Interdisciplinary Space Geodesy: Links with the Earth Sciences

By

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INTRODUCTION / MOTIVATION

- Earth is a dynamic system:
  - fluid, mobile atmosphere and ocean
  - continually changing distribution of ice, snow, and ground water
  - fluid core undergoing hydromagnetic motion
  - a mantle undergoing both thermal convection and rebound from glacial loading of the last ice age
  - mobile plates
- Processes affect the distribution of mass in the Earth and produce variations in the Earth's gravitational field on a variety of temporal and spatial time scales
- Observations of the Earth's time varying global gravitational field allows the isolation and subsequent investigation into the changing mass distribution of the Earth and the processes involved

Earth System Science and Gravity

- **Among the different areas of scientific concern in the Earth System Sciences, several would benefit from accurate measurements of the Earth's gravity field.**

- **Gravity field measurements serve as integral constraints on mass distribution and variations in the combined solid Earth, oceans and atmosphere system.**

- **Mapping of the Earth's gravity field from space offers global, continuous and homogeneous high quality monitoring of the static and time variable components of the Earth's gravity field.**

- **Potential areas of impact include Oceanography, Hydrology, Glaciology, the Solid Earth Sciences and Geodesy**

Climate Change Prediction

InterGovernmental Panel on Climate Change (1991):

" ... The key areas of scientific uncertainty are:

- ⋆ **clouds: primarily cloud formation, dissipation, and radiative properties, which influence the response of the atmosphere to greenhouse forcing;**
- ⋆ ***oceans:*** **the exchange of energy between the ocean and the atmosphere, between the upper layers of the ocean and the deep ocean, and transport within the ocean, all of which control the rate of global climate change the patterns of regional change;**
- ⋆ **greenhouse gases: quantification of the uptake and release of the greenhouse gases, their chemical reactions in the atmosphere, and how these may be influenced by climate change;**
- ⋆ ***polar ice sheets*****: which affect predictions of sea level rise.**

Studies of *land surface hydrology*, and of impact on ecosystems, are also important"

("CLIMATE CHANGE: The IPCC Scientific Assessment: Executive Summary")

Science Applications

STATIC GRAVITY FIELD

- **Satellite Altimetry**
  - ★ **Absolute Surface Geostrophic Currents**
  - ★ **Upper Ocean Heat Content and Heat Flux**
  - ★ **Long Term Sea Level Variations**
- **Solid Earth Science**
  - ★ **Mantle Structure and Density Variations**
  - ★ **Lithospheric Density Variations**
- **Geodesy**
  - ★ **Precise Positioning**
  - ★ **Improved Satellite Orbits (Re-Analysis of Historical Data)**
- **Mineral Exploration**
  - ★ **Datum for regional gravitational variations**

Science Applications

TIME VARIABLE GRAVITY FIELD

- **Oceanography**
  - ★ **Ocean Bottom Pressure, and Deep Ocean Circulation**
  - ★ **Long Term Sea Level Change**
  - ★ **Separation of Steric & Non-Steric Variations using Altimetry**

- **Hydrology (Global Water Cycle)**
  - ★ **Large Scale, Continental Scale Water Storage Changes**
    - ★ **(e.g. Integrated effects of evapo-transpiration, soil moisture change, aquifer depletion, etc.)**

- **Glaciology**
  - ★ **Polar Ice Sheet Mass Variations**
  - ★ **Post-Glacial Rebound**

