Mass Transport and Dynamics in the Earth System

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Forcing Mechanisms

- External
  - Tidal potential
    - Body, ocean, atmosphere
- Surficial
  - Atmospheric winds and surface pressure
  - Oceanic currents and bottom pressure
  - Water stored on land (liquid, snow, ice)
- Internal
  - Earthquakes and tectonic motions
  - Mantle convection
  - Outer core dynamics / coupling with mantle
  - Inner core dynamics / coupling with outer core and mantle

Geodetic Measures of Earth's Response

- Rotation
  - Angular momentum exchange (surface fluids, outer core)
  - Torques (external, surficial, internal)
  - Changes in inertia tensor (earthquakes, GIA)
- Gravity and geocenter
  - Mass distribution (static field)
  - Mass redistribution (time varying field)
  - Surface displacements (ground-based)
- Shape
  - Tidal displacements
  - Surface loading and unloading
  - Internal deformation
    - Earthquakes, core pressure => mantle deformation

Selected Scientific Questions

- Climate change
  - Global warming
    - Atmosphere, oceans, Earth surface
- Ice mass balance / sea level change
  - Mountain glaciers, grounded and floating ice sheets
- Natural hazards
  - Earthquakes, volcanoes, landslides, tsunamis
- Earth structure
  - Interior figure, mantle anelasticity, 3D mass distribution
- Mantle and core dynamics
  - Coupling mechanisms
- Origin of observed variations
  - Earth rotation, gravity and geocenter, shape

Pathways to Advancement

- Improved measurements
  - Accuracy, temporal resolution, duration
- Improved models
  - Forcing mechanisms
    - Atmosphere, oceans, hydrology, core
  - Earth’s response to forcing
    - Anelastic effects
- Improved theory
  - Higher order
  - Dynamic oceans and core
  - Core-mantle coupling
- Consistent computations
  - Love numbers

Earth Rotation Theory

- Assumptions made in current theory
  - Equations of motion have been linearized
    - Terms smaller than 1 part in 300 discarded
    - Separates polar motion from length-of-day variations (no spin-wobble coupling)
  - Earth is dynamically axisymmetric ($A = B << C$)
    - Chandler wobble is circular, not elliptical (semimajor/minor axes differ by few cm)
  - Oceans respond passively to wobble
    - Not valid for wobbles of period < ~10 days
  - Core responds passively to wobble
    - Core assumed to be homogeneous, incompressible, non-dissipative
  - Core is uncoupled from mantle
- Theory is accurate to about 1 part in 300
  - Measurements are more accurate than this
- IAU/IAG JWG on Theory of Earth Rotation formed

Consistency of Computations

- Example: Love numbers
  - Computations from different groups differ by a few percent
    - For same Earth model
- IERS Conventions
  - Helped impose consistency in data reduction procedures
- GGOS Conventions (?)
  - Would help impose consistency in geodetic computations

