# Global Constraint on ICE mass Change from SLR


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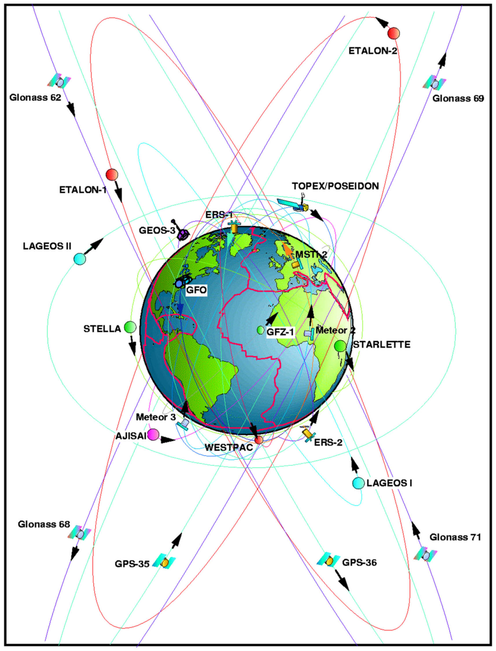



- SLR Solution
- J2 variations from SLR data
- Large scale mass changes from SLR
- Summary

# CSR SLR Solution

- 30-day estimates of C20 (or J2) (3x3 with geocenter motion) from 8 satellites from 1975 to date (Cheng et al., 2013).
- Weekly solutions for a 5x5 field (with geocenter motion)  from 5 satellites from 1983 to date based on models:
  - IERS 2003 (2010) standards, LPOD2005 (consistent with ITRF2005) for station coordinates, EGM08 gravity model, FES2004 ocean tide, and solid earth/ocean pole tide. Without AOD model.
- Monthly solutions for a 5x5 field (with geocenter motion) from 5 satellites consistent with GRACE model from Jan. 2001 to date (GRACE Note 7)
- Monthly solutions for a 5x5 field (with geocenter motion) consistent with GRACE model from Jan. 2001 to date (test case) from 8 satellites:

Starlette, Ajisai, Stella, Lageos-1& 2, BEC, Larets, LARES

# $\dot{J}_2$ from SLR data

- **-3.0 x10$^{-11}$/y by Yoder et al. [1983] from 5.5-year Lageos-1 orbit**
- **-2.5 x10$^{-11}$/y by Cheng et al, [1989] from analysis of 3 years Starlette data**
- **-2.6x10$^{-11}$/y by Nerem et al. [1993] from 10-year Lageos-1 data.**
- **-2.7(±0.4)x10$^{-11}$/y by Cheng et al, [1997] from 20-year data of 8 satellites.**
- **The estimates of J2 rate shown a decrease as the time span is increased from long-arc dynamic approach or time series fit. [Cheng and Tapley, 2009]**
- **The negative linear drift has been generally believed to be due to GIA [Peltier, 1983]. The prediction is ~30% large than the observed.**

| ΔT | J2 | J3 | J4 | J5 | J6 | Solution |
|---|---|---|---|---|---|---|
| 75-95 | -2.7±0.4 | -1.3±0.5 | -1.4±1.0 | 2.1±0.6 | 0.3±0.7 | JGR 1997 |
| 76-01 | -1.6 | -1.7 | -1.2 | 2.0 | 0.4 | Long-arc |
| 76-03 | -1.5 | -1.9 | -1.6 | 1.6 | 0.4 | “ |
| 76-08 | -1.8±0.2 | -1.2±0.3 | -1.1±0.3 | 2.2±0.4 | 0.4±0.1 | “ |
| GIA | -3.6 | 0.2 | -1.9 | 2.3 | -0.5 | P&W |

$$\dot{J}_3^L = \dot{J}_3 + 0.837\dot{J}_5$$

# Long-term variations of J2

The large fluctuation around 1998 called as ‘1998 anomaly’ [Cox & Chao, 2002] has been attracted significant attention and a subject of numerous discussion, see Cazenave & Nerem, 2002, Dickey et al. [2002].