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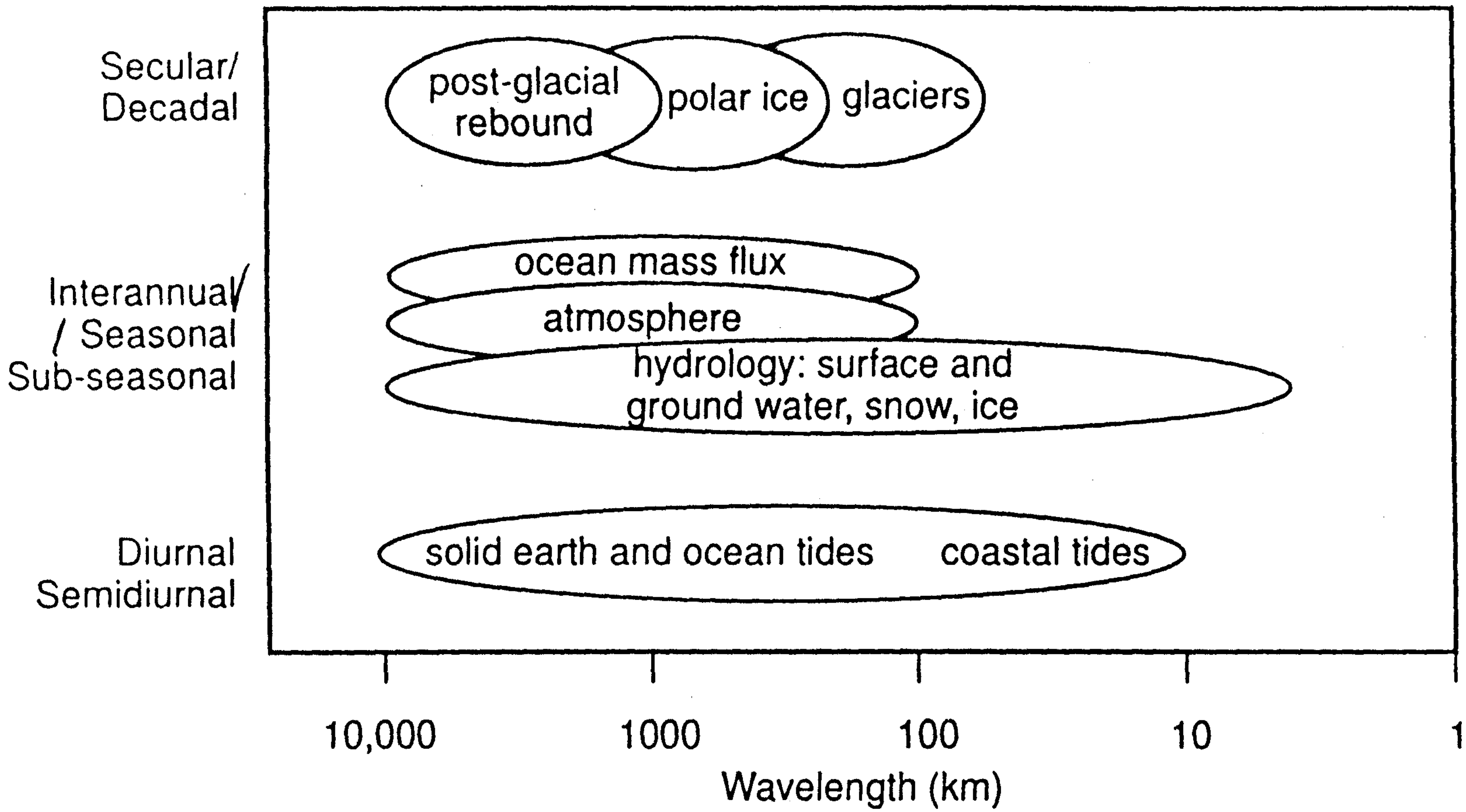
Spatial and Time Scales of Geoid Variations



Gravity Recovery and Climate Experiment
GRACE

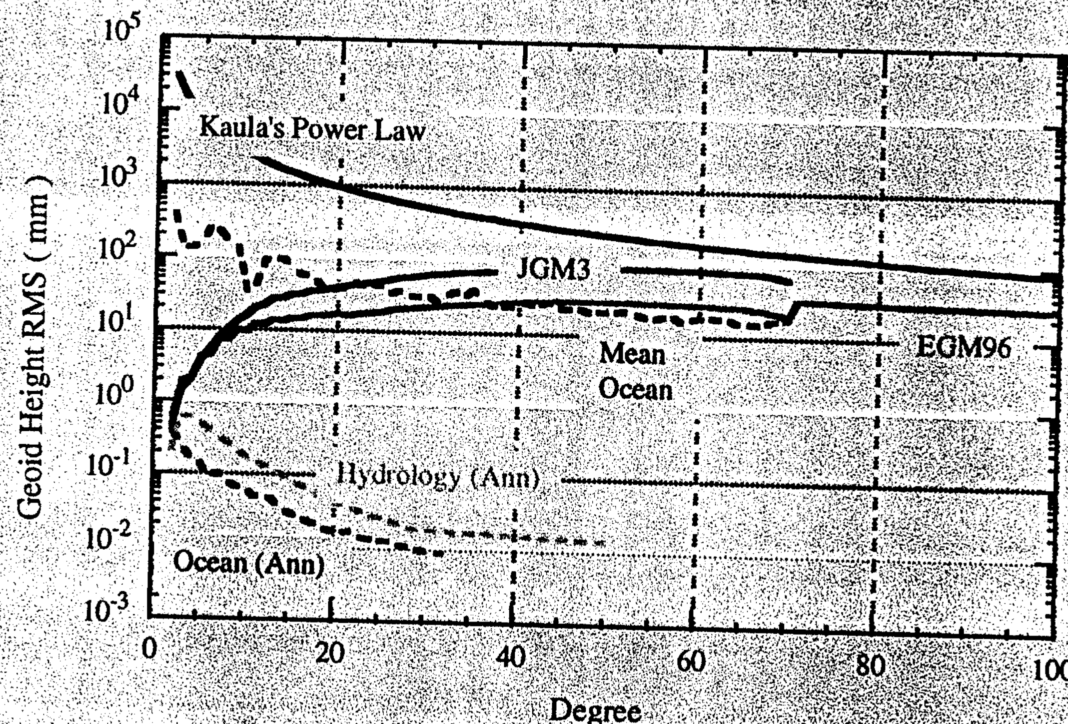
Mission Objective

Produce a new model of
the Earth's gravity field
with unprecedent accuracy
every 12 to 25 days for five years

