Surface Mass Loads from GRACE, GPS, and Earth Rotation

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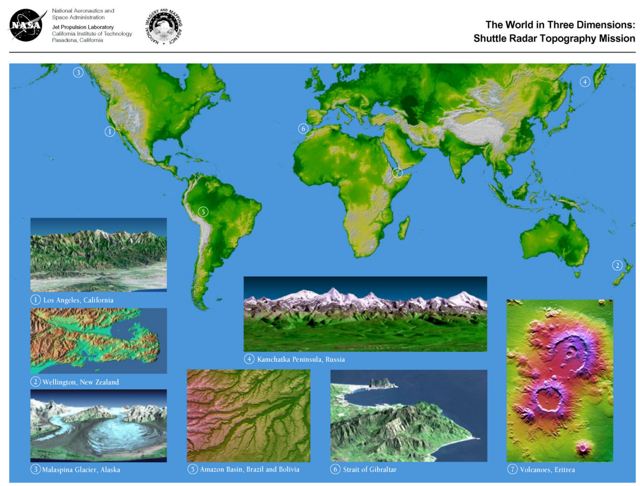
IGCP 565 Project
Workshop 1

December 11, 2008
San Francisco, California

The Three Pillars of Geodesy

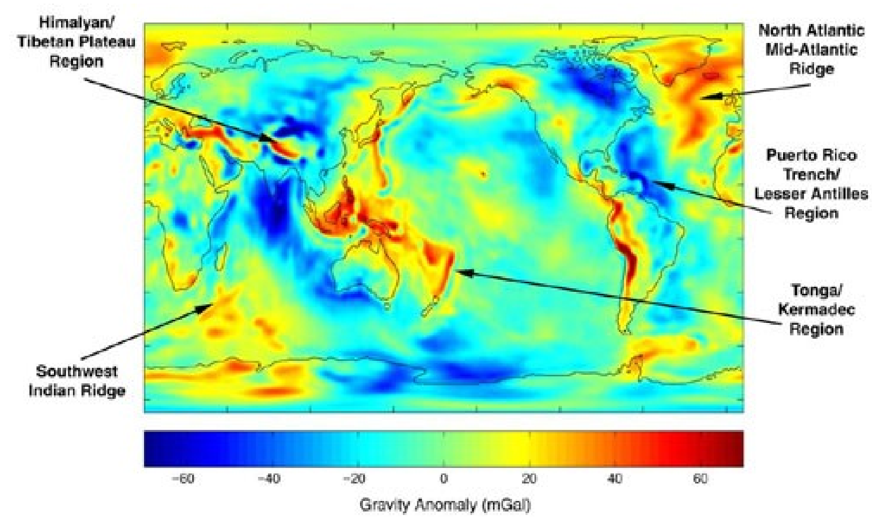


Shape & Deformation

Rotation

QuickTime▪ and a
YUV420 codec decompressor
are needed to see this picture.

Gravity & Geoid



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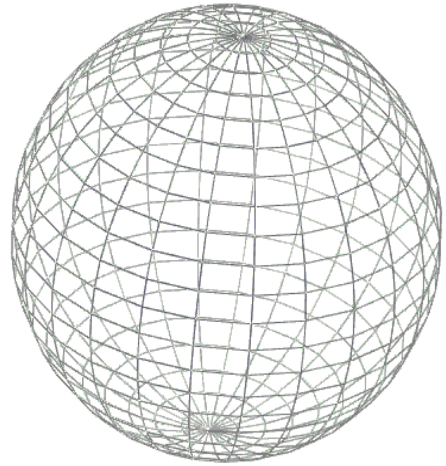

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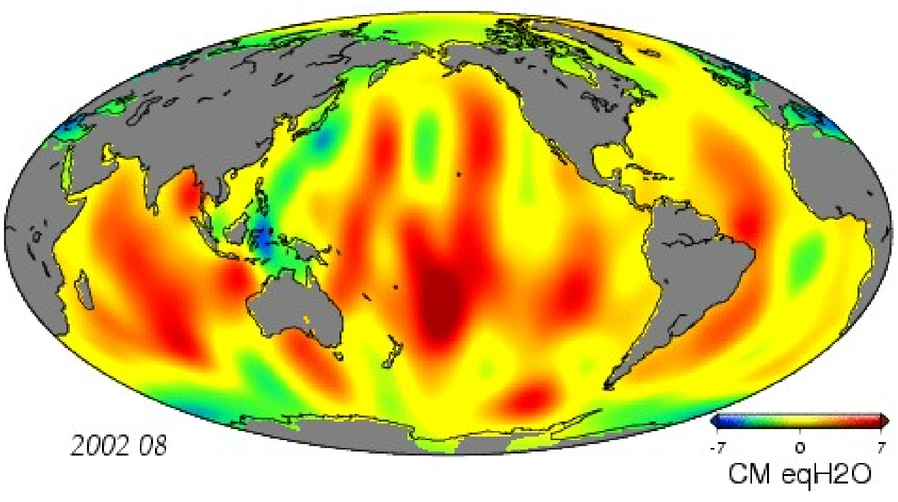
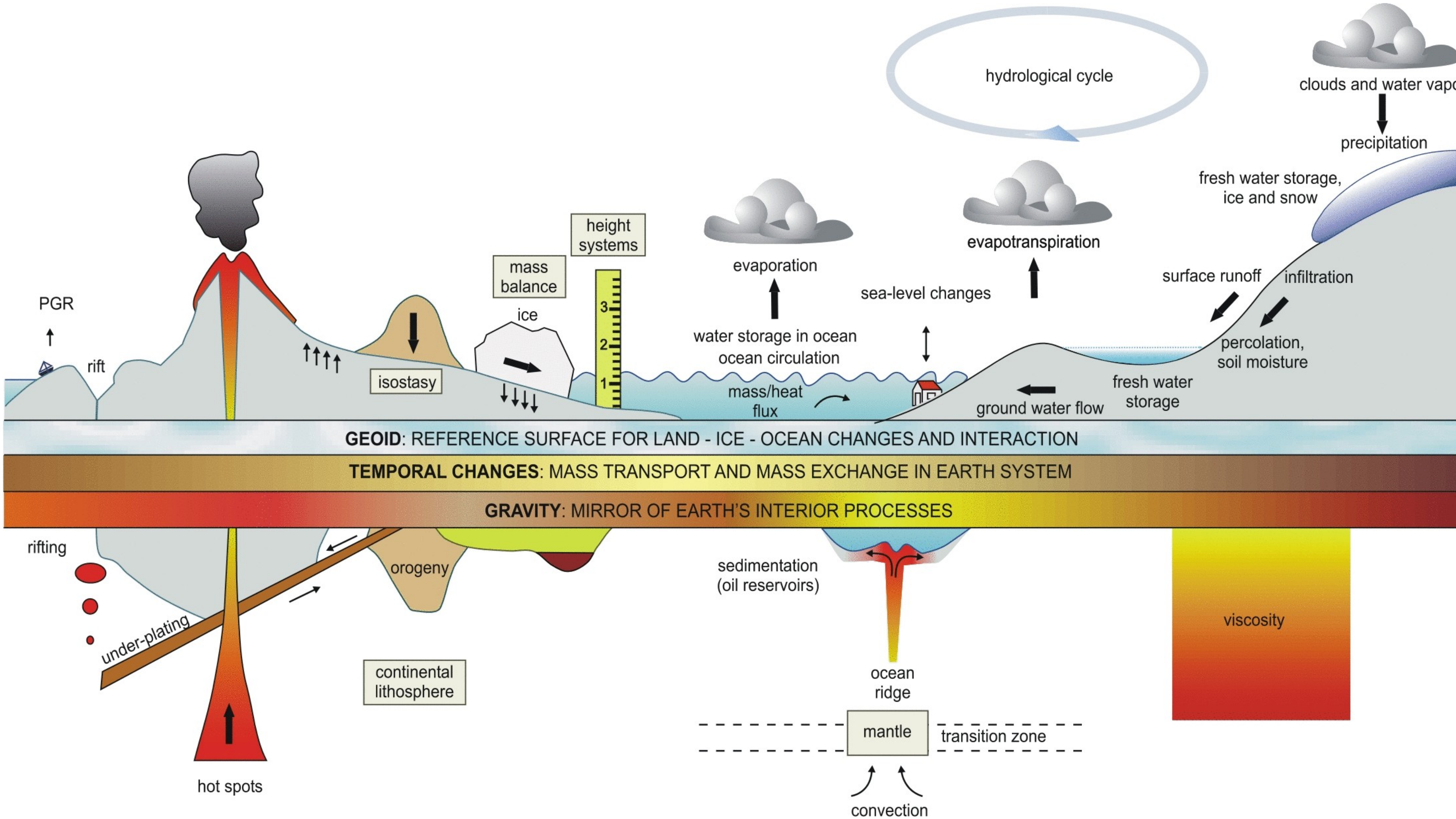


Mass Transport in the Earth System



Ilk et al. (2005)