Cheng and Tapley [2004] demonstrated that the ‘1998 anomaly’ was not a unique event; the superposition of the ‘decadal’ variation with the interannual ENSO related signal made the $J_2$ fluctuation appear to be anomalously large during the period of 1996-2002.

However, a significant fluctuation with time scale of > 20-year observed but could not be explained [Cheng and Tapley, 2004].

In recent study, a 30-day estimates of C20 (or J2) from 8 satellites over the period from 1975 to date (Cheng et al., 2013).

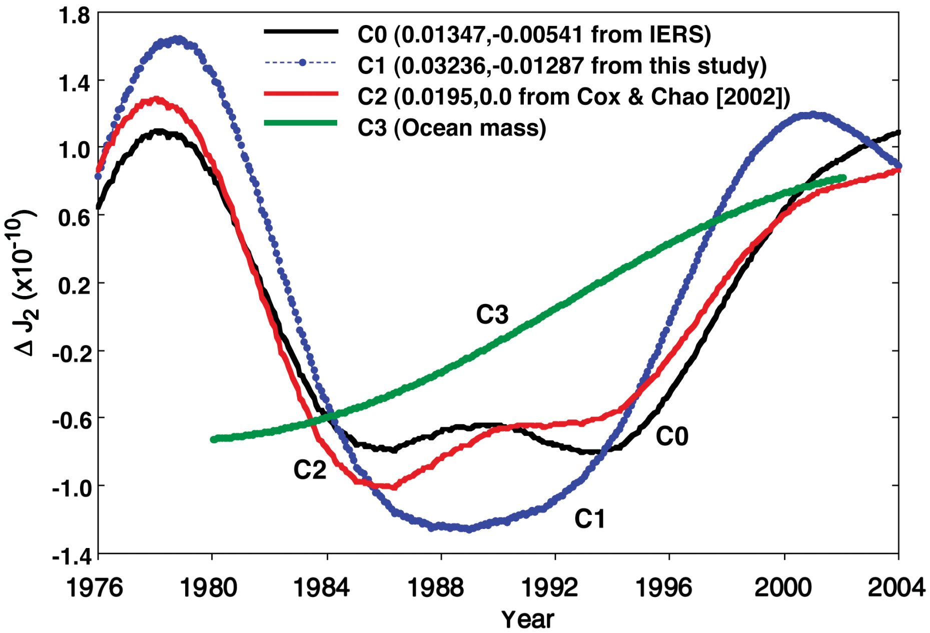
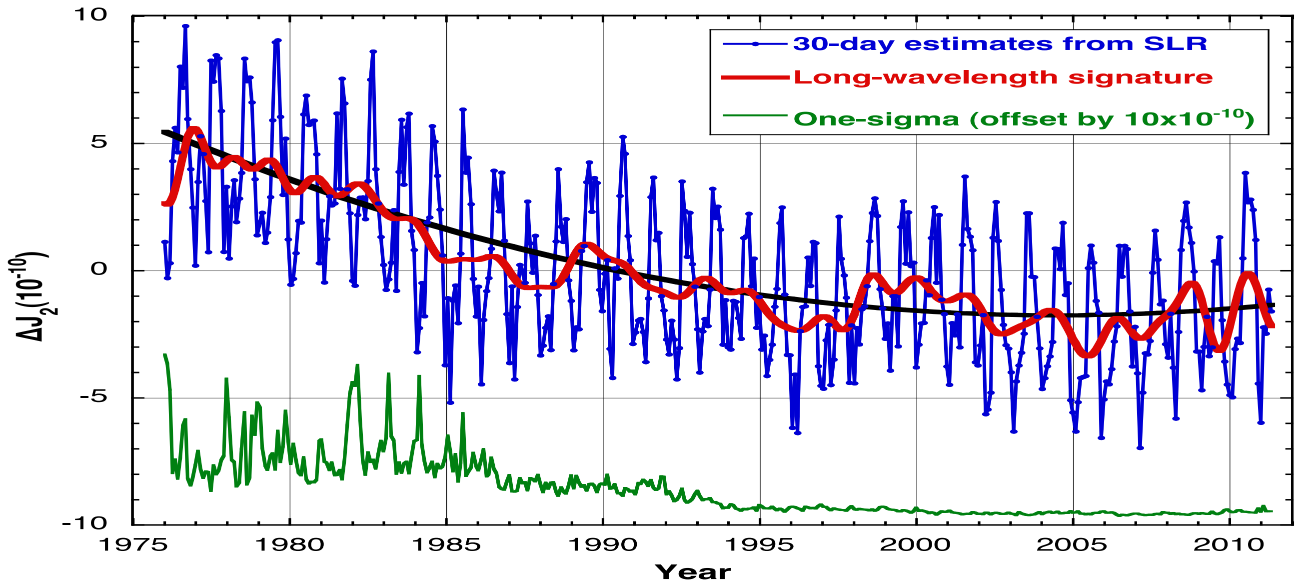
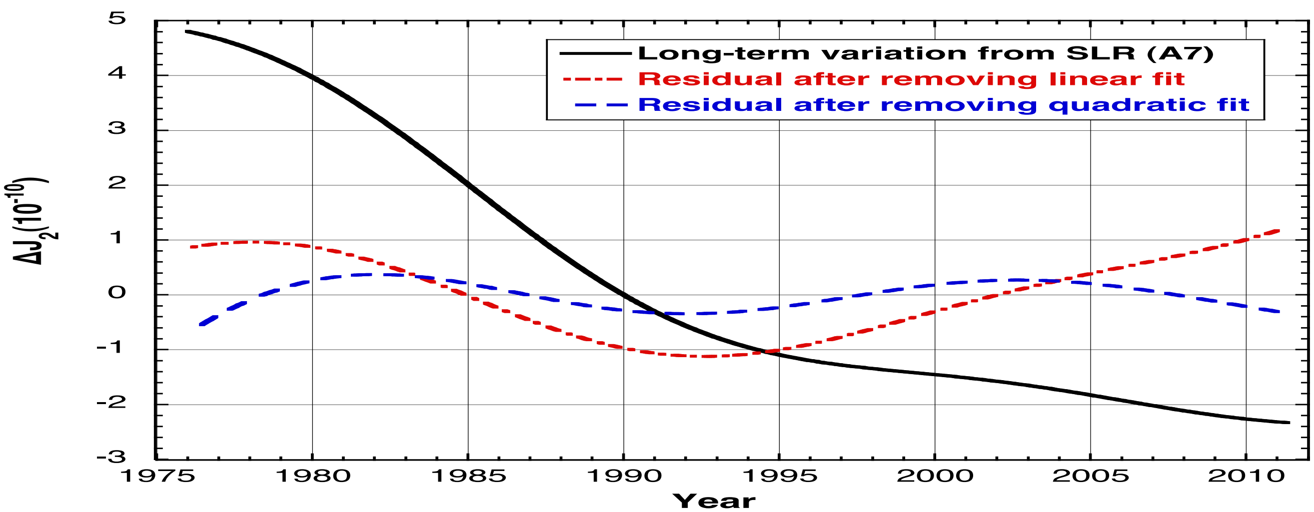



