Contributing Processes to the Mid-Pleistocene Transition
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University of Minnesota Climate Change Seminar
October 16, 2012
Outline

1. Explanation of the Mid-Pleistocene Transition (MPT).
2. Introduction to the model Saltzman and Maasch developed in 1990 (SM90).
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3. Introduction to phase-angle computations.
4. SM90 phaselocks to obliquity a la Huybers. But maybe not to eccentricity a la Lisiecki?

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5. Thus, it is a cosmic trick of fate that Milankovitch and Earth has 100kya period. They are only correlated- not causal.
6. Finally, I will outline the only 4 physical changes (1 terrestrial and 3 oceanic) which SM90 suggests may have caused the bifurcation parameter to shift.
Until 1.2 mya, the dominant period was 41kyr and associated to obliquity. After 1.2 mya, the dominant period is (approximately) 100kya cycles.
As a student of Ed Lorenz, Barry Saltzman knew a fair bit about building dynamic minimal complexity climate models. For many years Saltzman developed a 3 variable system to well reproduce the glacial cycles. (Saltzman 1987, 1988, 1990, 1991, 1994).
Saltzman Model of 1990 (SM90)

\( M \) = Milankovitch forcing at 65°N at summer solstice.
\( X \) = ice volume
\( Y \) = atmospheric CO\(_2\).
\( Z \) = North Atlantic Deepwater Formation.
\( \dot{} \) = time derivative.

All variables are deviations from the mean.

\[
\begin{align*}
\dot{X} &= -X - Y - uM(t) \\
\dot{Y} &= -pZ + rY + sZ^2 - Z^2Y \\
\dot{Z} &= -q(X + Z)
\end{align*}
\] (1)

Maasch and Saltzman show there exists a parameter shift which induces a change from a stable equilibrium solution to 100kyr cycles. The parameter shift is

\( p = 0.8 \rightarrow 1 \),
\( q = 1.2 \rightarrow 0.8 \),
\( r = 0.7 \rightarrow 0 \),
\( s = 0.8 \rightarrow 0 \),
\( u = 0.7 \rightarrow 0 \).

where \( p \) and \( r \) vary linearly in time.
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\[ p = 0.8 \to 1, \quad q = 1.2, \quad r = 0.7 \to 0.8, \quad s = 0.8, \quad \text{and} \quad u = 0.7 \]

where \( p \) and \( r \) vary linearly in time.
Saltzman Model of 1990 (SM90)

\[
\dot{X} = -X - Y - uM(t) \\
\dot{Y} = -p(a)Z + r(a)Y + sZ^2 - Z^2Y \\
\dot{Z} = -q(X + Z)
\]

For this research I will refine \( p \) and \( r \) in terms of a new parameter \( a \). We will consider SM90a for the remainder of the talk.

\[
p(a) = 0.8 + 0.2a \quad \text{and} \quad r(a) = 0.7 + 0.1a
\]

At equilibrium solutions of SM90a we have

\[
Z = Y = -X.
\]

The equilibrium solutions of SM90a are

\[
X = \frac{1}{2}(-s \pm \sqrt{s^2 - 4(0.1 + 0.1a)}).
\]
The lower branch of equilibrium solutions, lacking any external forcing, is stable from $a = 0$ until $a = 0.53$. At $a = 0.53$, the system undergoes a sub-critical Hopf’s bifurcation and the equilibrium solution becomes unstable. There exists some basin of attraction surrounding the stable manifold. Assuming the external forcing is not too great or too gradual, the solution should stay close to the stable solution until it passes the bifurcation value. Or, the system may exhibit hysteresis along the unstable manifold until $a$ reaches the fold point at $a = 0.6$ at which point the qualitative aspects of the system should change dramatically.
Mini-Goal: How to compute $\Delta$Phase and plot them.
Phase-angle Computations

\[ \Delta \text{Phase} = \left( \frac{b - a}{c - a} \right) 2\pi \]
“During the early Pleistocene deglaciations occur nearly every obliquity cycle giving a 40Ka timescale, while late Pleistocene deglaciations more often skip one or two obliquity beats, corresponding to 80 or 120 Ka glacial cycles which, on average, give the 100Ka variability.” [Huybers 2007, 2011]
Obliquity \( \Delta \)Phase for all time

Obliquity \( \Delta \)Phase since 1.2 MYA.

R is 0.594747 and Pray is 0.00108705.

R is 0.633795 and Pray is 0.000381016.
“The relative phase of eccentricity and glacial cycles has been stable since 1.2 Myr ago, supporting the hypothesis that 100,000-yr glacial cycles are paced by eccentricity.” [Lisiecki 2010]
Eccentricity $\Delta$Phase for all time

$R$ is 0.0757758 and $P_{\text{ray}}$ is 0.904205.

Eccentricity $\Delta$Phase since 1.2 MYA

$R$ is 0.471338 and $P_{\text{ray}}$ is 0.0162411.
Physical Implications

The dynamical system listed in equation 1 is a nondimensionalization of a more physically intuitive version of the model.

\[
\begin{align*}
\dot{I}' &= -a_0 I' - a_1 \mu' + uM \\
\dot{\mu}' &= -b_0 I' + b_1 \mu' - (b_2 - b_3 N')N' - b_4 N'^2 \mu' \\
\dot{N}' &= -c_0 I' - c_2 N'
\end{align*}
\]

When we consider the parameter shift from \( a = 0 \) to \( a = 1 \), the only parameters which alter in the above equation are \( b_1 \) and \( b_2 \) which alter from \( 7 \times 10^{-5} \) to \( 8 \times 10^{-5} \) and \( 2.52 \times 10^{-20} \) to \( 3.16 \times 10^{-20} \), respectively.
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1. Increased terrestrial carbon interaction with the glacial cycles,
2. A lesser dependence on atmospheric CO$_2$ in the north Atlantic deep water formation carbon sink,
3. Strengthening the solubility pump, or
4. Intensifying the pycnocline which would decrease overturning circulation.
Conclusions

In conclusion,

- SM90 has a bifurcation which is consistent the MPT.
- Through a climate regime shift SM90a produces an internal 100kyr cycle.

Thus, this model predicts that the current 100kyr cycles are not caused by Milankovitch cycles. Internal feedbacks phase lock to obliquity to create the illusion that the Milankovitch cycles are a driving force. Additionally, this model supports the work of Huybers and not Lisiecki (yet?). Further scientific exploration into the physical processes is necessary to learn more about the Mid-Pliocene Transition. SM90a provides a direction of inquiry by suggesting 4 likely physical candidates.
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