using climate models commenced around 1980. These studies documented a strong sensitivity of monsoons to orbital forcing, a conclusion that had been reached by a contemporary of Milankovitch, Spitaler, in 1921.

This paper summarizes Milankovitch's remarks about tropical climate variability, describes the key observational studies that began to implicate orbital changes as a possible factor in tropical climate change, illustrates the basic response of monsoons to orbital forcing, and outlines current research aimed at clarifying the role of oceans and the terrestrial biosphere in explaining the full magnitude and character of the climate's response to orbital forcing.

U11A-05 0935h

Simulating the Effect of Insolation Changes on Climate

Uwe Mikolajewicz (+49-40-41173-243;
mikolajewicz@dkrz.de)

Max-Planck-Institut fuer Meteorologie, Bundesstrasse 55, Hamburg D-20146, Germany

It has been known for a long time that changes in solar insolation are responsible for at least some of the past climate changes, which can be implied from a variety of proxy records. However the changes in solar insolation alone are not large enough to be able to account for both the magnitude as well as for the abruptness of some past climate variations. Obviously the external forcing must have been strongly modified by several (nonlinear) feedback mechanisms of the earth's climate system. Here a coupled atmosphere-ocean model has been used to investigate the effect of changes in insolation on the climate on the earth and to identify the most relevant feedback mechanisms.

U11A-06 0950h

MILANKOVITCH AND ICE CORE RECORDS

Jean JOUZEL (33 1 69 08 57 71;
jouzel@lscce.saclay cea.fr)

IPSL-LSCE, CE Saclay Orme des Merisiers Bat 709,
Gif sur Yvette 91191, France

At the time of the publication of the Hays, Imbrie and Shackleton article, available ice core records were too short to bring information relevant to the Milankovitch theory of the ice ages (no ice core was going beyond the last glacial period). The situation changed in the eighties with the Vostok ice core then covering a full glacial-interglacial cycle. Also measurements dealing with the composition of our atmosphere in the past (CO₂ and CH₄, two important greenhouse gases, and δ18O_{atm} the isotopic composition of atmospheric oxygen) became available, in addition to the isotopic composition of the ice classically used to reconstruct past temperature changes in polar regions. Those Vostok data, further extended to 4 climatic cycles, showed that orbital frequencies are strongly imprinted in all records with a dominance of the 100 kyr cycle for all series except δ18O_{atm} dominated by precession, and a strong contribution of obliquity to the temperature record probably linked to local insolation changes. They revealed a close correlation between greenhouse gases and climate, suggesting that greenhouse gases are important as amplifiers of the initial orbital forcing and may have significantly contributed to the glacial interglacial changes. They also pointed out to the fact that the interaction between insolation and climate is probably more complex than initially thought, with an important role of the Southern Hemisphere illustrated by the lead of Antarctic temperature and CO₂ with respect to ice volume. I will review how the Vostok records have shed light on the Milankovitch theory of the ice ages during the last 20 years and discuss recent advances (as the possibility of extracting information on sea level and sea surface temperature changes from ice core records). Still, further research is needed to fully understand the complex interactions between insolation, CO₂ and climate at those timescales. In this line, I will examine ongoing work aiming to improve ice core dating and the determination of the phasing between climate forcings and responses.

U11A-07 1025h

The Sea of Okhotsk; a Window on the Ice Age Ocean

James D. Hays¹ (845 365 8403;
jimhays@ldeo.columbia.edu)

Joseph Morley (845 365 8403;
morley@ldeo.columbia.edu)

¹Lamont Doherty Earth Obs. Columbia University,
Lamont Doherty Earth Obs., Palisades, NY 10964,
United States

Radiolarian faunas of glacial age high-latitude deep-sea sediments are dominated by *Cycladophora davisiana*. In recent sediments, only those of the Sea of Okhotsk have comparable relative abundances. The sea of Okhotsk supports an unusually abundant deep-water fauna (>200meters). A sediment trap array in the central Sea of Okhotsk, had annual daily mean radiolarian flux to the deep trap (1061 meters), more than four times that to the shallow trap (258). Ninety eight percent of *C. davisiana* flux was caught by the deep. Of the species that dominate Okhotsk radiolarian fauna, twice as many live below the shallow trap as live above it. Russian net zooplankton studies reflect a similar vertical partitioning with 80% of the biomass living below 200 meters. Estimates of carbon required to support the deep fauna are a high percentage of carbon fixed suggesting an efficient biological pump. Efficiency is probably enhanced by very cold water between 50 and 150 meters (near or below zero celsius), with low concentrations of zooplankton permitting phytoplankton production to sink to deeper levels.