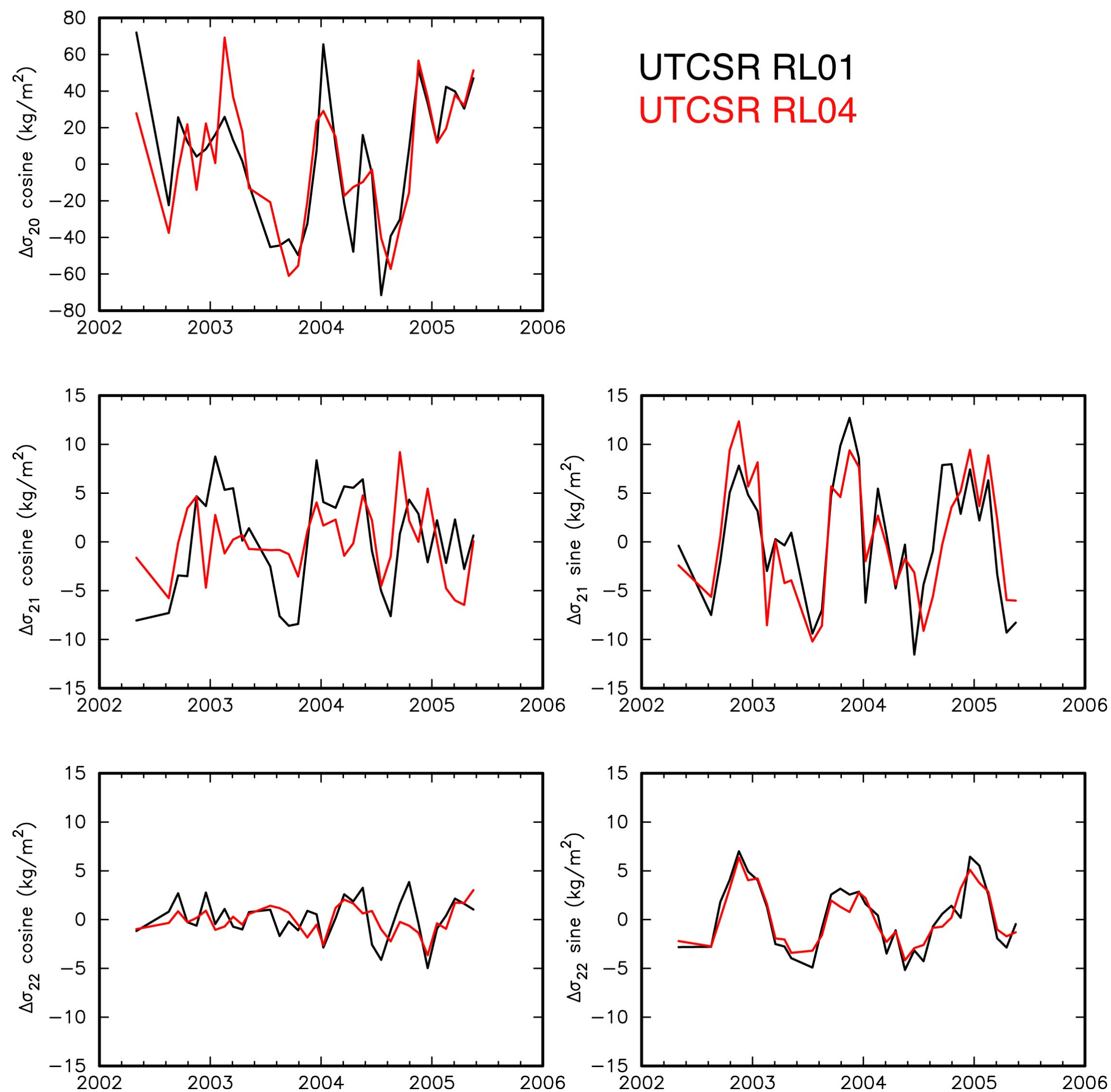
Overview

- Changes in the surface density field of the Earth
  - Change the Earth's shape
    - Measured by GPS
  - Change the Earth's rotation
    - Measured by various space-geodetic techniques
  - Change the Earth's gravitational field
    - Measured by SLR and GRACE
- Study the degree-2 harmonics of changing surface mass loads
  - Measurements
    - GRACE gravity (UTCSR RL01 & RL04)
    - SLR gravity
    - GPS shape
    - Earth rotation (SPACE2005)
  - Models
    - Atmospheric surface pressure (NCEP/NCAR Reanalysis)
    - Ocean bottom pressure (ECCO/JPL data assimilating model kf049f)
    - Land hydrology (LaDWorld-Euphrates)
    - Global surficial fluid mass conservation
- Assess consistency of measurements and models
  - Increases confidence in both measurements and models if they agree

GRACE Mass Load Measurements

- GRACE
  - Monthly values since April 2002
  - UTCSR RL01 and UTCSR RL04
    - 34 values spanning April 2002 to May 2005 (end of GPS data)
- Pre-processing
  - Add back monthly averaged AOD1B product
  - Remove effects of ocean pole tide from RL01 (but not RL04)
  - Convert degree-2 Stokes coefficients to coefficients of surface mass density
  - Remove mean and trend

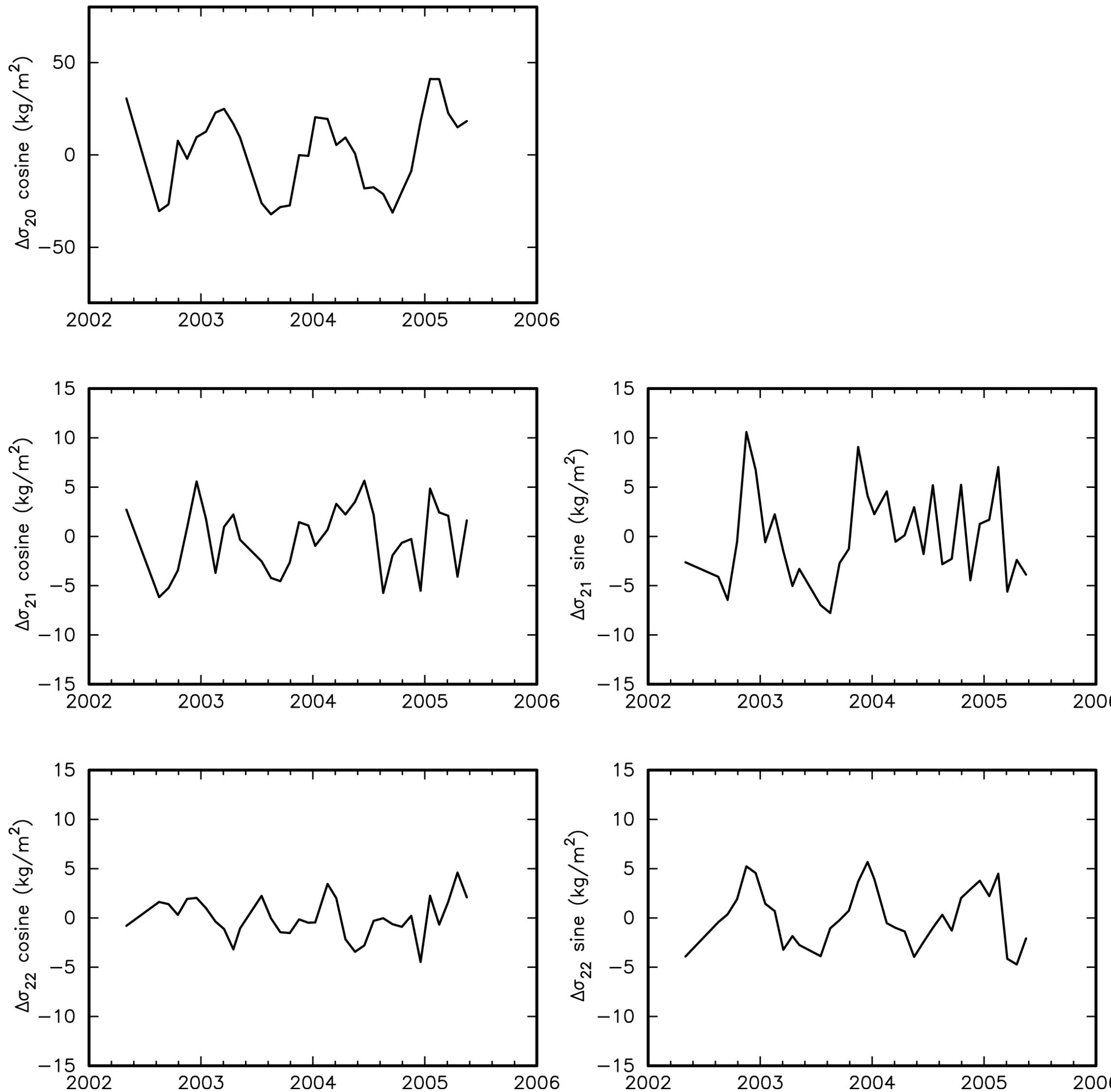
Degree-2 Mass Load Coefficients



SLR Mass Load Measurements

- UT Center for Space Research
  - GRACE replacement series
    - Provided to replace UTCSR RL01 C20 coefficient
    - C20 from GRACE Technical Note 05
    - C21, S21, C22, and S22 from Cheng (personal communication, 2007)
  - Monthly values since April 2002
    - 34 values spanning April 2002 to May 2005 (end of GPS data)
- Pre-processing
  - Add back monthly averaged AOD1B product
  - Remove effects of ocean pole tide
    - SLR series consistent with UTCSR RL01 which included ocean pole tide
  - Convert degree-2 Stokes coefficients to coefficients of surface mass density
  - Remove mean and trend

