Time-Variable Gravity Analysis Using Satellite-Laser-Ranging as a Tool for Observing Long-Term Changes in the Earth's Systems

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Zonal Rate Solutions - What's is happening?

Zonal gravity rate and long period tide solutions. All values are x10^{-11}

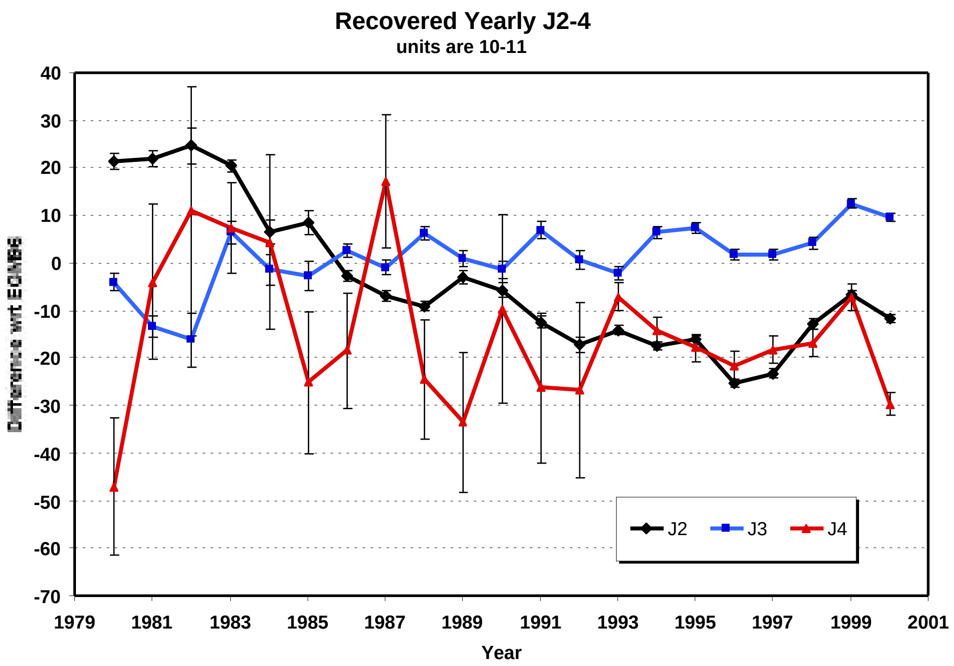
Study	$\dot{J}_2$	$\dot{J}_{ODD}$	$\dot{J}_3$	$\dot{J}_4$	$\dot{J}_5$	$\dot{J}_6$	18.6-yr Tide $C_{2,0}$ Amp. (cm)
Cheng, et al. [1989]	-2.5±0.3	1.2	-0.1±0.3	0.3±0.6	1.5±1.5		
Nerem & Klosko [1996]	-2.8±0.3	1.6±0.4		0.2±1.5			
Cazenave, et al. [1996]	-3.0±0.5	-1.8±0.1		-0.8±1.5			
Cheng, et al. [1997]	-2.7±0.4	0.5	-1.3±0.5	-1.4±1.0	2.1±0.6	0.3±0.7	1.56±0.2
From GGG2000:							
Base - Data through 1997	-3.0±0.4	0.3	-0.9±0.4	1.4±1.0	1.3±0.4	-1.0±0.6	1.41±0.07
Use only LAGEOS-1, Starlette, and Ajisai	-2.7±0.5	0.1	-0.9±0.5	0.1±1.6	1.2±0.5	-0.5±0.9	1.44±0.08
Upweight LAGEOS-1 2x	-3.1±0.5	0.3	-0.8±0.2	1.2±1.0	1.3±0.3	-0.8±0.5	1.51±0.06
Assume 2 m SLR weight	-2.0±0.3	0.9	-0.8±0.3	-2.7±1.0	1.9±0.4	1.2±0.7	1.54±0.09
Estimate only $\dot{J}_2$ - $\dot{J}_5$	-2.4±0.2	0.2	-0.9±0.4	0.1±0.6	1.3±0.4		1.41±0.07
Estimate only $\dot{J}_2$ - $\dot{J}_4$	-2.5±0.2	0.3±0.1		0.3±0.6			1.43±0.07
From EGS2001:							
Revised Base – Data through 1997	***-3.0±0.3***	***0.2***	***-0.5±0.4***	***1.6±0.8***	***0.8±0.4***	***-1.0±0.5***	***1.41±0.07***
+1998-1999	-0.9±0.3	0.5	1.1±0.4	-0.5±0.9	-0.7±0.4	-1.0±0.5	0.82±0.06
+2000	-0.6±0.5	0.5	1.8±0.5	-2.2±0.6	-1.4±0.4	0.2±0.5	0.85±0.06
+1998-2000	-0.2±0.3	0.7	2.6±0.4	-2.4±0.6	-2.3±0.4	0.0±0.5	0.77±0.05
+1998-2000	-1.0±0.3	0.7	2.6±0.4	-2.4±0.6	-1.5±0.4	-0.2±0.5	Fixed @ 1.22

The lumped $\boldsymbol{J}_{odd}$ rates were computed using the following relation derived from this study:

$$\boldsymbol{J}_{odd} = \boldsymbol{J}_3 + 0.864\, \boldsymbol{J}_5$$

Yearly Zonal Solutions

- Somewhere around 1996-1997 there is a distinct change in the yearly zonal averages
- Zonal rate solution tests show that this change is not attributable to any one spacecraft
  – Changes in the Lageos-1 “anomaly” during this period can not be the cause



Slopes of *simple* linear fits to the recovered zonal time series

Period of Fit	J_2 Slope	J_3 Slope	J_4 Slope
80-93	-3.3	0.8	-0.7
80-95	-3.0	0.9	-0.6
80-97	-2.9	0.7	-0.7
80-00	-2.1	0.7	-0.6
96-00	4.4	2.6	-0.5

