Response of paleoclimate models to external forcing

Key Questions:

1. Scientific
   (a) "100 kyr problem":
      i. What is the underlying cause of the slow glacial cycles in late Pleistocene?
      ii. Cause of MPT?
   (b) Are the cycles predictable?
      i. Are full melts triggered by fast forcing or based on internal dynamics?
      ii. What is the role of fast forcing: obliquity / precession in cycle timing?
      iii. Role of eccentricity? Envelope of precession?
      iv. Synchronicity?
   (c) "41 kyr problem":
      i. Why does response emphasize obliquity over precession time scales?
      ii. Linear response vs non-linear filter?
      iii. What is the appropriate temporal scope of the astronomical forcing: seasonal averaging v solstice
      iv. Insolation: latitudinal gradient vs high-latitude amplitude?
2. Modeling
   (a) What is the impact of mathematical model structure?
      i. Role of irreversibility in dynamics? (Smooth vs non-smooth models?)
      ii. Role of asymmetry in limit cycles?
      iii. Preservation / loss of memory of state / synchronicity?
      iv. Are these related?
   (b) Sensitivity to choice of astronomical forcing.
   (c) Model response to quasi-periodic forcing.
   (d) Model response to statistical forcing.
   (e) Combination of both above forcing types.
   (f) Model validation against observed features.

Key new hypothesis:

- Observed cycles caused by non-linear interaction between forcing & internal cycles.
- Timing of warming caused by high insolation.
- Varying impedance caused by internal cycle.
- Gradual growth of impedance **OR** appearance of new source of impedance.

Key concepts in forced dynamical systems

1. Pullback attractors
2. Excitation
3. Phase-locking /synchronization
   - Arnold Tongues
4. Stochastic Resonance
5. Predictability / Chaotic behavior

Features of glacial cycles

1. Timescales of oscillation
   (a) Cross-correlations IMFs vs astronomical forcing
2. Amplitude ratios across time scales
   (a) IMFs: Early 41, Late 100, Late 40, Early & late 20 (kyr)
3. Identification of full and partial melts
4. Timing of full melts
5. Timing of partial melts
6. Asymmetry of cycles
7. Asymmetric memory of state within cycle
8. Synchronicity: loss of memory
9. initial growth of slow cycle

Tasks

1. Analysis tools
   (a) Precession cross-correlation
   (b) ID of melts from ice volume
   (c) Circle statistics for timing of melts
   (d) Asymmetry of cycle measures
   (e) Within-cycle correlations of ice volume
   (f) Clustering of trajectory cross-sections

2. Models

   (a) PP04

      i. Drift runs vs extended fixed param. runs

      ii.

   (b) SM models

      i. Compare anomaly models to full models

      ii. Improve "model switch" analyses (ice volume based)

      iii. Identify "impedance" with examples

   (c) SV models

      i. Implement

      ii. Extended fixed param runs

      iii. Drift

      iv. Anomaly vs full?

      v. Isolate "impedance" to forcing

Key Papers

- Paillard, Quaternary glaciations: from observations to theories. *Quaternary Science Reviews*, 2017
- Tziperman, et. al, Consequences of pacing the Pleistocene 100 kyr ice ages by nonlinear phase locking to Milankovitch forcing. *Paleoceanography*, 21(4), 2006
- B De Saedeleer, M Crucifix, and S Wieczorek. Is the astronomical forcing a reliable and unique pacemaker for climate? A conceptual model study. *Climate Dynamics*, 40(1-2): 273?294, 2013
- M Kominz, G Pisias, Pleistocene Climate; Deterministic or Stochastic, *Science*, 1979
- Mitsui-Aihara, Dynamics between order and chaos in conceptual models of glacial cycles, *Clim. Dyn.*, 2014
- Mitsui-Crucifix-Aihara, Bifurcations and strange nonchaotic attractors in a phase oscillator model of glacial?interglacial cycles, *Physica D*, 2015
- D Palliard, Climate and the orbital parameters of the Earth, *Comp. Ren. Geosci.*, 2010
- D Palliard, Glacial Cycles: Towards a new paradigm, *Rev. Goeohys.*, 2001
- PALEOSENS, Making sense of palaeoclimate sensitivity, Nature, 2012
- Raymo, Unlocking the mysteries of the ice ages, Huybers, Nature, 2008