GRACE unravels global climatic issues by:

- Enabling a better understanding of ocean surface currents and ocean heat transport
- Measuring changes in sea-floor pressure
- Watching the mass of the oceans change
- Measuring the mass balance of ice sheets and glaciers
- Monitoring changes in the storage of water and snow on continents

Gravity Field: Current Status



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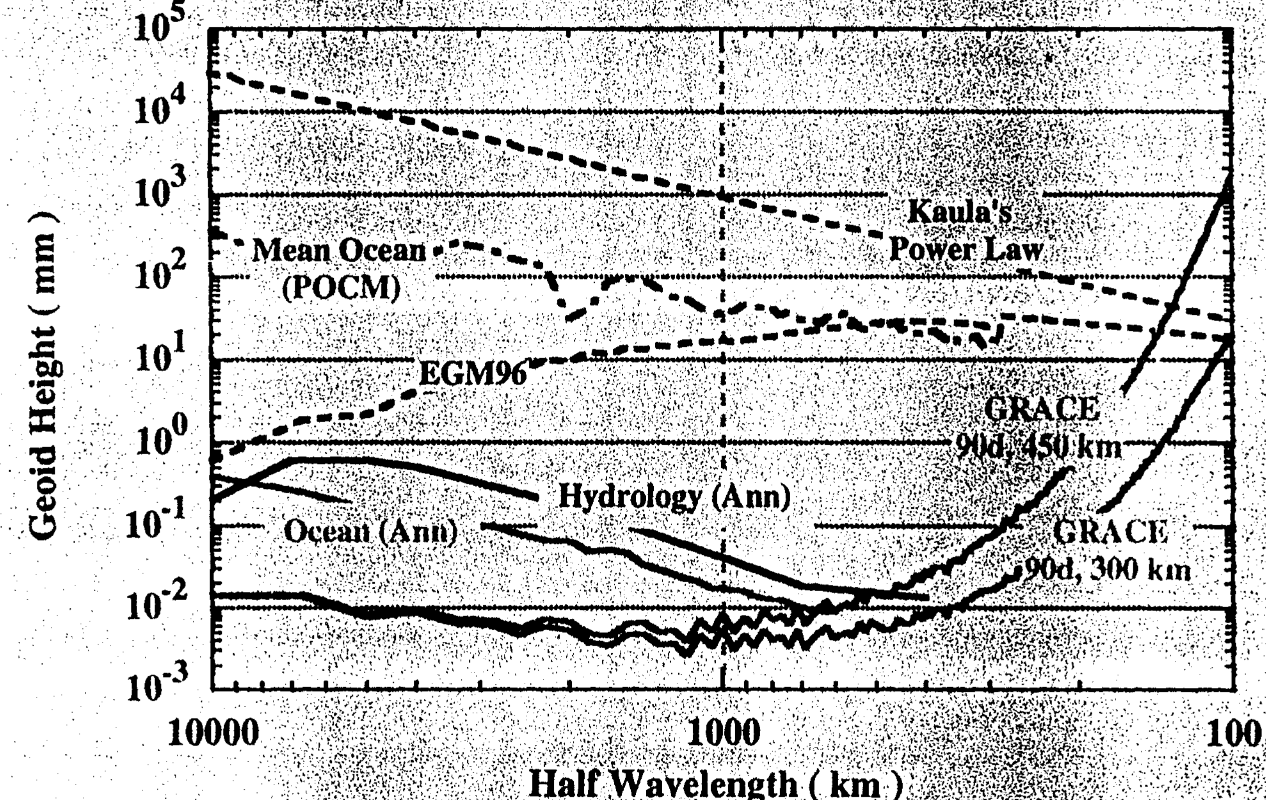
GRACE: Expected Results