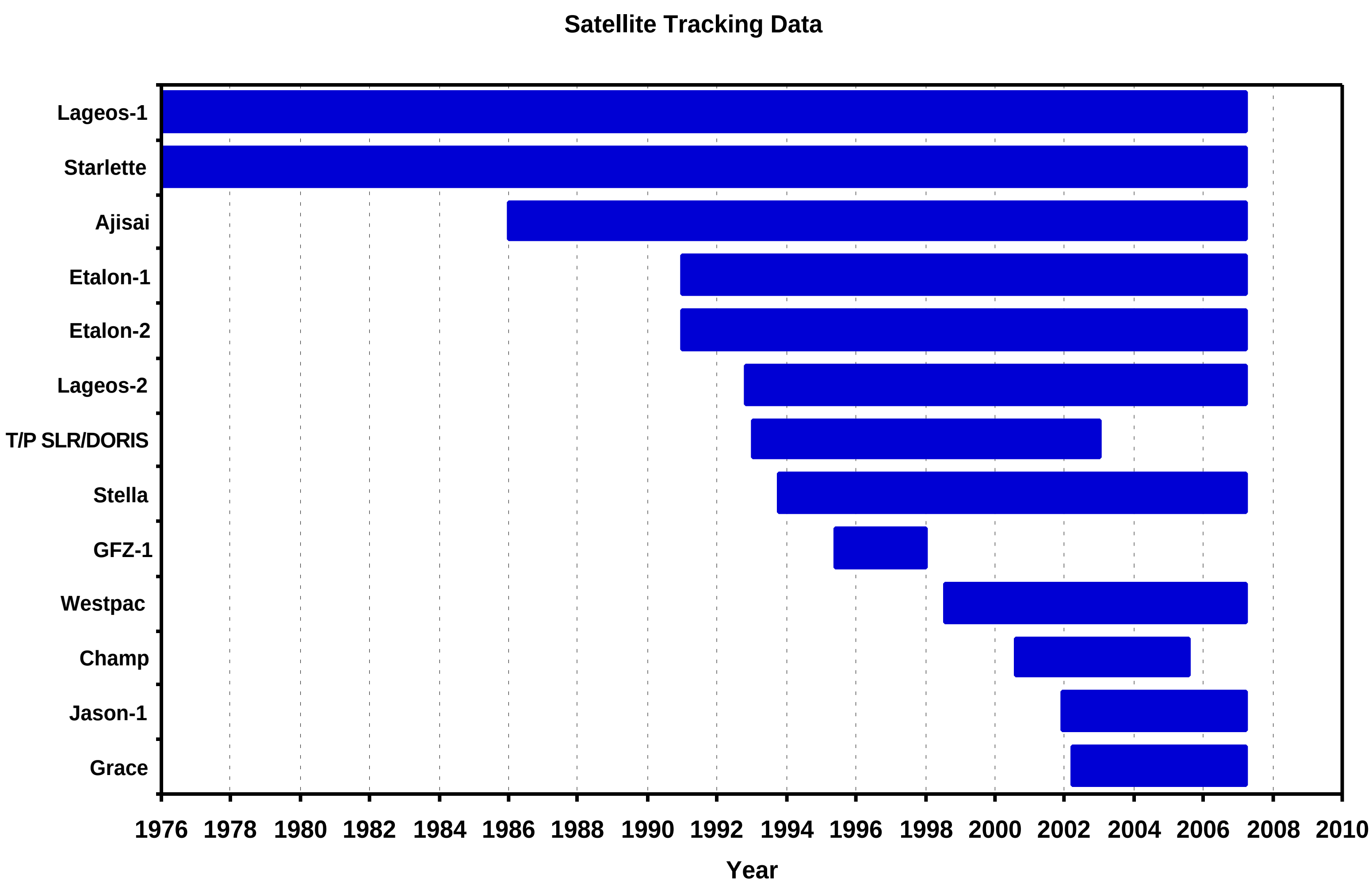
Slopes of *weighted* linear fits to the recovered zonal time series

Period of Fit	J_2 Slope	J_3 Slope	J_4 Slope
80-93	-3.0	0.5	0.3
80-95	-2.6	0.7	-0.5
80-97	-2.6	0.4	-0.8
80-00	-1.6	0.6	-0.9
96-00	4.3	2.5	0.0

Satellite Derived Geopotential Series

- **Uses Lageos-1, Lageos-2, Starlette, Stella, Westpac, Ajisai, TOPEX/POSEIDON (T/P), GFZ-1, Etalon-1, and Etalon-2 SLR tracking data, and the DORIS tracking of T/P**
- **Data weights were based on those resulting from the calibration of long-period gravity rate and seasonal phase/amplitude solutions of *Cox et al.* [2000b]**
  - **~1-2 m overall for the SLR, relative DORIS/SLR weight matches the POEs**
- **Data were aggregated into nominal 60-day (pre 92) and 30-day (post 91) periods**
  - **30-day periods correspond to three T/P repeat cycles**
  - **Lageos-1/2 and Etalon-1/2 30-day arcs, Lageos-1 are 90 days in 1979**
  - **10-day arcs for the rest**
- **Tides:**
  - **The Sa, Ssa, at nominal equilibrium values**
  - **The 18.6 yr, and 9.3 year tides from the comprehensive solutions**
  - **The rest of the tides are from the EGM96 solution, with Schrama/Ray background.**
- **No *a priori* gravity rates were applied, consequently trends should appear in the plots**
- **No *a priori* atmospheric gravity was applied - results will contain the effects of atmospheric mass perturbations**

Timeline of Precise Satellite Tracking Data



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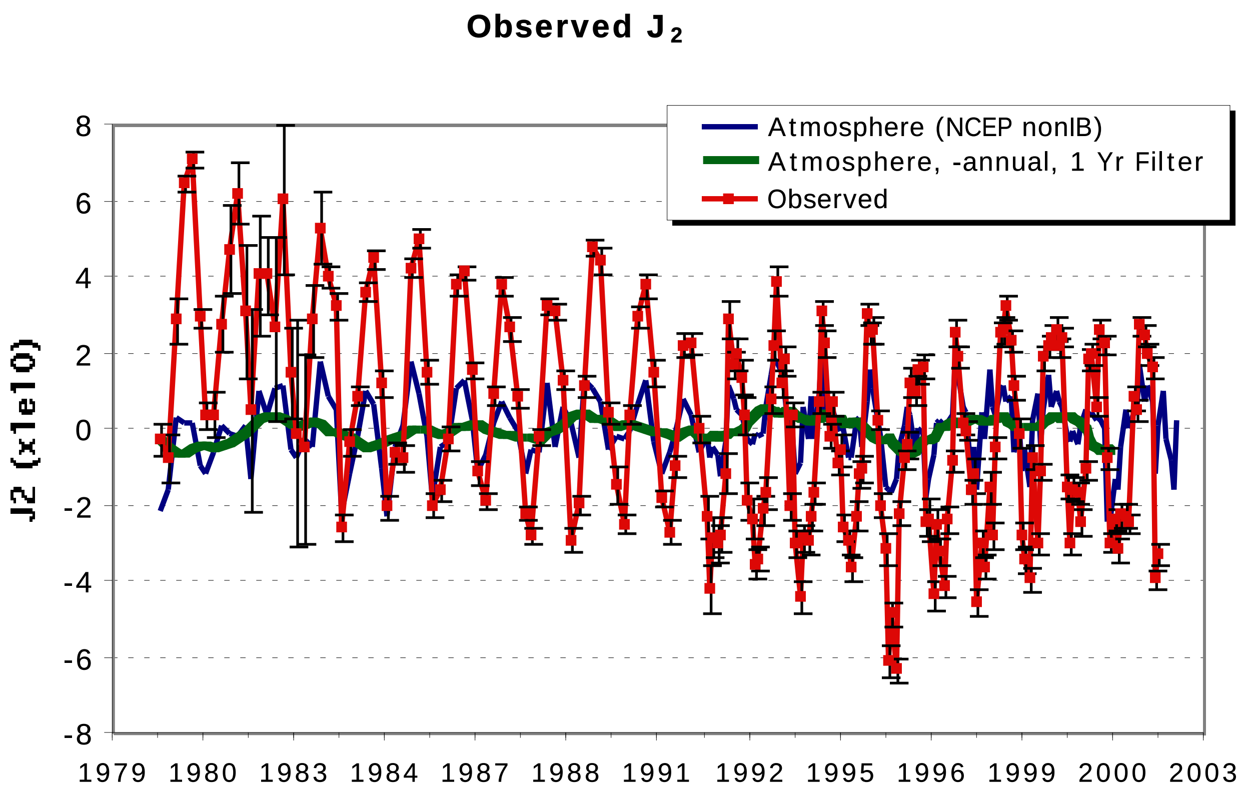
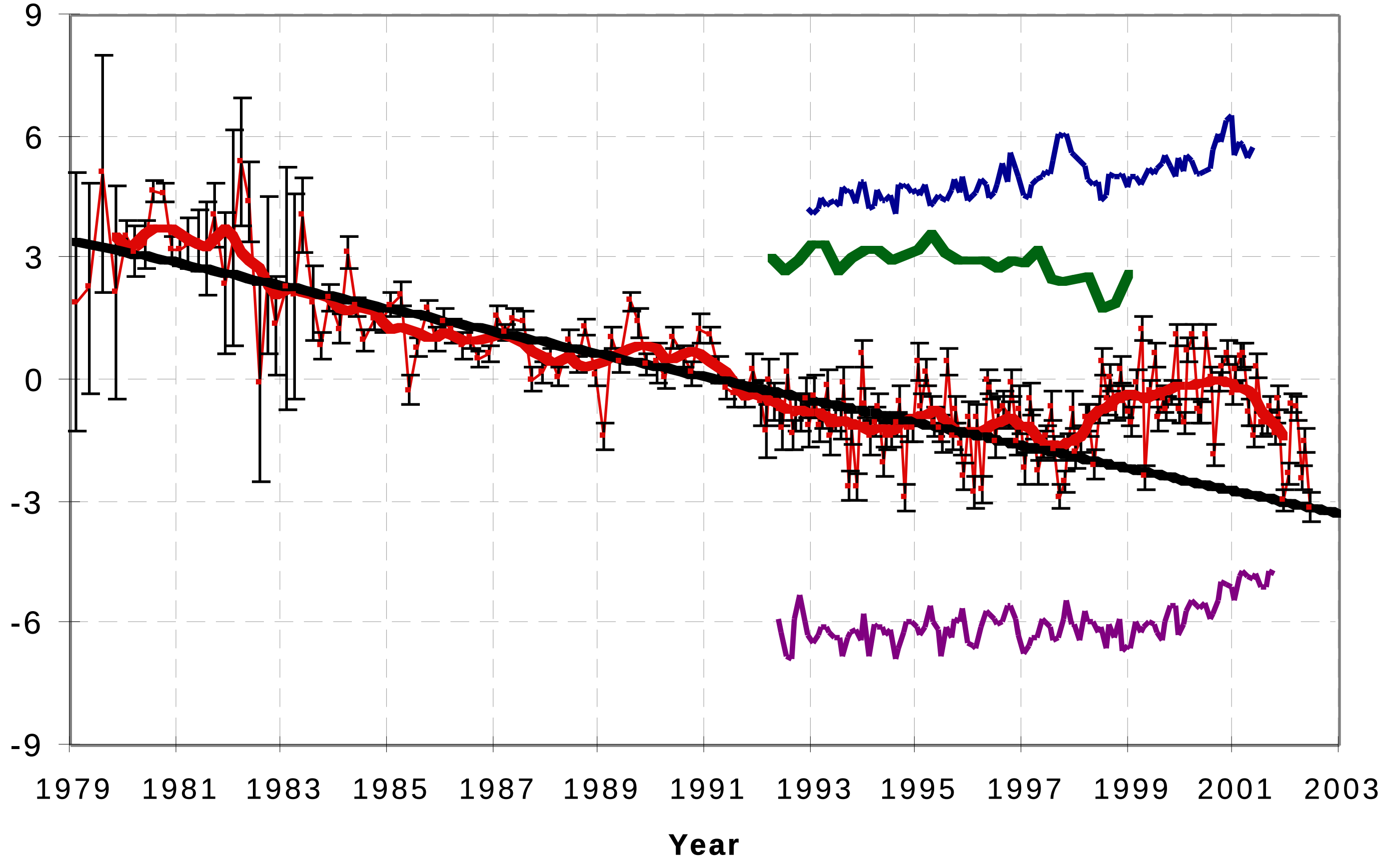
Observed J2 and Atmosphere