U11A-08 1040h

Present Status and Applications of the Astronomical (Polarity) Time Scale for the Mediterranean Late Neogene

Frederik Hilgen (+31-302535173; fhilgen@geo.uu.nl)
 IPPU, Faculty of Earth Sciences Budapestlaan 4,
 Utrecht 3584 CD, Netherlands

Following the initial tuning of late Pliocene-Pleistocene $\delta^{18}\text{O}$ records from the open ocean, the astronomical time scale was extended to the base of the Pliocene, using sedimentary cycle patterns observed in land-based marine sections from the Mediterranean. Here I will present a review of the progress subsequently made in establishing an Astronomical (Polarity) Time Scale (A(P)TS) for the Mediterranean Neogene by our research group and (inter)national collaborators. Firstly, the astronomical time scale has been extended back to 13.6 Ma. Secondly, this time scale has been evaluated and the accuracy of astronomical solutions quantitatively assessed by means of a detailed statistical comparison of precession/obliquity interference patterns in climatic proxy records and astronomical target curves. Thirdly, the existent Messinian gap in the time scale has been closed, showing that the onset of the Messinian salinity crisis started at exactly the same time all over the Mediterranean. Fourthly, the continental record is increasingly being incorporated, allowing detailed "bed-to-bed" correlations with the marine record and extension of the APTS back to 13 Ma. Fifthly, $^{40}\text{Ar}/^{39}\text{Ar}$ dating of volcanic ash beds intercalated in astronomically dated successions aims at the intercalibration of astronomical and radio-isotopic time. Sixthly, identification and astronomical tuning of Milankovitch-type of cyclicity facilitates detection of sub-Milankovitch cycles both in the marine and in the continental record. Seventhly, climate modelling is applied to get a comprehensive understanding of climate system(s) responsible for sedimentary cycle formation in the Mediterranean late Neogene. Finally, the influence of longer-term astronomical cycles which operate on tectonic time scales has been evidenced and the astronomical time scale has been successfully applied in studies of seafloor spreading rate histories.

U11A-09 1055h INVITED

Variations in the Earth's Orbit: Pacemaker of the Indian Monsoon.

Steven C. Clemens (1-401-863-1964;
 Steven.Clemens@Brown.edu)

Brown University, Geological Sciences, Providence, RI
 02912-1846, United States

Much has changed in the 25 years since Hayes, Imbrie and Shackleton (Science, 1976) developed their SIMPLEX, ELBOW AND TUNE-UP age models. Highly resolved paleoclimate records are far longer, the number of reliable climate proxies has greatly increased, and numerical modeling of paleoclimate has advanced significantly, now linking atmospheric, oceanic, and terrestrial subsystems. However, one crucial aspect of our science remains the same, we still live and die by the age model, struggling to understand the physical links between external insolation forcing and the internal climate response. Our interpretations of these relationships often depend on critical assumptions we employ in age-model development. The Plio-Pleistocene summer monsoon system is a good example. The critical assumption in the age model used here is that phase of the oxygen isotope response to orbital forcing is invariant (set at the SPECMAP defined lags of 69 degrees for the 41-kyr obliquity cycle and 78 degrees for the 23-kyr precession cycle). The assumption of constant phase relationships between a tuning parameter and orbital forcing is nearly universal in age model development for Plio-Pleistocene records.

Using the SPECMAP chronology, the late Pleistocene summer monsoon record (350 Ka) is in phase with Northern Hemisphere summer radiation forcing for the obliquity band but lags by 7 to 8 kyrs for the precession band. While somewhat complex, the phase response can be understood within the context modern monsoon meteorology, which indicates that much of the interannual variability is related to the export of latent heat from the southern subtropical Indian Ocean. The obliquity- and precession-band phase relationships can be interpreted in the same context, the timing of Southern Hemisphere latent heat export sets the phase of monsoon maxima within each 41- and 23-kyr cycle. This interpretation indicates that the monsoon is more sensitive to internal climate interactions in the Southern Hemisphere than to external insolation forcing in the Northern Hemisphere.