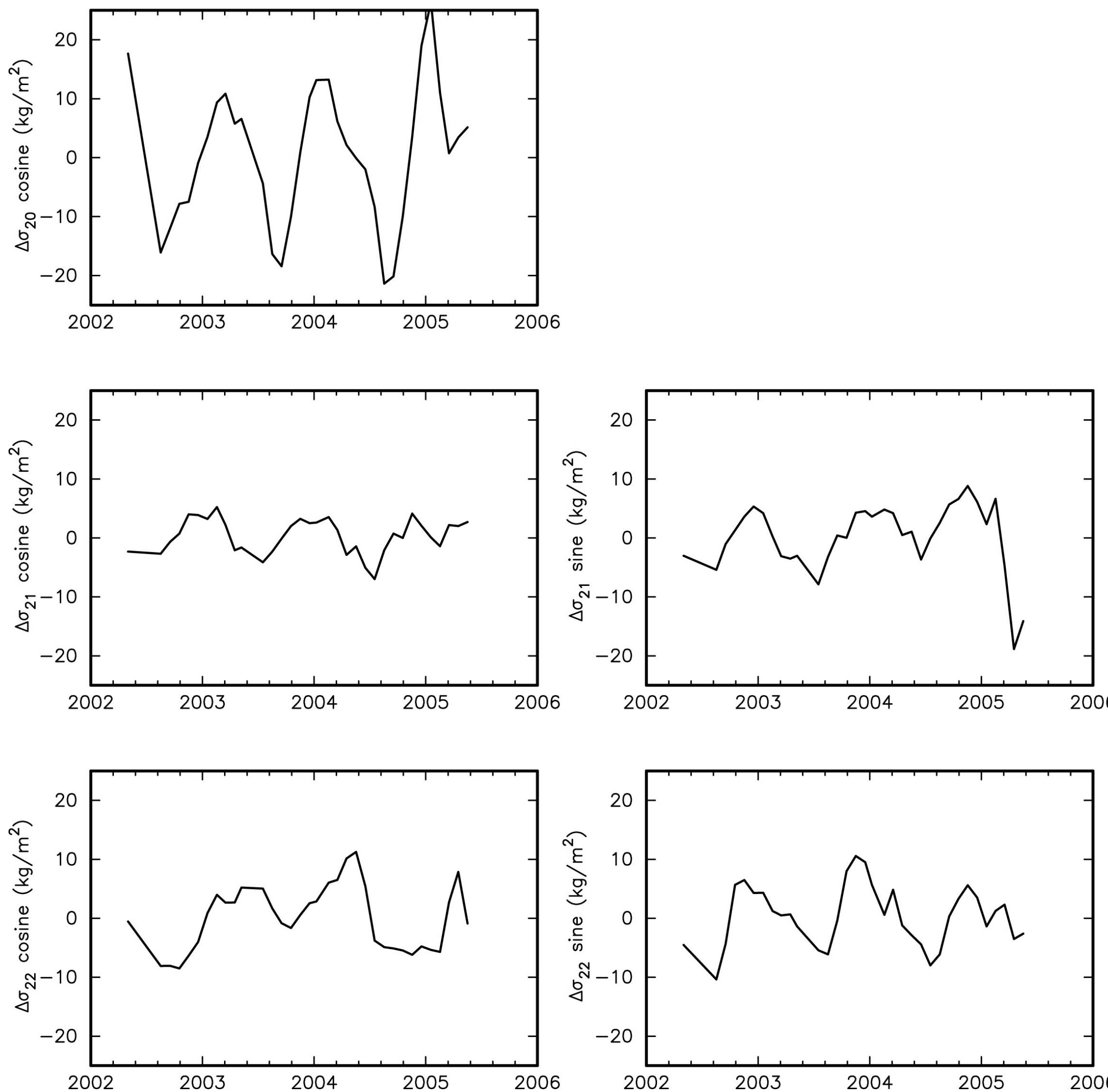
Degree-2 Mass Load Coefficients



GPS Mass Load Measurements

- GPS station distribution
  - Land-rich, ocean-poor
- Surface mass load
  - Strong over land, weak over oceans
- Designer basis functions (Clarke *et al.*, 2007)
  - Expand load over just the land
  - Ocean load included by conserving mass
    - Land-ocean mass transfer
    - Equilibrium response of oceans to load
  - Transform coefficients of new basis functions back to SH coefficients
- GPS mass load series
  - From SIO reanalysis GPS data
  - Spans 1996.0 – 2005.4 at fortnightly intervals
- Pre-processing
  - Form monthly averages
  - Linearly interpolate to epochs of GRACE data
  - Remove mean and trend

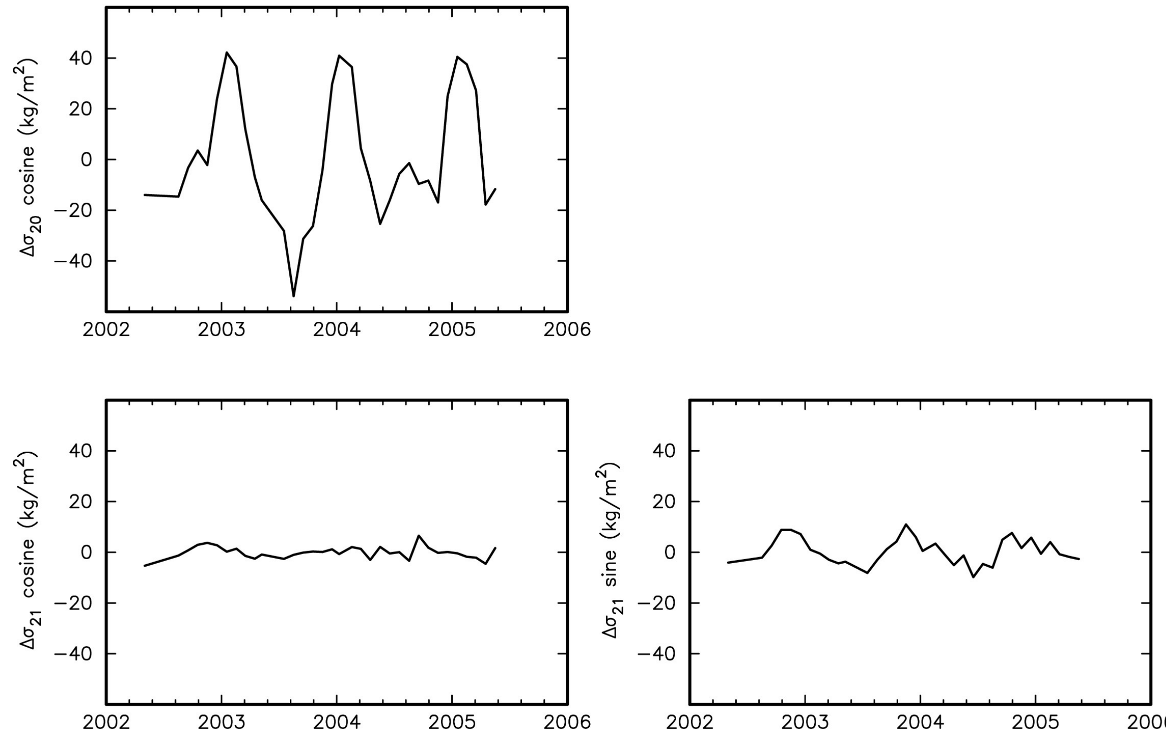
Degree-2 Mass Load Coefficients



Earth Rotation Mass Load Measurements

- Combined EOP Series
  - SPACE2005
    - Kalman filter-based combination of LLR, SLR, VLBI, and GPS Earth orientation measurements
    - Kalman filter self-consistently estimates polar motion rate & hence polar motion excitation functions
    - Spans 1976 – 2005 at daily intervals
- Pre-processing
  - Remove long-period tidal effects
  - High pass filter with 4-year cutoff period to remove signals longer than span of GRACE data
  - Remove NCEP Reanalysis winds and ECCO/JPL data assimilative (kf049f) currents
  - Convert residual to degree-2 harmonics of surface mass density
  - Form monthly averages to be consistent with GRACE and land hydrology data
  - Linearly interpolate to epochs of GRACE data
  - Remove mean and trend