- •The atmospheric inter-annual variation amplitude is ~.5x10^{-10}
- •The atmospheric Inter-annual rate alternates between +/- .3 x10^{-10}, as large as the long term observed rate

(Observed J2 - Atmosphere), and Ocean and Ice



- •Red: (Observed-NCEP IB)-annual
- •Black: Pre 1997 fit, slope =-2.8x10^{-11} per year
- •Blue: GSL inferred J2 change
- •Purple: T/P SSH Inferred J2 change
- •Green: Greenland+West Antarctica [Zwally et al., 2001]

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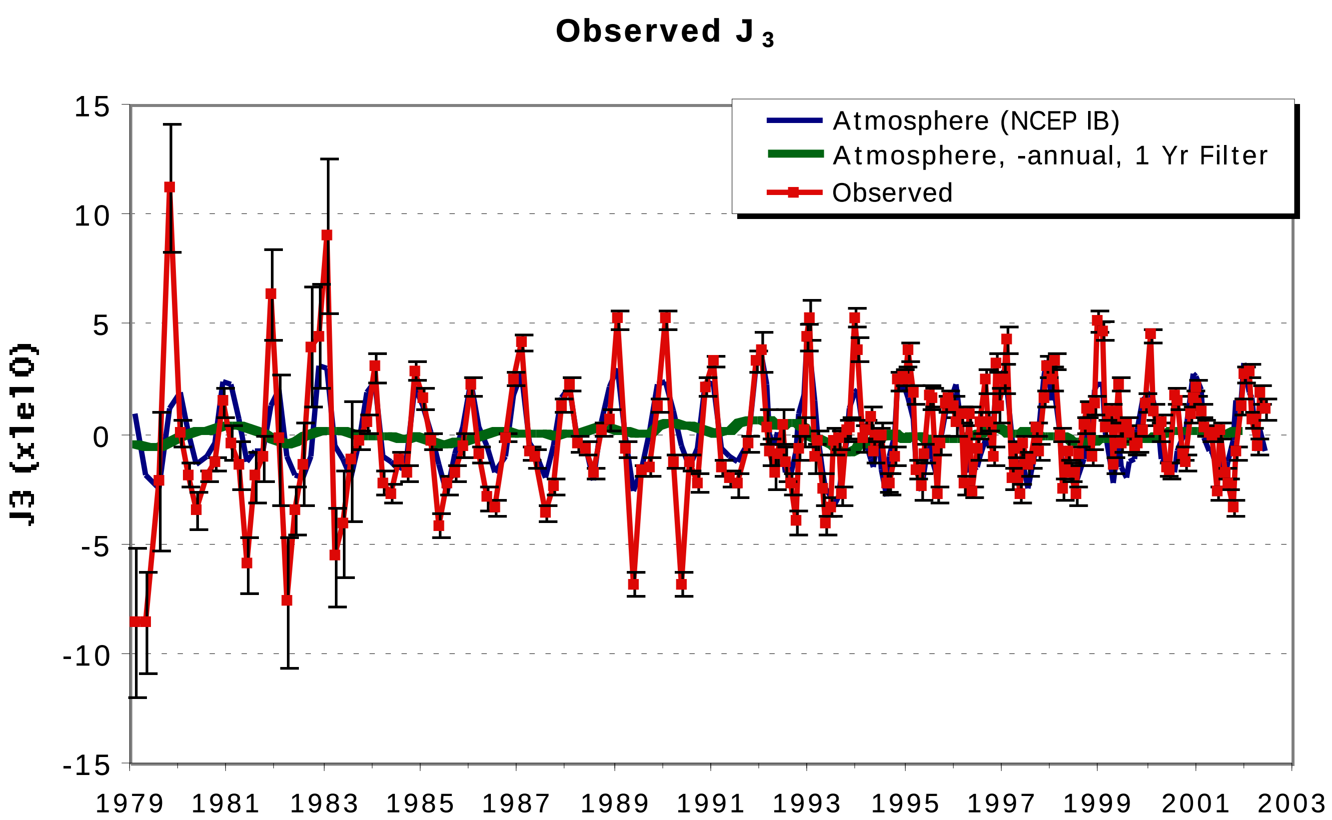
Observed J3 and Atmosphere