Fig. 3

# Variations in C20 (J2) from SLR




J2 undergoes significant long-wavelength variations, which is better represented by the superposition of a quadratic and 18.6 year variations.

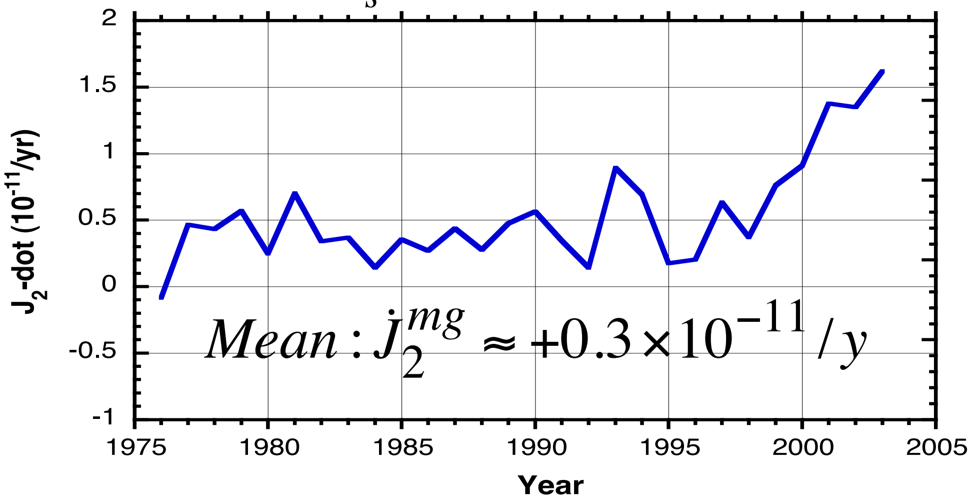
$$\ddot{J}_2 \approx +1.8\times10^{-12}\ /\ y^2$$

Recent increases in mass loss from ice sheets may explain the departure from the GIA induced long-term trend in J2.

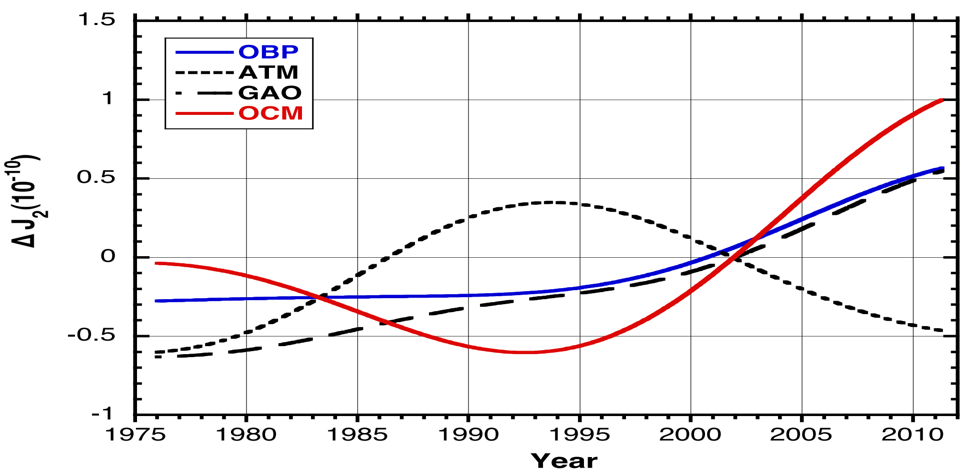
**Time series of J2 can be obtained from csr.ftp.utexas.edu/ftp/slr**

# Contributions to the Deceleration of J2

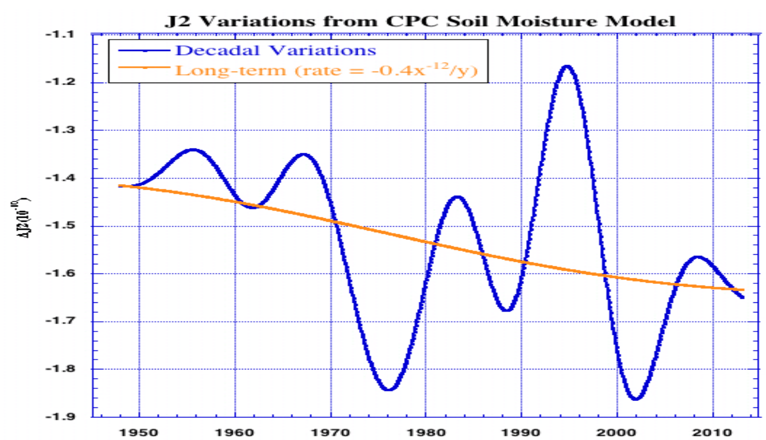
$$\dot{j}_2^{ice} = -\frac{1+k_2^{'}}{5}\frac{A_e^2}{M}\int_s \Delta\dot{M}(\theta,\lambda)\bar{P}_2(\cos\theta)F(\varphi,\lambda)\,dS$$




Based on NSIDC Mountain glacier data [Dyurgerov & Meier, 2005]. 49 primary systems in 12 larger glacier region over the period from 1961 to 2003. There is a an acceleration after 1995.