Period and Q of Chandler Wobble

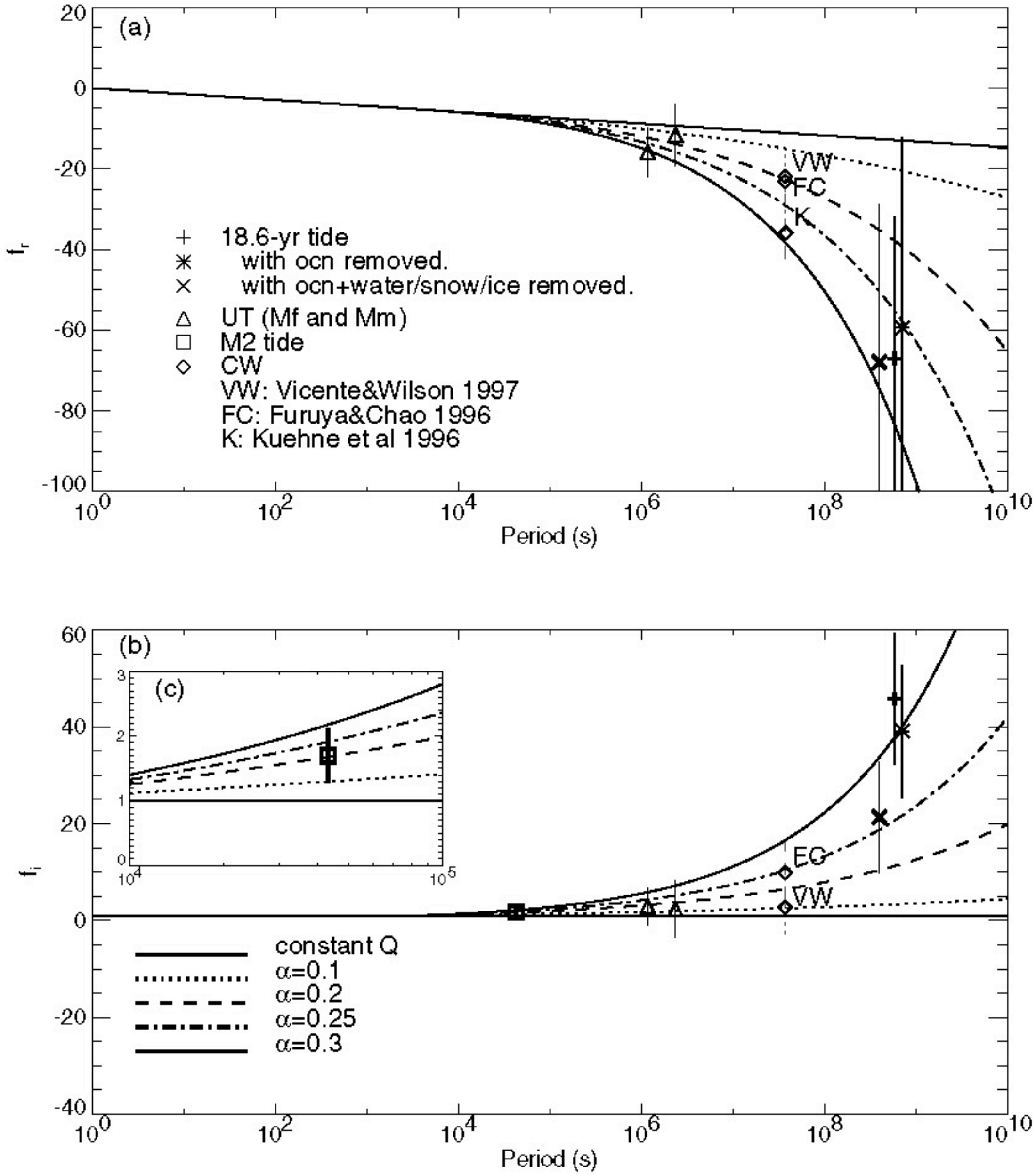
Table 12 Estimated period and Q of Chandler wobble

Period (solar days)	*Q*	*Data span (years)*	*Source*
Statistical excitation			
433.2 ± 2.2	63 (36, 192)	67.6	(a)
434.0 ± 2.6	100 (50, 400)	70	(b)
434.8 ± 2.0	96 (50, 300)	76	(c)
433.3 ± 3.1	170 (47, 1000)	78	(d)
433.0 ± 1.1	**179 (74, 789)**	**86**	**(e)**
433.1 ± 1.7	—	93	(f)
Atmospheric excitation			
439.5 ± 2.1	72 (30, 500)	8.6	(g)
433.7 ± 1.8	49 (35, 100)	10.8	(h)
430.8	41	10	(i)
Atmospheric and oceanic excitation			
429.4	107	10	(i)
431.9	83	51	(i)
432.98	97	60	(j)
Semi-analytic			
430.3	88.4	20	(k)
433.03	100.20	20	(l)

The recommended estimate is given in bold. The 1σ confidence interval for the Q estimates is given in parentheses. Sources: (a) Jeffreys (1972); (b) Wilson and Haubrich (1976); (c) Ooe (1978); (d) Wilson and Vicente (1980); (e) Wilson and Vicente (1990); (f) Vicente and Wilson (1997); (g) Kuehne *et al*. (1996); (h) Furuya and Chao (1996); (i) Gross (2005b); (j) Seitz *et al*. (2012); (k) Mathews *et al*. (2002); (l) Chen and Shen (2010).