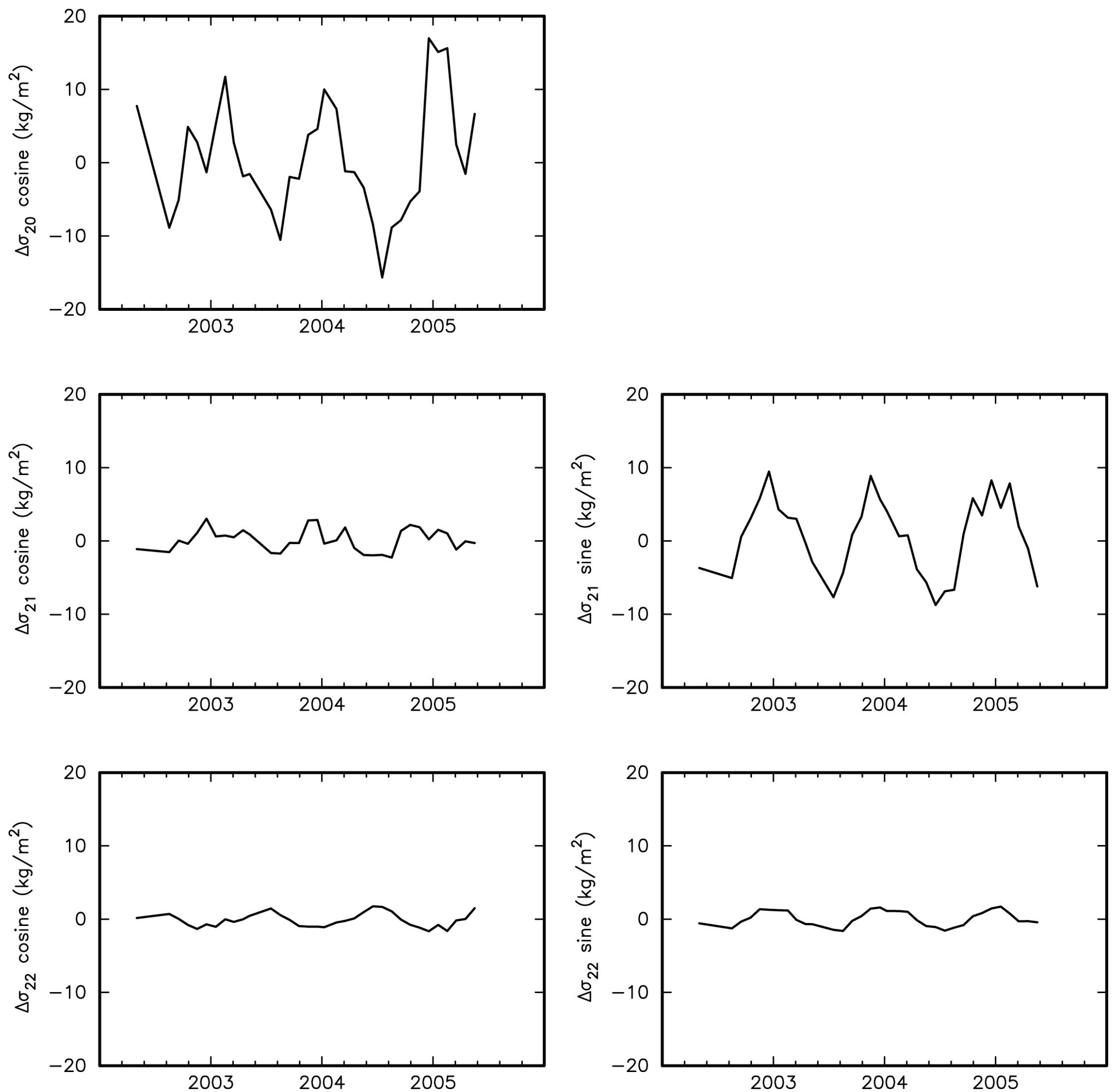
Degree-2 Mass Load Coefficients



Atmospheric Surface Pressure Model

- NCEP/NCAR Reanalysis
  - 6-hour values
  - Spans 1948 to present
  - Inverted barometer approximation
  - Obtained from IERS Special Bureau for the Atmosphere
- Pre-processing
  - Determine degree-2 harmonics of surface mass density
  - Form monthly averages to be consistent with GRACE and land hydrology data
  - Linearly interpolate to epochs of GRACE data
  - Remove mean and trend

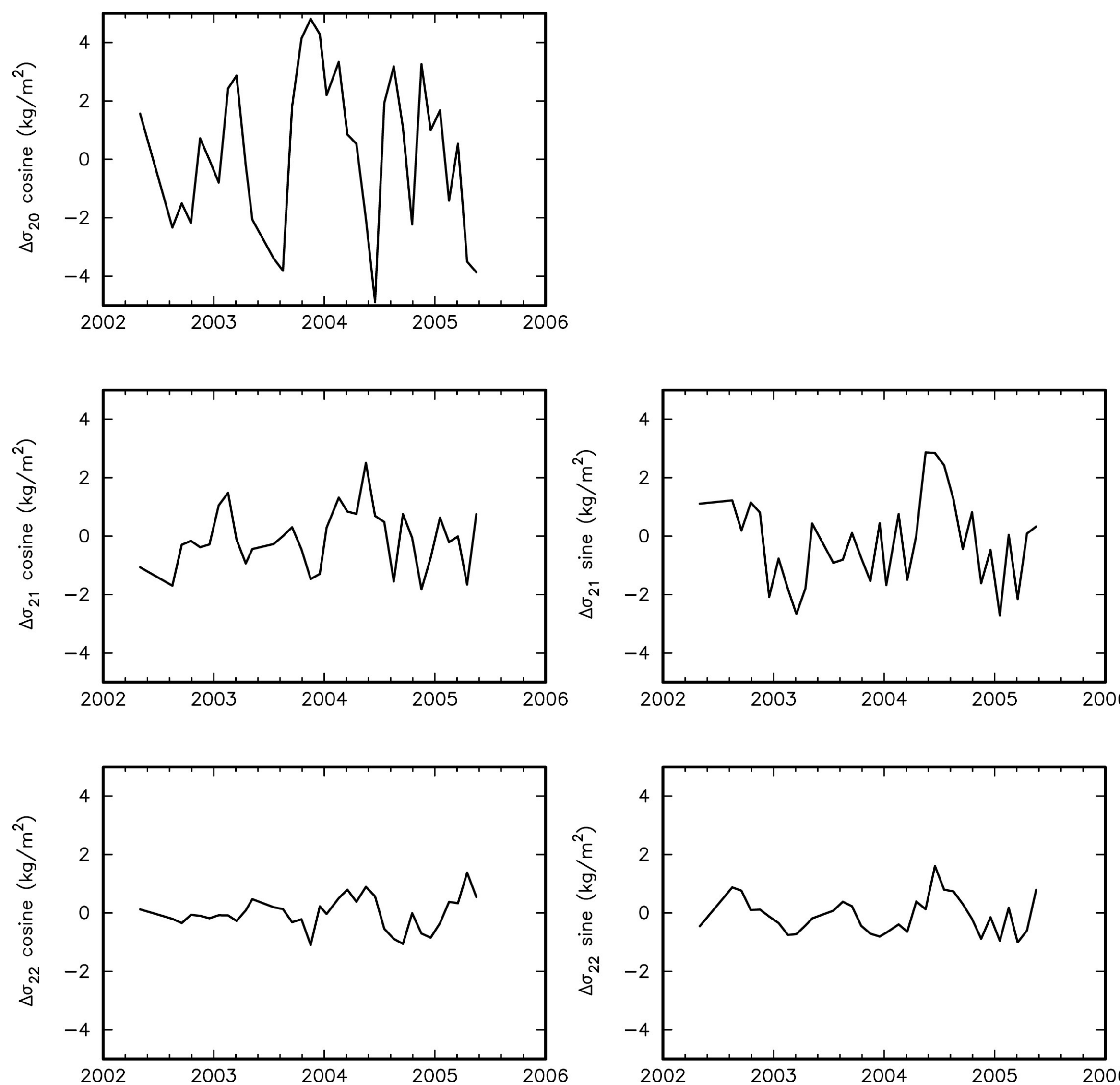
Degree-2 Mass Load Coefficients



Ocean Bottom Pressure Model

- ECCO/JPL data assimilative
  - Spans 1993 – 2006.2 at 12-hour intervals
  - Near global spatial domain
    - 72.5°S to 72.5°N latitude with a variable resolution of 1/3° at equator to 1° at poles and a longitudinal resolution of 1°
    - 46 vertical levels with thickness ranging from 10 m at surface to 400 m at depth
  - Forced with NCEP/NCAR reanalysis surface fluxes
    - Twice daily wind stress
    - Daily heat flux and evaporation-precipitation fields (freshening only)
    - Atmospheric surface pressure not used
  - Assimilated altimetry and XBT data
  - Series designator: kf049f
- Pre-processing
  - Correct for Boussinesq effects
  - Determine degree-2 harmonics of surface mass density
  - Form monthly averages
  - Linearly interpolate to epochs of GRACE data
  - Remove mean and trend

