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 δ^{18}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 sa-linity 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}Ar/^{39}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 successful applied in studies of seafloor spreading rate histories.

U11A-09 1055h INVITED

Variations in the Earths 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 Zachos[1] (831-459-4644; jzachos@es.ucsc.edu)

Justin Revenaugh[1] (jsr@es.ucsc.edu)

Nicholas J Shackleton[2] (njs5@rock.esc.cam.ac.uk)

Heiko Palike[2] (hp201@hermes.cam.ac.uk)

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

[2]Cambridge 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 cored 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 nannofossil 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 Head[1] (James_Head_III@brown.edu)

Barbara Thompson[2]

Eric Sundquist[3]

Ed Sarachik[4]

[1]Brown University, Dept of Earth Sciences, United States

[2]NASA Goddard Space Flight Center, Dept of Earth Sciences, United States

[3]USGS-Woods Hole, Dept of Earth Sciences, United States

[4]University of Washington, Dept of Earth Sciences, United States

Four presentations given on the topics of Comparative Planetology, Solar Variability, Carbon Cycle, and Climate Modeling.

U12A MC: Hall D Monday 1330h

Milankovitch and Climate: Twenty-five Years Later II

Presiding: **T J Crowley,** Duke University**; W Prell,** Brown University

U12A-0001 1330h POSTER

Did Climate Friction Really Change the Earth Obliquity ?

Benjamin LEVRARD[1] ((33) 1 40 51 21 32; blevrard@bdl.fr)

Jacques LASKAR[1] ((33) 1 40 51 21 24; laskar@bdl.fr)

[1]ASD/IMC, Observatoire de Paris, 77 av Denfert-Rochereau, Paris 75014, France

The lagged response of continental ice sheets to climate changes of the Earth resulting from obliquity variations and viscoelastic response of the Earth may induce a secular trend in the obliquity (Bills, 1994; Rubincam, 1995; Ito et al, 1995; D.M Williams et al., 1998) although the amplitude of this phenomena called climate friction is still very controversial.

(Ito et al, 1995) predicted a positive drift of $0.04^{\circ}/Ma$ with Late Pleistocene glacial conditions, while D.M Williams et al.(1998) proposed a large decrease of 30° during 100 Ma around the Late Precambrian-Cambrian (ca. 550 Ma) boundary, favoured by the presence of hypothetical huge extented ice cap on a South polar supercontinent, and thus arguing in favor of G.E Williams' high obliquity scenario (1993) as an explanation of low-latitude Precambrian glaciations.

However, these models have considered obliquity as the only ice-age driver, while ice sheets are also probably driven by others Milankovitch periods from eccentricity or climatic precession, or they have used extreme palaeogeographic continental and glacial distributions.

We have revisited the 'climate friction' scenario for the Earth, and show that the absolute value of the secular drift of the Earth's obliquity should not have exceed $0.01^{\circ}/Ma$ for the Late Pleistocene and $0.05^{\circ}/Ma$ for each Neoproterozoic glacial interval. Futhermore, we show that widespread continental glaciations from low to high-latitude during Varanger glacial interval (ca. 610-570 Ma) on Pannotia supercontinent and low-latitude Sturtian continental glaciations (ca. 750-700 Ma) on an equator-straddling Rodinia supercontinent have probably drifted the obliquity in opposite directions inducing a global invariancy of the obliquity during Neoproterozoic Era.

If the Earth suffered a global or partial ice-covered period (Snowball Earth hypothesis), the climate friction effect would be even reduced.

If we take account of possible massive and long Permo-Carboniferous glaciations (ca. 340-260 Ma), we predict that climate friction has probably not changed the Earth obliquity by more than 1 or 2° during the last 800 Ma.

U12A-0002 1330h POSTER

Re-evaluating the Orbital Theory of Pleistocene Climate

Peter Huybers (617-492-7279; phuybers@mit.edu)

Massachusetts Institute of Technology, Bldg 54 rm 17-24 77 Massachusetts Avenue, Cambridge, MA 02139, United States

The presence of orbital-like variation in the $\delta^{18}O$ record was firmly established by Hays et al in 1976. Evaluating the significance of orbital variations in forcing the climate, however, remains an open question. Relying on the numerous long and highly resolved isotopic records made available in the last 25 years, I attempt to evaluate the geographic and temporal variations in the $\delta^{18}O$ record using a minimum number of assumptions. I begin by generating a minimally tuned common time scale for 23 separate $\delta^{18}O$ records, each of which extends through the Brunhes Matuyama magnetic reversal. I then assess the plausible range of observed variability linearly and non-linearly attributable to orbital variations. I find that the phasing and magnitude of the earth's response to orbital changes varies according to both climate state and location.