Geoid Signals and Accuracies expected from GRACE



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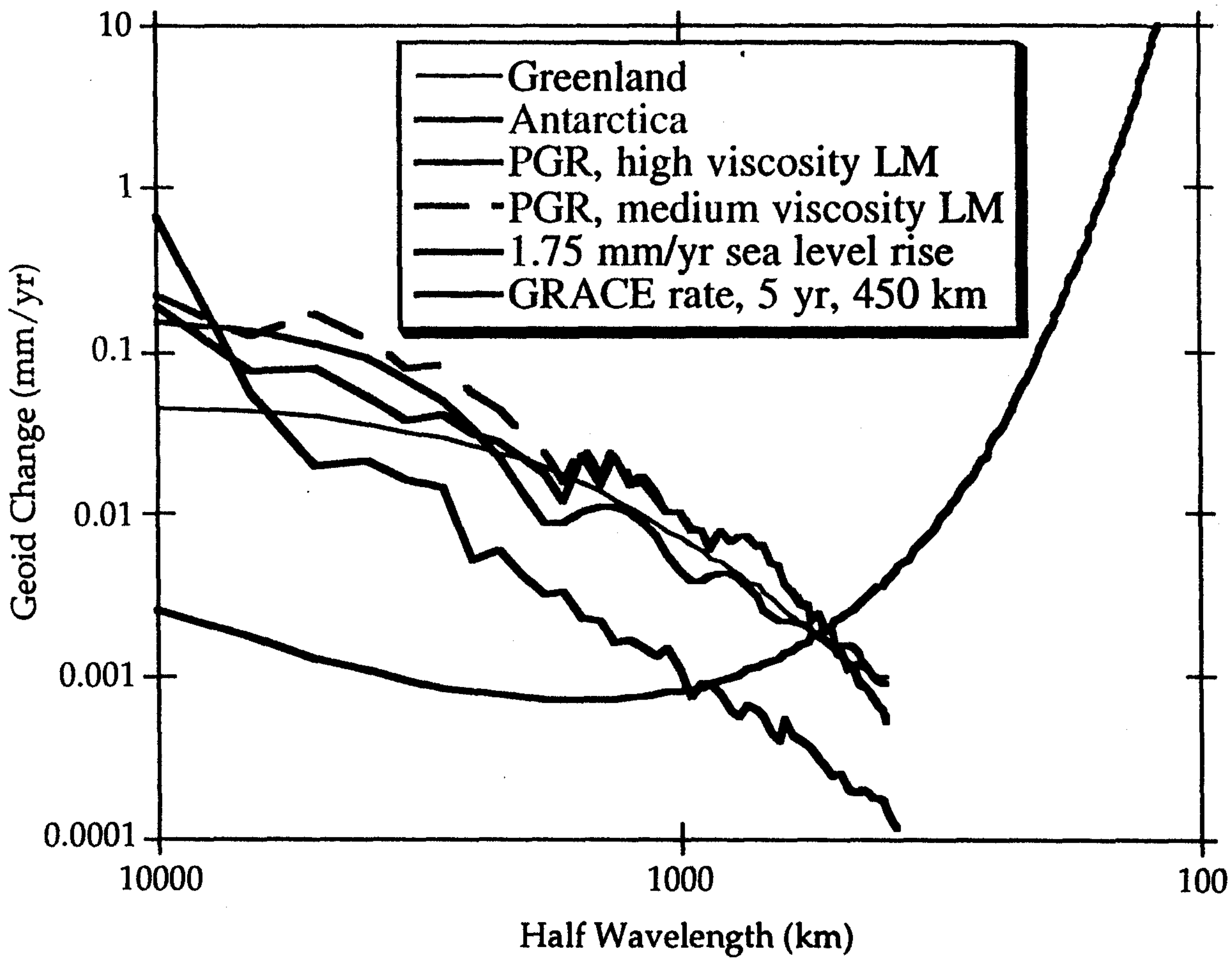
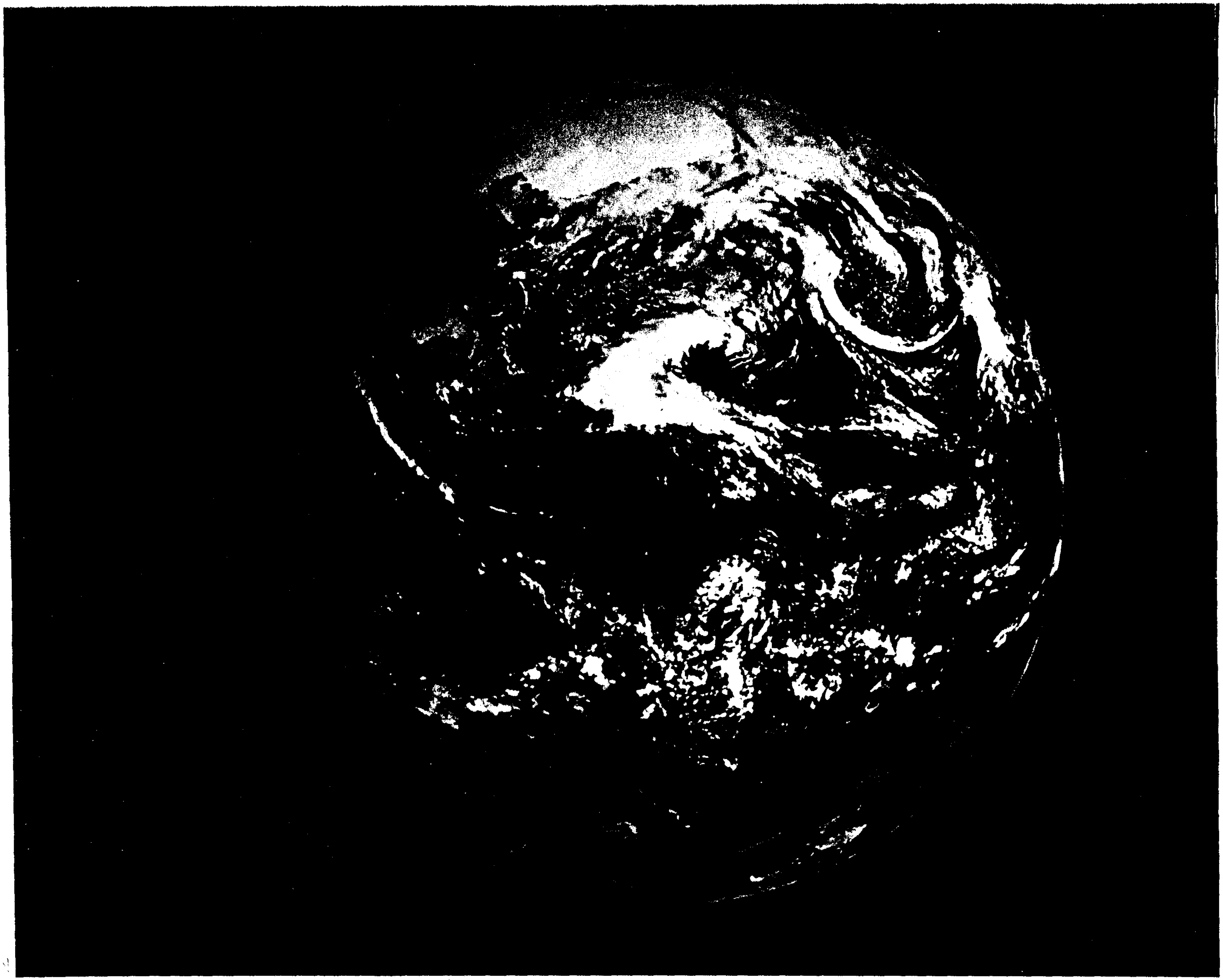
GRACE