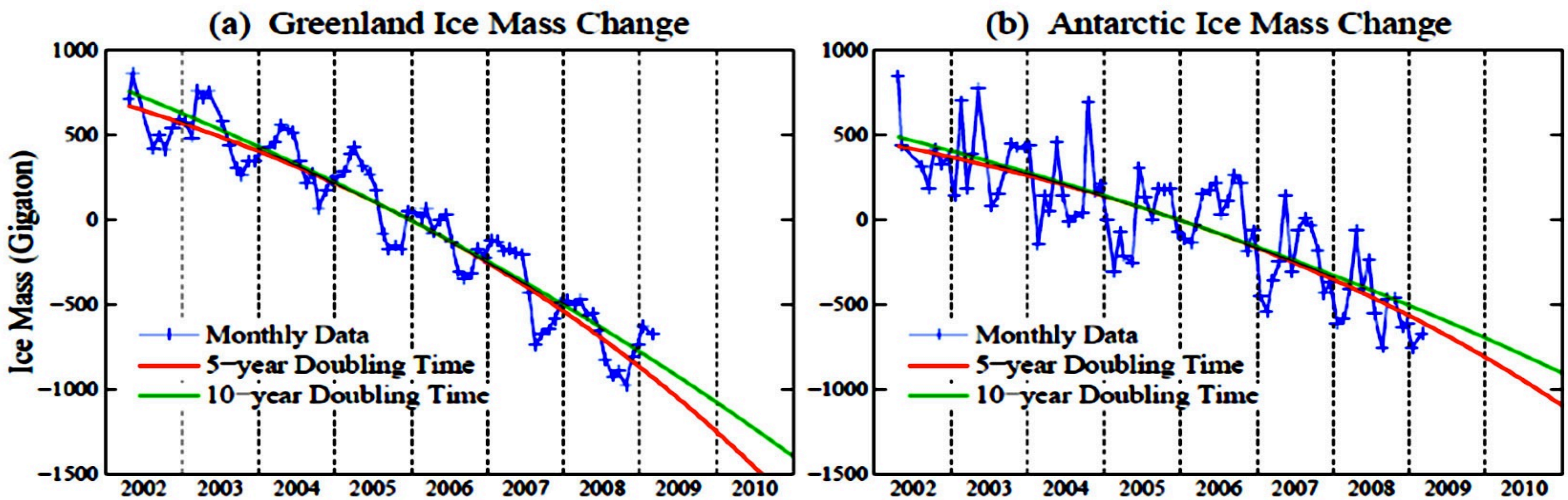



$$\dot{j}_2^{A+o} \approx +0.3\times10^{-11}/y$$




$$\dot{j}_2^{water} \approx -0.4\times10^{-12}/y$$

# Mass Change over Ice Sheets from GRACE



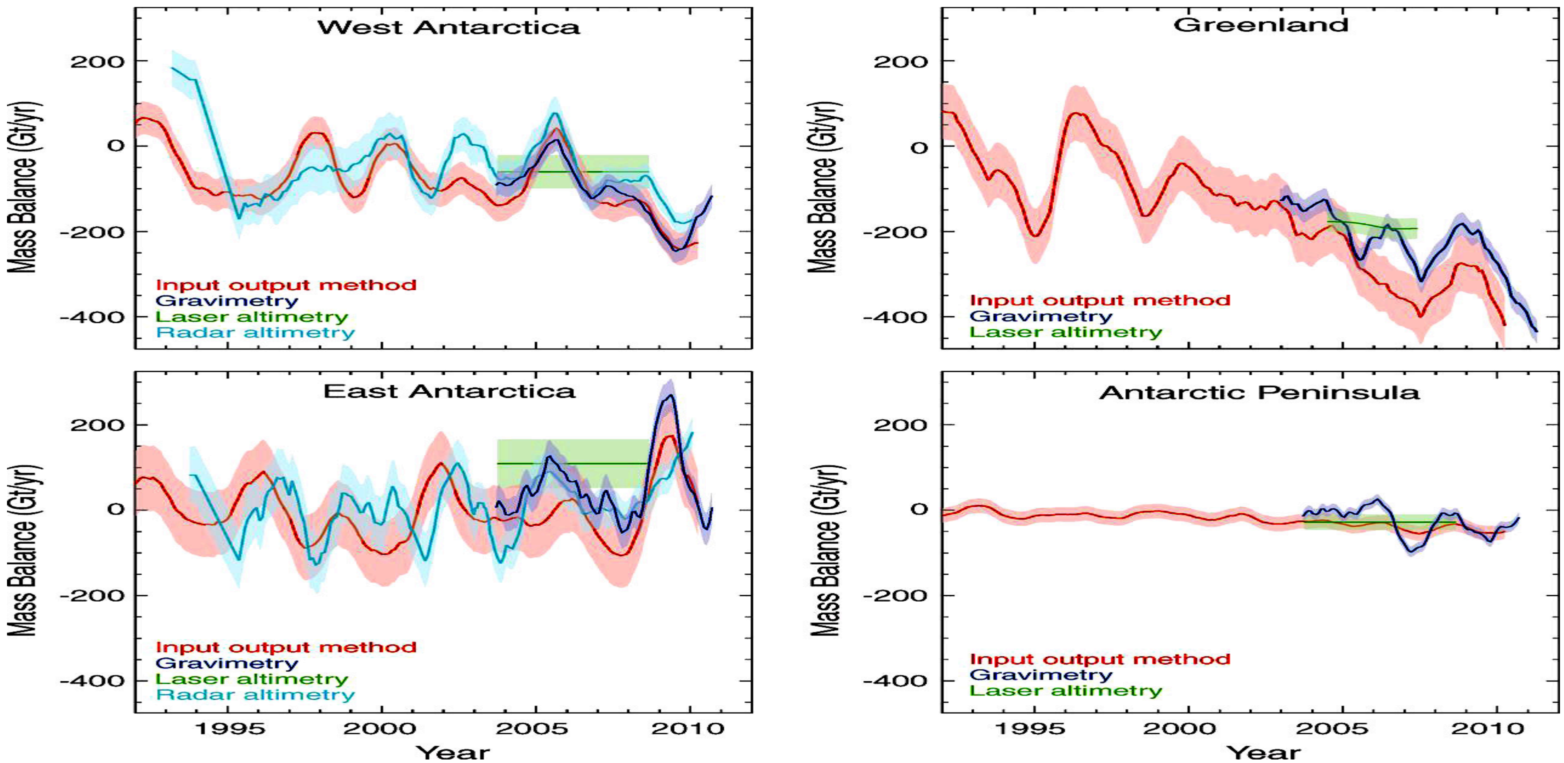

$$\dot{M}_G = 230 \pm 30\ Gt/y;\quad \dot{M}_A = 143 = 73\ \ Gt/y\ [Veliconga\ et\ al, 2009]$$

$$\dot{J}_2^{G+A} = \dot{J}_2^{ice} + \dot{J}_2^{RSL}$$

$$\dot{J}_2^{ice} = 3.87\dot{h}_A(mm/y) + 3.74\dot{h}_G(mm/y) - \dot{J}_2^{RSL} \quad [James\ \&\ Ivins, 1997]$$

$$\dot{J}_2^{ice} \approx +4 \times 10^{-11}/y\ \text{ from } \dot{h}_A \approx 0.4, \dot{h}_A \approx 0.7 mm/y\ from\ GRACE$$

# Mass Change over Greenland and Antarctica




Shepherd et al, Science, 2012

$$\Delta\dot{M}_G = -142 \pm 49;\ \Delta\dot{M}_{WA} = -65 \pm 26;\ \Delta\dot{M}_{EA} = +14 \pm 43;\ \Delta\dot{M}_{AP} = -20 \pm 14$$

$$\Delta\dot{J}_2^{ice} = 2.2 \times 10^{-11} / y \ \textit{based on drainage system of ice sheet}$$

$$\Delta\dot{J}_2^{ice}(-) = 3.5 \times 10^{-11} / y;\ \Delta\dot{J}_2^{ice}(+) = 1.3 \times 10^{-11} / y$$