When the same phase-locked chronology is applied to the Plio-Pleistocene record (2.5 Ma) the phase of the monsoon systematically drifts relative to oxygen isotopes, by 83 degrees in the precession band and 124 degrees in the obliquity band. The timing of strong monsoons within each cycle moves away from the developing ice maxima suggesting that the development of Northern Hemisphere glacial boundary conditions weaken the summer monsoon. This phase drift is independent of the age model in that the oxygen isotopes and monsoon indicators are from the same samples. Phase relationships relative to external forcing

are more complex. The non-stationary phase implies that the monsoon response, the oxygen isotope response, or both are nonstationary relative to orbital forcing. This calls into question the common assumption used in Plio-Pleistocene age models, that the climate response is necessarily phase-locked to orbital forcing during the interval of time spanning the intensification of Northern Hemisphere glaciation. So, after 25 years we still struggle with similar questions Hayes, Imbrie and Shackleton grappled with, only now applied to older but equally dynamic periods of Earth history.

U11A-10 1110h INVITED

Climate Response to Orbital Forcing Across the Oligocene/Miocene Boundary (19.5-26.0 Mya)

James C Zachos¹ (831-459-4644;
 jzachos@es.ucsc.edu)

Justin Revenaugh¹ (jrs@es.ucsc.edu)

Nicholas J Shackleton² (njs5@rock.esc.cam.ac.uk)

Heiko Palike² (hp201@hermes.cam.ac.uk)

¹University of California, Earth Sciences Dept.,
 Santa Cruz, CA 95060, United States

²Cambridge University, Godwin Laboratory for Quaternary Studies, Cambridge CB2 3SA, United Kingdom

Since the publication of Hays et al. (1976), earth scientists have labored to extend high-resolution isotope-based paleoclimate records back in time, well beyond the period of Northern Hemisphere glaciations. This effort has been motivated in part by the desire to develop astronomically calibrated time-scales for more ancient periods, and in part by the desire to observe the climate response to orbital forcing under boundary conditions significantly different than present. Progress toward these objectives, which was initially hampered by the lack of high quality sedimentary sequences, has accelerated over the last decade, primarily due to efforts of the Ocean Drilling Program. As a result, high fidelity isotope records with sufficient resolution to capture orbital scale cyclicity now exist for several discrete intervals of the Neogene and Paleogene. This paper focuses on one of these records, a continuous 5.5 Myr long, high-fidelity composite benthic isotope time-series spanning the late Oligocene-early Miocene interval of ODP Sites 926 and 926 from the western equatorial Atlantic. This record shows the unquestionable signature of orbital forcing with variance concentrated at all Milankovitch frequencies. Unlike the Pleistocene, the isotope records show unusually strong power at the primary eccentricity band periods of 406, 125, and 95-ky with an extremely close correlation between the amplitude modulation of the orbital eccentricity signal and that of the oxygen isotope record. The low frequency oxygen isotope cycles, which represent in part glacial advances and retreats of Antarctic ice-sheets, also increase in amplitude across the O/M boundary suggesting a shift in climate sensitivity to forcing, possibly due to a reduction in greenhouse gas levels. Here, we explore the potential implications of these findings for fundamental theories of orbital forcing and climate.

U11A-11 1125h INVITED

Grand Cycles of the Milankovitch Band

Paul Eric Olsen (845-365-8491;
 polsen@ldeo.columbia.edu)

Lamont-Doherty Earth Observatory, Rt 9W, Palisades, NY 10964, United States

Celestial mechanical theory predicts not just the familiar set of Milankovitch cycles of about 21, 41, and 100 ky, the climatic significance of which was established 25 years ago by Hays, Imbrie, and Shackleton (1); but also longer period cycles "grand cycles" with present day periods of about 400 ky, and 1.25, 2.35 and 4.6 my. The effects of these longer period cycles are only potentially discernable, convincingly, in very long climate records spanning several to tens of millions of years. However, long term chaotic drift in the fundamental frequencies of the planets makes the actual value of all - except the 400 ky - grand cycles, unpredictable for records older than about 50 Ma (2). Added uncertainty exists because of the poorly understood evolution of the Earth-Moon system, which makes calibration by the high frequency precession and obliquity cycles unreliable for distant times. The 400 ky cycle provides a reliable tuning target for long ancient records because it is caused by the gravitational interaction of Jupiter and Venus, the former of which has an extremely stable orbit.