Predicted 5-year Geoid Signals & GRACE Errors





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The Dynamic Atmosphere

- Knowledge of atmospheric variation is vital to unraveling the effects of the other subsystems (such as the hydrological cycle) involved in gravity
- Reliable extended-range forecasting which would require interactive coupling between the atmosphere and water in soils and the ocean would benefit from hydrological constraints and improved understanding of ocean dynamics
- Gravity data may serve as a proxy data type in some data-poor regions; however, it would be more efficient to increase meteorological measurements (i.e., barometric networks)

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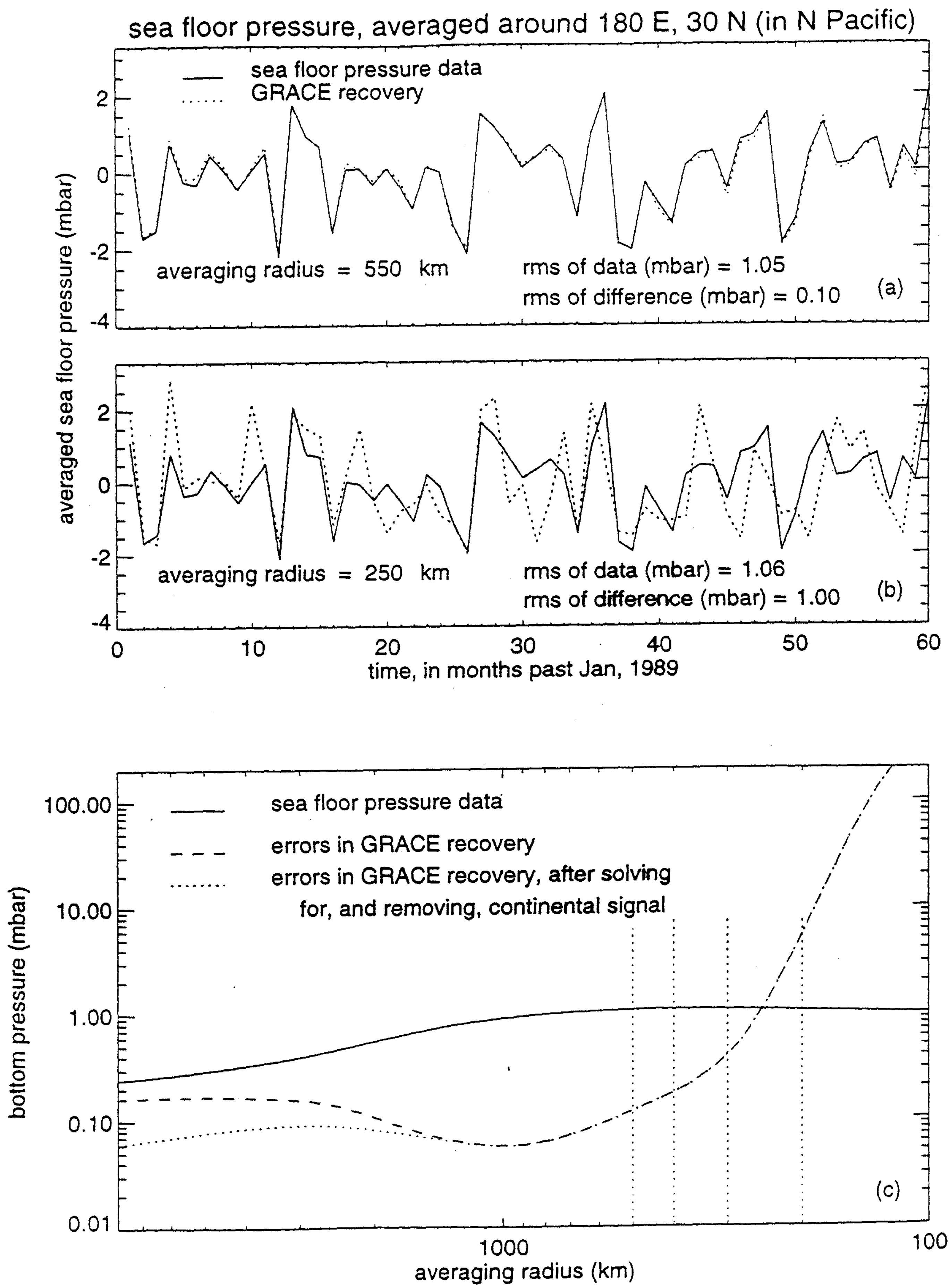
Ocean Dynamics and Heat Flux