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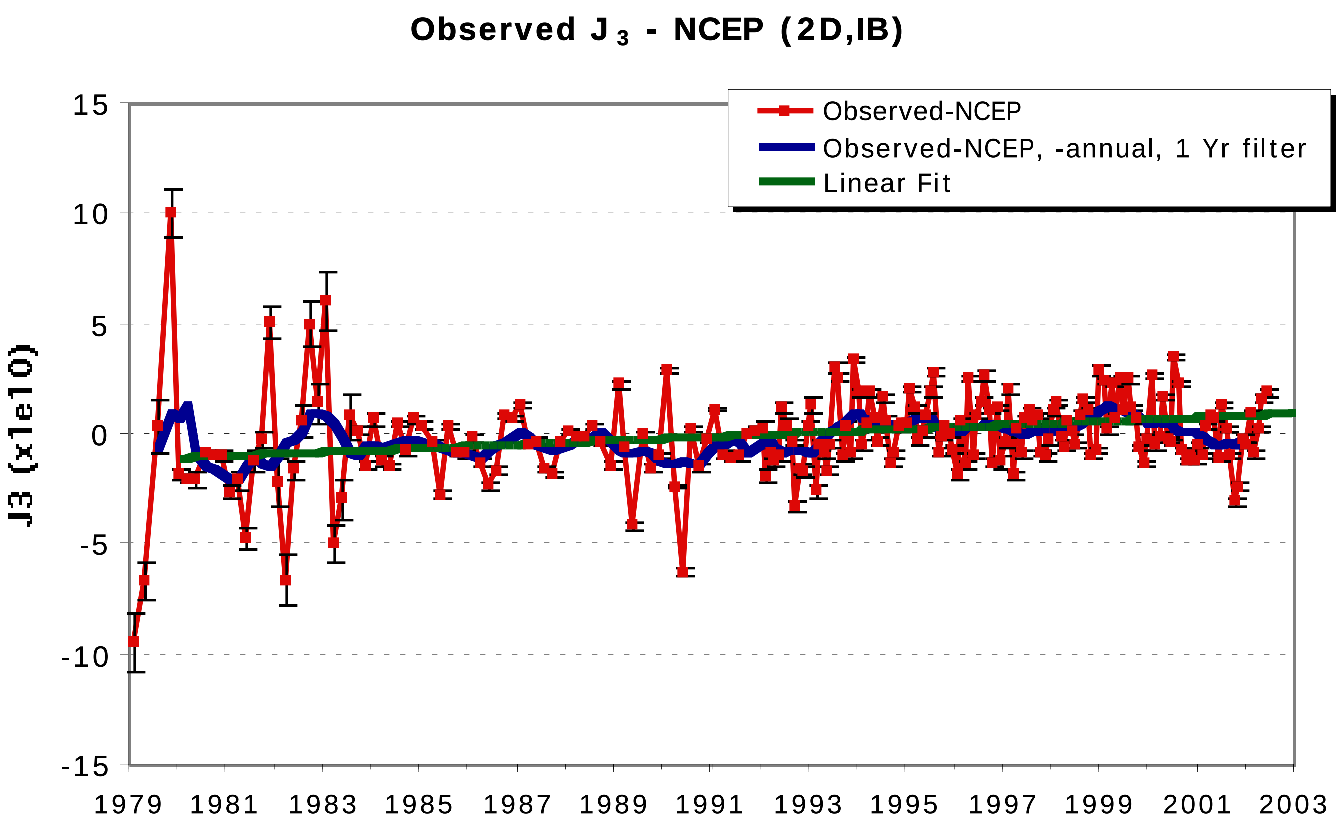
Observed J3 - Atmosphere



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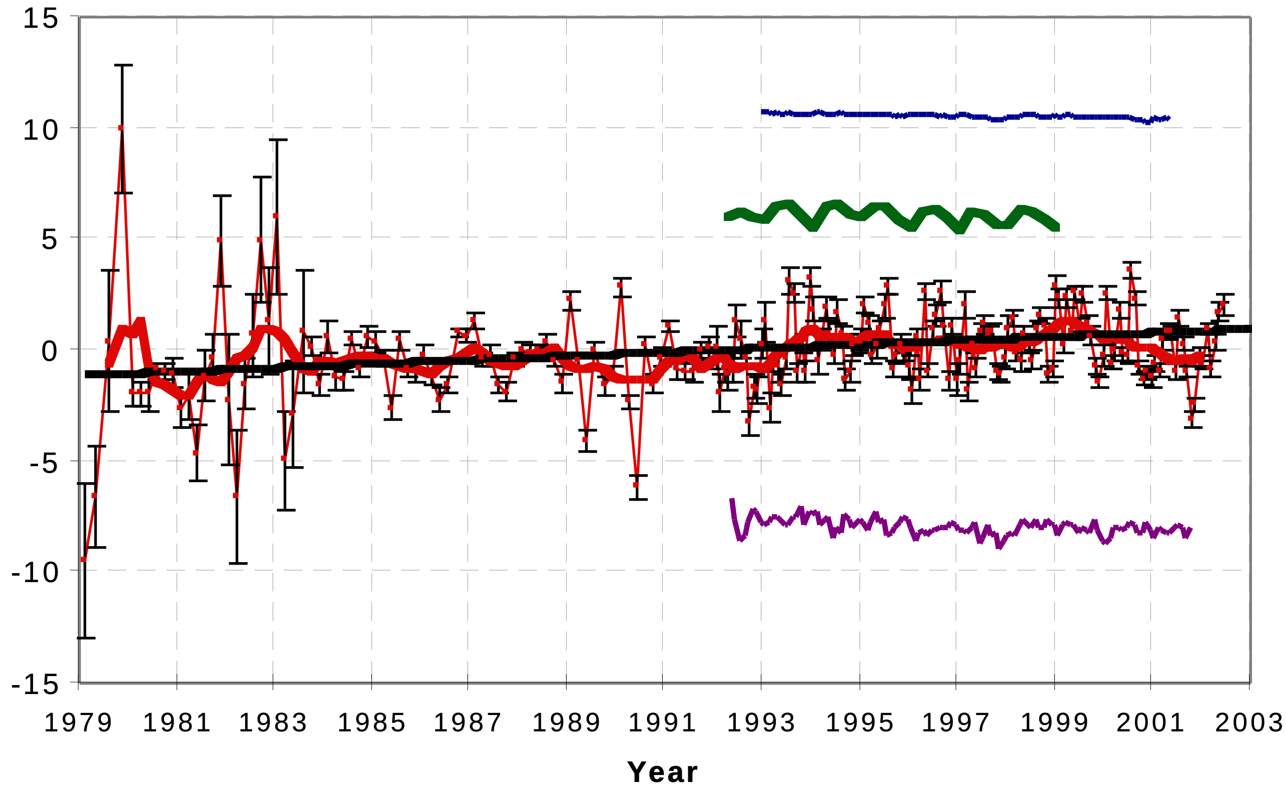
(Observed J3 - Atmosphere), and Ocean and Ice



- Red: (Observed-NCEP IB)-annual
- Black: Linear fit, slope = 0.9×10^{-11} per year
- Blue: GSL inferred J3 change
- Purple: T/P SSH Inferred J3 change
- Green: Greenland+West Antarctica [Zwally et al., 2001]

