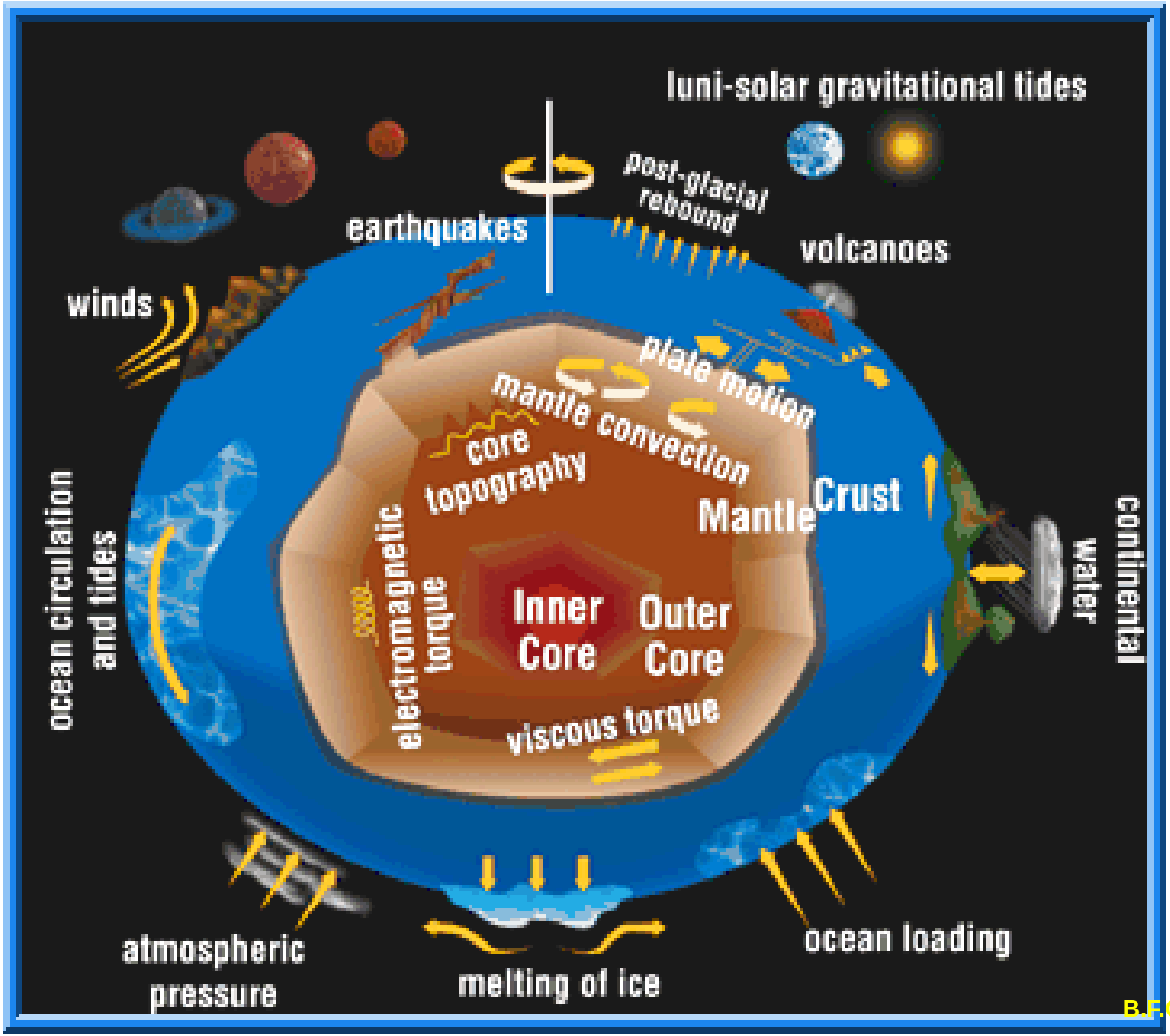
Earth Rotation, Gravity, and all that

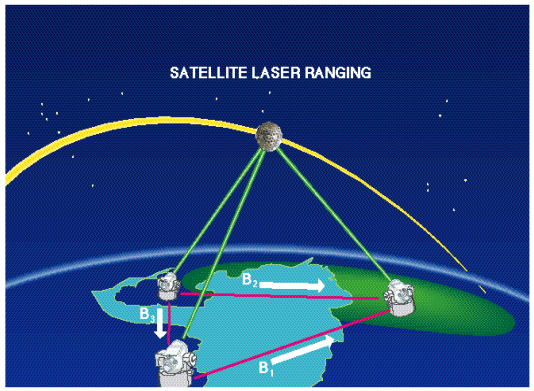
趙丰

中央研究院 地球科學研究所

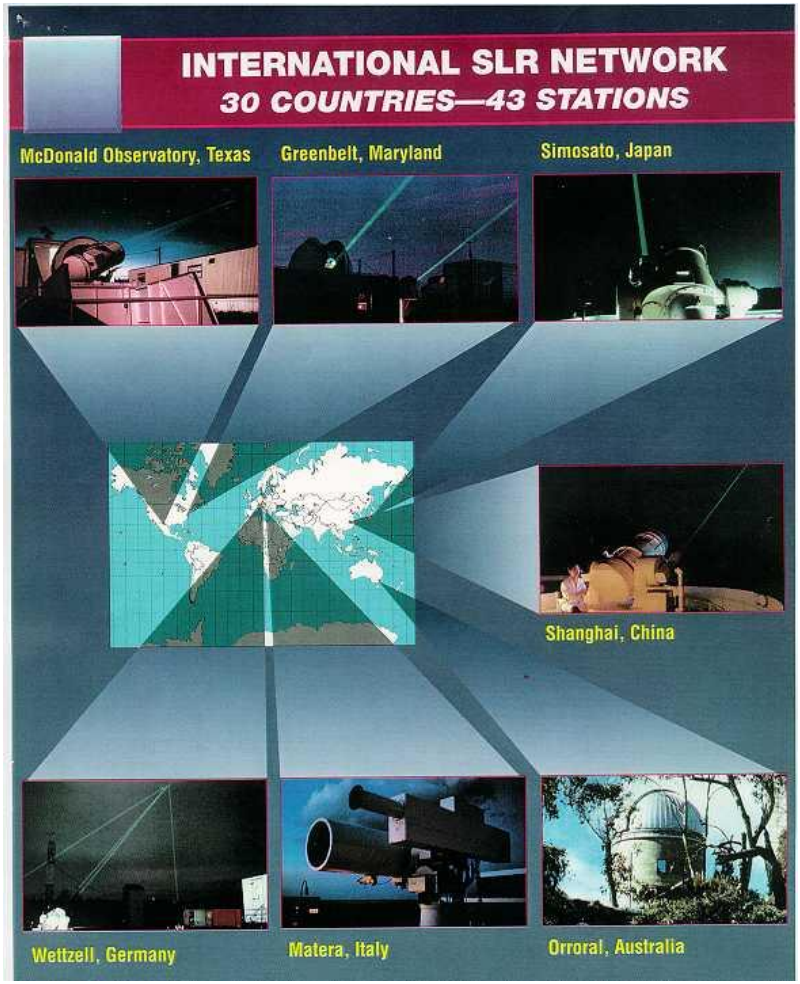
Earth's Rotation, 3-D

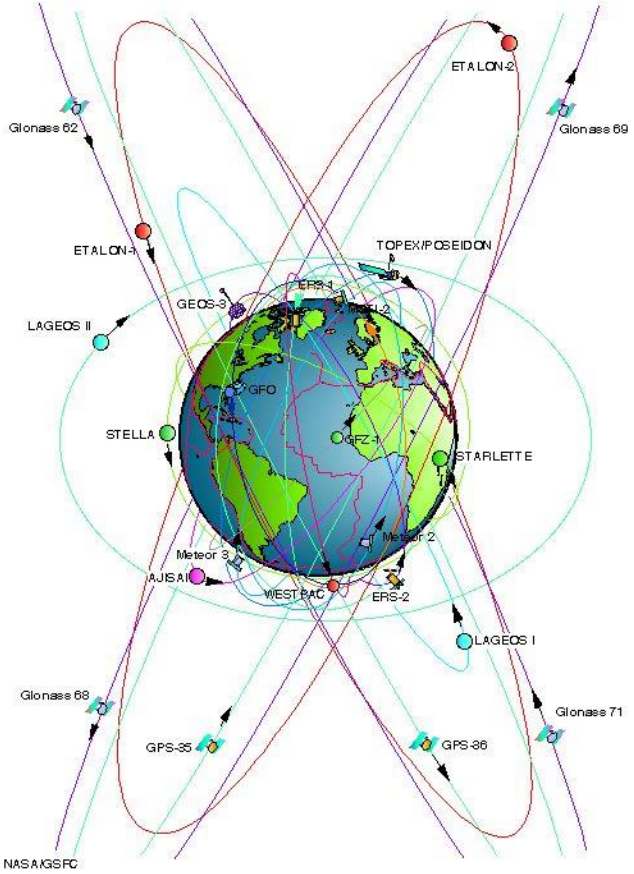
- Earth rotates in space once every 24 hours (wrong!)
- Earth rotates in space once every 23 hr 56 m 04.09074 s (sidereal day)
- Earth rotates w.r.t. Sun every 24 hours (mean solar day)
- Earth rotation varies -- small ($< 10^{-9}$), slow
- It is stable because:
  - Angular momentum (~ large)
  - Equatorial bulge (~1/300)


luni-solar gravitational tides
post-glacial rebound
earthquakes
volcanoes
winds
plate motion
mantle convection
core topography
Crust
Mantle
Inner Core
Outer Core
electromagnetic torque
viscous torque
ocean circulation and tides
continental water
atmospheric pressure
melting of ice
ocean loading
B.F.Chao

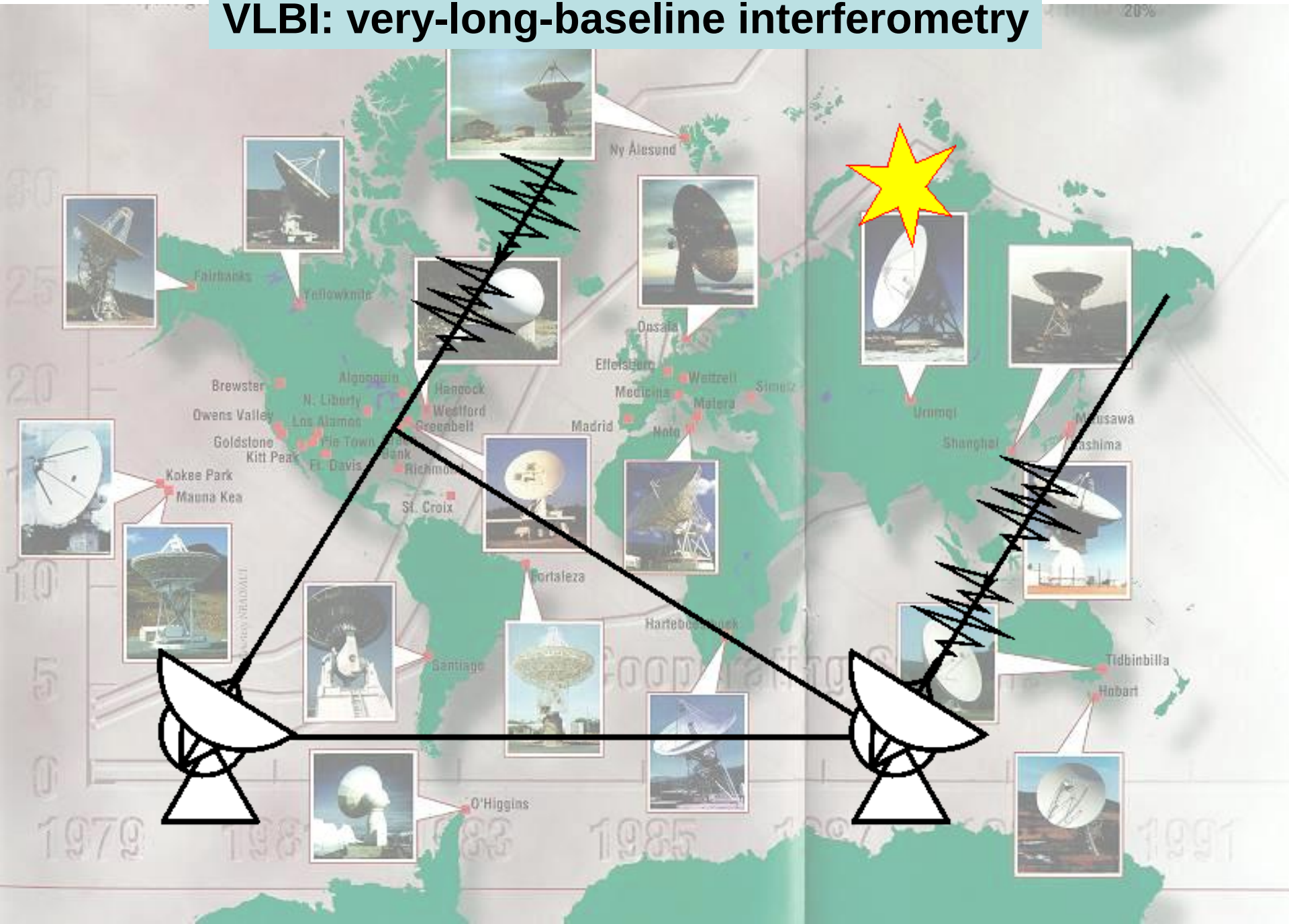


Satellites Laser Ranging

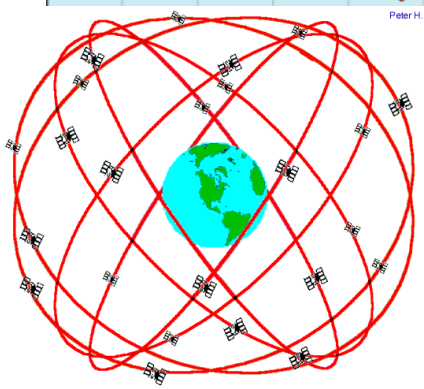




VLBI: very-long-baseline interferometry



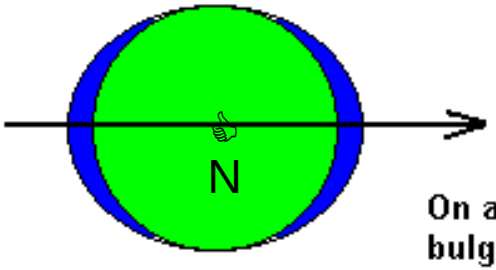
International GNSS Service network sites



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

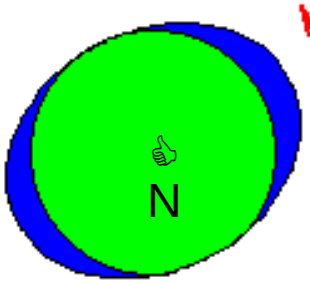
Earth's Rotation Variations, 3-D

- **Astronomical** (external torques → angular momentum change)
  - Precession (進動), Nutations (章動), Librations (晃動)
  - Milankovitz cycles
  - Tidal braking (潮汐摩擦)
- **Geophysical** (internal forces → no angular momentum change)
  - Length-of-day change (日長變化)
    - secular, long-term
    - decadal
    - interannual, seasonal, sub-seasonal, tidal
  - Polar motion (極移)
    - secular, long-term, seasonal, sub-seasonal, tidal
    - Chandler wobble (擺動), annual wobble
    - core nutations/wobbles



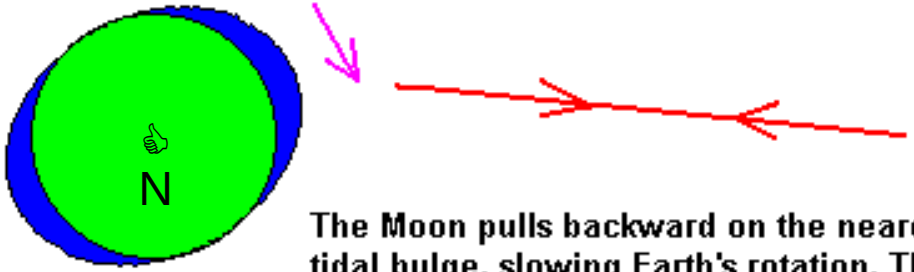
Moon

On an ideal, frictionless Earth, tidal bulges would point directly at the Moon.



Moon

On the real Earth, friction and obstructions to ocean movement cause the bulges to lead the Moon.



Moon

The Moon pulls backward on the nearer tidal bulge, slowing Earth's rotation. The nearer bulge, in turn, pulls ahead on the Moon, accelerating it into a higher orbit.

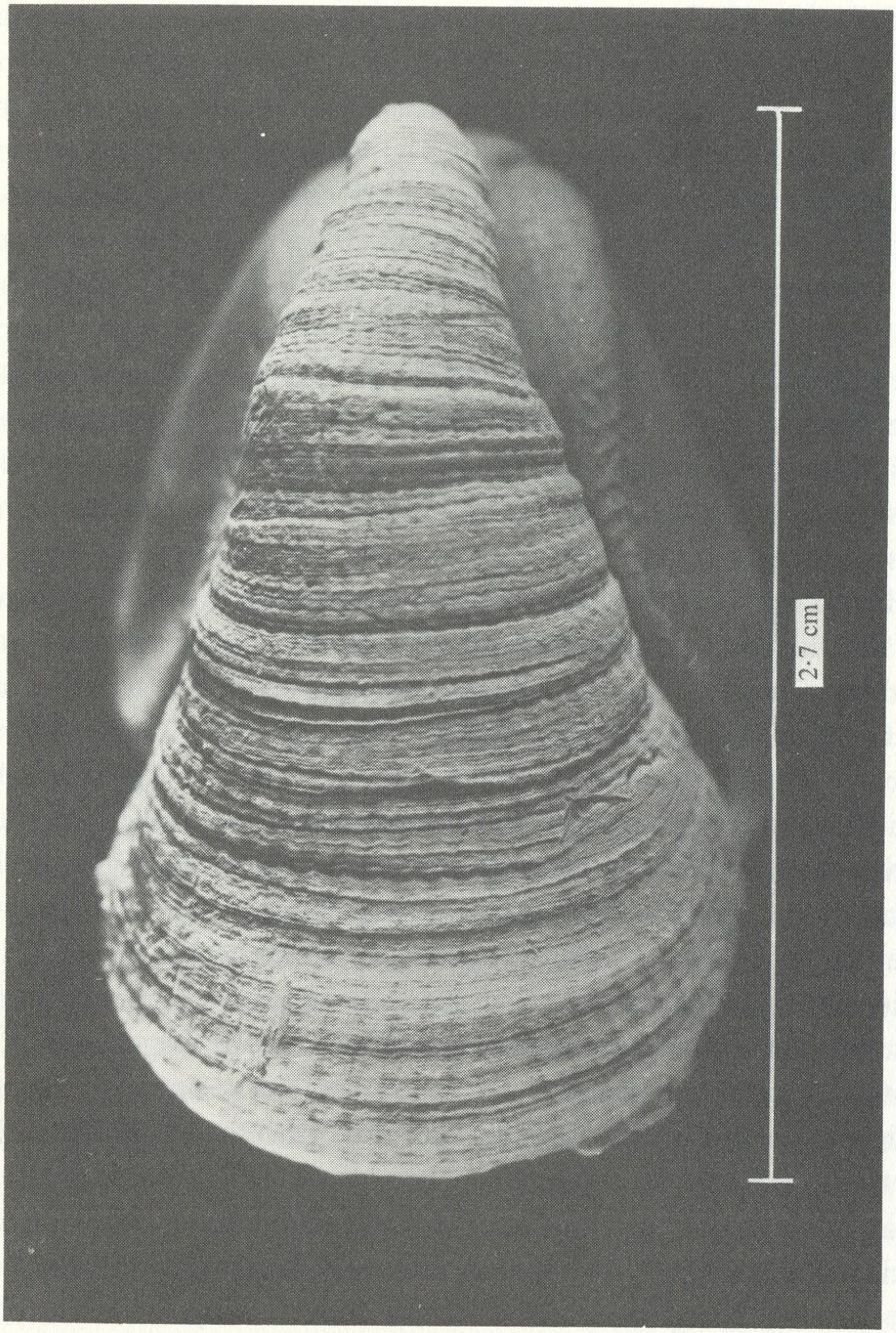
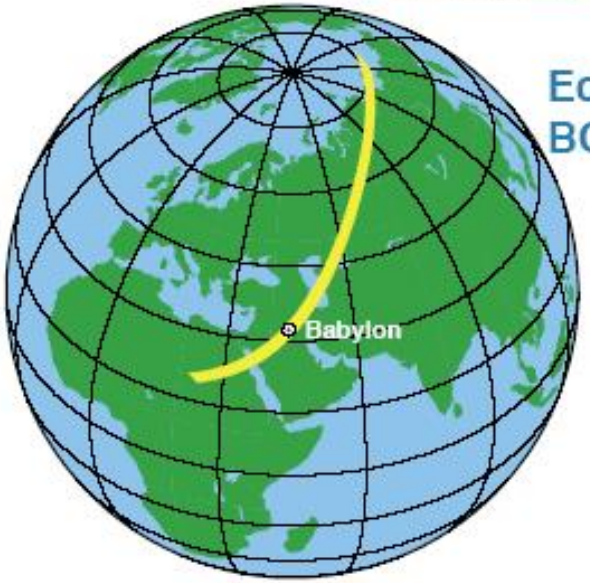