One of the longest paleoclimate records available is that resulting from the Newark Basin Coring Project (NBCP), with 6700 m of Triassic-Jurassic lacustrine strata, spanning about 30 my years. Based on evolutive thickness-frequency spectrograms, the major higher-frequency precession-related cycles are all present, with an especially strong 400 ky signal. Tuning to the 400 ky cycle reveals significant low-frequency cycles of 1.75

and 3.5 my (3). The former is homologous to the present day 2.35 my grand cycle, which modulates climatic precession, and is caused by the gravitational interaction of Earth (g3) and Mars (g4); the observed difference is well within the predicted chaotic region (4) of the fundamental frequencies (g4-g3). The latter 3.5 million year cycle is a homologue of the present day 4.6 my grand cycle. This cycle is a consequence of the secular resonance, theta (2(g4-g3) - (s4-s3)) (2,4).

Identification of these long period cycles is essential, because what may appear to be unique climatic transitions could actually be nodes of the grand cycles superimposed on a longer climatic trend. Also, because the NBCP record has virtually no expression of high frequency obliquity cycles (as expected by its tropical position), the presence of the 3.5 my cycle suggests some large-scale climate system telecommunication between the Triassic continental tropics and regions sensitive to obliquity, perhaps through weathering-modulated atmospheric CO₂. In addition, the presence of the 1.75 and 3.5 my grand cycles suggests that the mode of the secular resonance in the Triassic was not different to that of today, as is theoretically possible (2). Finally, the long period cycles should be globally synchronous, and hence they offer a new low-frequency means of cyclostratigraphic correlation. References: (1) Hays, J. D., Imbrie, J. and Shackleton, N. J. 1976. Science 194:1121. (2) Laskar, J. 1999. Phil. Trans. Roy. Soc. Lond. A, 357:1735. (3) Olsen, P. E. and Kent, D. V. 1999. Phil. Trans. Roy. Soc. Lond. A, 357:1761. (4) Laskar, J. 1990. Icarus 88:266.

URL: <http://www.ldeo.columbia.edu/~polsen/nbcp/nbcp.html>

U11A-12 1140h

Milankovitch in the Miocene

Nicholas J Shackleton (44-1223-334876;
 njs5@cam.ac.uk)

University of Cambridge, Dept of Earth Sciences,
 Godwin Laboratory Pembroke Street, Cambridge
 CB2 3SA, United Kingdom

Even without Shackleton's collaboration it is highly probable that an important paper by Hays and Imbrie relating to the astronomical theory of the Pleistocene ice ages would have appeared in the mid 1970's with the important data being Hays' radiolarian counts. Given Hays' expertise in the stratigraphic correlation of core sequences it is also likely that soon after, attempts would have been made to develop an astronomically calibrated time scale even in the absence of stable isotope records. In fact for sequences older than about 2.5 Ma stable isotope data have played a relatively minor part in facilitating astronomical time scale development. The prime requirement has been an ability to handle and interpret complex arrays of stratigraphic data together with the existence of geological deposits that display lithological cyclicity.

The Middle Miocene has proved to be a challenging interval of time to calibrate to an astronomical template. Few continuous sequences are available; good biostratigraphic datums are sparse; and the underlying climatic responses were probably almost as complex as they were in the late Pleistocene. ODP Site 925 on Ceara Rise contains a good sequence from which we have benthic stable isotope data, proxies for percent carbonate, proxies for carbonate dissolution and precise nanofossil biostratigraphy, all in an orbitally calibrated record. In this interval the oxygen isotope record almost certainly records variability in (Antarctic) ice volume as well as temperature, while percent carbonate certainly records variability in all of terrigenous input, carbonate production and carbonate dissolution. The beauty of an astronomical time scale is that even with data from only a single site it becomes possible to begin to tease apart such a complex array of responses, just as Hays and colleagues were able to learn so much about the Pleistocene from a single location in the Southern Ocean.

The Middle Miocene also anticipates the greatest challenge facing the astronomical theory of the Pleistocene ice ages: the 100,000 year cycle. The Middle Miocene data imply 100,000 year cycles in Antarctic ice volume, with increased terrigenous input at this period being associated with glacio-eustatic low stands. However neither the stable isotope signal nor the dissolution proxies have significant precessional variability so that precessional variability in terrigenous content is probably driven by varying river transport. Unlike the Pleistocene, glacial maxima are associated with high eccentricity.

U11B MC: 131 Monday 0830h

Union Education Tutorials

U11B-01 0830h

Union Education Tutorials

James W Head¹ (James.Head_III@brown.edu)