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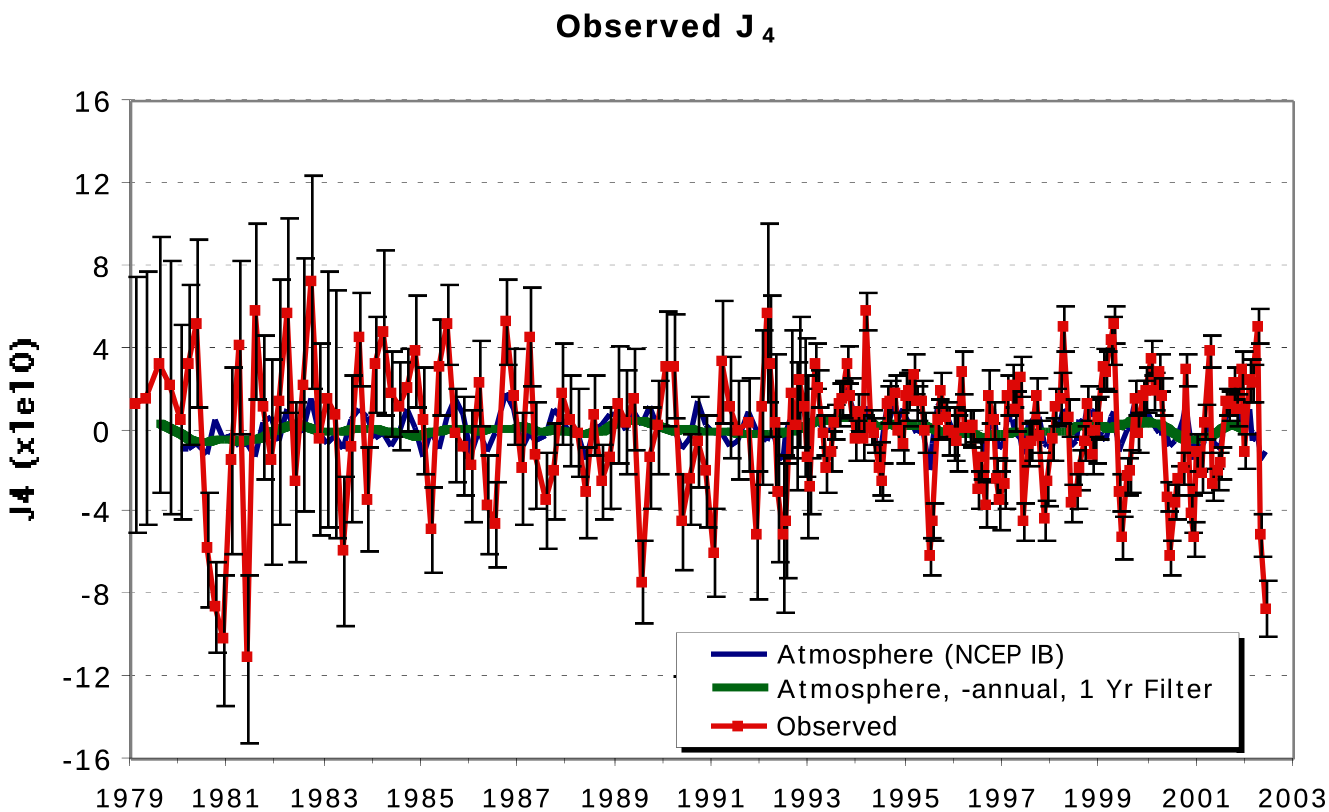
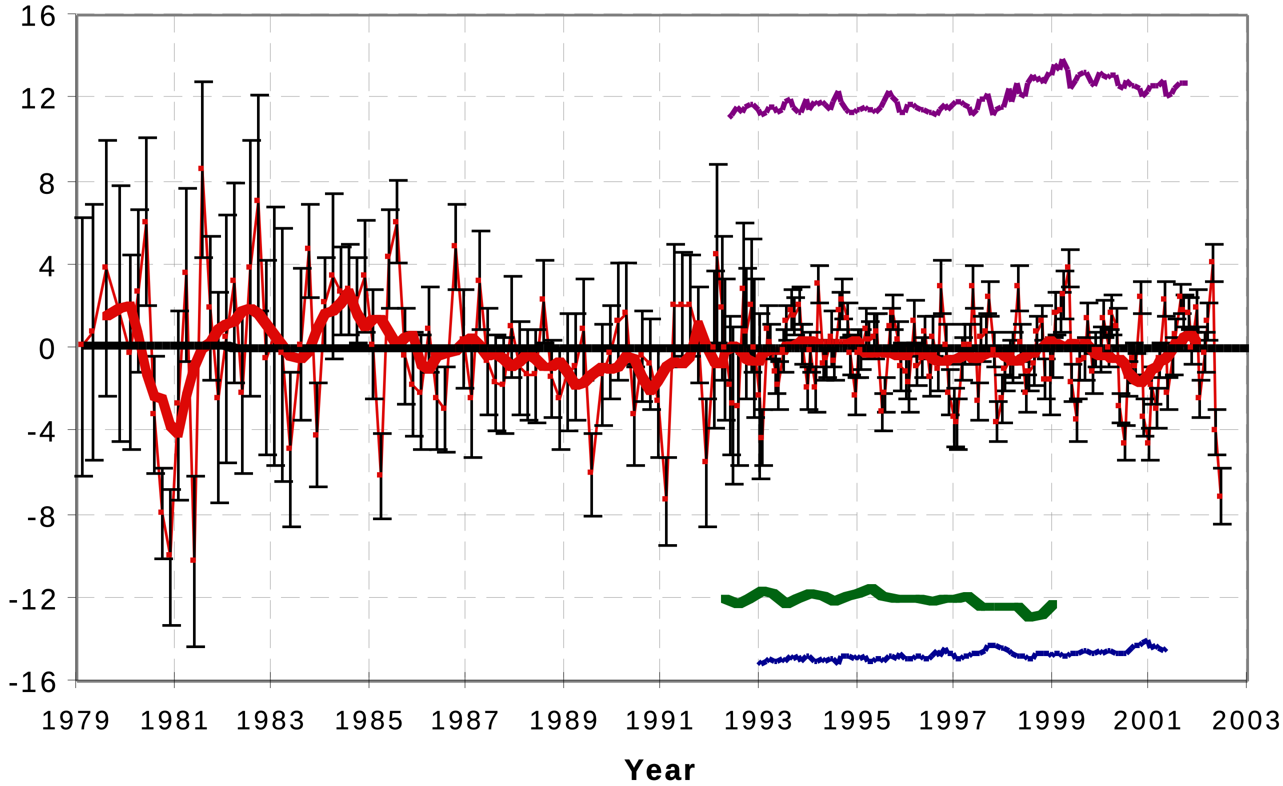
Observed J4 and Atmosphere



•**The observed C4,0 does exhibit the same post 97 deviation the C2,0 does**

(Observed J4 - Atmosphere), and Ocean and Ice



- Red: (Observed-NCEP IB)-annual
- Black: Linear fit, slope = -0.1×10^{-11} per year
- Blue: GSL inferred J4 change
- Purple: T/P SSH Inferred J4 change
- Green: Greenland+West Antarctica [Zwally et al., 2001]