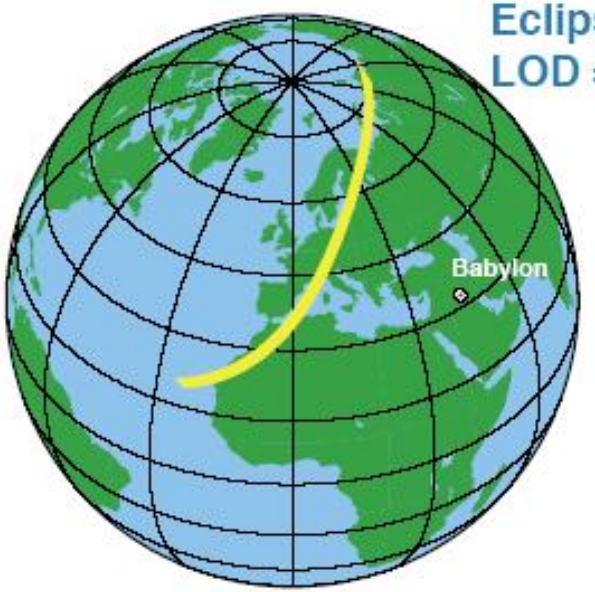
Figure 11.6. Middle Devonian coral epitheca from Michigan, U.S.A., illustrating 13 well-developed bands, each with an average of 30.8 ridges (supplied by C. T. Scrutton).

Secular Braking of Earth's Rotation

Determination of dΩ/dt from Ancient Eclipses



Eclipse path on
BC 136 April 15



Eclipse path if
LOD = constant

Eclipse path from Fred Espenak, GSFC

Babylonian diary from the year 87 BC (©The British Museum).

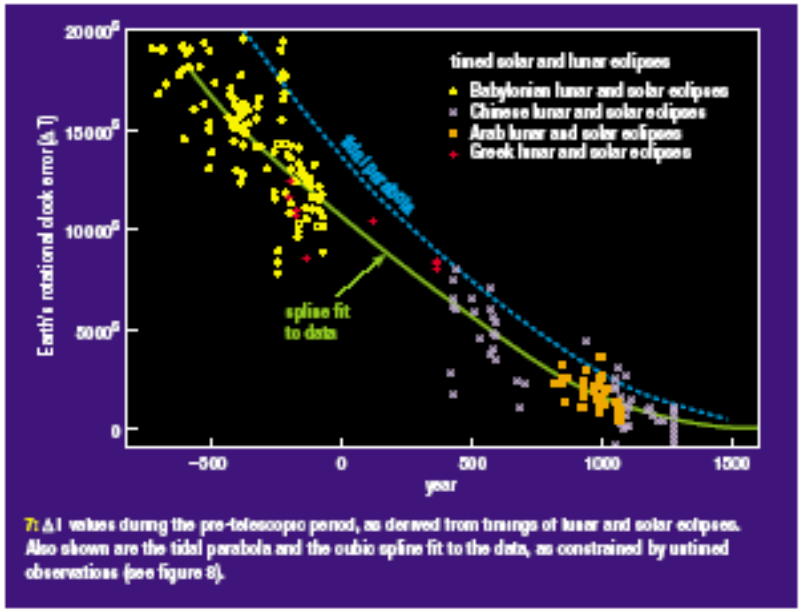
ΔT = 11680 ± 460 seconds (3.2 hrs)

(Uncertainties are strict upper/lower bounds)
(Assumes modern $dn/dt = -26''/cy^2$)

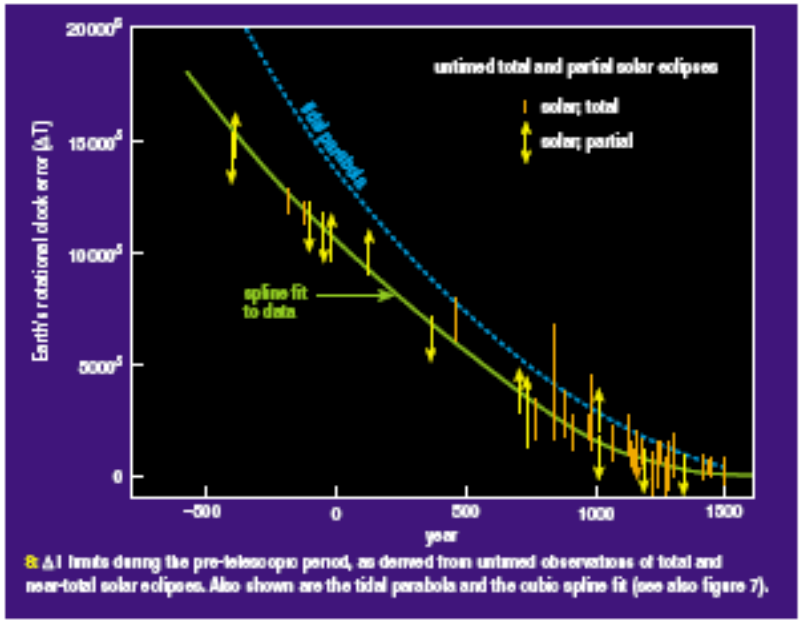
Implies $d\Lambda/dt = 1.71 \pm 0.07$ ms/century

A Babylonian day was ~37 ms shorter than ours.

A very precise estimate from one single eclipse!



7: ΔT values during the pre-telescopic period, as derived from timings of lunar and solar eclipses. Also shown are the tidal parabola and the cubic spline fit to the data, as constrained by untimed observations (see figure 8).



8: ΔT limits during the pre-telescopic period, as derived from untimed observations of total and near-total solar eclipses. Also shown are the tidal parabola and the cubic spline fit (see also figure 7).

From F. Richard Stephenson's Jeffreys Lecture, *Astronomy & Geophysics*, April 2003.

Stephenson & Morrison (1995):

Observed $d\Lambda/dt$ = +1.7 ms/century
Adopted tidal $d\Lambda/dt$ = +2.3 ± 0.1 ms/century*

The discrepancy between these two curves is an important datum for interpretation of past sea levels and GIA, especially Late Holocene melting.

For example, see:
Munk, *PNAS 99*, 6550-5, 2002.
Mitrovica, Wahr, Matsuyama, Paulson, Tamisiea, *EPSL 243*, 390-9, 2006.

* A more recent estimate: 2.28 ± 0.04 ms/cy

Secular Acceleration of the Moon: Recent

Apollo-11 retroflector

Lunar Laser Ranging

Chapront et al. (2002): $\dot{a}$ = 3.8194 ± .0004 cm/yr <—> $\dot{n}$ = –25.858 ± .003"/cy^2

(formal error)

J. Williams: Contribution from dissipation in Earth ≈ –26.0"/cy^2

Contribution from dissipation in Moon ≈ + 0.3"/cy^2 (model dependent)

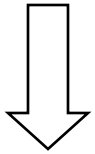
Other LLR applications: Lunar geophysics (Williams et al., *JGR*, 2001)

Gravitational physics (Williams et al., *Phys. Rev.*, 2004)

Conservation of angular momentum

angular momentum of entire Earth system

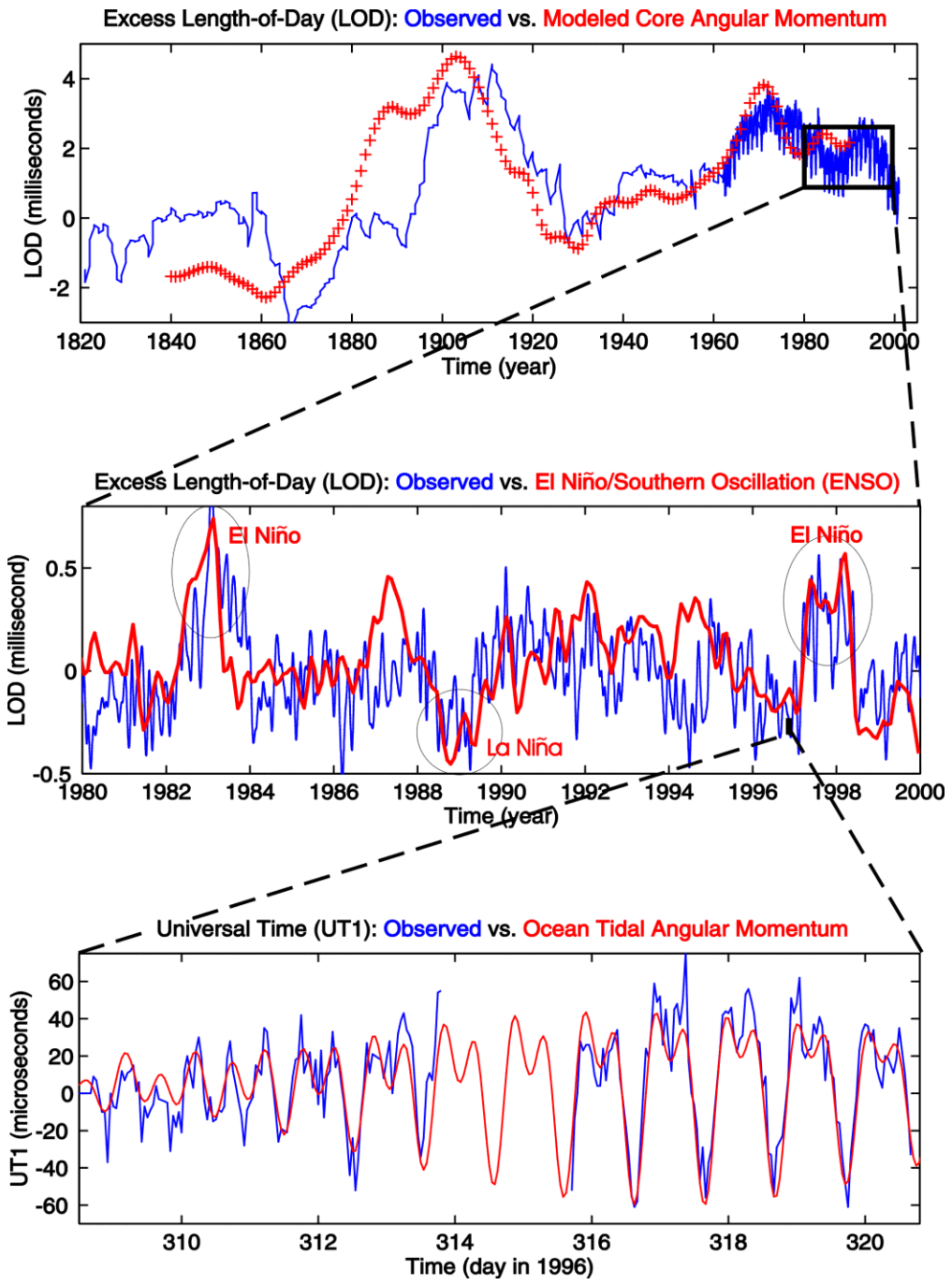
= constant



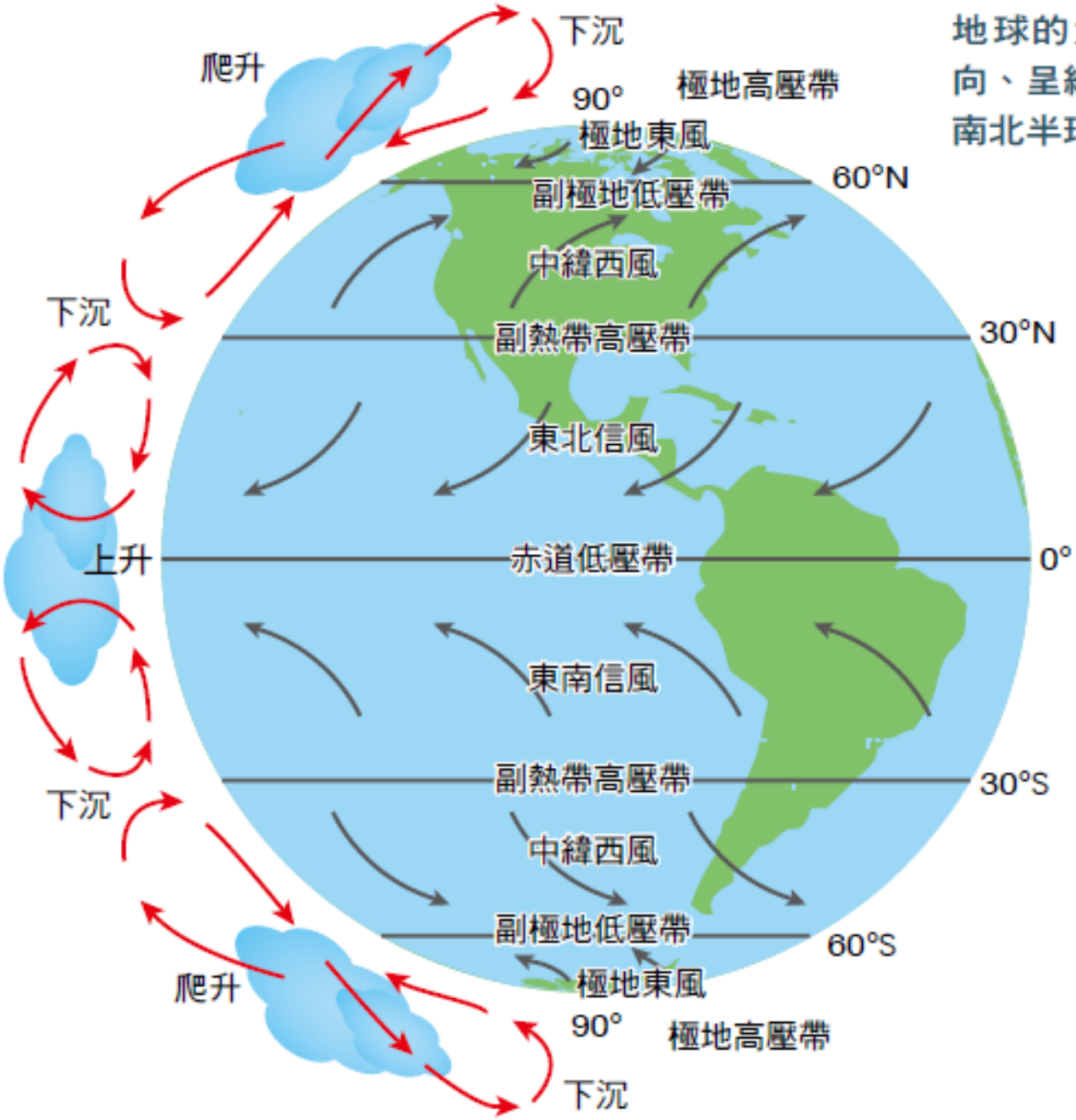
Δ(solid Earth rotation angular momentum)

= - Δ(AAM + OAM + HAM + other AMs)

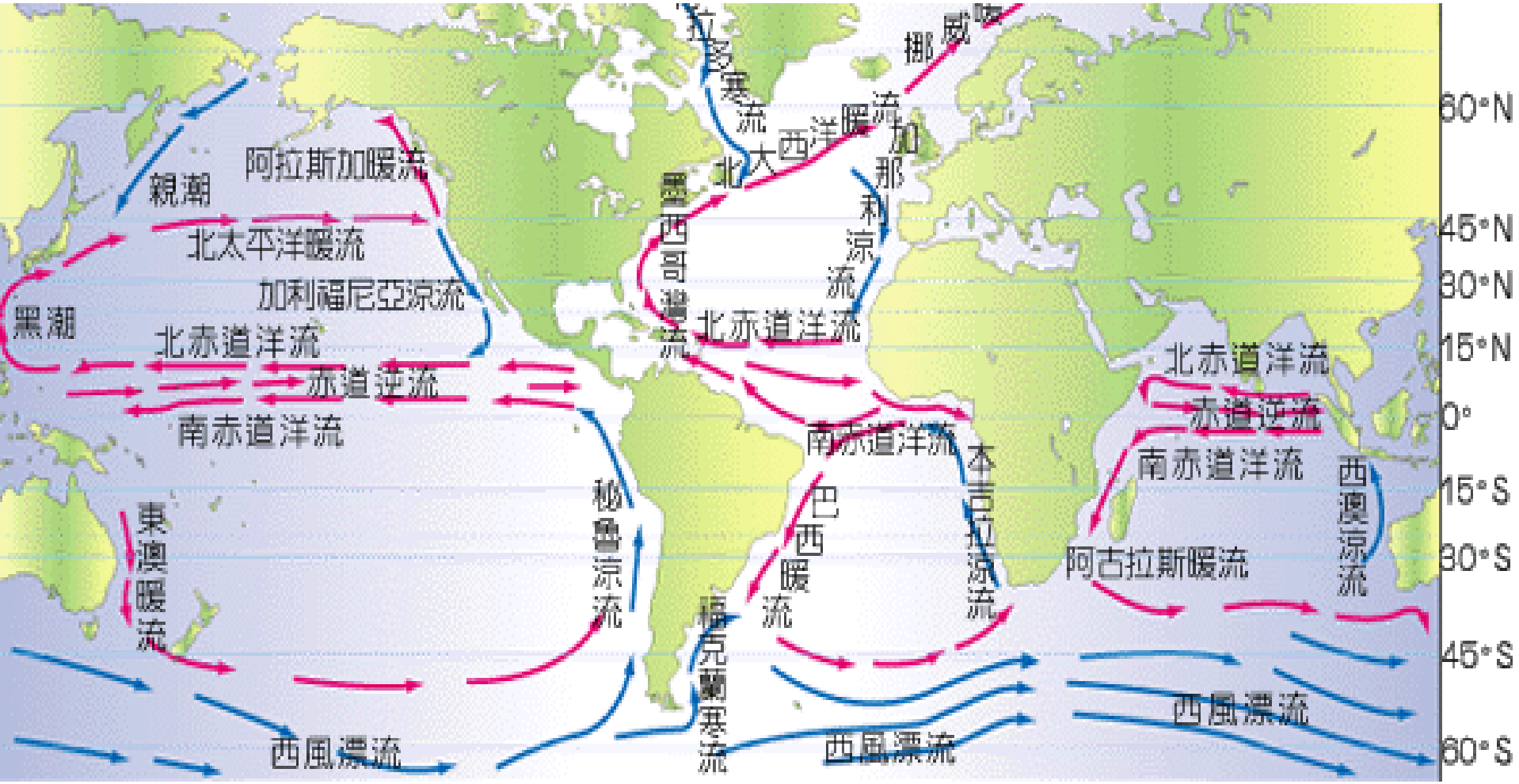
= global integral (velocity, pressure)