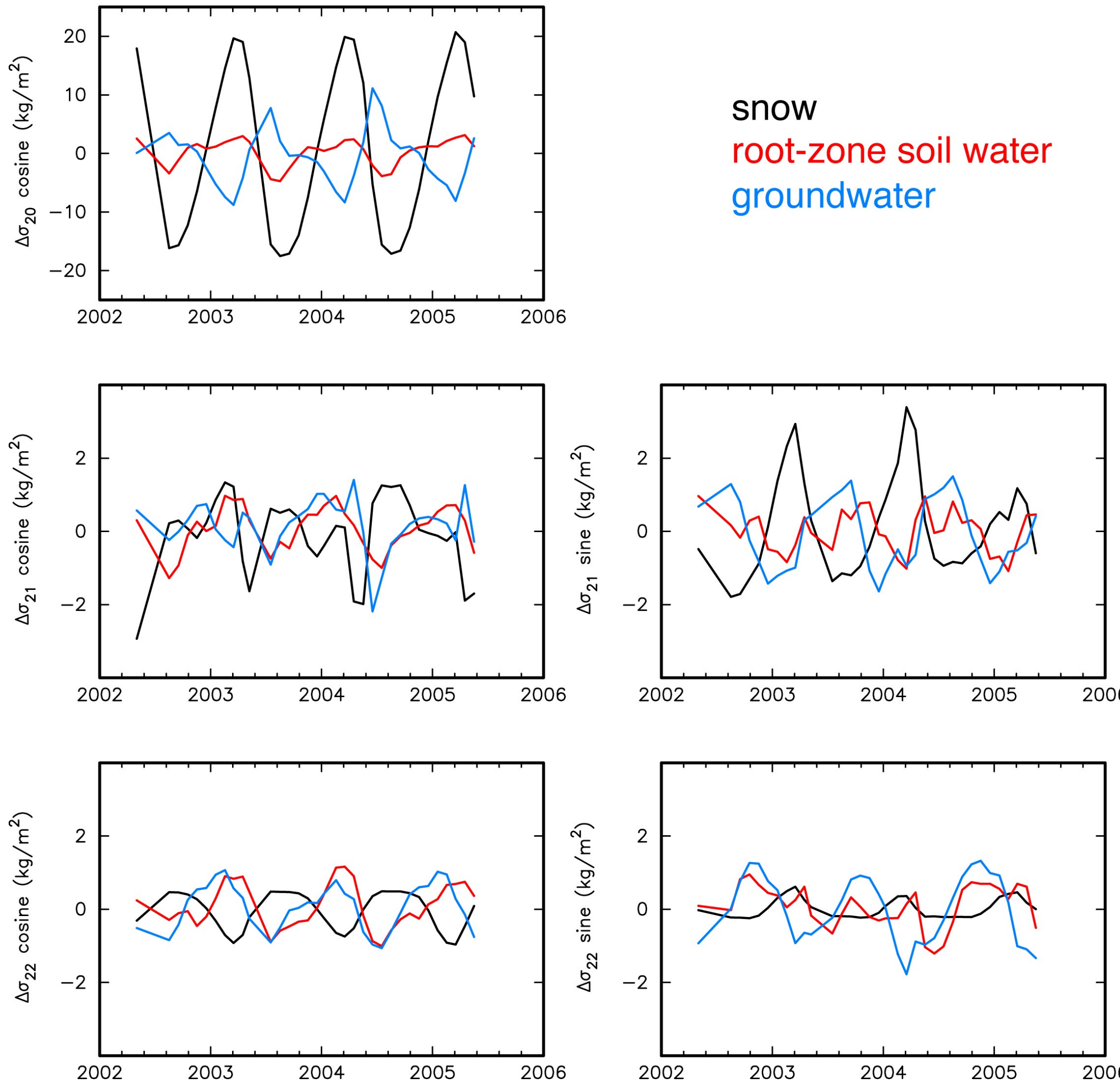
Degree-2 Mass Load Coefficients



Land Hydrology Model

- LaDWorld (Euphrates)
  - Land Dynamics (LaD) model of Milly and Shmakin (2002)
  - Global spatial domain
    - 89.5°S to 89.5°N latitude with a 1°x1° horizontal resolution
  - Forced by
    - Climate Prediction Center Merged Analysis of Precipitation (CMAP)
    - Near-surface air temperature, humidity, and wind speed
    - Radiation
  - Spans 1980–2005.4 at monthly intervals
- Pre-processing
  - Determine degree-2 harmonics of surface mass density
  - Sum contributions of snow, root-zone soil water, and groundwater
  - Linearly interpolate to epochs of GRACE data
  - Remove mean and trend

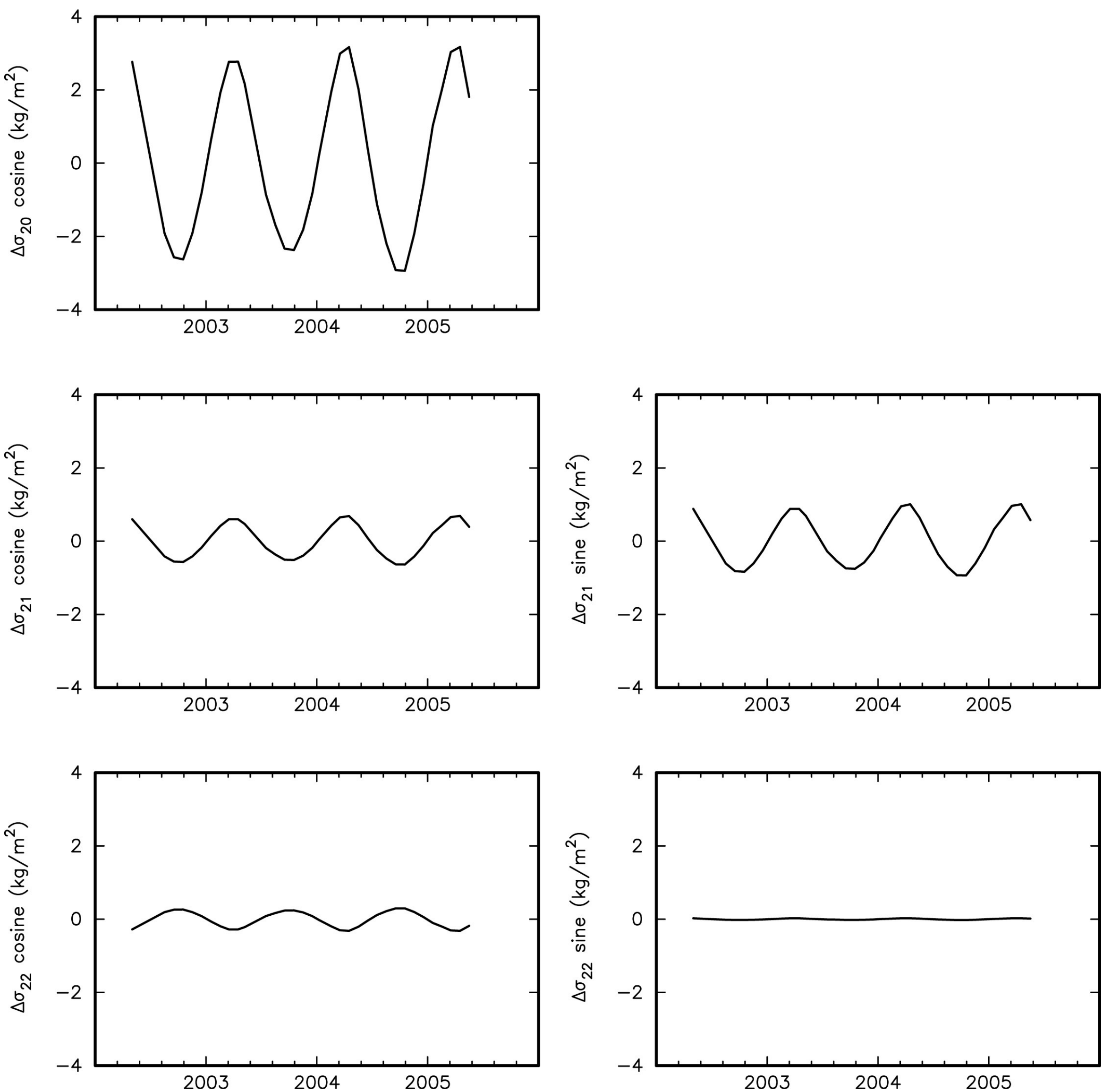
Degree-2 Mass Load Coefficients



Global Mass Conservation

- Impose global mass conservation
  - Total mass of atmosphere, oceans, and land water should be constant
    - Mass of an individual component, such as the atmosphere, will change as water in its various phases cycles through it
  - Models of atmosphere and land hydrology include mass changes
  - Ocean model does not
    - Applied forcing mechanisms do not change mass of ocean model
  - Add layer of water to surface of oceans of just the right time varying thickness to make total mass of atmosphere, oceans, and land water a constant
- Pre-processing
  - Determine degree-2 harmonics of surface mass density of this global mass conserving layer
  - Remove mean and trend

Degree-2 Mass Load Coefficients



Mass Load Measurements

Correlation

(95% significance level = 0.51)

(2,0) cosine

	RL01	*RL04*	*SLR*	*GPS*	*EOP*
RL01	1.0	0.83	0.65	0.61	0.47
RL04		1.0	0.73	0.71	0.53
SLR			1.0	0.87	0.68
GPS				1.0	0.60
EOP					1.0