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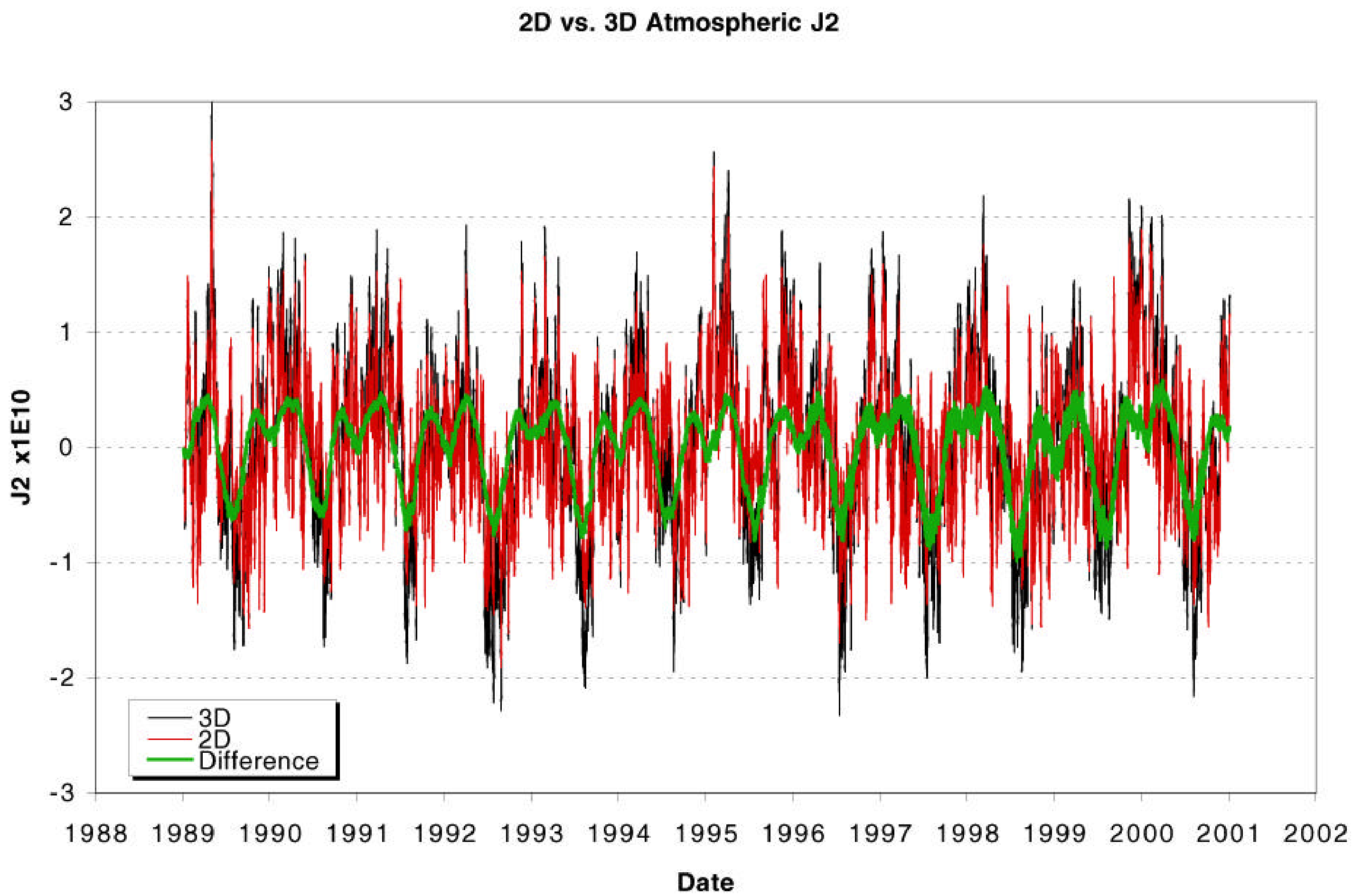
Observed J2 - What could change the slope?

- First guess: Ice
  - In order to overshadow PGR, Greenland would loose about 500 Gt annually, for a net GSL rate of ~ +1.4 mm/yr
  - Greenland and W. Antarctica implied gravity rates derived from radar altimetry [Zwally, 2001]
    - Ice height -derived GSL for Greenland : -.22 mm/yr
    - Ice height -derived GSL for West Antarctica : -.08 mm/yr
  - Greenland result matches Ice mass balance inferences from inverse solutions using gravity zonals, pole rates and GSL rate
  - Have the wrong sign to explain the deviation
  - East Antarctica?
    - Would need to contribute ~2 mm/yr to GSL, depending on the scenario
  - Glaciers?
    - Using Meier's 1984 numbers, a sea level contribution of ~2 mm/yr is needed
- If it is Ice, where is the change in GSL?

Observed J2 - What could change the slope?

- Atmosphere
  - 2D computations based on NCEP do not explain it
    - Excellent annual agreement with J3, implying that the general handling of the data is correct
  - What of 3D computations?
    - Differences between 2D and 3D computations are also too small
      - Effect on J2 is only about ~2x10-10, with little interannual variation
      - Effect on J3 near zero
- Water impoundment
  - Really large dams can cause a jump of ~0.2×10^{-10} in J2, but it's not enough
- Hydrology?
  - Lack of data…presently

J2 Atmospheric Gravity - 2D vs 3D



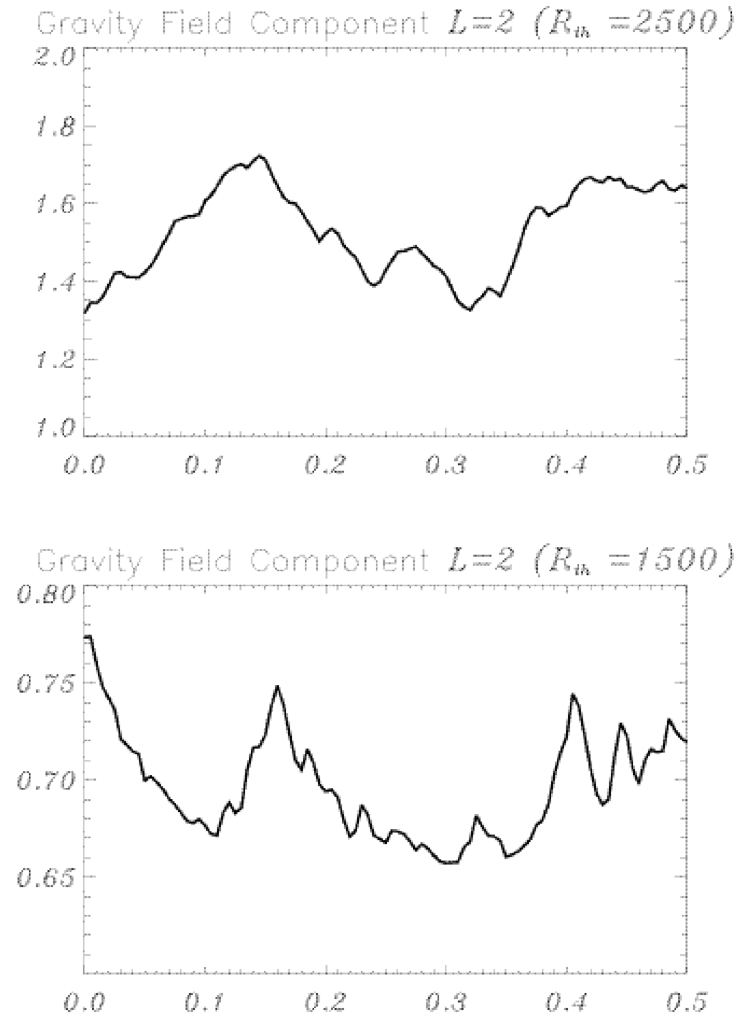
Observed J2 - What could change the slope?