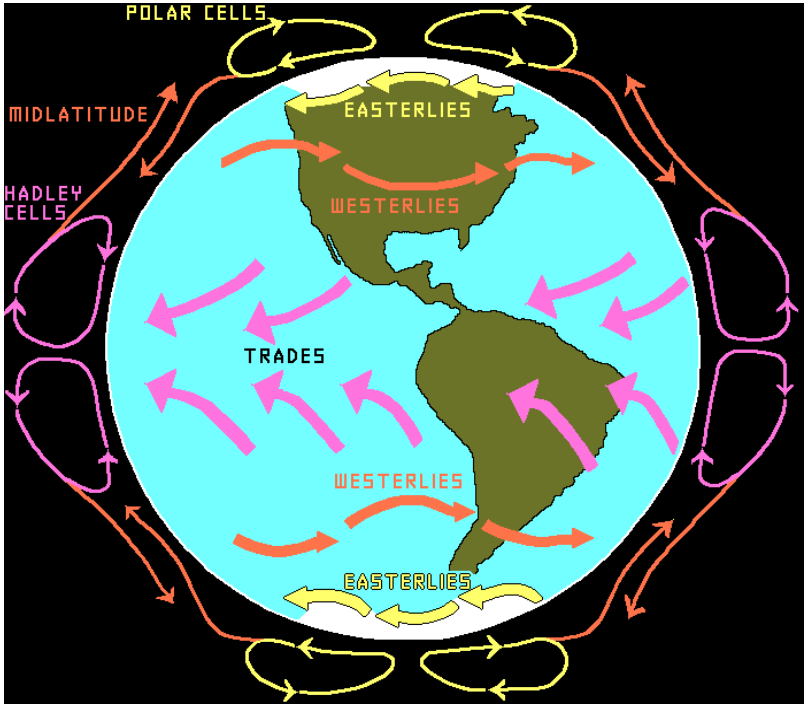

Excess Length-of-Day (LOD): Observed vs. Modeled Core Angular Momentum
LOD (milliseconds)
Time (year)
Excess Length-of-Day (LOD): Observed vs. El Niño/Southern Oscillation (ENSO)
El Niño
El Niño
La Niña
LOD (millisecond)
Time (year)
Universal Time (UT1): Observed vs. Ocean Tidal Angular Momentum
UT1 (microseconds)
Time (day in 1996)

(Chao, 2003)

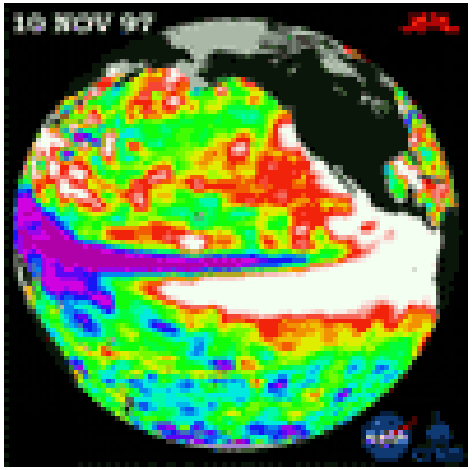


地球的大
向、呈緯度
南北半球呈

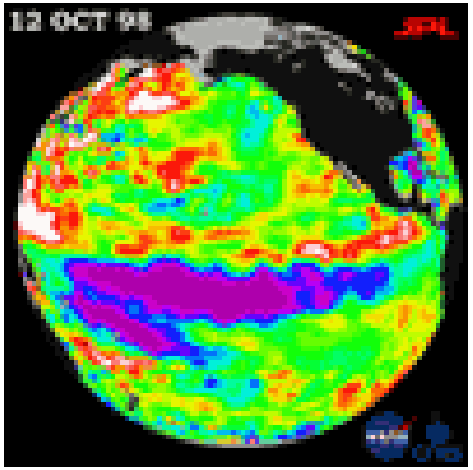

親潮
阿拉斯加暖流
北太平洋暖流
加利福尼亞涼流
黑潮
北赤道洋流
赤道逆流
南赤道洋流
東澳暖流
西風漂流
秘魯涼流
拉布拉多寒流
墨西哥灣流
北大西洋暖流
挪威寒流
加那利涼流
北赤道洋流
南赤道洋流
巴西暖流
福克蘭寒流
西風漂流
本吉拉涼流
北赤道洋流
赤道逆流
南赤道洋流
阿古拉斯暖流
西澳涼流
西風漂流
60°N
45°N
30°N
15°N
0°
15°S
30°S
45°S
60°S

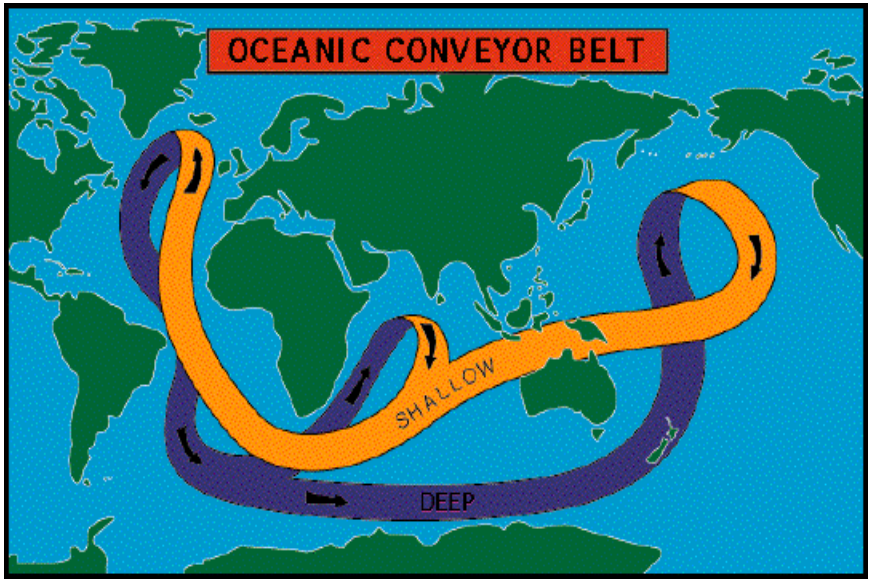


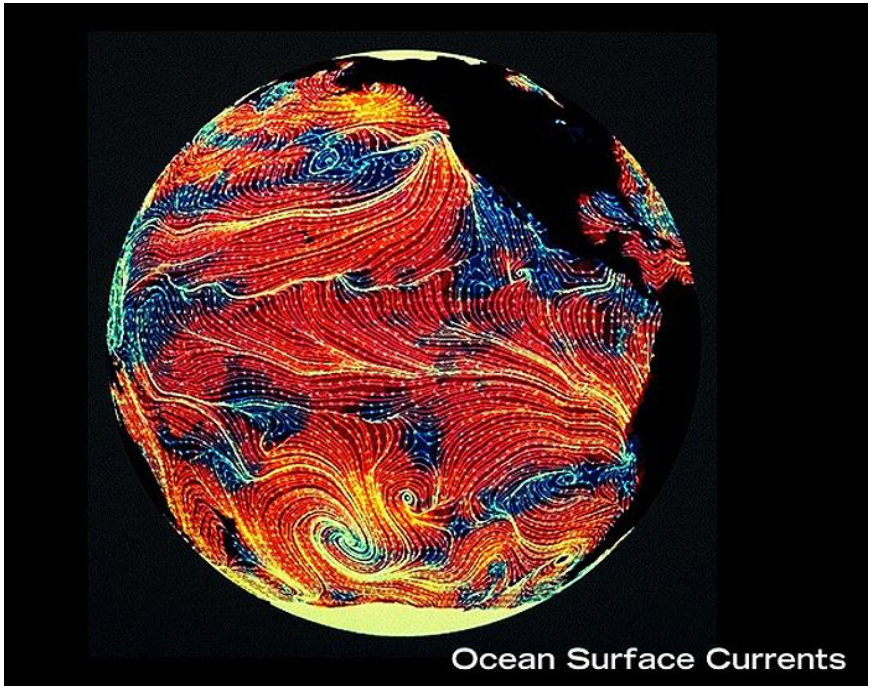
El Niño (11/1997)

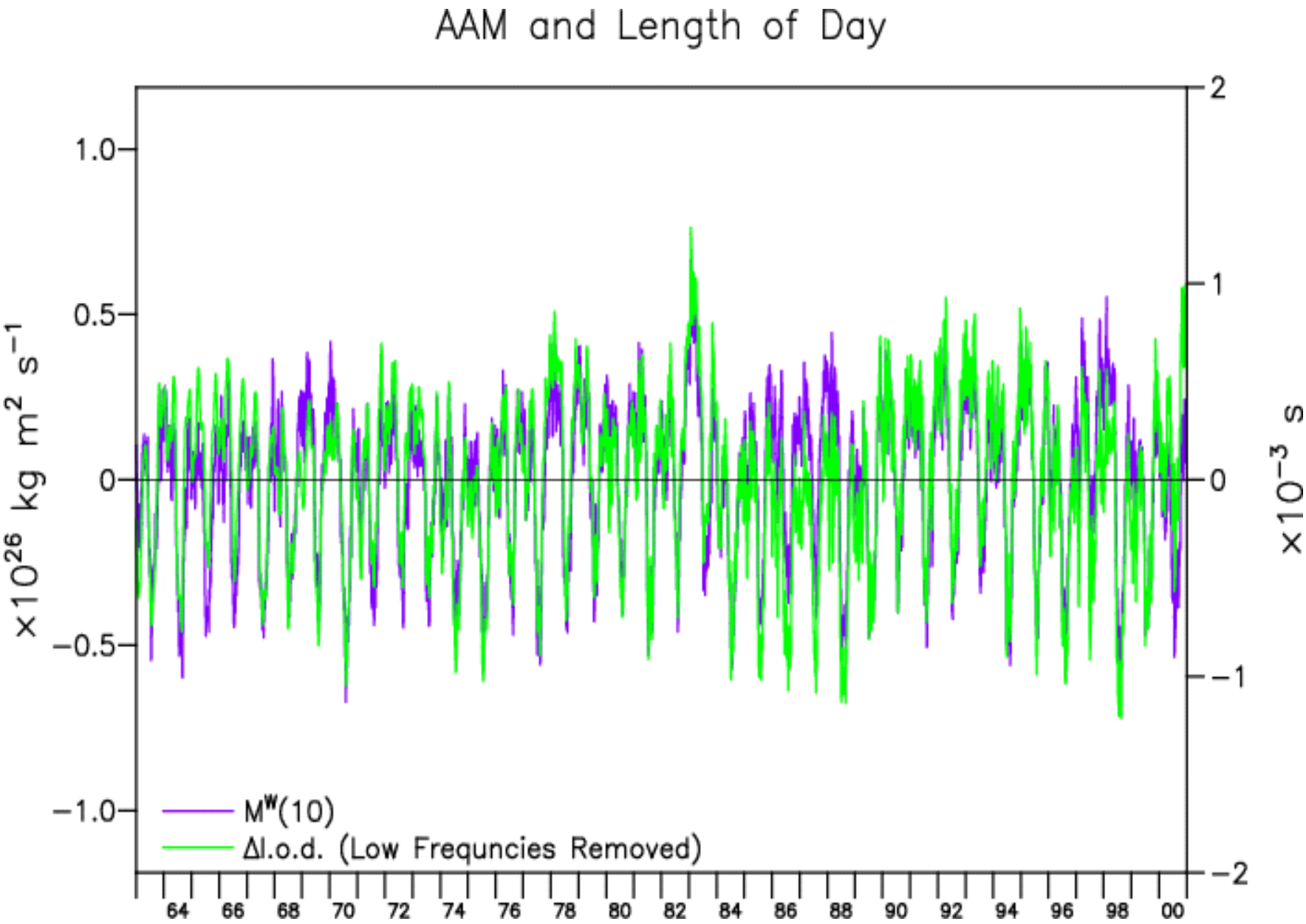


La Niña (10/1998)



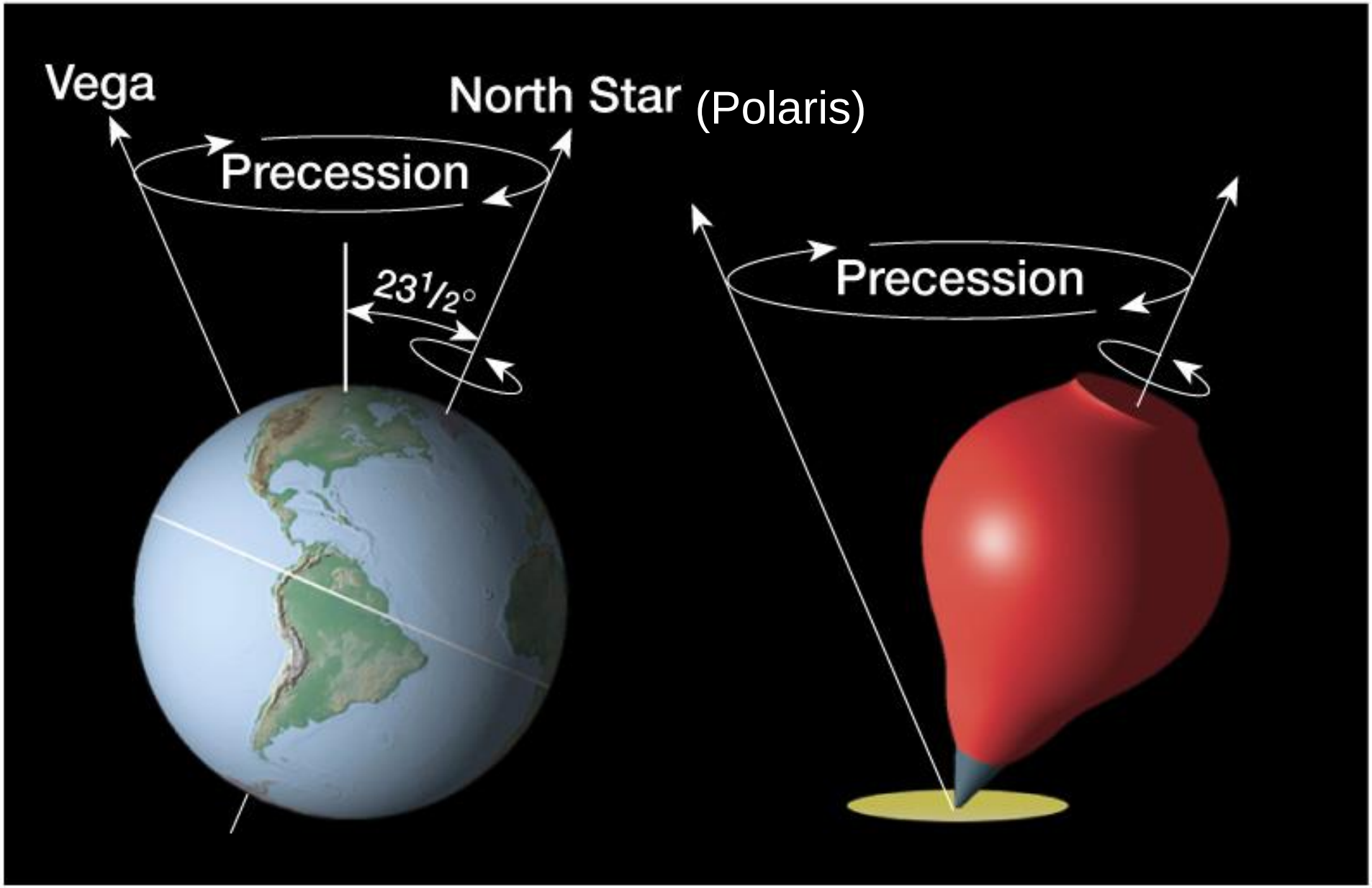






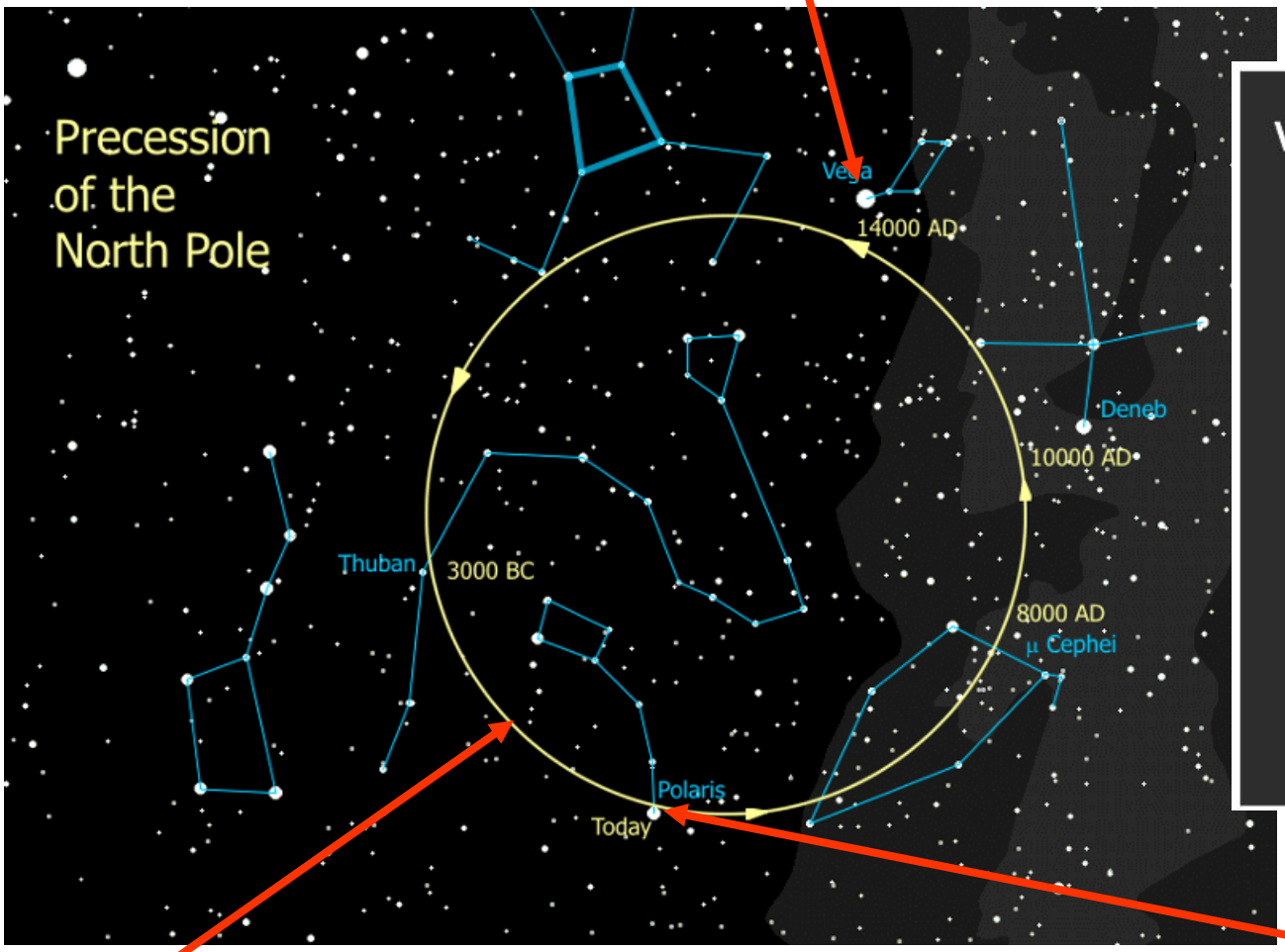
(courtesy D. Salstein)

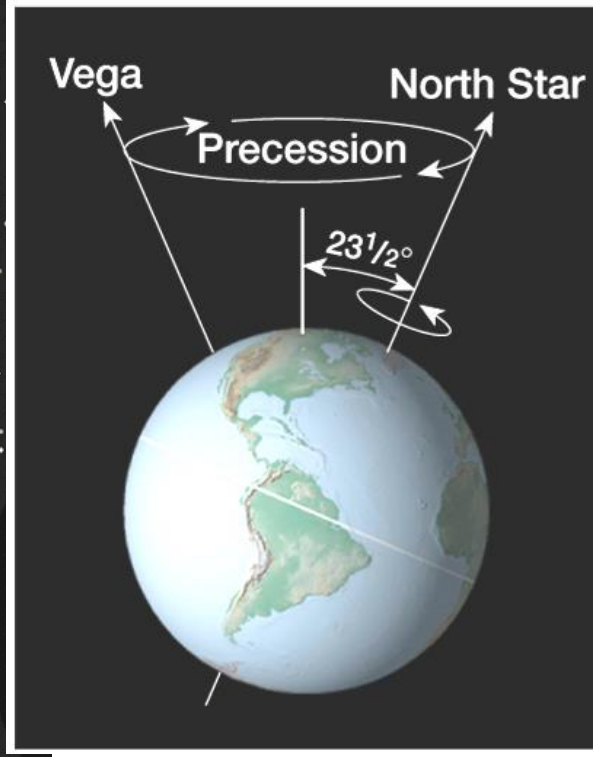
“The Earth precesses/nutates like a top.”