(2,1) cosine

	RL01	*RL04*	*SLR*	*GPS*	*EOP*
RL01	1.0	0.40	0.52	0.49	0.37
RL04		1.0	0.03	0.19	0.59
SLR			1.0	–0.03	0.07
GPS				1.0	0.40
EOP					1.0

(2,1) sine

	RL01	*RL04*	*SLR*	*GPS*	*EOP*
RL01	1.0	0.81	0.56	0.71	0.83
RL04		1.0	0.53	0.61	0.81
SLR			1.0	0.53	0.60
GPS				1.0	0.56
EOP					1.0

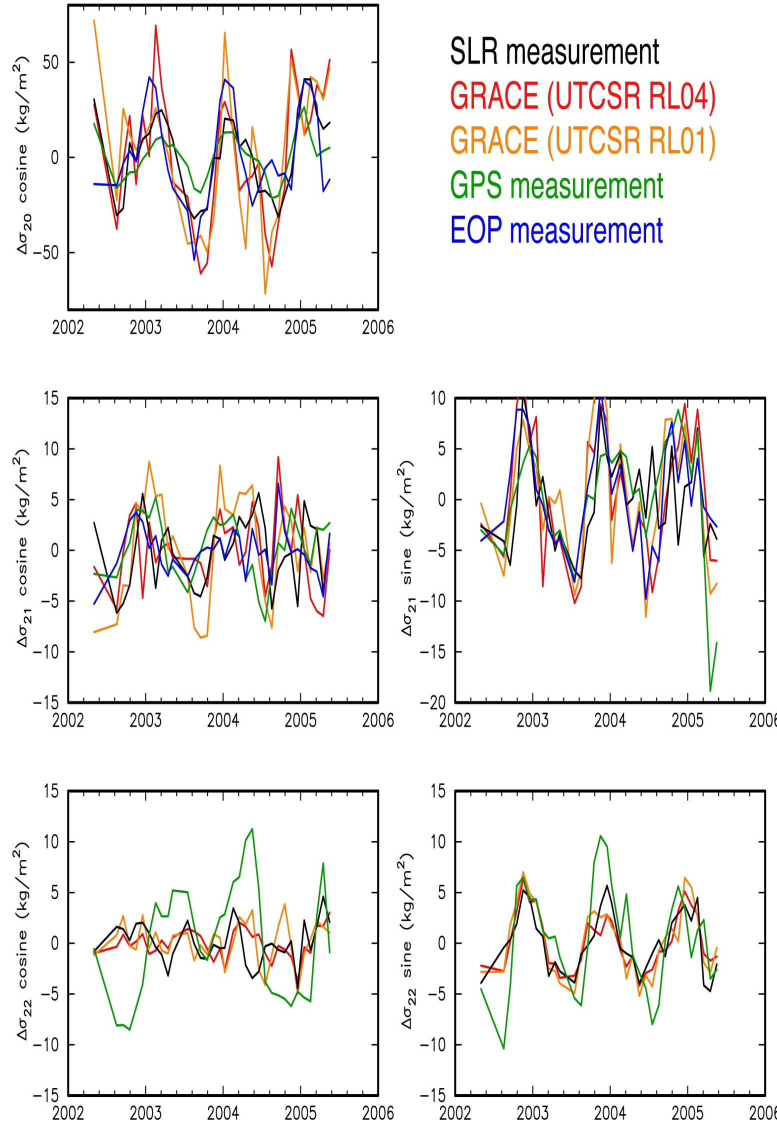
(2,2) cosine

	RL01	*RL04*	*SLR*	*GPS*
RL01	1.0	0.55	0.34	0.18
RL04		1.0	0.45	0.43
SLR			1.0	–0.09
GPS				1.0

(2,2) sine

	RL01	*RL04*	*SLR*	*GPS*
RL01	1.0	0.95	0.83	0.61
RL04		1.0	0.85	0.64
SLR			1.0	0.63
GPS				1.0

Degree-2 Mass Load Coefficients



Earth Rotation Measurements & Models

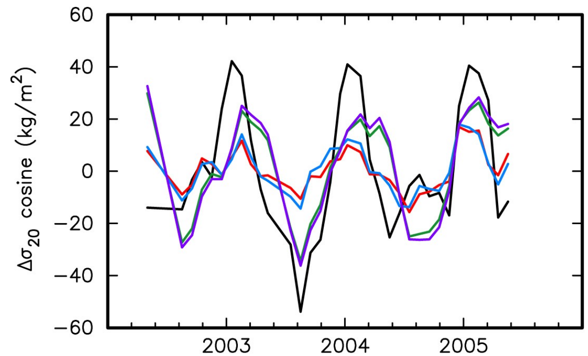
Correlation & Variance Explained

(95% significance level = 0.51)

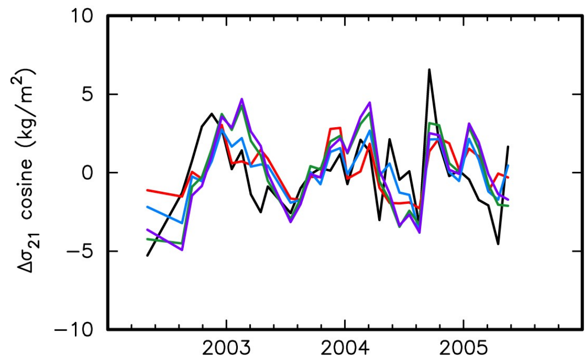
0.71	34.9%
0.74	40.0%
0.59	32.4%
0.57	25.7%

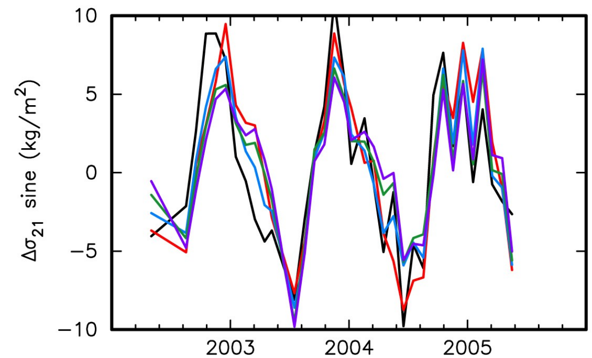
0.40	11.2%	0.84	66.9%
0.63	39.4%	0.90	80.5%
0.55	6.9%	0.86	72.6%
0.46	–14.9%	0.78	61.0%

Degree-2 Mass Load Coefficients



Earth rotation measurement
atmos
atmos+ocn
atmos+ocn+land
atmos+ocn+land conserved