- Core or mantle?
  - Mantle acts too slow
  - Core was assumed to be small
    - W. Kuang of UMBC reviewed his models…under some assumptions changes as large as ~0.5x-11 per year are possible
      - How probable? Remains to be seen... More work
- Ocean
  - Timing of onset corresponds with last big ENSO event
  - T/P SSH data implies changes that are consistent and comparable to the observed gravity changes

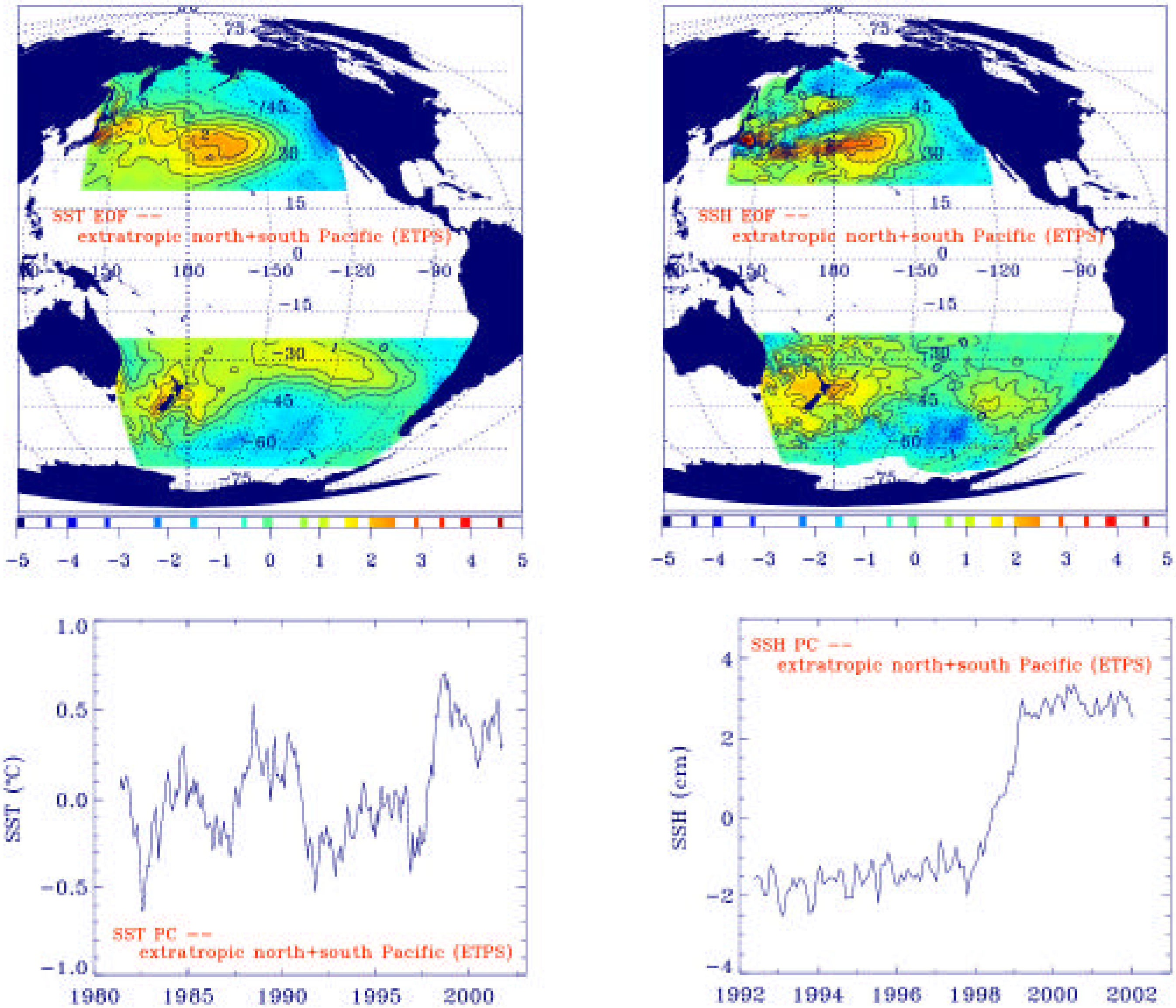
The Core and J_2

J_2 signals ($\times 10^{10}$) from geodynamo simulations. Time scale is non dimensional, but is of the order of decades.

Figure Courtesy of
W. Kuang (NASA GSFC)



Sea Surface Temperature and Height EOF/PC



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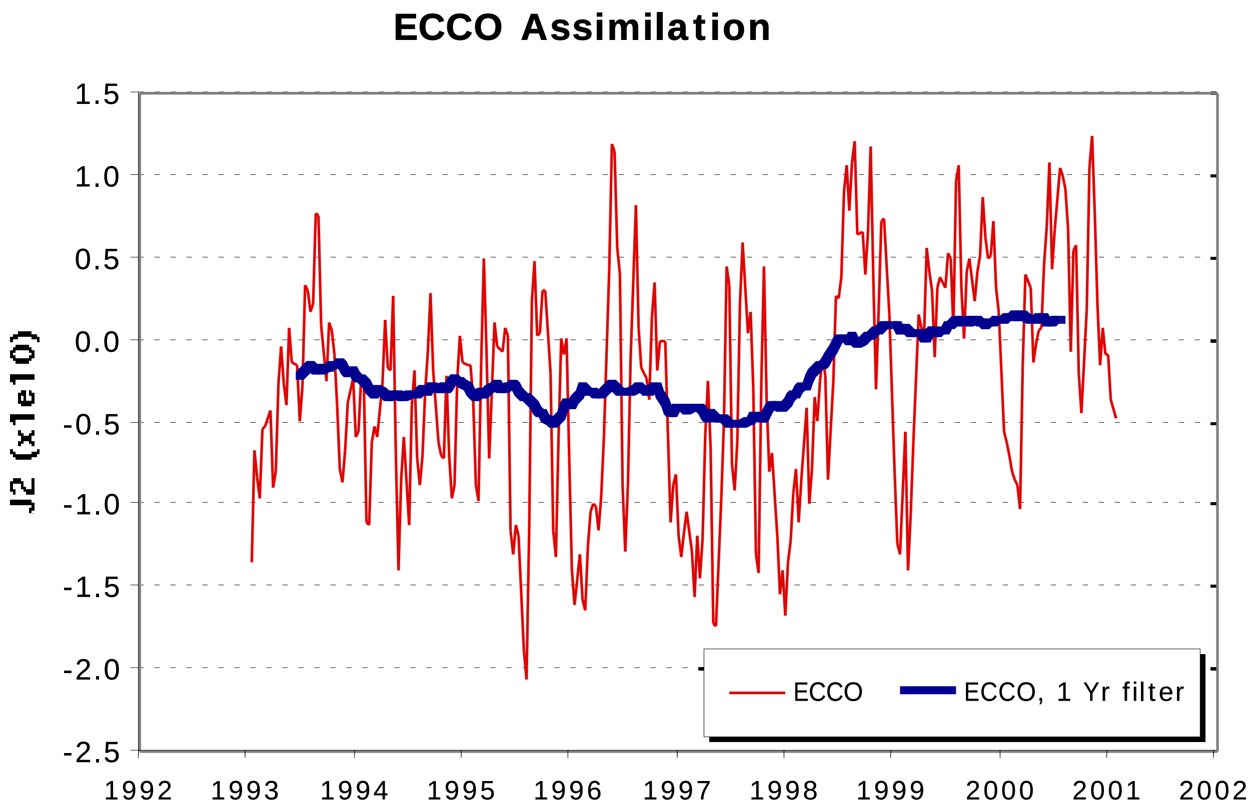
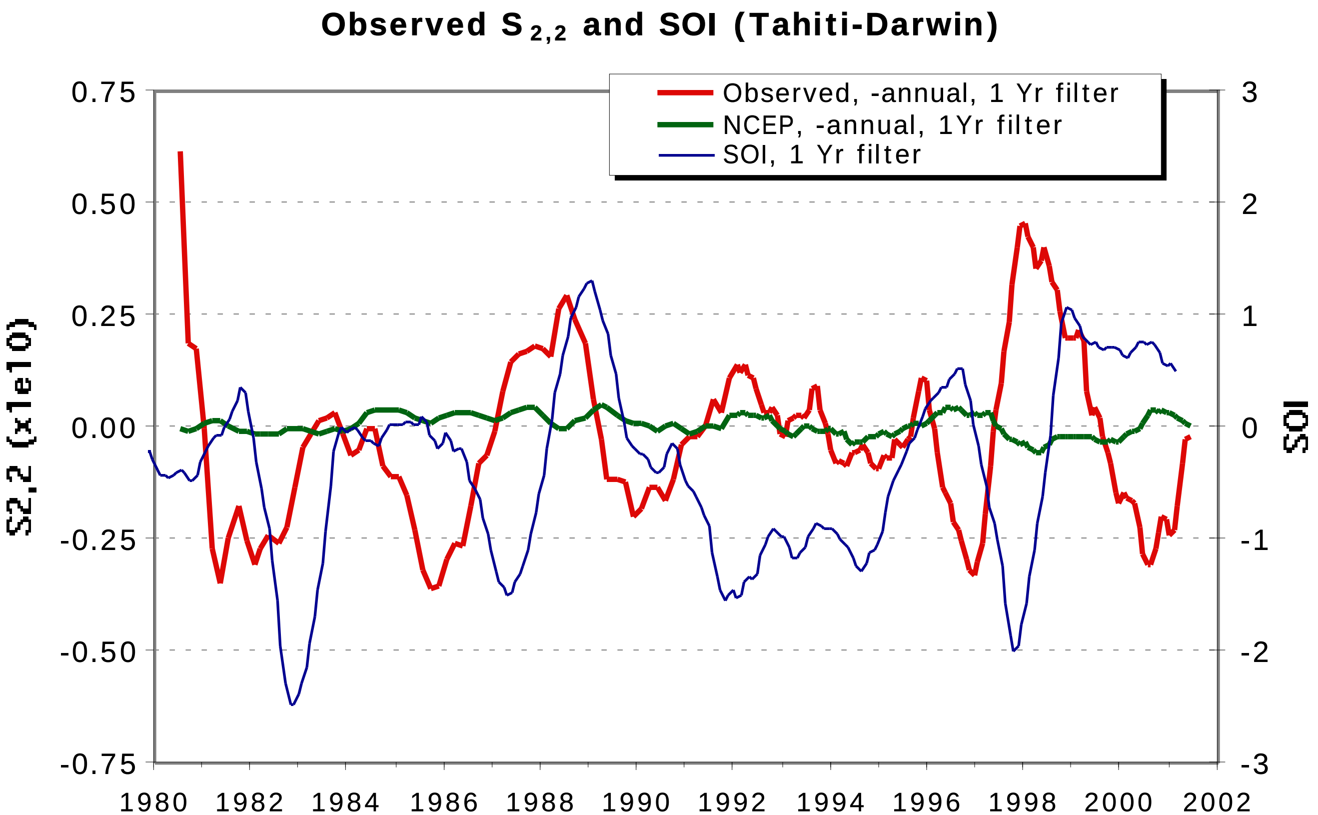
ECCO - Total J_2 Contribution