- Several mission scenarios (SGG, SST, SSI, and SSE) offer dramatic improvement in our knowledge of absolute dynamic topography and surface circulation from satellite altimetry, especially at basin scales (~300–3000 km), effectively eliminating the geoid as an error source on these spatial scales
- Combination of gravity and altimetry data will provide a powerful constraint on the ocean circulation and allow for the separation of the time-dependent steric and nonsteric components of sea level
- A time-varying geoid would allow the determination of sea floor pressure variations over the world oceans at spatial scales of a few hundred km or longer and thereby variable deep ocean currents could be inferred


sea floor pressure, averaged around 180 E, 30 N (in N Pacific)
sea floor pressure data
GRACE recovery
averaging radius = 550 km
rms of data (mbar) = 1.05
rms of difference (mbar) = 0.10
(a)
averaged sea floor pressure (mbar)
averaging radius = 250 km
rms of data (mbar) = 1.06
rms of difference (mbar) = 1.00
(b)
time, in months past Jan, 1989
sea floor pressure data
errors in GRACE recovery
errors in GRACE recovery, after solving
for, and removing, continental signal
bottom pressure (mbar)
(c)
averaging radius (km)

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Water and Energy Cycling

- Variations in groundwater and soil moisture levels can be potentially measured with a high level of accuracy at subcontinental length scales
  - Great value in forecasting conditions for agriculture, monitoring snow pack, assessing the likelihood of floods and the runoff available for irrigation
  - Scientific insight into hydrologic cycle
  - Valuable for monitoring secular water level decline in aquifers

- Gravity measurements of changes in water storage are important:

  In hydrology: the connection between hydrological processes at traditional hydrological length scales (tens of km and less) and longer scales for estimating global water and energy balances