Vega
North Star (Polaris)
Precession
23 1/2°
Precession

“歲差”現象 (astronomical precession)

織女星



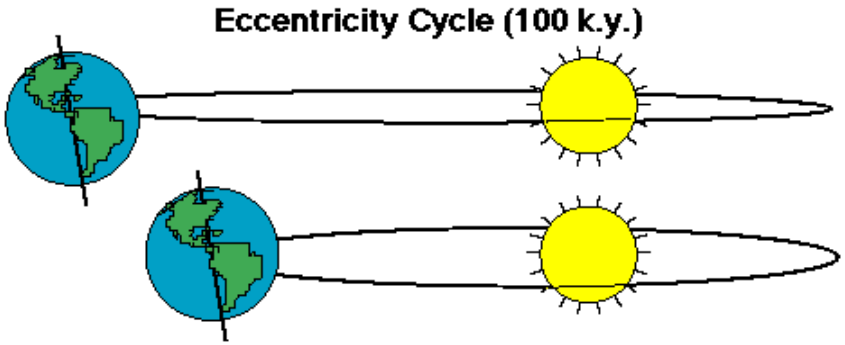


(今天的)北極星

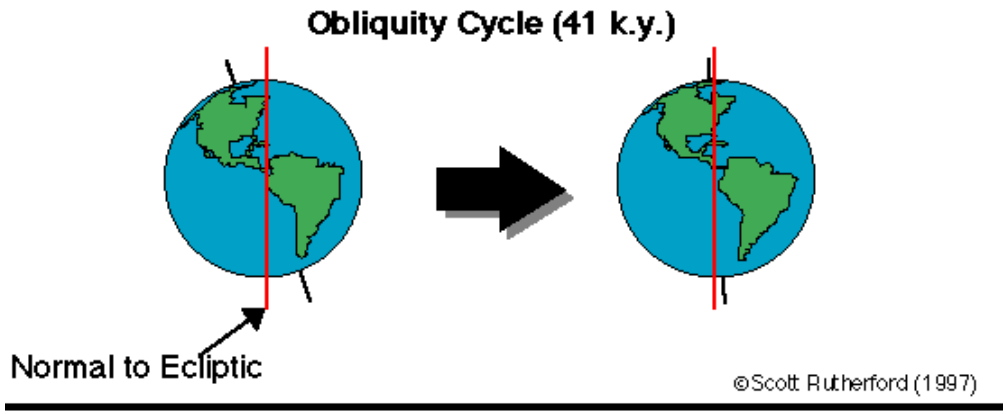
子曰：為政以德，譬如北辰，居其所，而眾星拱之。《論語》

Milankovitch Cycles

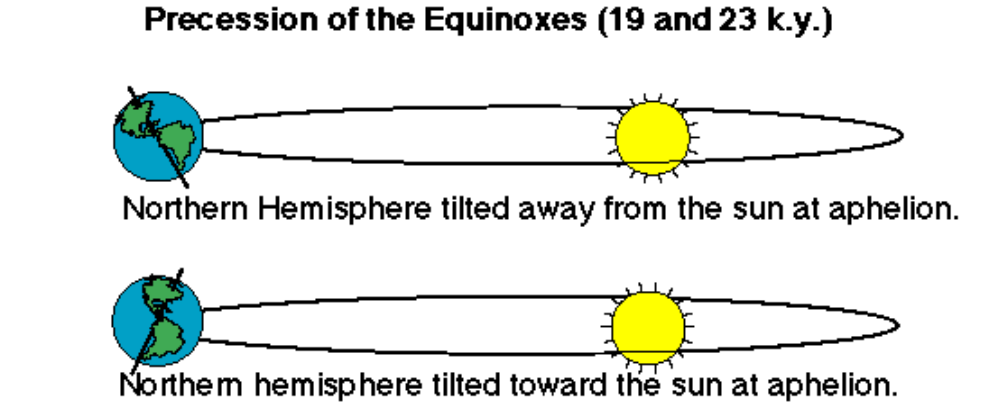
(1)

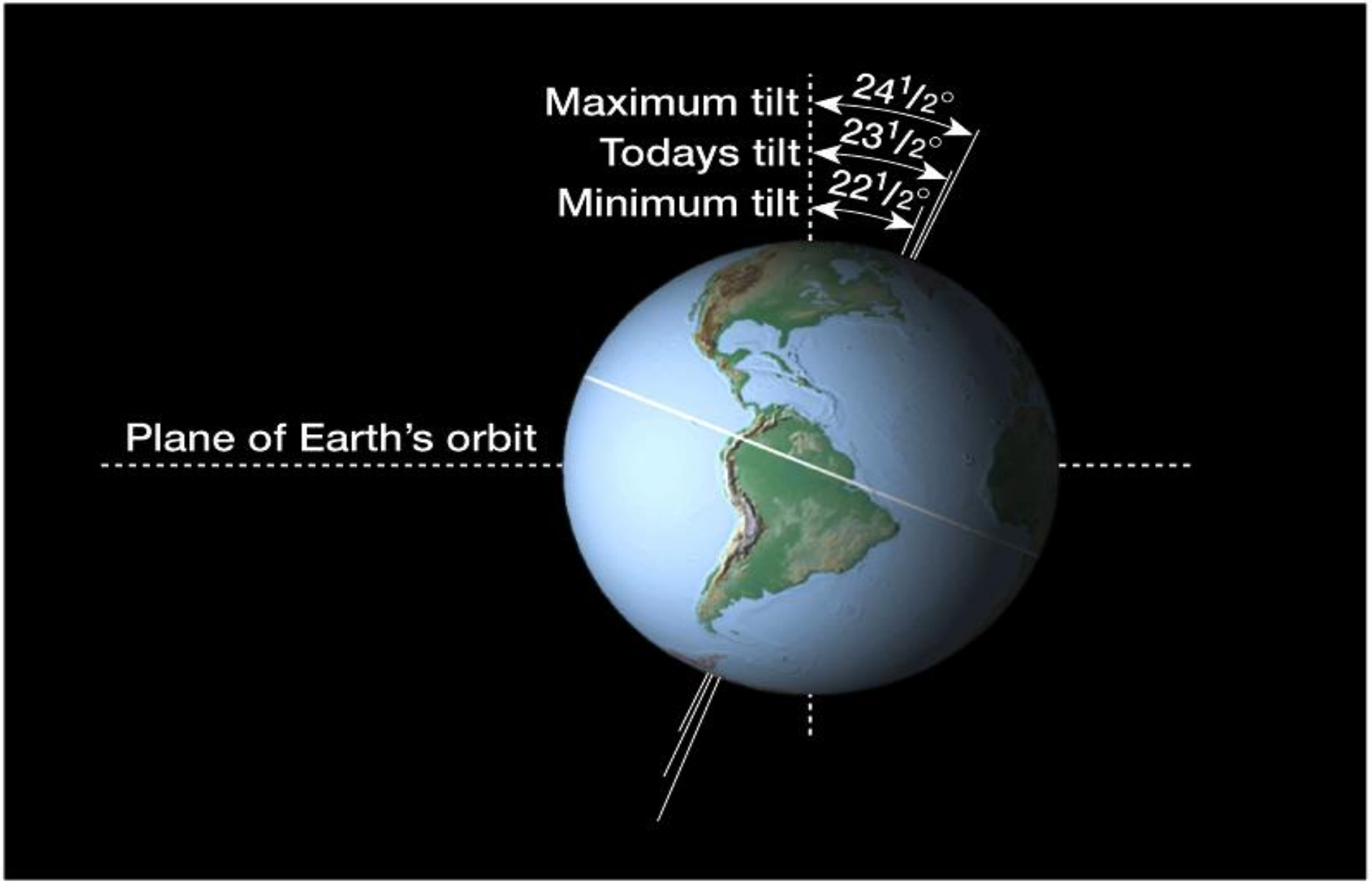


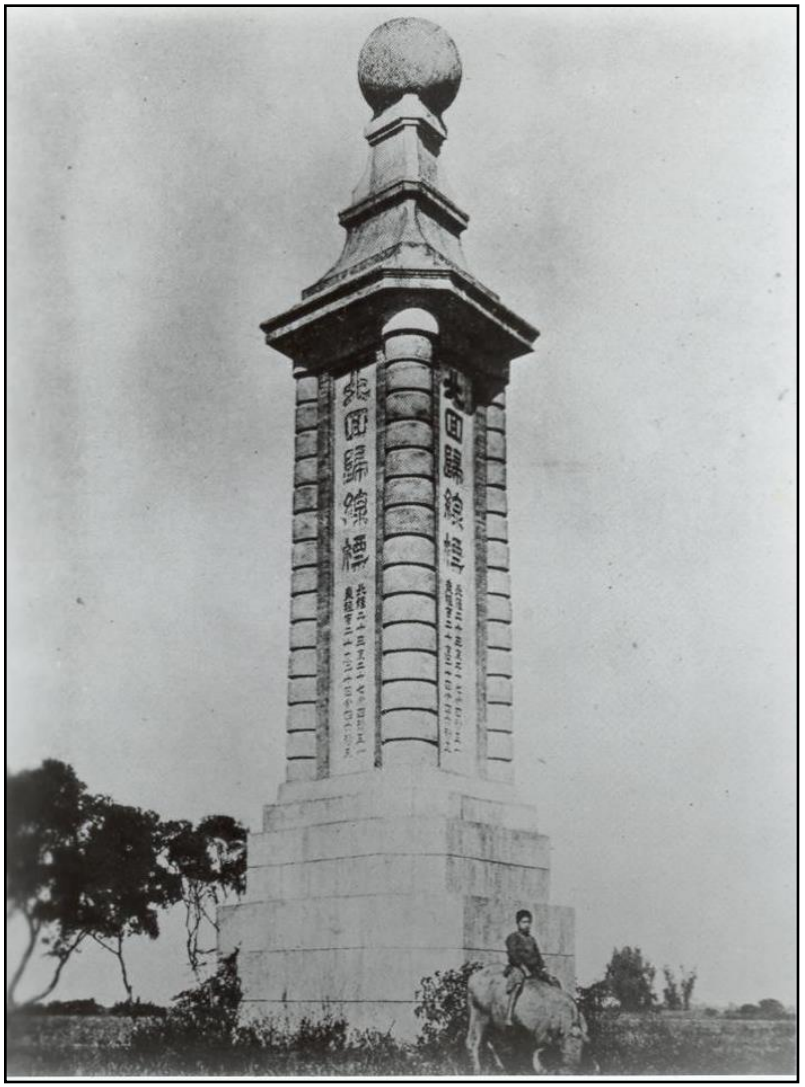
(2)



(3)

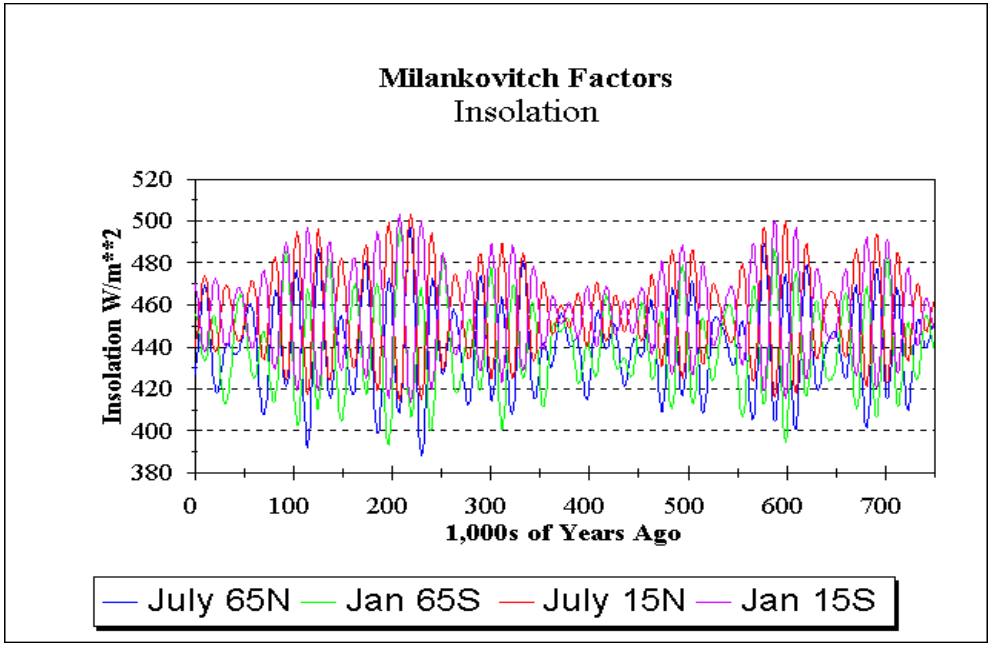


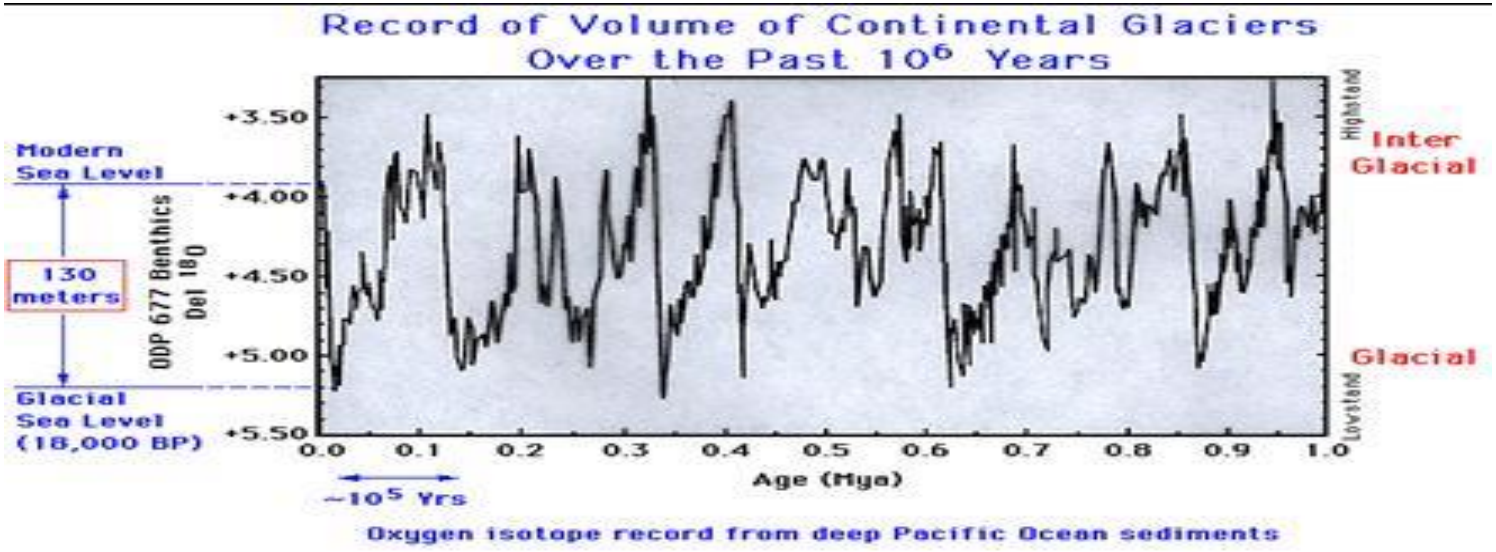

Maximum tilt
Todays tilt
Minimum tilt
24 1/2°
23 1/2°
22 1/2°
Plane of Earth's orbit

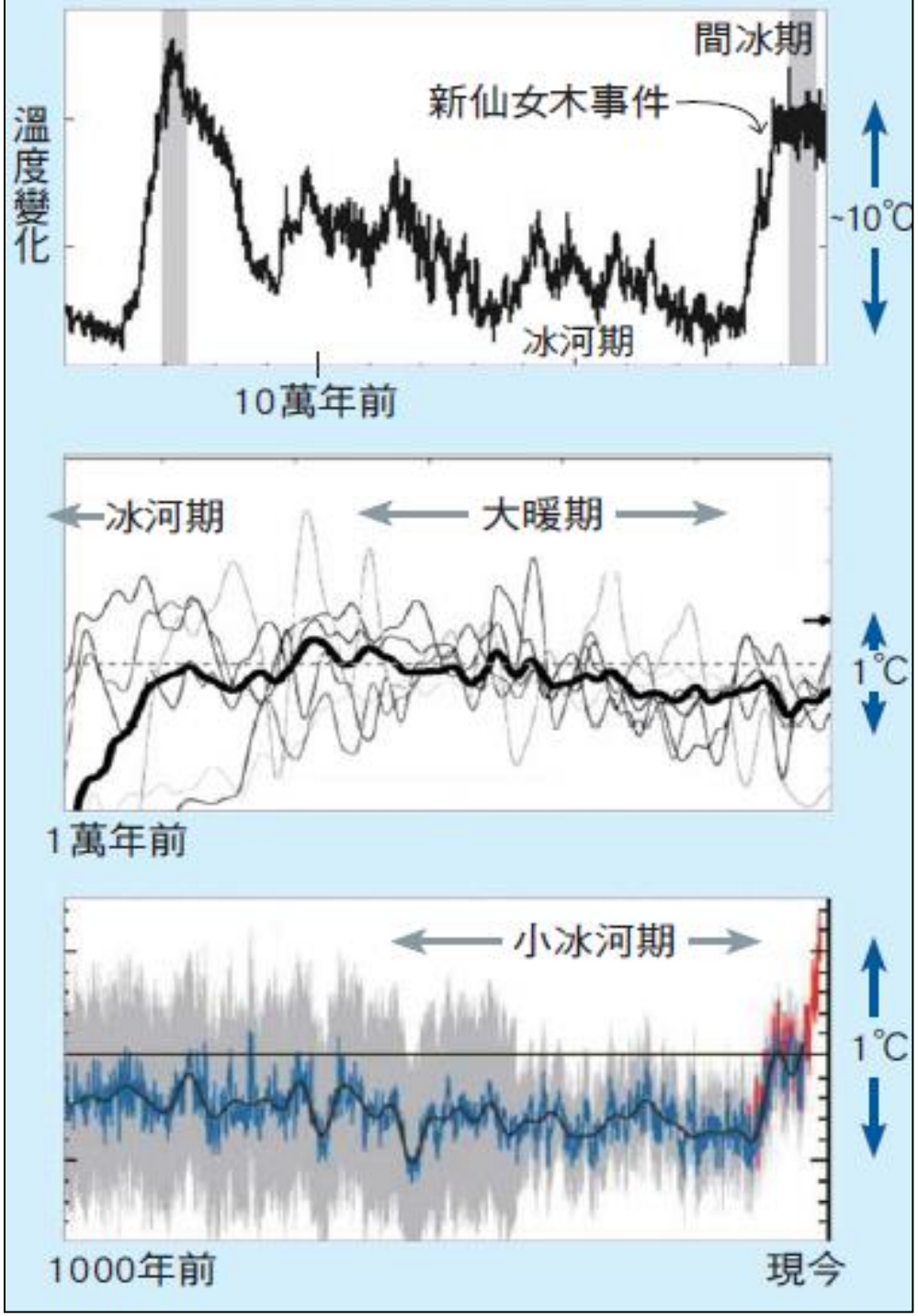


嘉義北回歸線標

哥倫布遇見北美原住民


Milankovitch Factors
Insolation
Insolation W/m**2
520
500
480
460
440
420
400
380
0
100
200
300
400
500
600
700
1,000s of Years Ago
July 65N
Jan 65S
July 15N
Jan 15S