URL: http://web.mit.edu/phuybers

U12A-0003 1330h POSTER

Physical Record of Milankovitch Cycles from Variations in Sea Level and Ice Sheet Extent on the Antarctic Continent 24 Ma ago

Peter J Barrett[1,2] (*1-650-735-6830; peter.barrett@vuw.ac.nz); Timothy R Naish[3]; Gary S Wilson[4]; Ross D Powell[5]; Peter N Webb[6]; Ken J Woolfe[7]; Cape Roberts Science Team

[1]Antarctic Research Centre, Victoria University of Wellington, P O Box 600, Wellington, New Zealand

[2]Department of Geological & Environmental Sciences Sciences, Stanford University, Stanford, CA 94305, United States

[3]Institute of Geological and Nuclear Sciences, P O Box 30368, Lower Hutt, New Zealand

[4]Department of Earth Sciences, University of Oxford, Parks Road, Oxford, United Kingdom

[5]Department of Geological Sciences, Northern Illinois University, DeKalb, IL, United States

[6]Department of geological Sciences, Ohio State University, Columbus, OH 43210, United States

[7]School of Earth Sciences, James Cook University, Townesville 4811, Australia

Between 1997 and 1999 the Cape Roberts Project (CRP) drilled 3 holes to recover 1500 m of Oligocene and early Miocene strata from the western margin of the Victoria Land Basin (average recovery 95%). The cores record 46 unconformity-bound glacimarine cycles, or depositional sequences, many of which include the direct evidence of grounded ice. The site lies just seaward of the Transantarctic Mountains and of the margin of the present day East Antarctic Ice Sheet, and is thus well-placed to record ice sheet and sea level changes in the distant past.

Studies of the sedimentary facies, paleoecology and seismic geometries indicate that the entire sequence accumulated in shallow coastal waters as part of a laterally extensive seaward-thickening nearshore wedge. The cycles typically begin with an erosion surface followed by glacial deposition (diamictite, sandstone), relatively ice-free open marine sedimentation (mudstone) and shoaling before the overlying unconformity (well sorted sandstone).

Three of the cycles (9, 10 & 11) from 130 to 307 mbsf at the second drill site (CRP-2A) are unusually thick (around 60 m) and have been rather well dated within the range 23.7 to 24.1 Ma. Two biostratigraphic datums and four strontium isotope ages constrain correlation of a robust magnetic polarity stratigraphy with the geomagnetic polarity time scale (GPTS). Single crystal 39Ar40Ar laser fusion ages on anorthoclase phenocrysts from tephra layers at 190 and 280 mbsf confirm and independently calibrate the integrated age model.

These time constraints make it plain that the frequency of these 3 cycles, and most likely the other thinner and less complete cycles in the CRP sequences, lies in the range of those identified by Milankovitch as derived from the earth's orbital parameters. These frequencies are also recorded for this time period in the oxygen isotope record from the western Atlantic Ocean, ODP site 929.

Our chronology for cycles 11 and 10 shows them to have been deposited entirely within the 119 ka Chron C6Cn.3n, and hence likely to be 40 ka obliquity-driven cycles, as are the cycles at this time at ODP Site 929. Cycle 9, which rests on an erosion surface, spans the uppermost part of C6Cn.2r, all of C6Cn.2n and the lowermost part of C6Cn.1r, and is 120 ka in duration. We suggest that the erosion and hiatus at the base of cycle 9 represents ice sheet expansion that is correlative with the oxygen isotope Mi1 event and that cycle 9 is correlative to the major 100 ka cycle at 23.8 Ma immediately following the Mi1 event.

We think it most likely that all of the 46 Antarctic ice sheet expansions and contractions recorded in the Cape Roberts core too place at Milankovitch frequencies. If so, this means that much more is lost in sequence-bounding unconformities from the stratigraphic record of continental margins than is preserved (in this case 46 cycles from a possible 300 or more, presuming most are of 40 ka duration). The record also indicates that the cycles of climate and sea level change now accepted for the Quaternary era should be part of our thinking at least back to earliest Oligocene times.