  In meteorology: these measurements reflect the variations in soil moisture

The Global Hydrologic Cycle

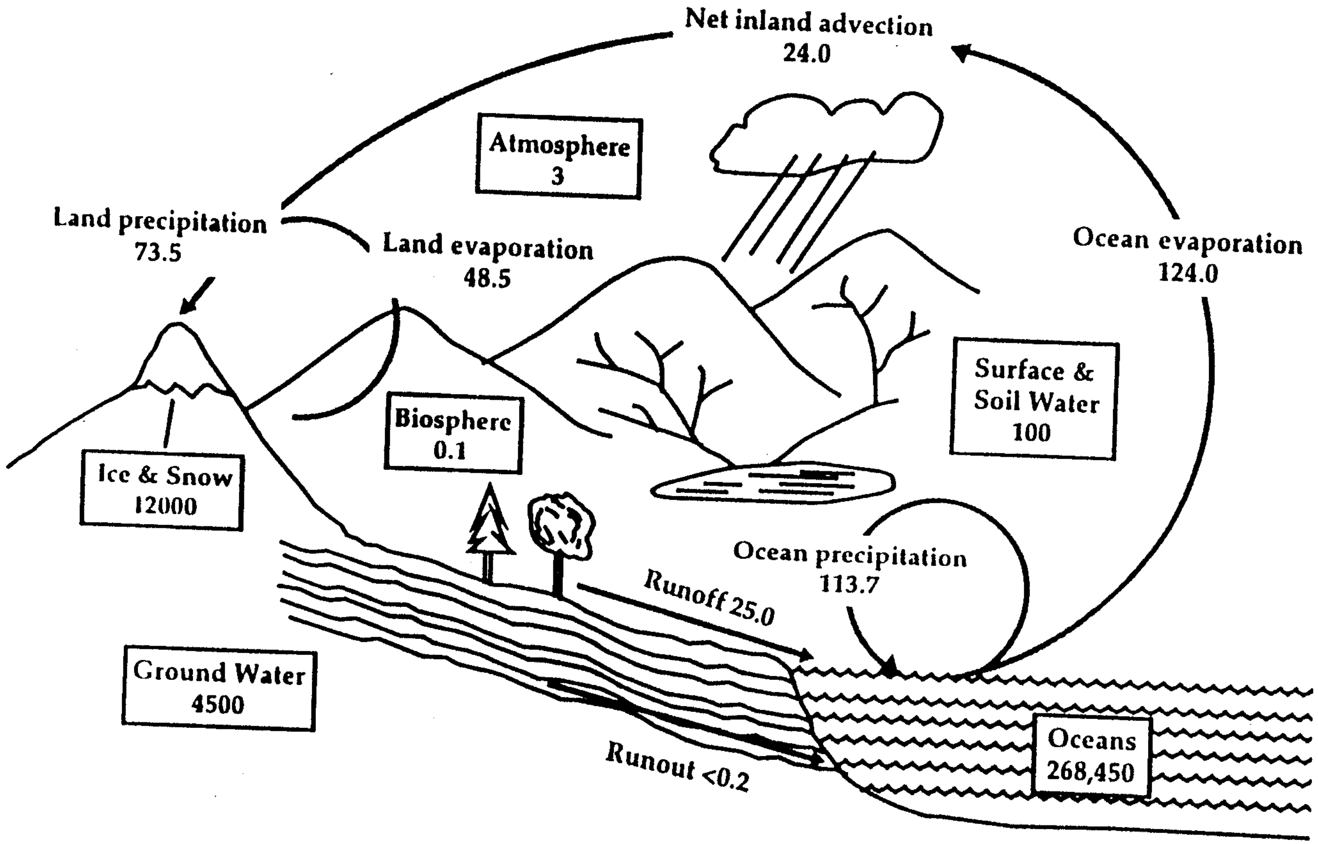


FIGURE 6.1. The global hydrologic cycle, illustrating storages in 10^6 cubic kilometers (boxed) and fluxes in 10^6 cubic kilometers per year. (source: NRC, 1986; Berner and Berner, 1987).

How well can GRACE recover the hydrology signal?

Construct monthly, synthetic geoids that include effects of:

(1) **the "signal":** soil moisture + snow cover (from Huang, et al, 1996)

(2) redistribution of mass in the oceans (from POP ocean circulation model of Dukowicz & Smith, 1994; data provided by Frank Bryan and Mery Molenaar)

(3) errors in post-glacial-rebound model: uses difference between model results for 1×10^{22} Pa-sec and for 5×10^{22} Pa-sec lower mantle viscosity