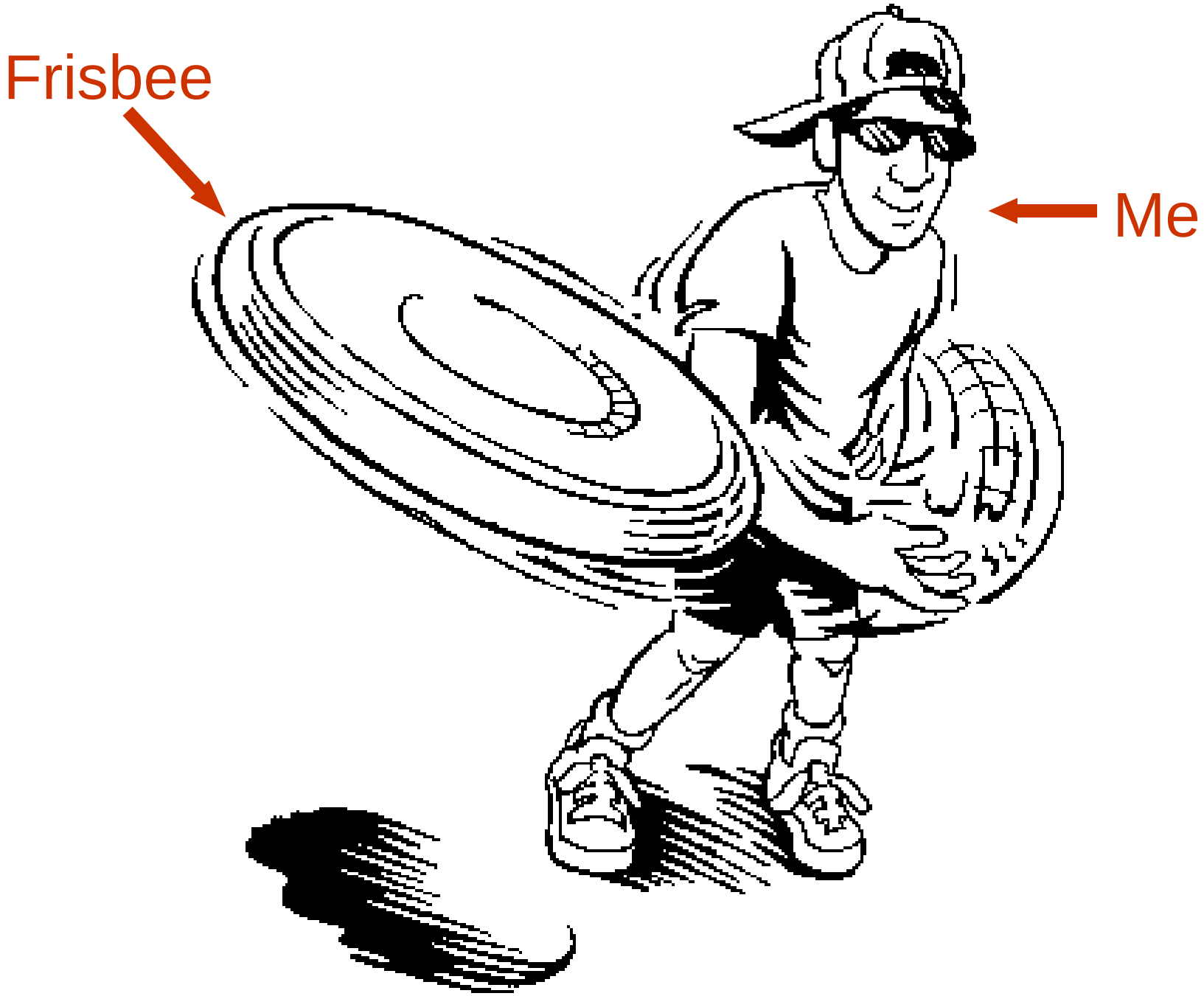

Record of Volume of Continental Glaciers
Over the Past 10⁶ Years
Modern
Sea Level
130
meters
Glacial
Sea Level
(18,000 BP)
ODP 677 Benthics
Del ¹⁸O
+3.50
+4.00
+4.50
+5.00
+5.50
Highstand
Lowstand
Inter
Glacial
Glacial
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Age (Mya)
~10⁵ Yrs
Oxygen isotope record from deep Pacific Ocean sediments

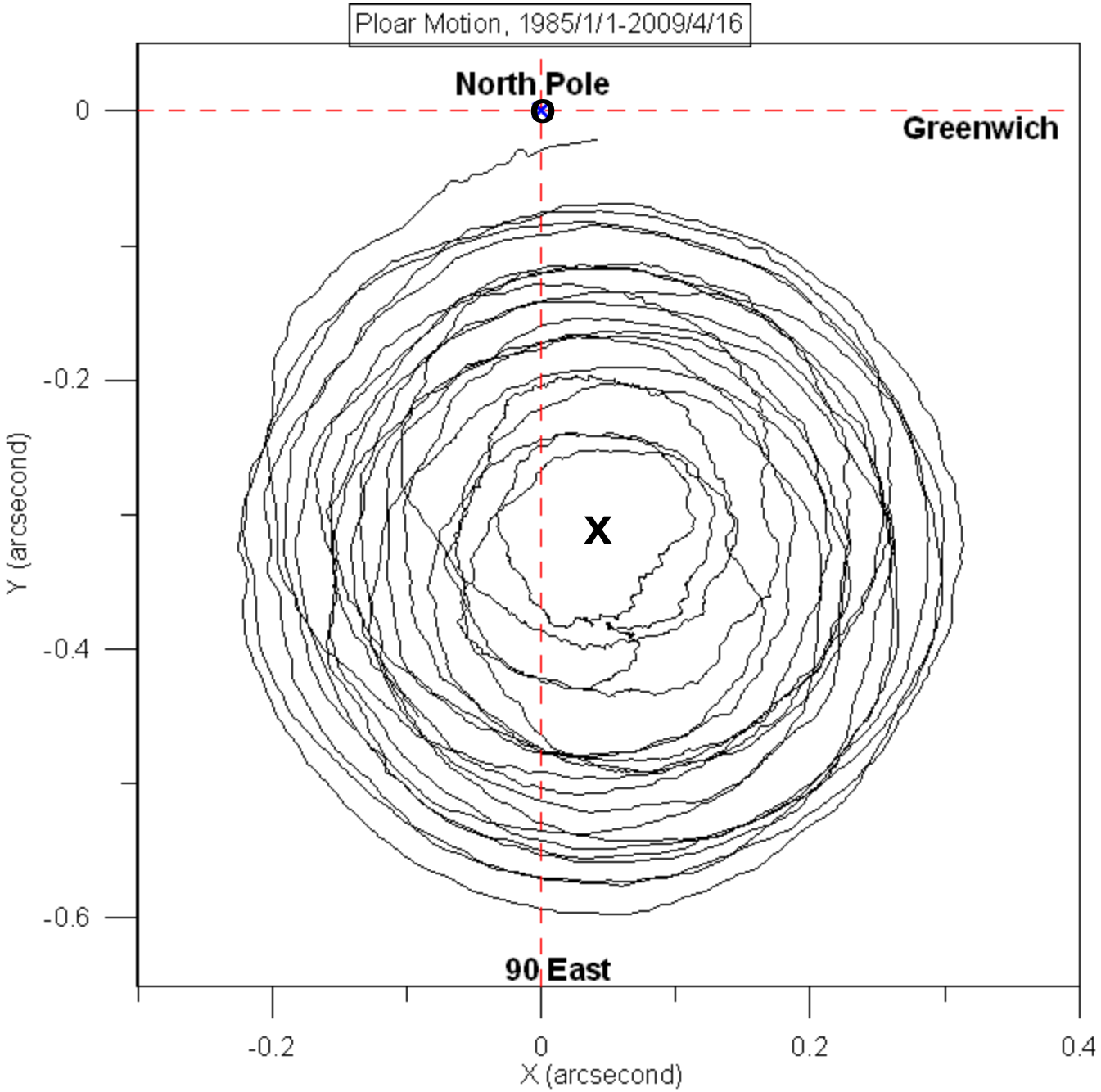

間冰期
新仙女木事件
溫度變化
~10℃
冰河期
10萬年前
冰河期
大暖期
1℃
1萬年前
小冰河期
1℃
1000年前
現今

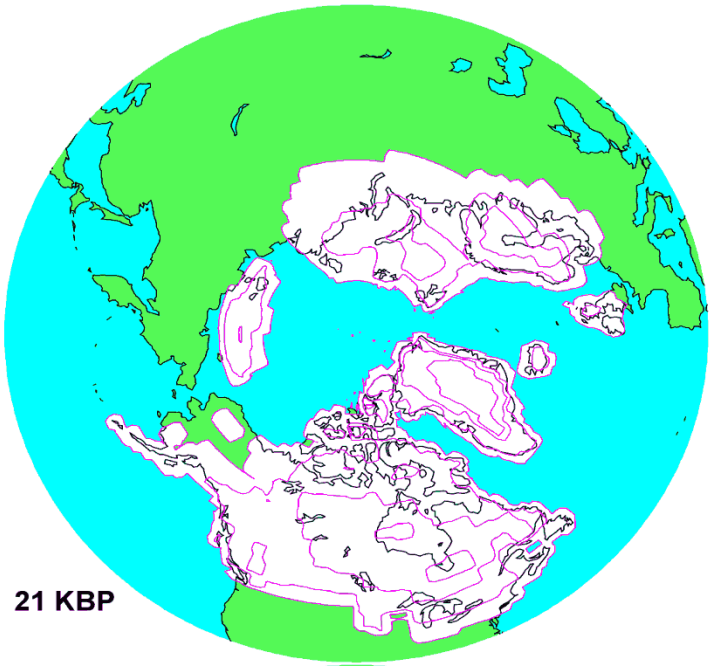
“The Earth precesses/nutates like a top.”

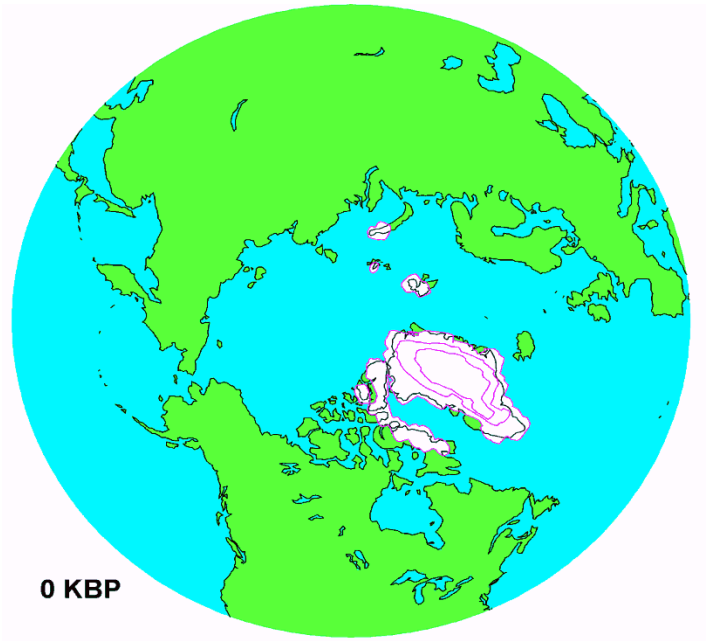
“The Earth librates like a tortional pendulum.”

“The Earth wobbles like a frisbee.”

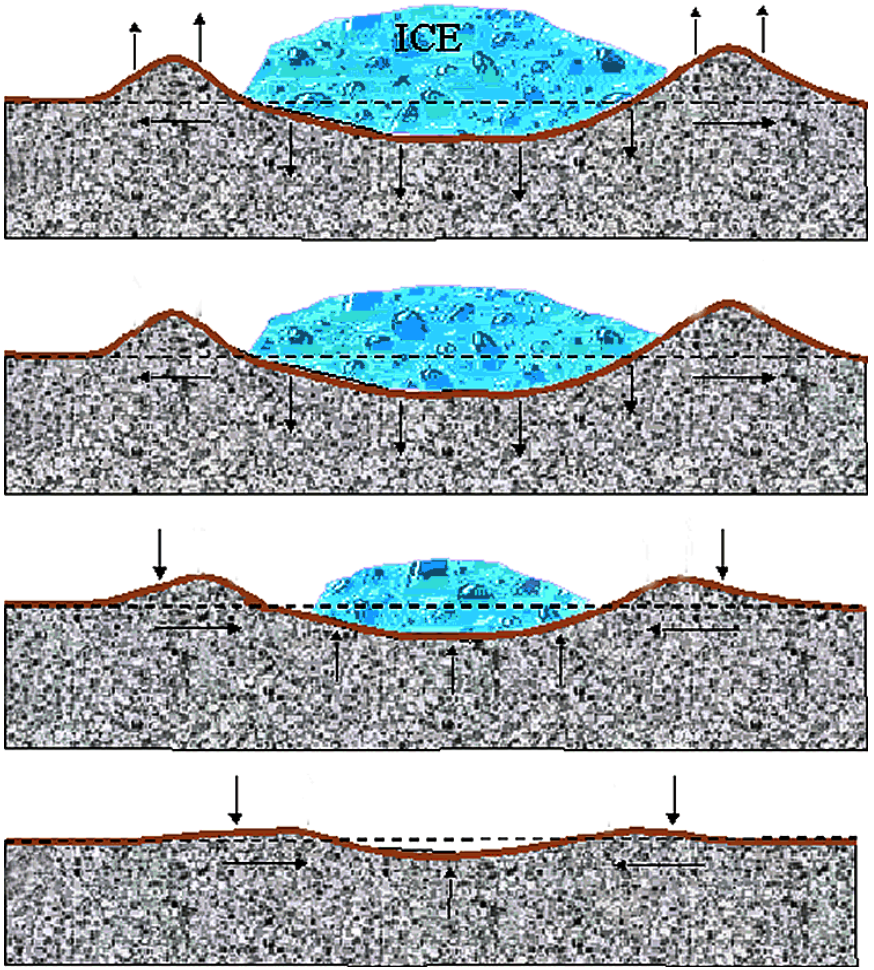

Frisbee
Me


Ploar Motion, 1985/1/1-2009/4/16
North Pole
Greenwich
90 East
0
-0.2
-0.4
-0.6
Y (arcsecond)
-0.2
0
0.2
0.4
X (arcsecond)
X

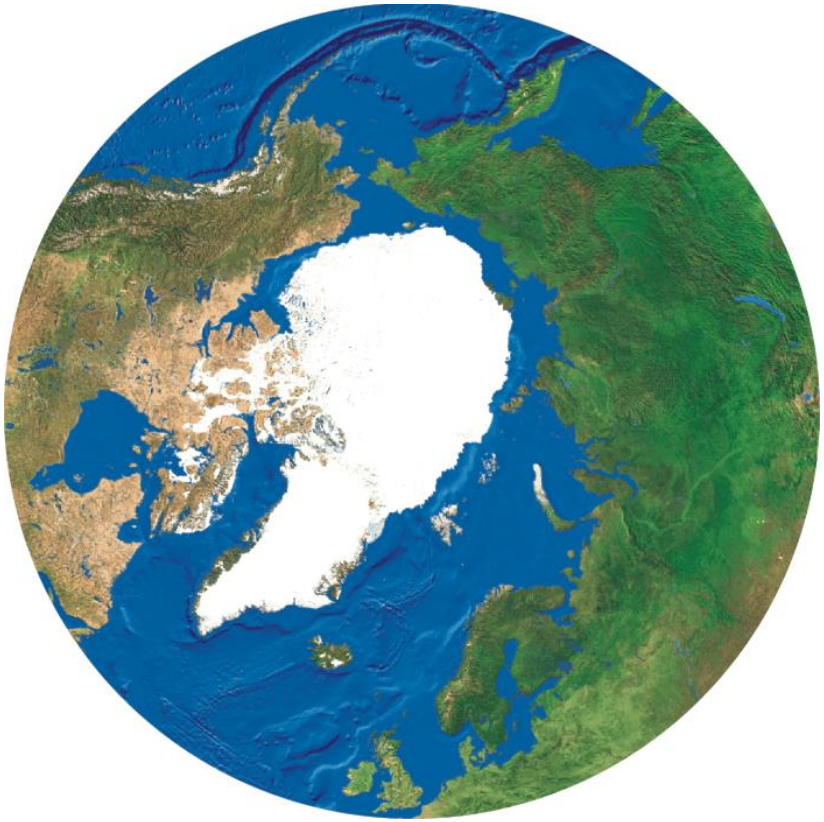




Since the peak of last great ice age, 20K years ago...