Gross (2014)

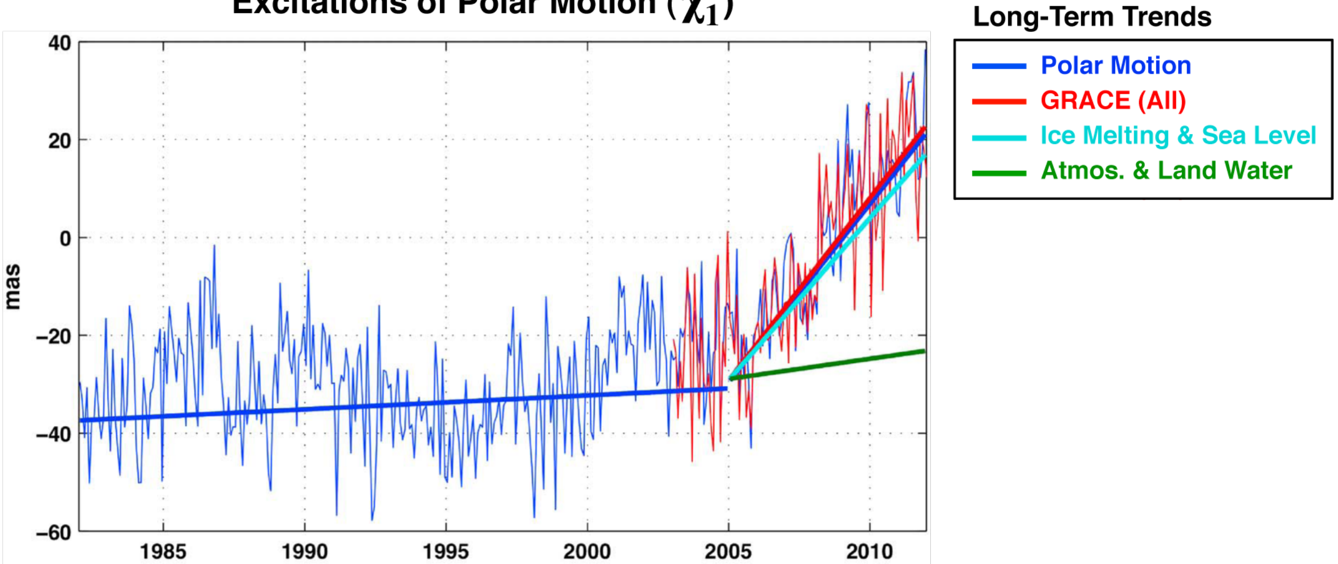
Constraints on Mantle Anelasticity



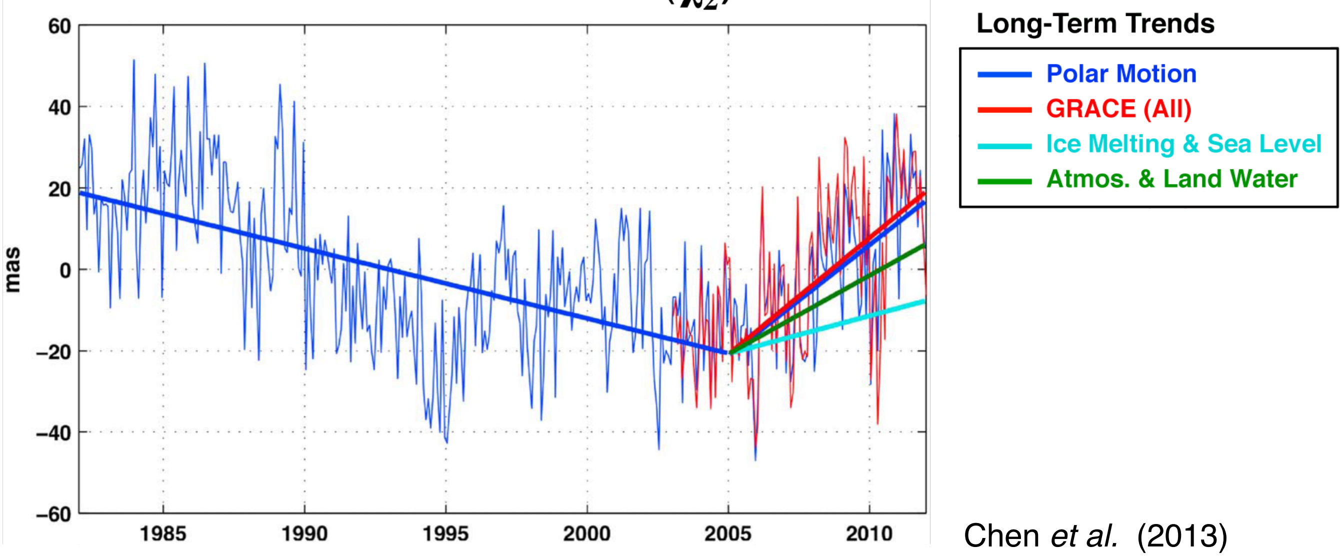
Benjamin *et al.* (2006)