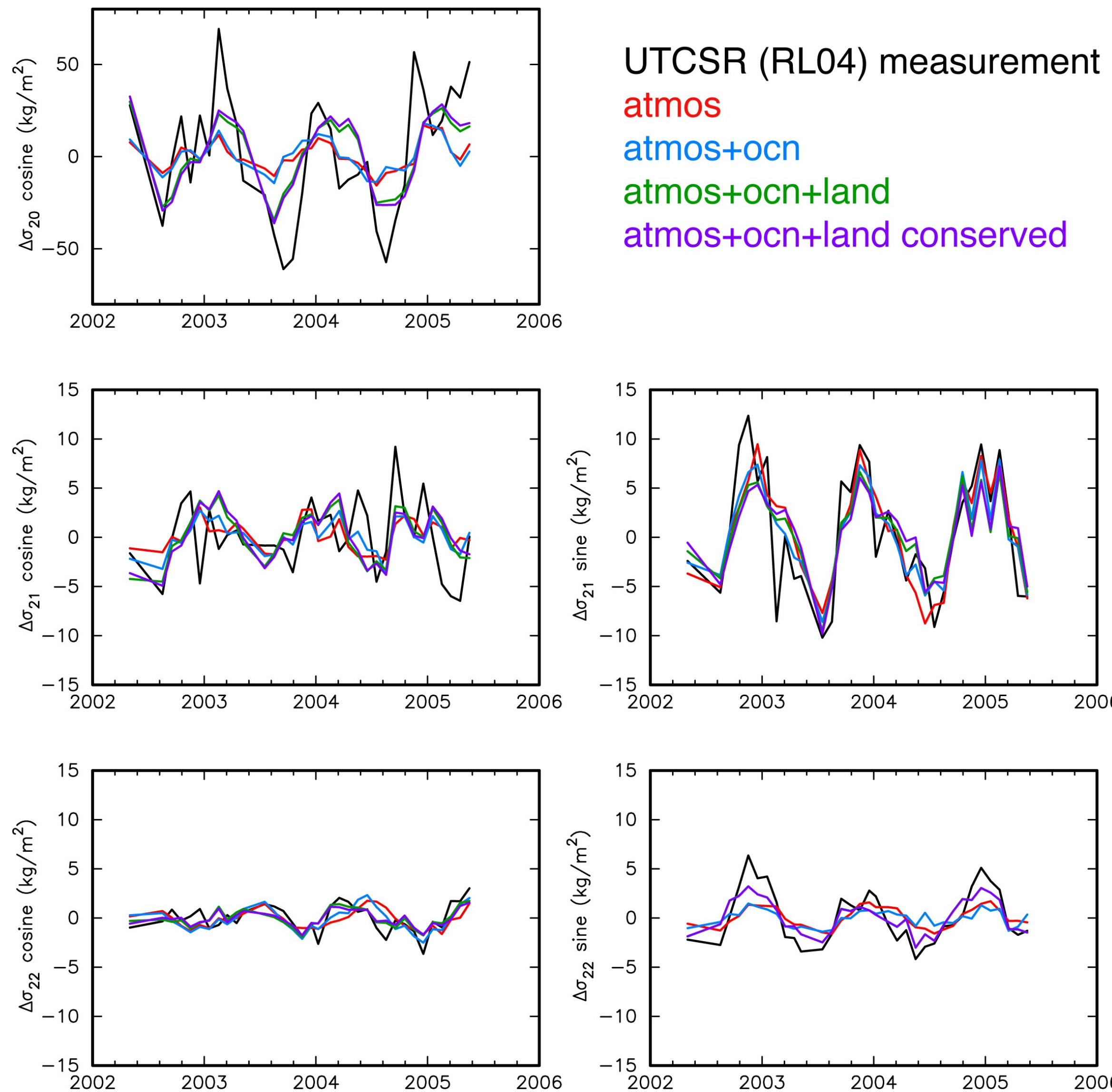
GRACE Measurements and Models

Correlation & Variance Explained

(95% significance level = 0.51)

0.63	24.0%		
0.56	22.7%		
0.71	48.2%		
0.70	48.5%		
0.21	–0.20%	0.80	64.7%
0.38	13.7%	0.87	73.1%
0.31	–5.5%	0.83	64.7%
0.26	–14.4%	0.78	58.9%
0.45	16.1%	0.79	44.6%
0.66	39.2%	0.76	36.1%
0.72	51.4%	0.92	76.0%
0.74	51.4%	0.92	75.9%

Degree-2 Mass Load Coefficients



GPS Measurements and Models

Correlation & Variance Explained

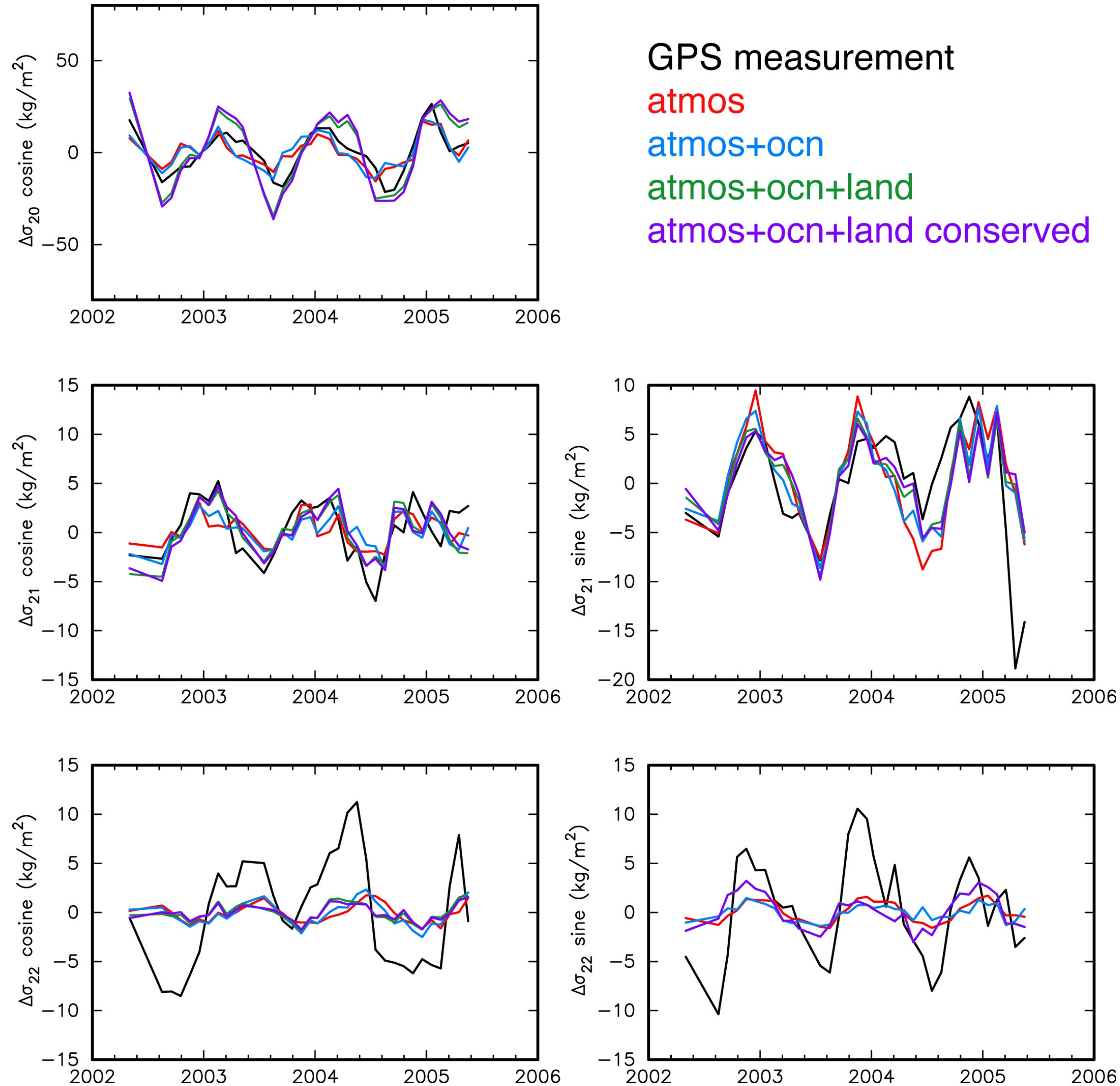
(95% significance level = 0.51)

0.78	59.7%
0.75	56.2%
0.89	32.0%
0.88	6.1%

0.61	36.2%	0.58	25.5%
0.55	30.2%	0.63	37.6%
0.66	40.7%	0.62	38.4%
0.65	38.1%	0.56	30.2%

0.31	7.7%	0.80	28.4%
0.54	19.1%	0.54	14.8%
0.67	19.9%	0.60	29.1%
0.59	15.2%	0.60	29.1%

Degree-2 Mass Load Coefficients



Mass Load Measurements & Models

(95% significance level of correlation = 0.51)

greatest correlation between independent measurements

greatest correlation with models

(variance of measurement explained by models in percent)

(greatest variance explained)

(2,0) cosine

	Models	*RL01*	*RL04*	*SLR*	*GPS*	*EOP*
Models	1.0	0.62	0.70	0.94	0.88	0.57
RL01	(37.9)	1.0	0.83	0.65	0.61	0.47
RL04	(48.5)		1.0	0.73	0.71	0.53
SLR	(88.3)			1.0	0.87	0.68
GPS	(6.1)				1.0	0.60
EOP	(25.7)					1.0

(2,1) cosine

	Models	*RL01*	*RL04*	*SLR*	*GPS*	*EOP*
Models	1.0	0.70	0.26	0.33	0.65	0.46
RL01	(44.4)	1.0	0.40	0.52	0.49	0.37
RL04	(–14.4)		1.0	0.03	0.19	0.59
SLR	(–5.9)			1.0	–0.03	0.07
GPS	(38.1)				1.0	0.40
EOP	(–14.9)					1.0

(2,1) sine

	Models	*RL01*	*RL04*	*SLR*	*GPS*	*EOP*
Models	1.0	0.76	0.78	0.67	0.56	0.78
RL01	(55.9)	1.0	0.81	0.56	0.71	0.83
RL04	(58.9)		1.0	0.53	0.61	0.81
SLR	(42.4)			1.0	0.53	0.60
GPS	(30.2)				1.0	0.56
EOP	(61.0)					1.0

(2,2) cosine

	Models	*RL01*	*RL04*	*SLR*	*GPS*
Models	1.0	0.40	0.74	0.26	0.59
RL01	(16.2)	1.0	0.55	0.34	0.18
RL04	(51.4)		1.0	0.45	0.43
SLR	(5.0)			1.0	–0.09
GPS	(15.2)				1.0

(2,2) sine

	Models	*RL01*	*RL04*	*SLR*	*GPS*
Models	1.0	0.93	0.92	0.82	0.60
RL01	(69.2)	1.0	0.95	0.83	0.61
RL04	(75.9)		1.0	0.85	0.64
SLR	(61.9)			1.0	0.63
GPS	(29.1)				1.0