Potential sea level rise (slr)



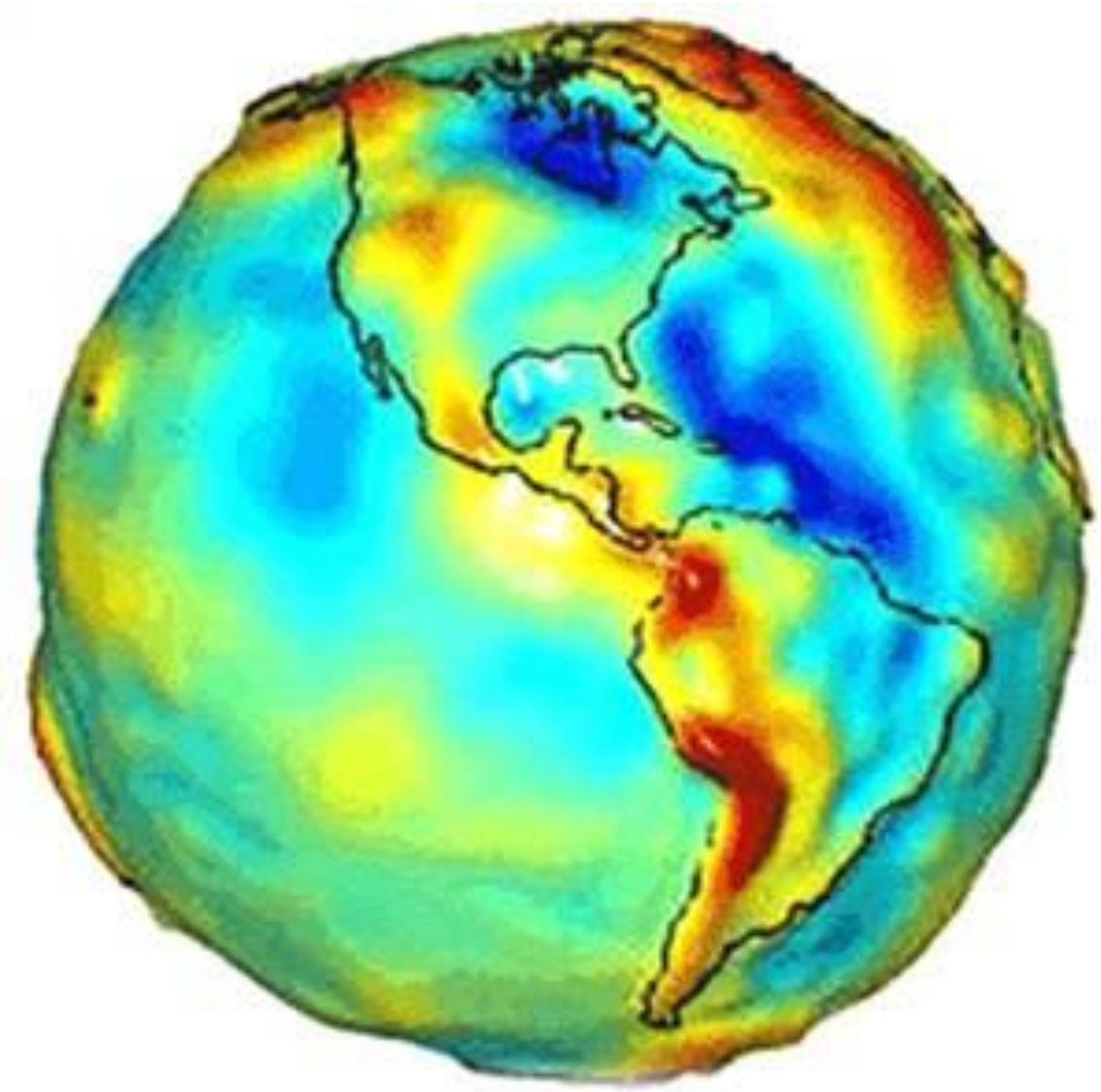
Arctic sea ice = 0 slr
Greenland ice = ~7 m slr

Antacrtica ice = ~70 m slr

First, the **STATIC** gravity field…..

(which is 99.9999..% of the gravity field)

Earth's Geoid (Static)



Gravitational Potential Field (Geoid)

Multi-pole expansion of Newton's formula:

$$U(\mathbf{r}) = G \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \frac{1}{(2n+1)\, r^{n+1}} \left[\iiint_{V_0} \rho(\mathbf{r}_0)\, r_0^{\,n}\, Y_{nm}(\Omega_0)\, dV_0 \right] Y_{nm}^{\,*}(\Omega)$$

Conventional expression (satisfying Laplace Eq. in terms of Stokes Coeff.):

$$U(r,\theta,\lambda) = \frac{GM}{a} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r} \right)^{n+1} P_{nm}(\cos\theta) \left(C_{nm} \cos m\lambda + S_{nm} \sin m\lambda \right)$$

$$\Rightarrow \quad C_{nm} + iS_{nm} = \frac{1}{(2n+1)\, Ma^{n}} \iiint_{V_0} \rho(\mathbf{r})\, r^{n}\, Y_{nm}(\Omega)\, dV$$

Measuring Gravity

- Surface
  - centrifugal (pseudo-)force correction
  - free-air anomaly
  - Bouguer anomaly
- Air-borne, Ship-borne
  - centrifugal (pseudo-)force correction
  - Coriolis (pseudo-)force correction (Eötvös effect)
  - platform acceleration (“noise”)
- Space-born
  - gravity canceled by centrifugal force (free fall)

    ⇨ need orbit perturbations, hence “tracking”

"Measuring" Gravity from Space : Milestones

- 1957 Sputnik II – J_2 (Earth oblateness)
- Kaula's (1966) theory (spherical harmonics)
- Early 1970s, Satellite-laser-ranging
- Spherical harmonic solutions
  - ~1970s, 10 x 10
  - ~1980s, 36 x 36, 70 x 70
  - ~1990s, 180 x 180, 360 x 360
  - "EGM 2008", degree/order 2159 (!)
- time-variable: "J_2 dot" (1980s)
- time-variable: J_2 and low-degree variations (1990s)
- CHAMP (2000), GRACE (2002), GOCE (2009)

Now, **TIME-VARIABLE** gravity field…

(which is 0.0…1% of the gravity field)

new observable!

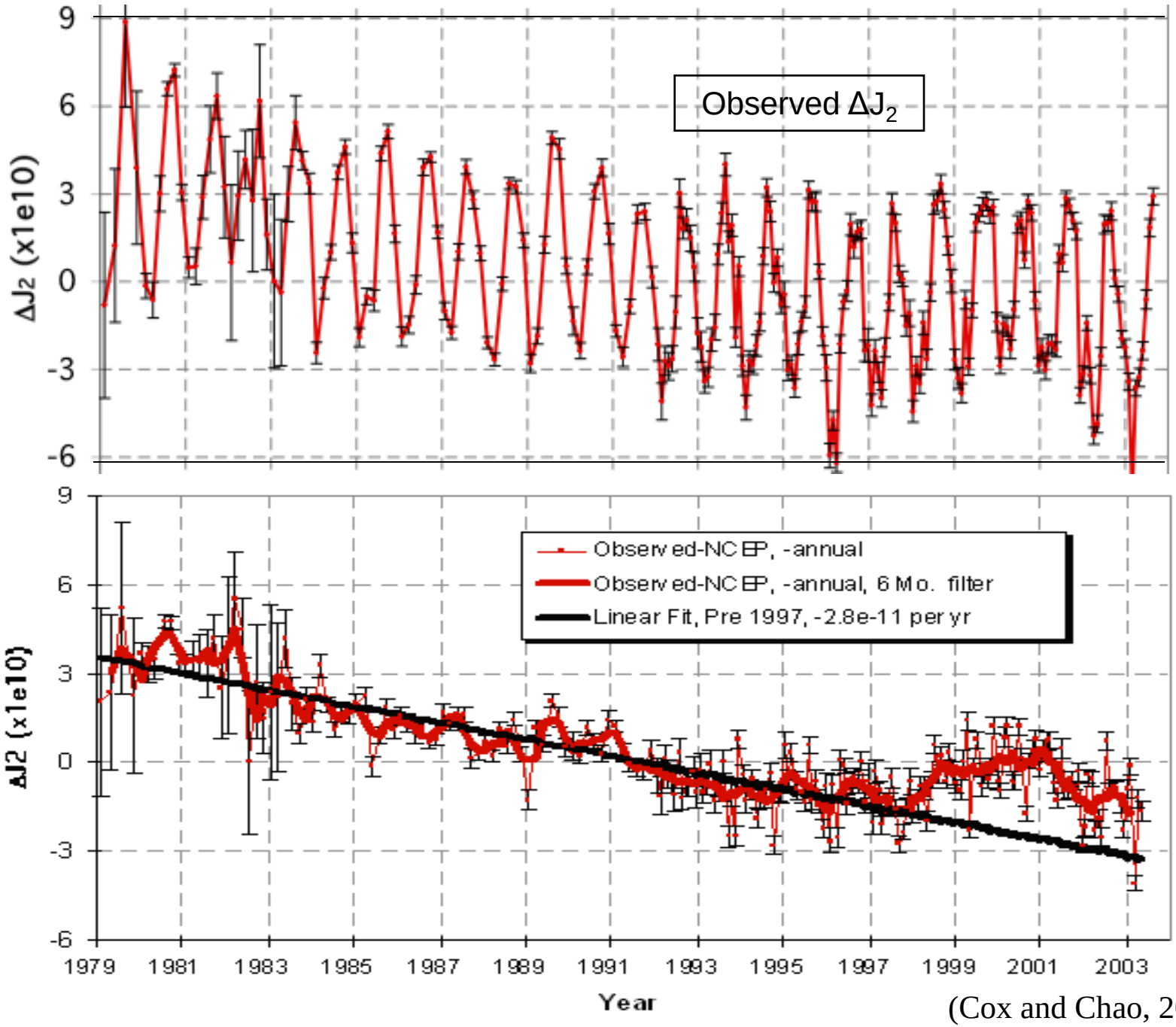
new data type!

J_2 (Earth's oblateness)

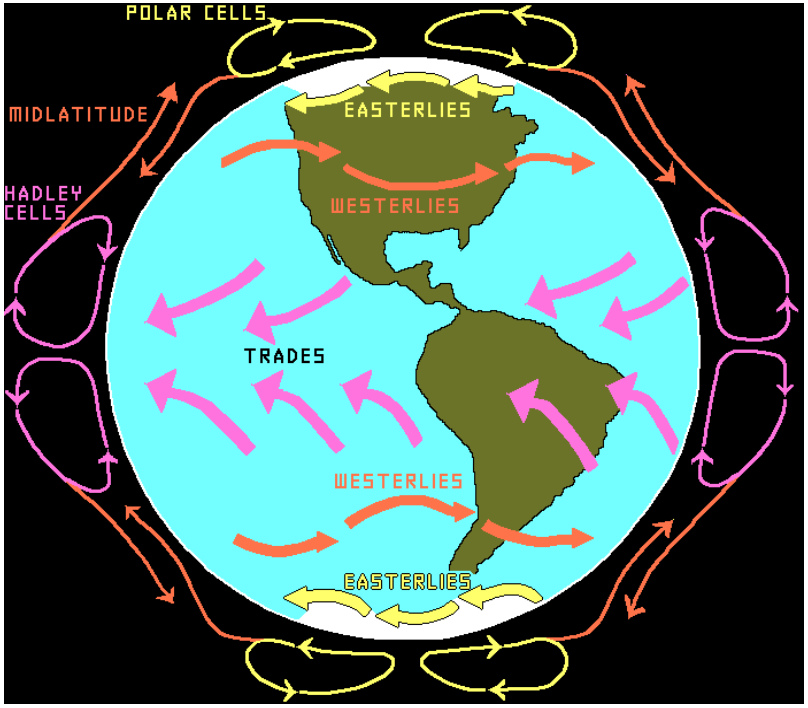
- by far the largest gravity "anomaly"
- ~100% due to rotational equilibrium
- = 0.0010826265…
- corresponds to a geoid "flattening" ~1/300

  ~ centrifugal force / gravity

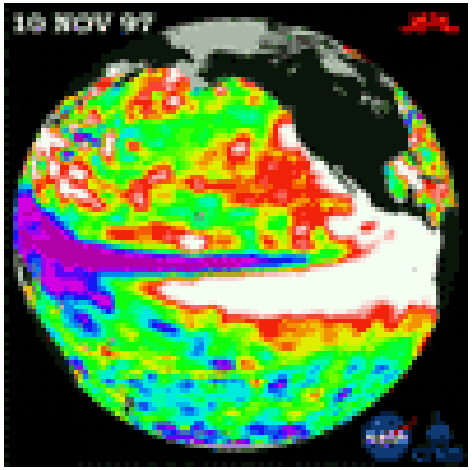
  ~ equatorial bulge / Earth radius
- varies at and beyond the last digit, due to geophysical and climatic mass redistributions.



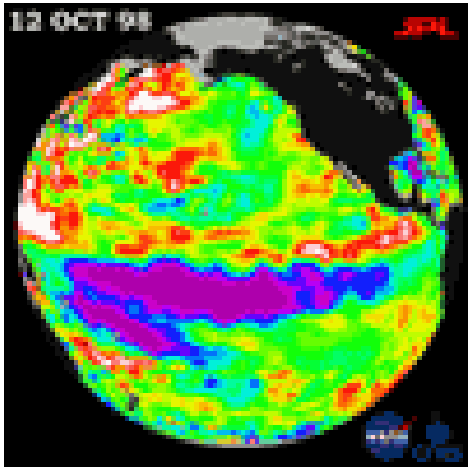
(Cox and Chao, 2002)

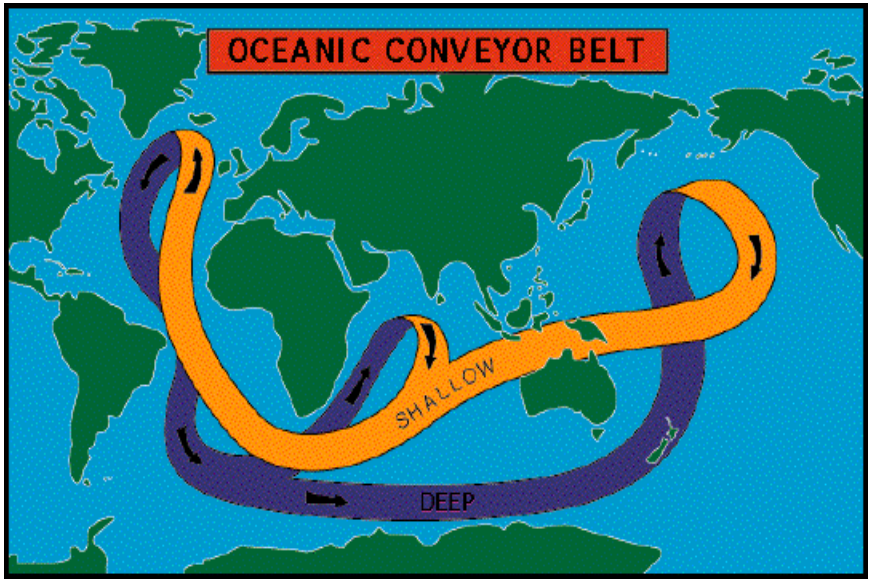


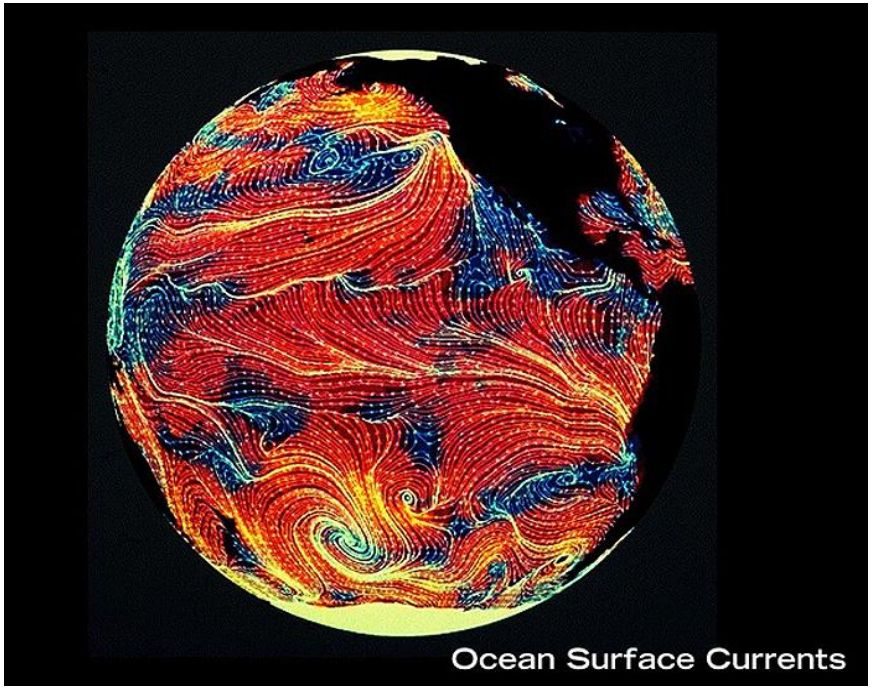
El Niño (11/1997)



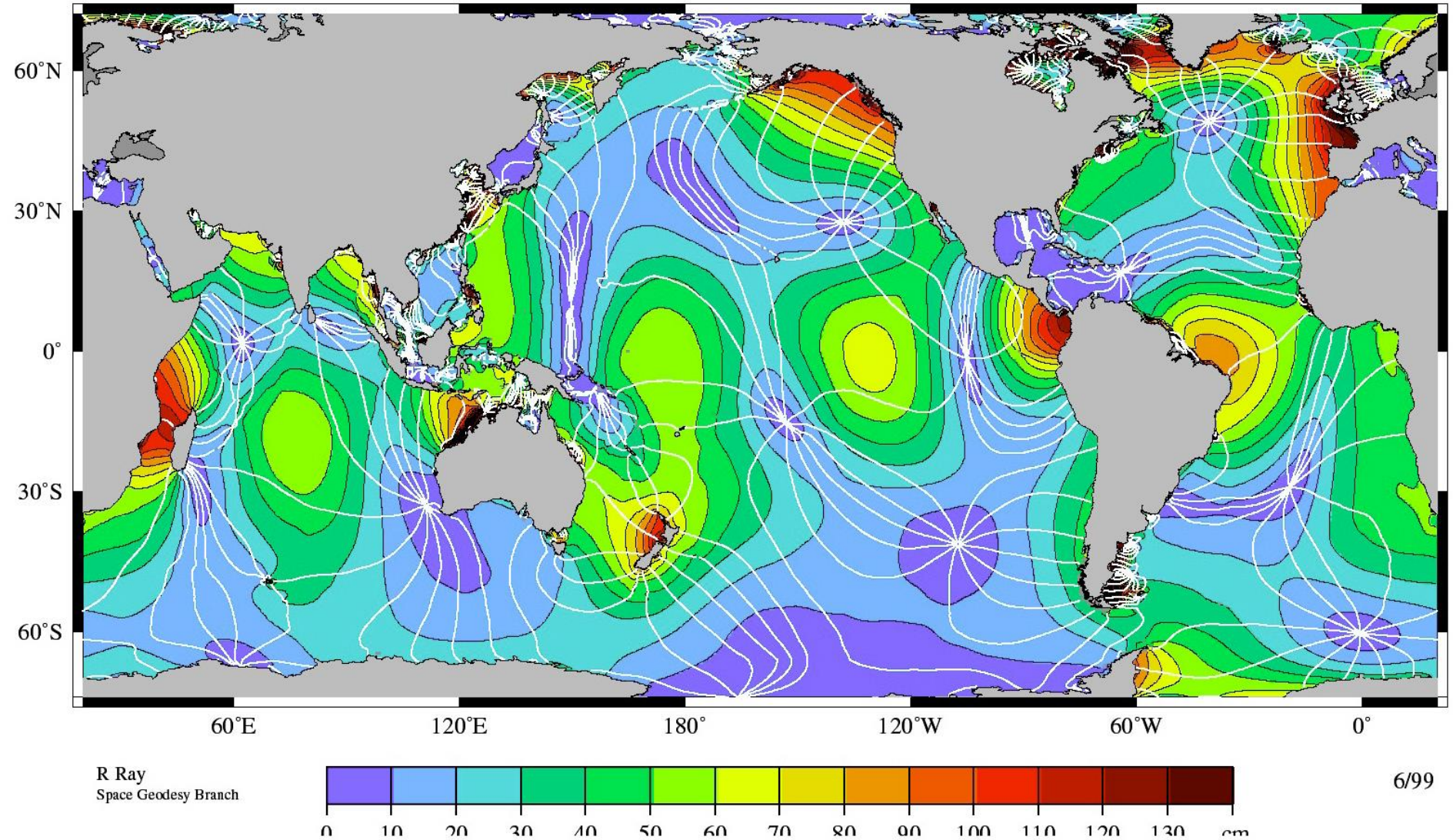
La Niña (10/1998)