Trend in Pole Path

(a) Non-Seasonal & Long-Term Excitations of Polar Motion (χ_1)

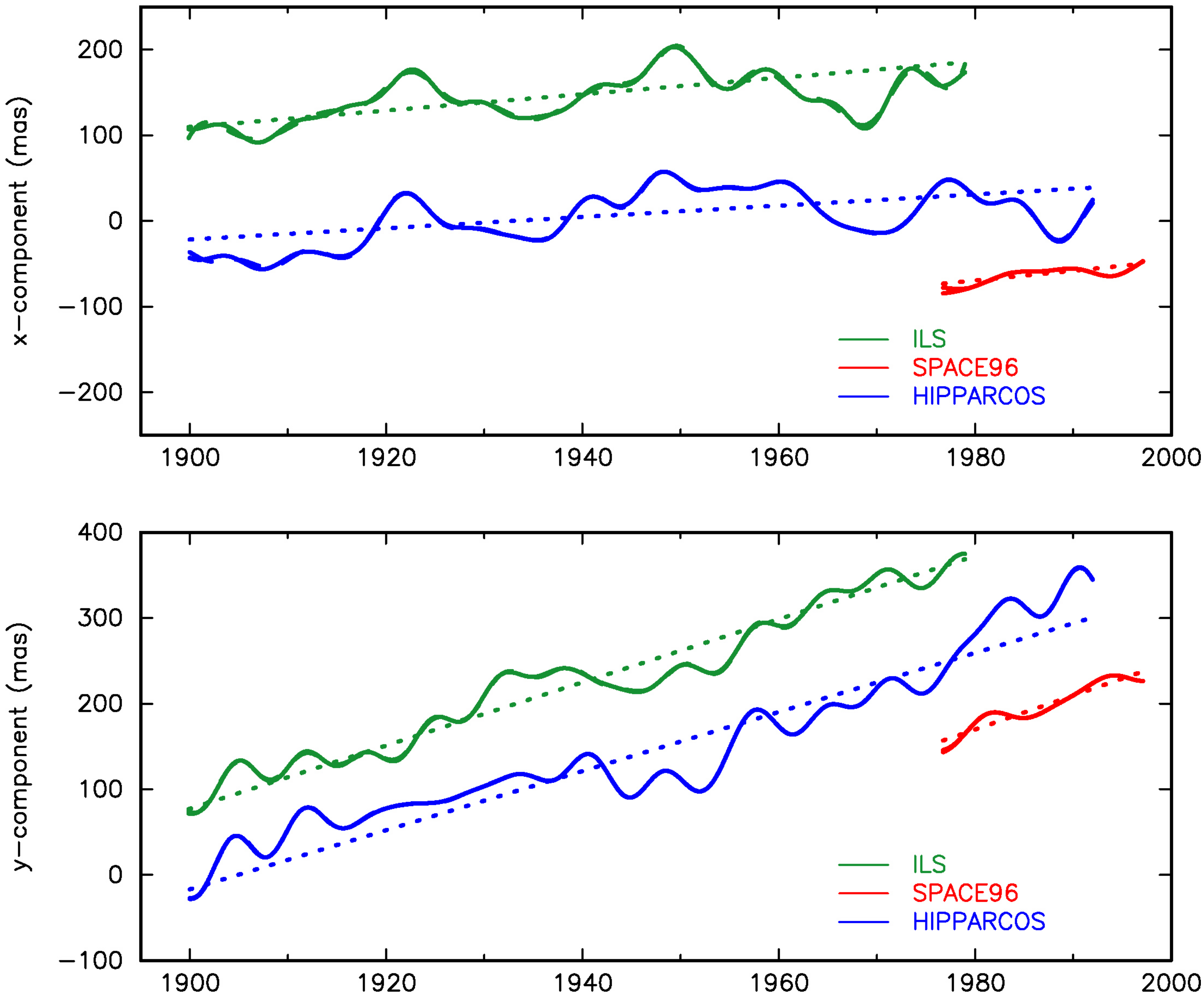


(b) Non-Seasonal & Long-Term Excitations of Polar Motion (χ_2)



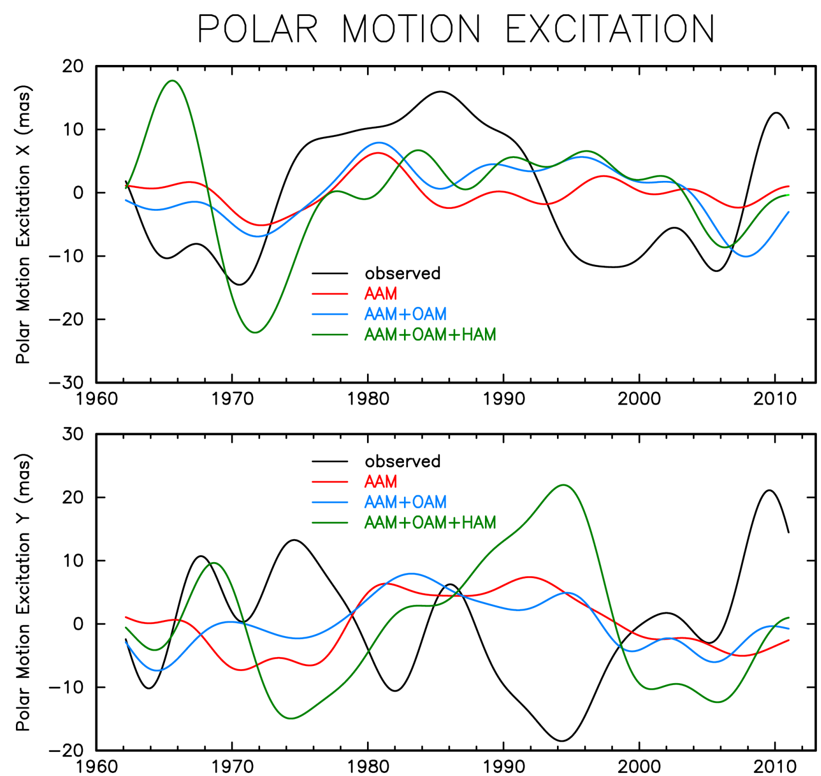
Chen *et al.* (2013)

Decadal Polar Motion Variations



Decadal Polar Motion Variations

- Observed excitation
  - COMB2010
    - Combination of optical astrometric, LLR, SLR, VLBI, and GPS observations
    - Spans 1962.0 – 2011.5 at daily intervals



- Modeled excitation
  - Helmholtz Centre Potsdam
  - Consistent estimates of AAM, OAM, and HAM
    - AAM computed from ECMWF
    - OAM computed from Ocean Model for Circulation and Tides (OMCT)
    - HAM computed from Land-Surface Discharge Model (LSDM)
    - Ocean and hydrology models driven by ECMWF
    - Global atmosphere/oceans/hydrology mass conservation imposed
- Detrended & low pass filtered
    - Cutoff period of 6 years

Future Research Directions

- Extend theory (IAU/IAG JWG on ThER)
  - Triaxial, deformable body with fluid core & dynamic (!) oceans
- Improve existing models
  - Oceanic (tidal and non-tidal)
    - Mass, not volume, conserving non-tidal OGCMs
  - Hydrologic
    - Daily values
  - Core-mantle interactions
- Develop new models
  - Present-day ice mass / sea level change
- Signal of unknown origin
  - Markowitz wobble
    - Quasi-periodic wobble on decadal time scales; amplitude of about 30 mas
    - Caused by terrestrial water variations? Ice sheet mass / sea level? Core-mantle?