# Mass Change over Ice Sheets from GRACE


$$\dot{J}_2^{SLR} = \dot{J}_2^{ice} + \dot{J}_2^{GIA} + \dot{J}_2^{RSL} + \dot{J}_2^{mg}$$

$$\dot{h} = 1.3 \pm 0.6\ mm/y \text{ for period of 2002 - 2010 } [\textit{Willis et al.}, 2010]$$

| Ice | SLR | GIA | RSL | mg | period |
|---|---|---|---|---|---|
| 3.8 | 0.7 | -3.6 | 0.2 | 0.3 | 2002-2010 |
| 3.2 | 0.2 | -3.6 | 0.3 | 0.3 | 1993-2012 |
| 0.4 | -2.6 | -3.6 | 0.3 | 0.3 | 1975-1997 |

**Recent increases in mass loss from ice sheets may explain the departure from the GIA induced long-term trend in J2. The melting rate could be underestimated for 1992-2011 by Shepher et al, 2012]**

# Mass Change of Ice Sheets over 1976-1995

$$\dot{J}_n^{SLR} = \dot{J}_n^{A} + \dot{J}_n^{G} + \dot{J}_n^{GIA} + \dot{J}_n^{RSL} + \dot{J}_n^{mg} \quad [James \,\&\, Ivins,\ 1997]$$

$$\dot{J}_n^{i} = -\frac{1+k_n^{'}}{(2n+1)}\frac{A_e^2}{M_e}\frac{\dot{M}_i}{A_i}\int_s \overline{P}_n(\cos\theta)\,dS = F_n^i \dot{M}_i$$

$$\dot{J}_n^{RSL} = 8.54\times 10^{-10}\frac{(1+k_n^{'})}{(2n+1)}a_{n0}\dot{h}(mm/y) \quad [Chao \,\&\, O'Connor, 1988]$$

$$\dot{h} = 1.7 \pm 0.5\ mm/y \text{ for } 20th\ cnetry\ [IPCC]$$

$$= 1.5 \pm 0.1 mm/y \text{ since } 1880\ from\ Ti\deg auge\ data[Spada \,\&\, Galassi, 2012]$$

$$\dot{J}_n^{SLR} = F_n^A \dot{M}_A + F_n^G \dot{M}_G + \dot{J}_n^{RSL} + \dot{J}_n^{mg} \quad (n = 2,..6)$$

$$\dot{M}_A = 105\ Gt/y,\ \dot{M}_G = -37\ Gt/y$$

Based on the rates of J2-J6 over 1976-1995 of Cheng et al, [1997]
Rate for Antarctica is sensitive to GIA model.

# Summary

- J2 undergoes significant inter-annual variations, and there is a significant change in the long-term trend from analysis of 36 years of SLR data.

- The long-term variation of $J_2$ appears to be more quadratic than linear in nature. The superposition of a quadratic and an 18.6-year variation leads to the 'unknown decadal variation' reported by Cheng and Tapley [2004].

- Although the primary trend is expected to be linear due to global isostatic adjustment (GIA), there is an evident deceleration ($1.8\text{x}10^{-12}/\text{y}^2$) in the rate of the $J_2$ during the last few decades. Result indicates that the deceleration of $J_2$ can be explained by recent melting of continental glaciers, and the SLR-derived estimates may provide some constraints on the magnitude of recent melting of continental glaciers, but the results depend on the accuracy of the estimate of GIA. The IERS conventional rate of $-2.6\times10^{-11}$/yr determined from SLR tracking of geodetic satellites before 1996 likely represents the combination of GIA and GIC (Glaciers and Ice Caps) melting over the earlier period, assuming the GIA contribution to is at the level of $-3.6\times10^{-11}$/yr. At this point, we can conclude that the long-term variation of Earth's dynamical oblateness is well understood.