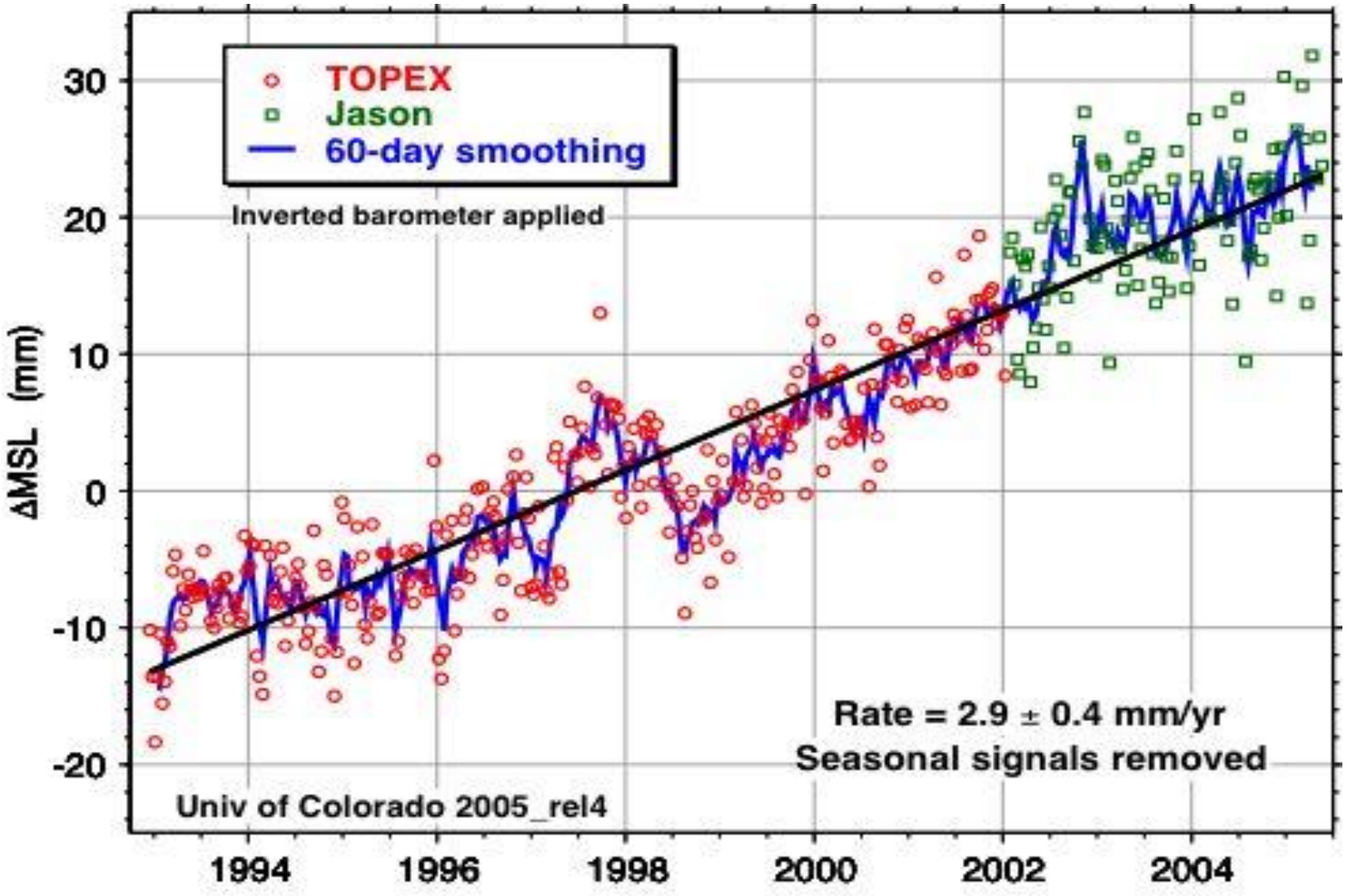




M_2 Lunar Tide in the Ocean



(GOT99, courtesy R. Ray)



Global Sea Level Rise From Topex/Poseidon

(courtesy S. Nerem)

The Three-Gorges Dam Project

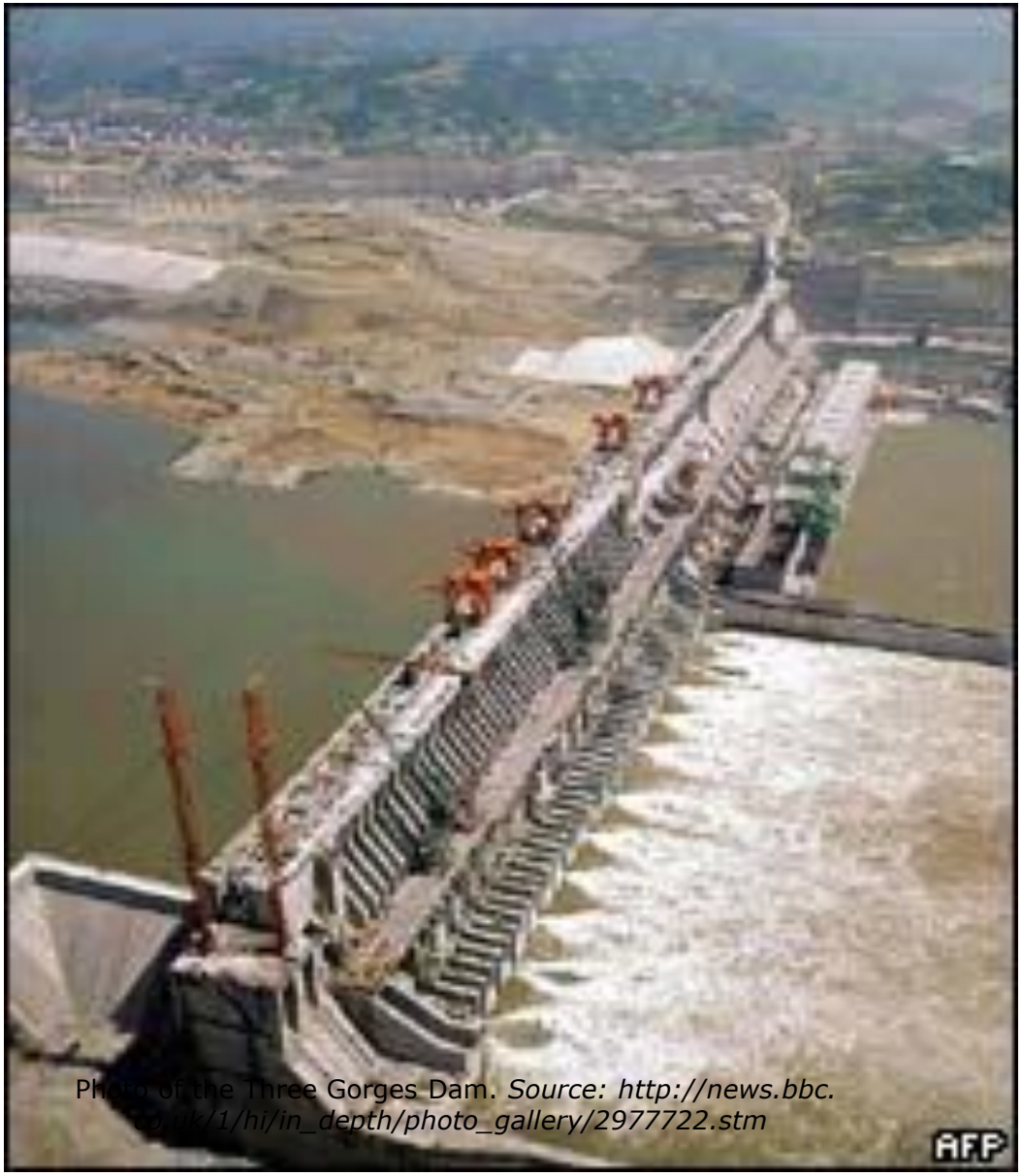


Photo of the Three Gorges Dam. *Source: http://news.bbc.co.uk/1/hi/in_depth/photo_gallery/2977722.stm*

History:

Dr. Sun Yatsen, 1917

Savage Report, 1940s

Debates in 1950-60s

GeZhouBa Project, 1981

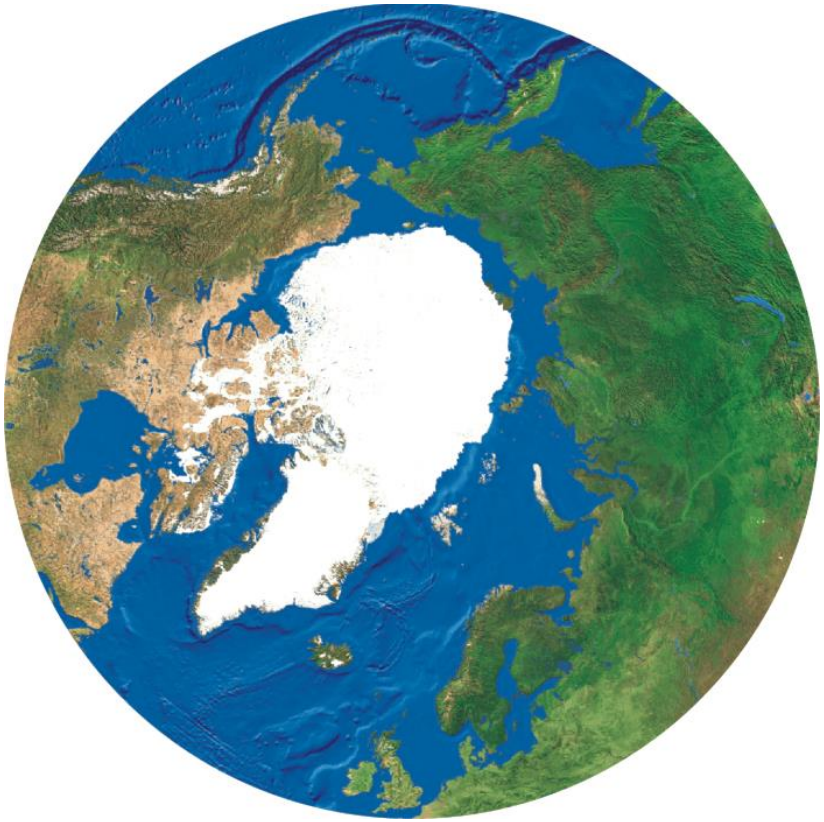
Three-Gorges Dam decided in 1992.

Phase 1 (1993-1997): Block the river and divert the flow.

Phase 2 (1998-2003): First power generation units in operation and permanent boat locks. Also, the reservoir will begin to fill to a level of 135 meters.

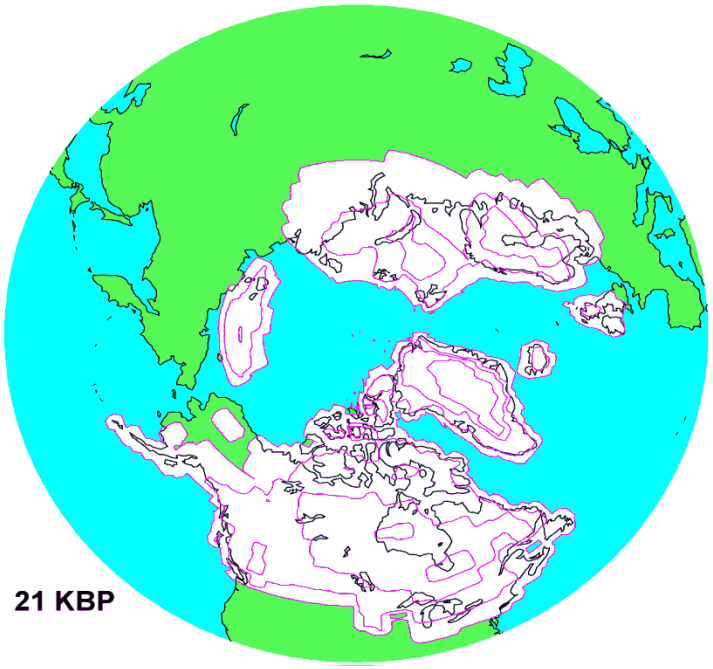
Phase 3 (2004-2009): Put all generation units into operation. The height of the water will reach 175 meters high.

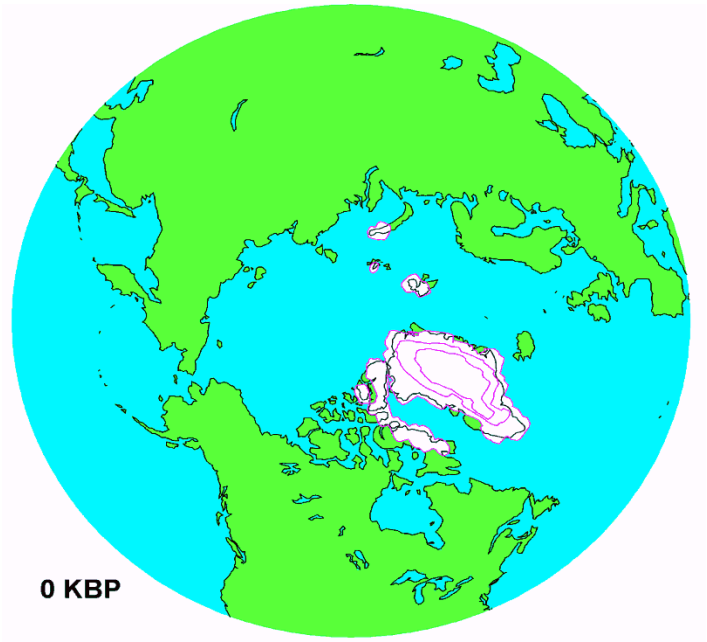
Potential sea level rise (slr)



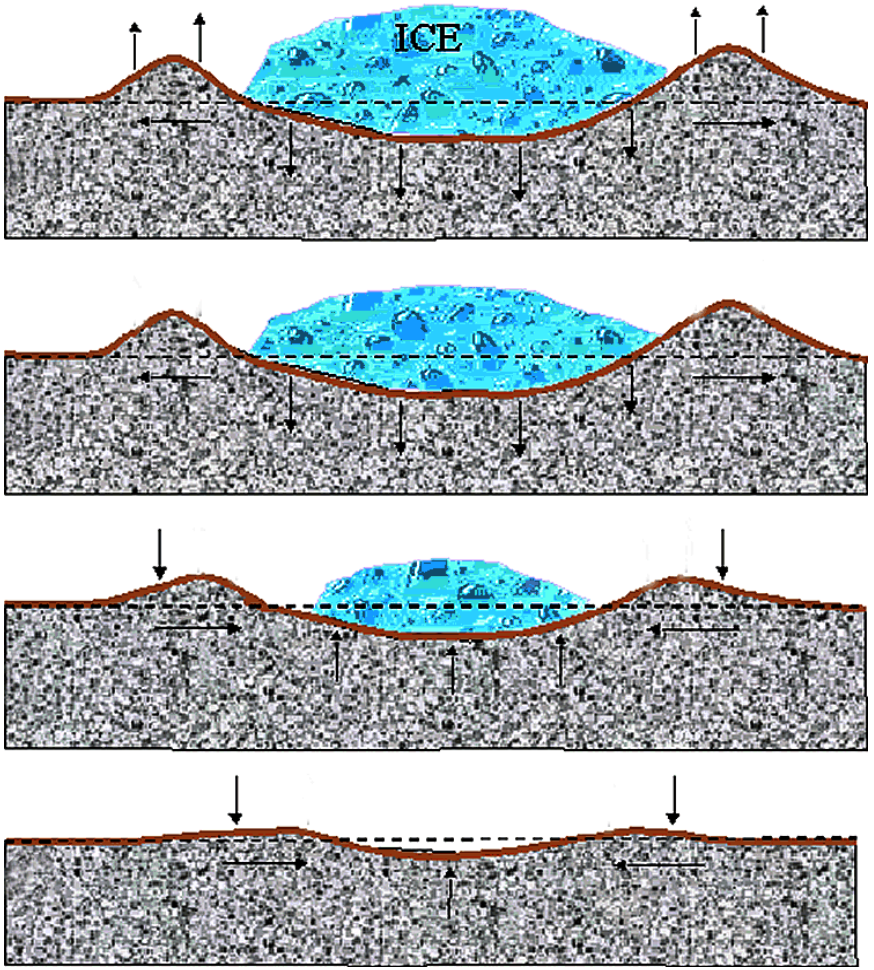
Arctic sea ice = 0 slr
Greenland ice = ~7 m slr

Antacrtica ice = ~70 m slr

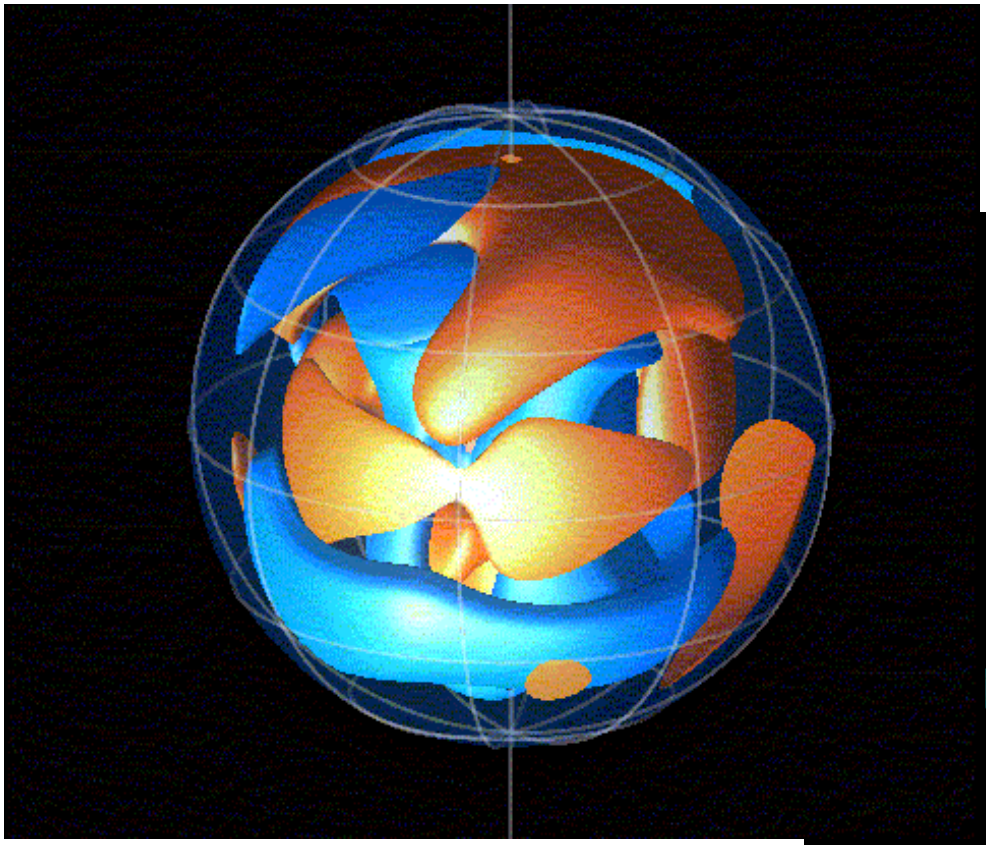


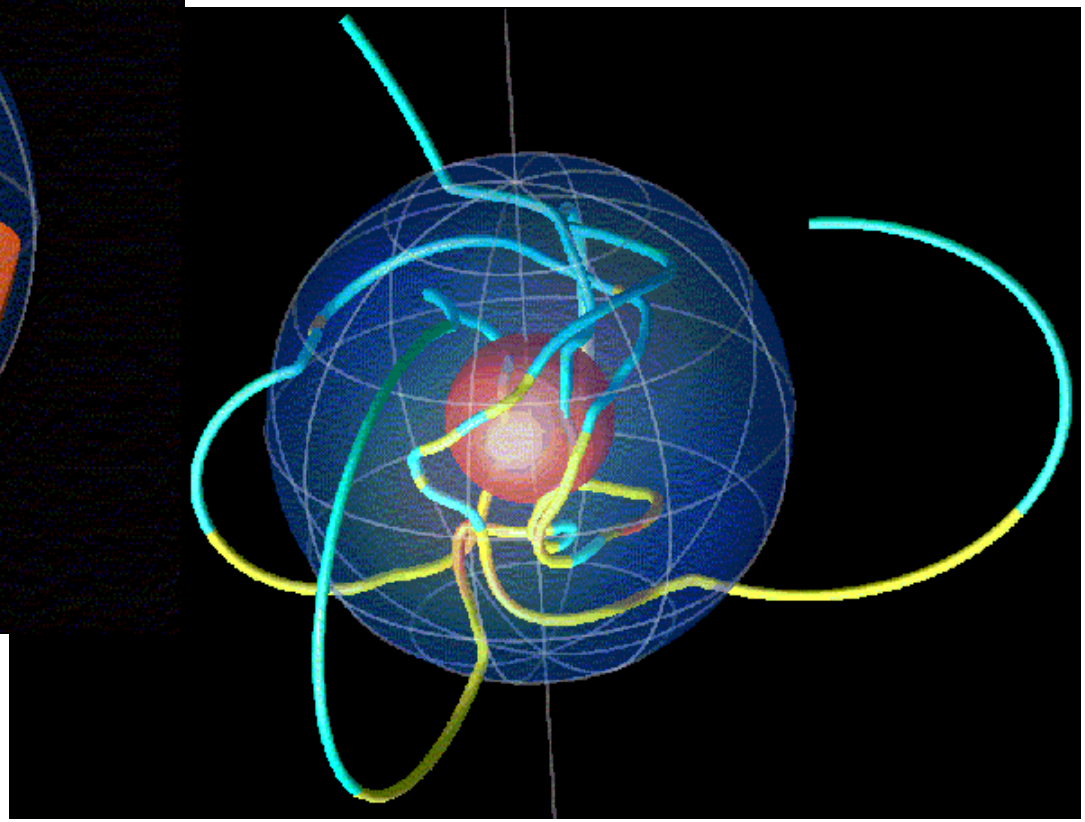


Since the peak of last great ice age, 20K years ago...