The ECCO assimilation mode ocean model bottom pressure contribution to J_2

The ECCO model run incorporates the TOPEX/POSEIDON altimeter data

ENSO and S2,2?



- **Correlation is 0.65with a 12 month delay in the observed series**
- **Implication that ENSO events buildup may be observable**
- **Error bars on monthly observations exceed 1x10^{-10}**

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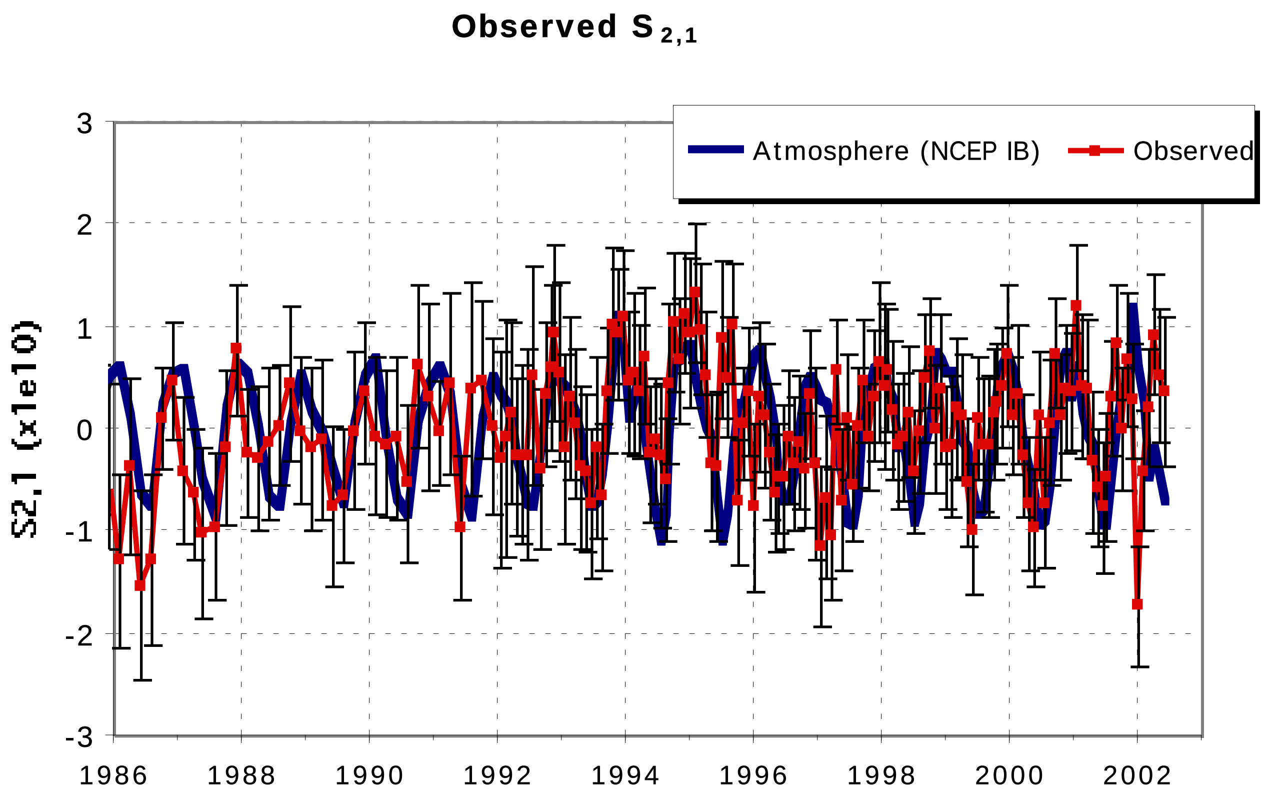
Atmosphere and S2,1?



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Conclusion

- **Significant interannual signals at the $1x10^{-10}$ level for C2,0 and C3,0**
  - Differences in temporal data distribution, weighting, and technique will likely effect results of long-term rate estimation
  - Strong inter-annual periodicity requires long temporal baselines in order to try and recover decadal (and longer) rates
  - Need to improve accounting for mass exchange

    Need to account for atmosphere to assess surface mass transport
- **Apparent Environmental signals present in more than just Zonals**
  - ENSO in S2,2?
  - Atmospheric Mass in 2,1 terms
- **Large change in J_2 rate**
  - Short term deviation or something more?
  - Not atmosphere
  - Ice Melting scenarios large enough to explain this produce far too much GSL change
  - Ocean?

    Changes consistent with extratropic SST and SSH changes