Degree-2 Summary

- Studied degree-2 harmonics of the Earth's surface mass load
  - Gravity (GRACE & SLR), displacement (GPS), and rotation measurements
  - Atmosphere, ocean, and land hydrology models including global mass conservation
  - During April 2002 (start of GRACE) through April 2005 (end of GPS)
- GRACE measurements
  - RL04 & RL01 agree best with models of surface mass load for (2,2) sine coefficient
  - RL04 agrees best with models of surface mass load for (2,2) cosine coefficient
  - RL01 agrees best with models of surface mass load for (2,1) cosine coefficient
- GPS measurements
  - Agree nearly as well with models of surface mass load as RL01 for (2,1) cosine
- SLR measurements
  - Agree best with models of surface mass load for (2,0) cosine coefficient
- Earth rotation measurements
  - Agree best with models of surface mass load for (2,1) sine coefficient
- Each technique contributes to understanding surface mass load

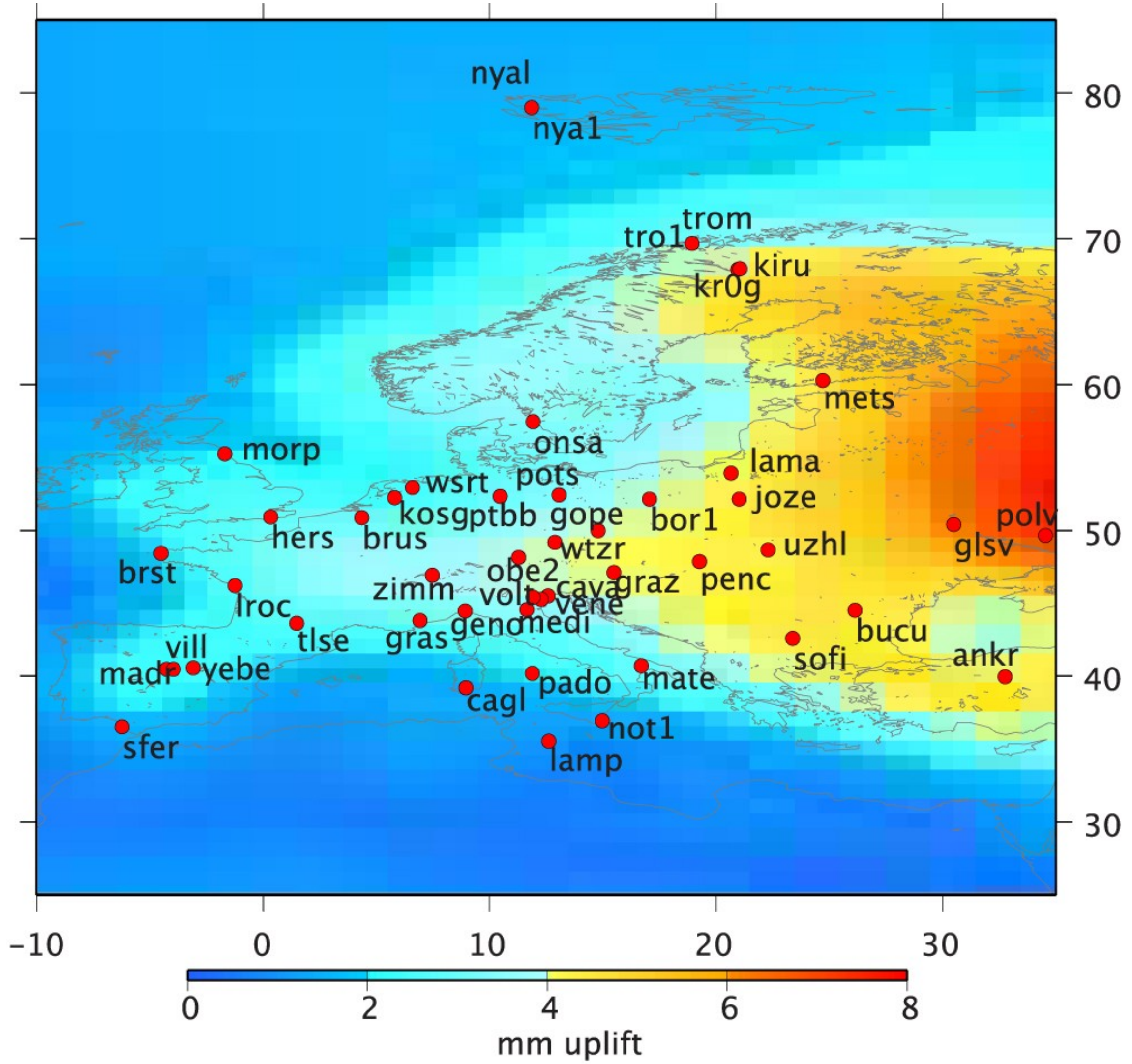


Figure 2. Location of GPS sites overlaid on a gridded estimate of the amplitude of the annual height signal predicted from 25 years of output from a model of water storage.

Van Dam et al. (2006)

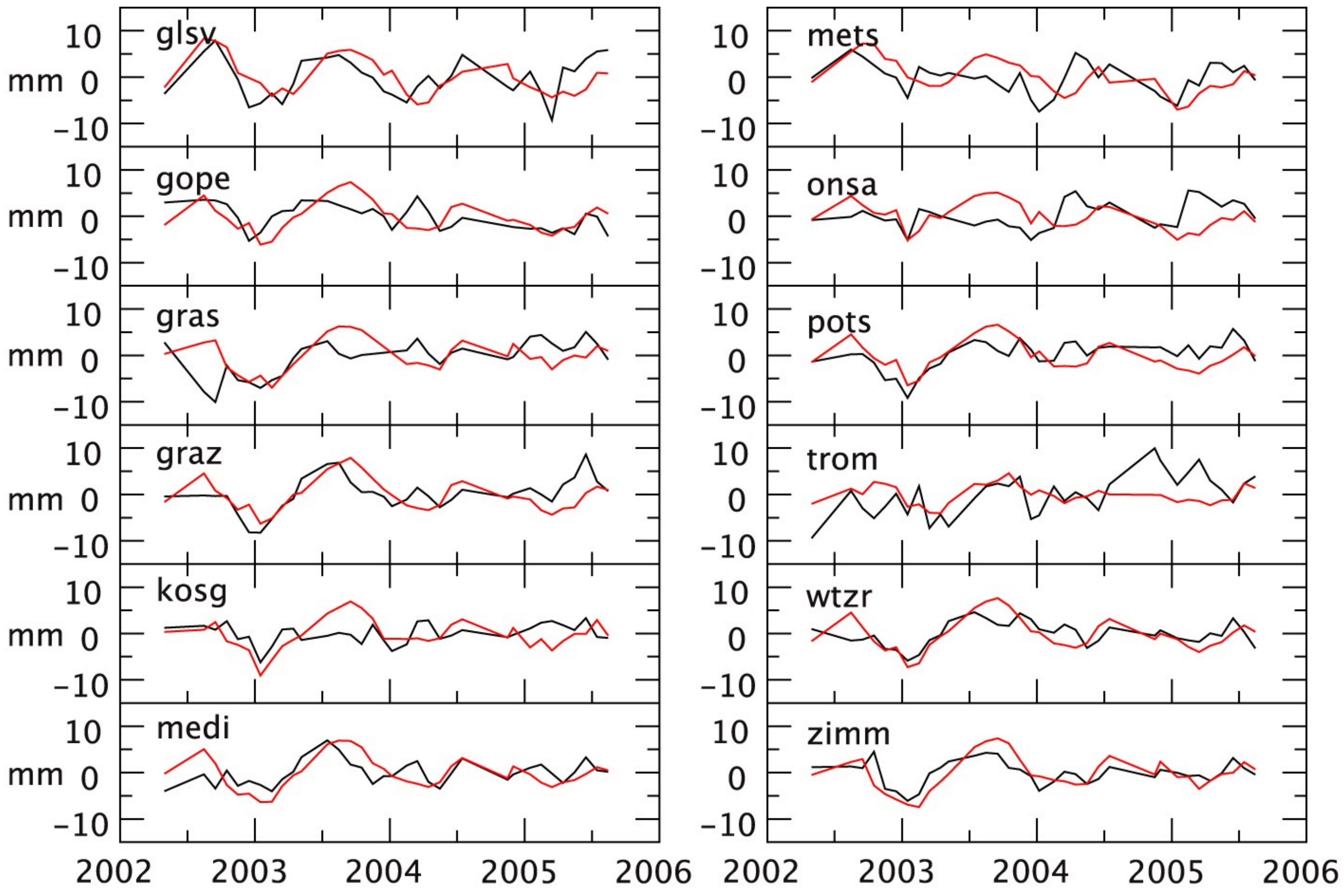


Figure 1. IGS observed height residuals (black) and predicted vertical surface displacements from GRACE (red). Locations of sites are shown in Figure 2.

Van Dam et al. (2006)

Summary

- Changing surface mass load
  - Changes the Earth's shape, rotation, and gravity
- Surface mass load can be studied with geodetic measurements
  - Atmosphere
    - Can be accurately modeled and removed from geodetic measurements
  - Oceans
    - Can be accurately modeled and removed from geodetic measurements
  - Land water storage
    - Can be estimated from geodetic measurements after removing atmospheric and oceanic effects
- Combining measurements from different geodetic techniques will provide best estimate
  - For example, site displacement (GPS) and gravity (GRACE) measurements
  - Must account for differences in accuracy and spatial / temporal resolution