Fluid Core Motions and Geomagnetic Field



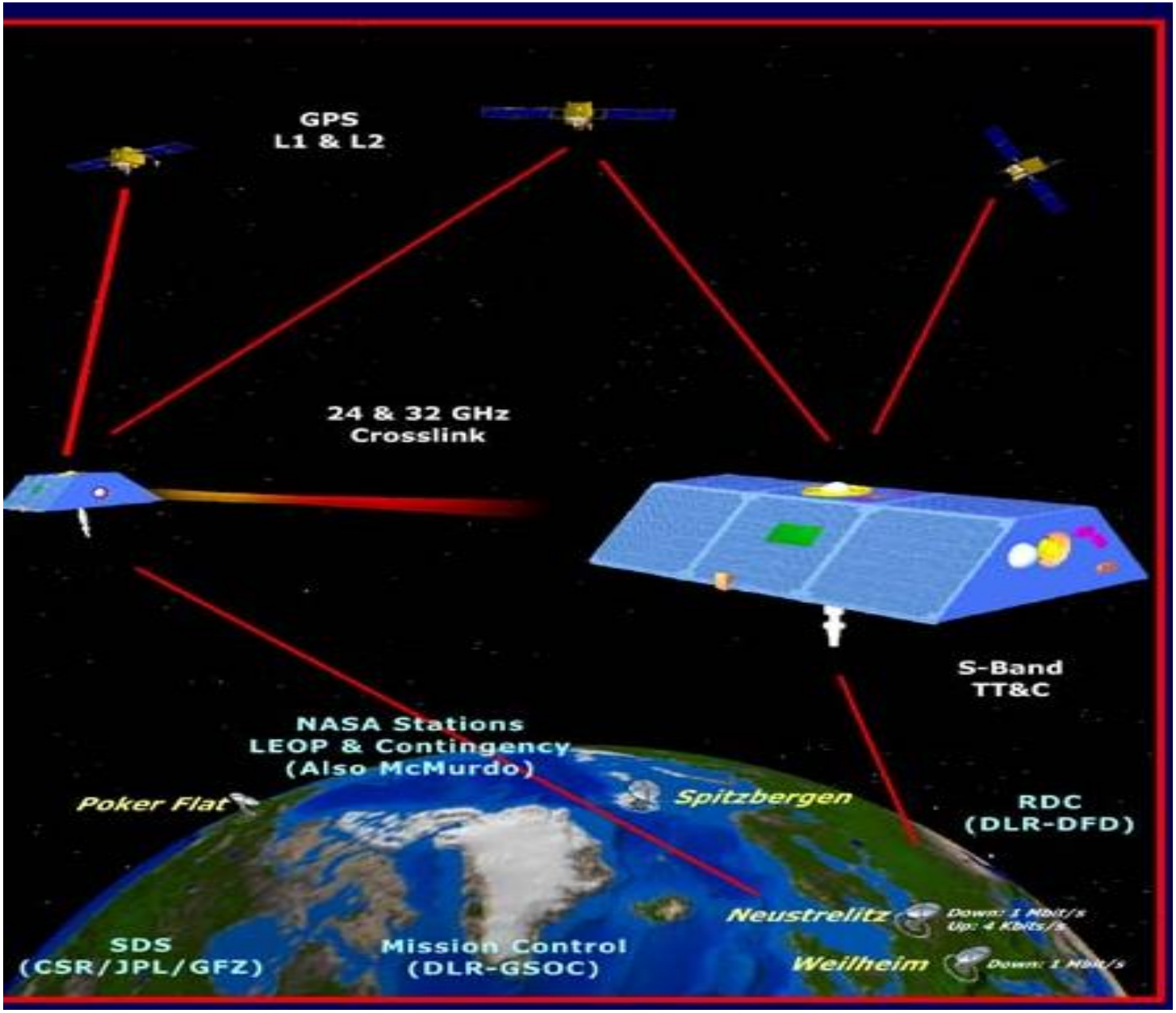


MoSST geodynamo model

(Kuang & Chao, 2003)

Alaska Earthquake March 27, 1964. Hanning Bay fault scarp on Montague Island, looking northwest. Vertical displacement in the foreground, in rock, is about 12 feet. The maximum measured displacement of 14 feet is at the beach ridge near the trees in the background. (U.S. Geological Survey)

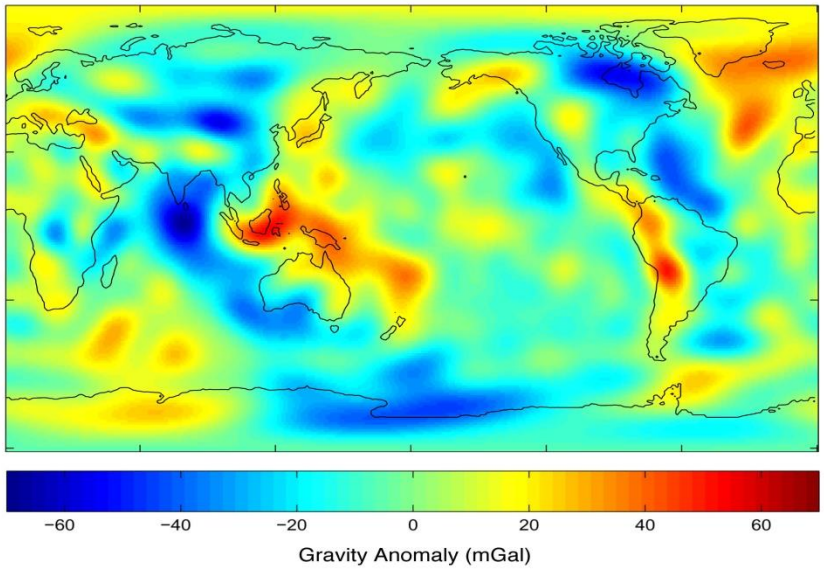
GRACE (Gravity Recovery And Climate Experiment)



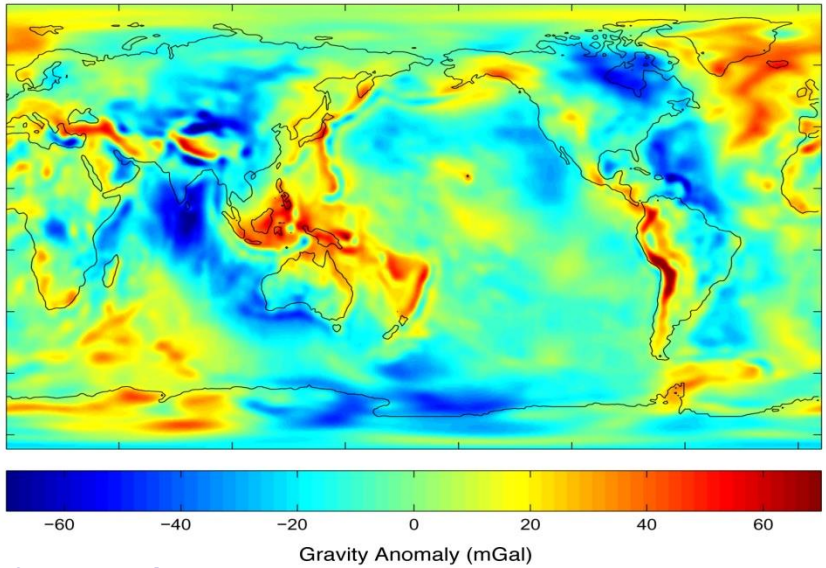

GOCE
SCIENCEphotoLIBRARY

Static Gravity Anomaly

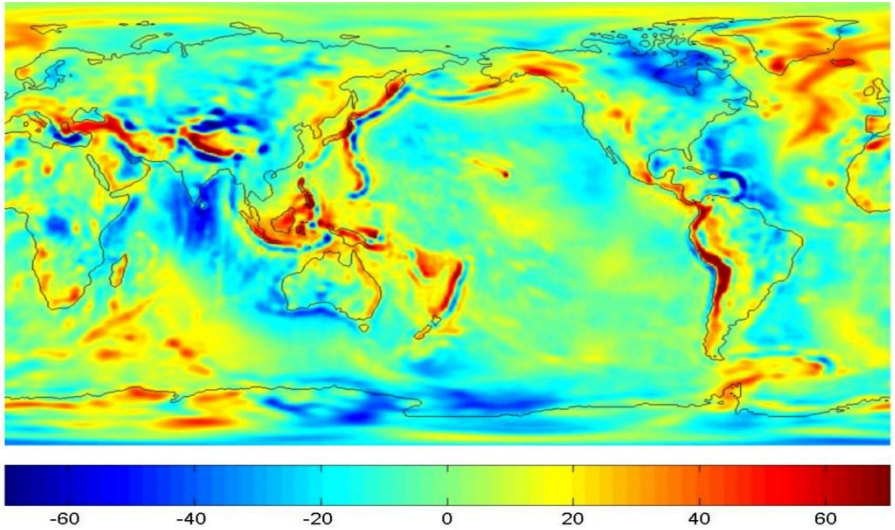
4 Decades of tracking to geodetic satellites



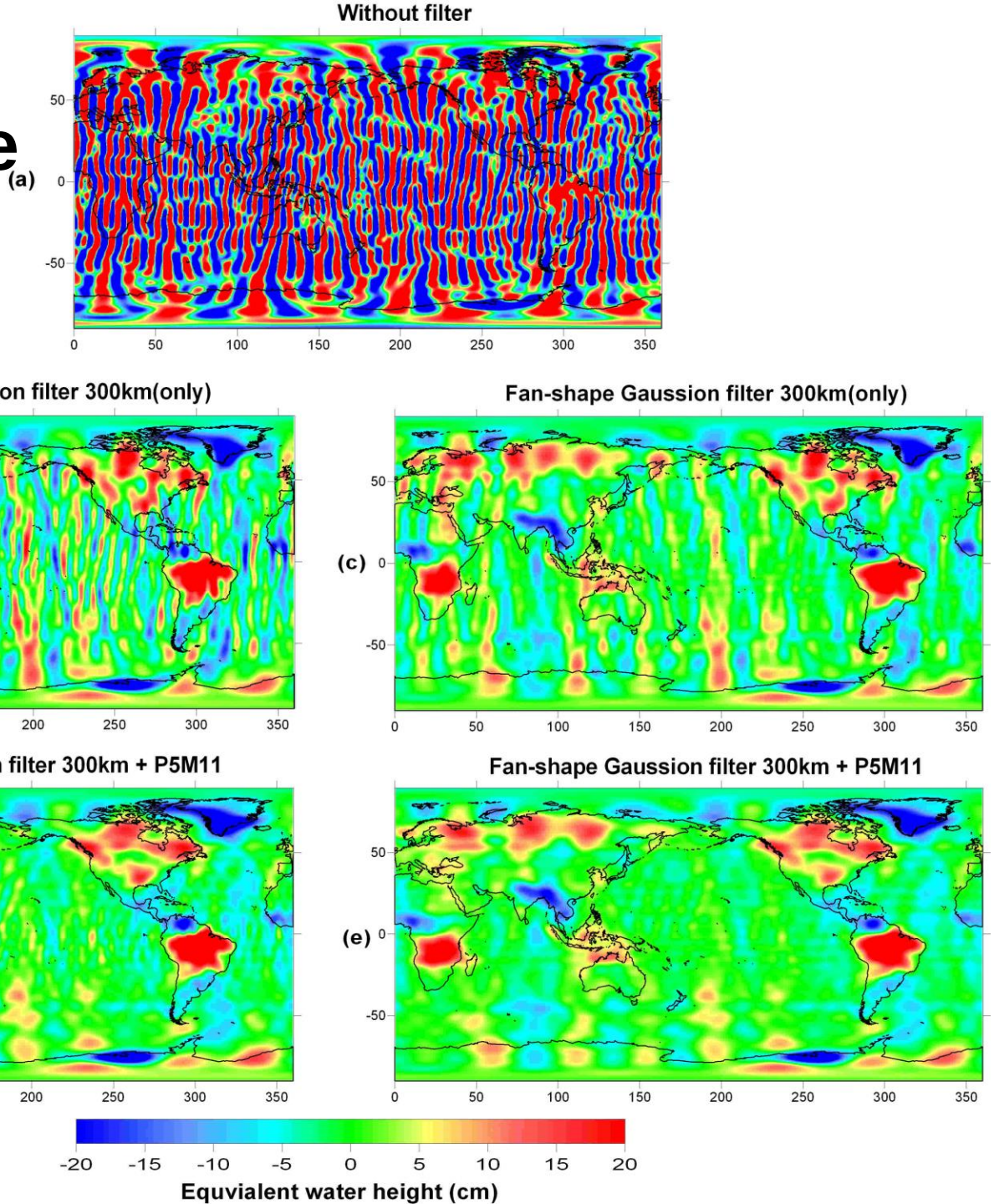
111 days of GRACE data



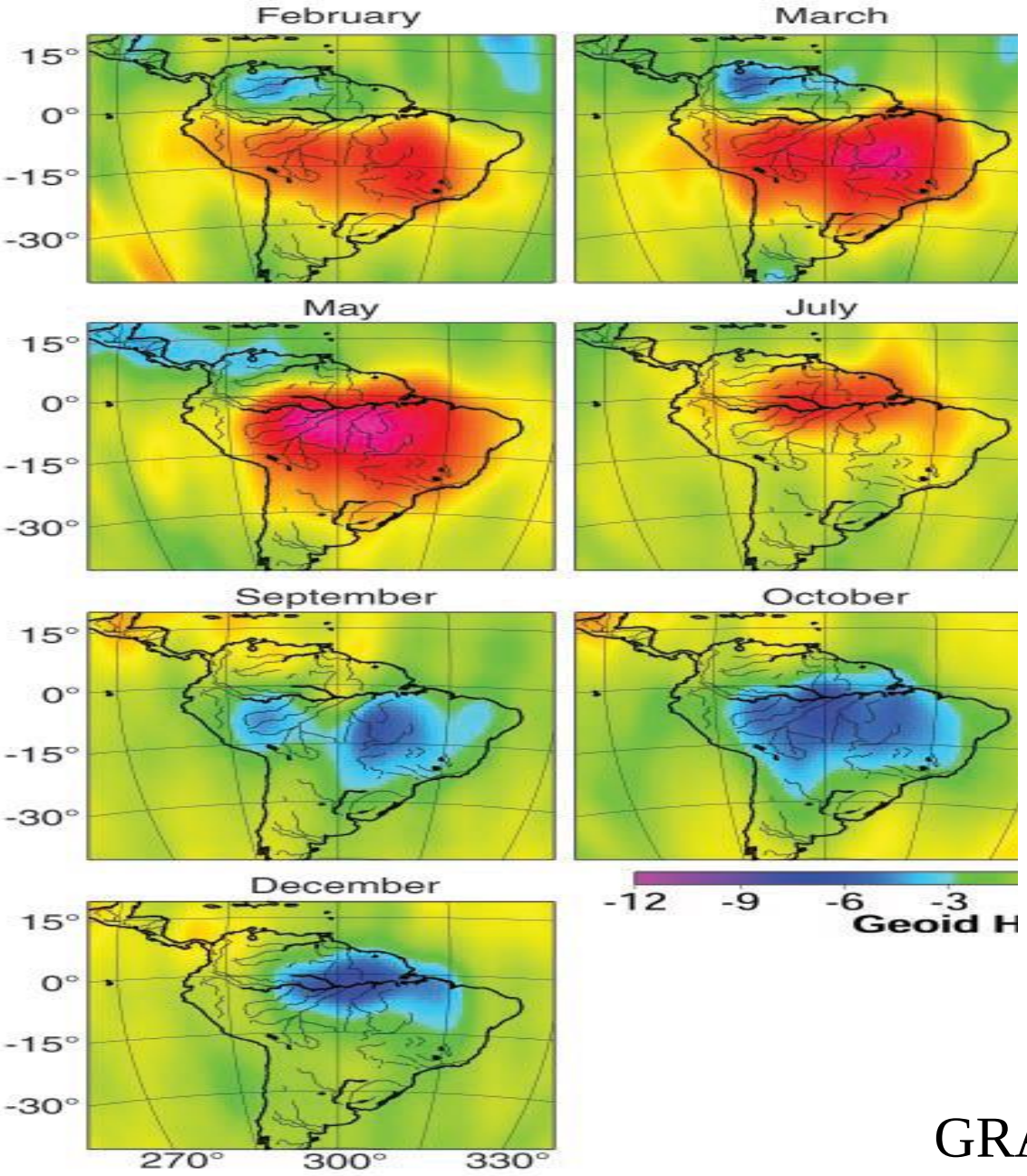
13 months of GRACE data



Time-Variable Gravity



CSR 2008/04



GRACE, 2003
(Tapley et al, 2004)

Trend of global gravity anomaly changes from GRACE (by fan filter 300km)