URL: http://www.geo.vuw.ac.nz/croberts

U12A-0004 1330h POSTER

Warming at 140 ka: Causality Problem for Milankovitch?

Jonathan Levine[1] (510-704-7510; jlevine@socrates.berkeley.edu)

Daniel B Karner[1]

Richard A Muller[1]

[1]University of California - Berkeley, Deparment of Physics, Berkeley, CA 94720, United States

Sediment cores that contain records of both temperature and global ice volume indicate a major warming at about 140 ka. This is a potential causality problem for Milankovitch theory, because summertime, high-latitude, northern hemisphere insolation is at a low point at 140 ka, and does not peak until 127 ka. Such "early warming" is observed in the North Atlantic, Equatorial Atlantic, East Pacific, and West Pacific. Thus the phenomenon is more widespread than previously appreciated. Because it is observed at sites around the world, and because the warming is of a scale similar to that of deglaciation - itself the largest amplitude climate change of the Quaternary - its failure to be explained by Milankovitch forcing is a serious shortcoming for the theory.

U12A-0005 1330h POSTER

Milankovitch Cyclicity in the Eocene Green River Formation of Colorado and Wyoming

Malka Machlus[1] (machlus@ldeo.columbia.edu)

Paul E Olsen[1] (polsen@ldeo.columbia.edu)

Nicholas Christie-Blick[1] (ncb@ldeo.columbia.edu)

Sidney R Hemming[1] (sidney@ldeo.columbia.edu)

[1]Lamont-Doherty Earth Observatory of Columbia University, 61 Rt 9W, Palisades, NY 10964-8000, United States

The Eocene Green River Formation is a classic example of cyclic lacustrine sediments. Following Bradley (1929, U.S.G.S. Prof. Paper 158-E), many descriptive studies suggested precession and eccentricity as the probable climatic forcing to produce the cyclic pattern. Here we report spectral analysis results that confirm this hypothesis. Furthermore, we have identified the presence of a surprisingly large amplitude obliquity cycle, the long-period eccentricity cycle (400 k.y.) and the long period modulators of obliquity.

Spectral analyses of data from Colorado were undertaken on an outcrop section and core data using two different proxies for lake depth. In a section measured in the west Piceance Creek basin, three lithologies (ranks) were used as a proxy for relative water depth, from relatively shallow to deep water: laminated marlstones; microlaminated, light-colored oil-shales; and microlaminated black oil shales. A multi-tapered spectrum of the 190-m-thick record in the depth domain shows significant peaks at periods of 2.1, 3.4, 12 and 39 m. These are interpreted as the precession, obliquity and eccentricity cycles. The precession cycle confirms Bradley's independent estimate of 2.4 m per 20 k.y. cycle, based on varve counts at the same location. A high-amplitude, continuous 3.4 m (obliquity) cycle exists in the evolutive spectrum of this record. A second spectral analysis of an oil-shale-yield record was made on a 530 m core near the basin depocenter. This record includes the time-equivalent of the outcrop section, spans a longer interval of time, and has a higher sedimentation rate. Peaks are found at 5, 10, 25 and 79 m. Again, the probable obliquity peak, at 10 m, is continuous along the record. Initial tuning of this record to a 39.9 k.y. cosine wave improves the resolution of the precession, short and long eccentricity cycles.

Spectral analysis of oil shale yield and sonic velocity data of cores from the Green River basin, Wyoming, gives similar results. Spectral peaks at 6, 13, 31 and 122 m appear mainly in the Tipton and the Wilkins Peak members. The correlation between oil shale yield, lithology and relative water depth was examined in the upper part of the Wilkins Peak Member and the Lower part of the Laney Member. The succession from microlaminated black oil shale to laminated micrite corresponds with documented lateral changes in facies from deep to shallow environments, thus confirming the use of these facies as relative water-depth proxies. Furthermore, the upsection record of oil shale yields correlates with these facies, with higher yields corresponding to deeper water facies. This correlation supports the use of the oil shale yield record as a proxy for short-term lake-level changes, and therefore a proxy for climate.

The spectral analysis results from both basins show the importance of the obliquity cycle in these continental records. This cycle cannot be identified by cycle-counting, and therefore was not previously recognized. Earlier published attempts at spectral analysis of short records from the Piceance Creek and Uinta basins misinterpreted the observed cycles. This is the first time both the obliquity cycle and the long-term eccentricity cycle have been identified in the Green River and Piceance Creek basins.