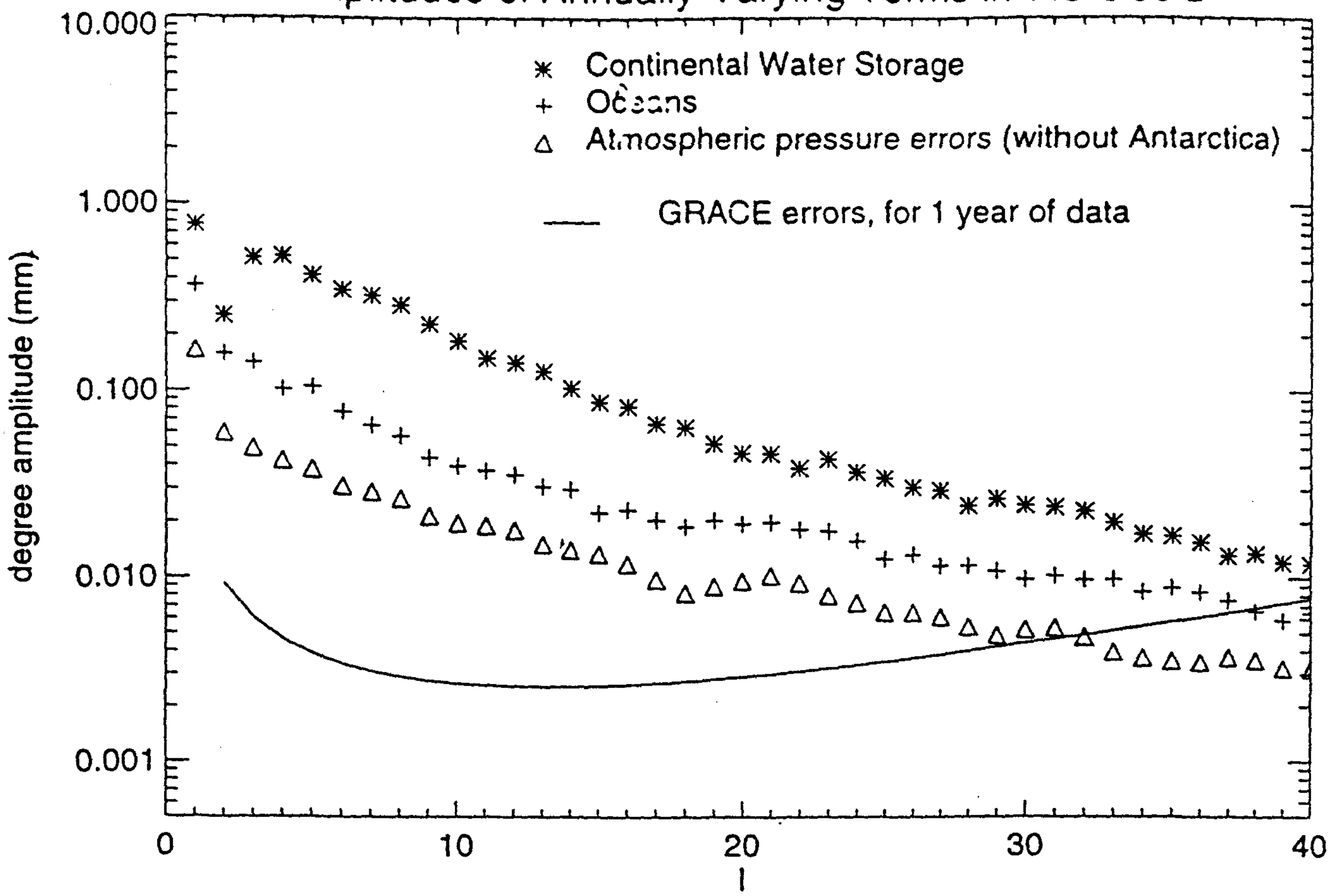
(4) errors in atmospheric pressure: (NMC-ECMWF) / $\sqrt{2}$. Assume inverted barometer response of ocean.

(5) simulated GRACE errors (from Thomas & Watkins, and Bettadpur)

Use the geoid to find monthly values of surface mass on land, averaged over regions

Compare with averages found directly from the soil moisture + snow cover data

Amplitudes of Annually-Varying Terms in the Geoid



Water Storage: Uses global soil moisture estimates of Huang, et al (1996)

Oceans: Uses output from Los Alamos POP model (Dukowicz & Smith, 1994).

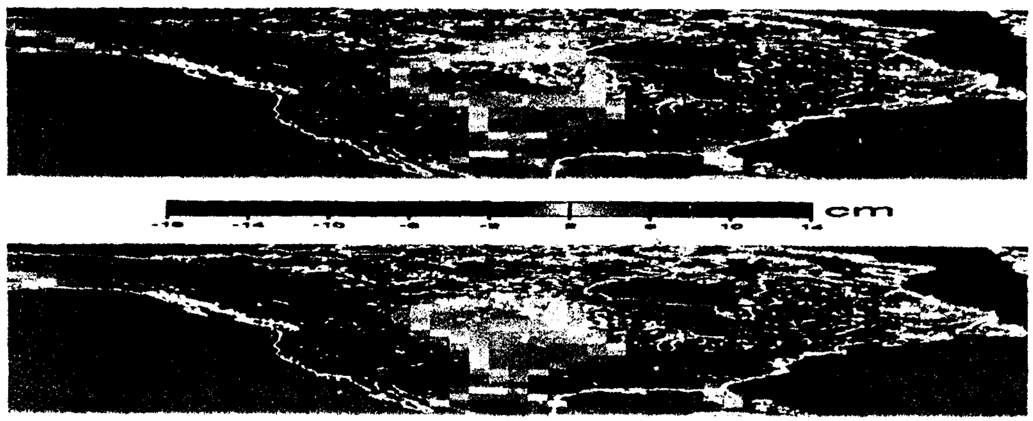
Atmos Press Errors: Estimated as $(P_{ECMWF} - P_{NMC})/\sqrt{2}$ over land; set to 0 over ocean.

GRACE Errors: From Thomas & Watkins (JPL) and Bettadpur (U Texas)

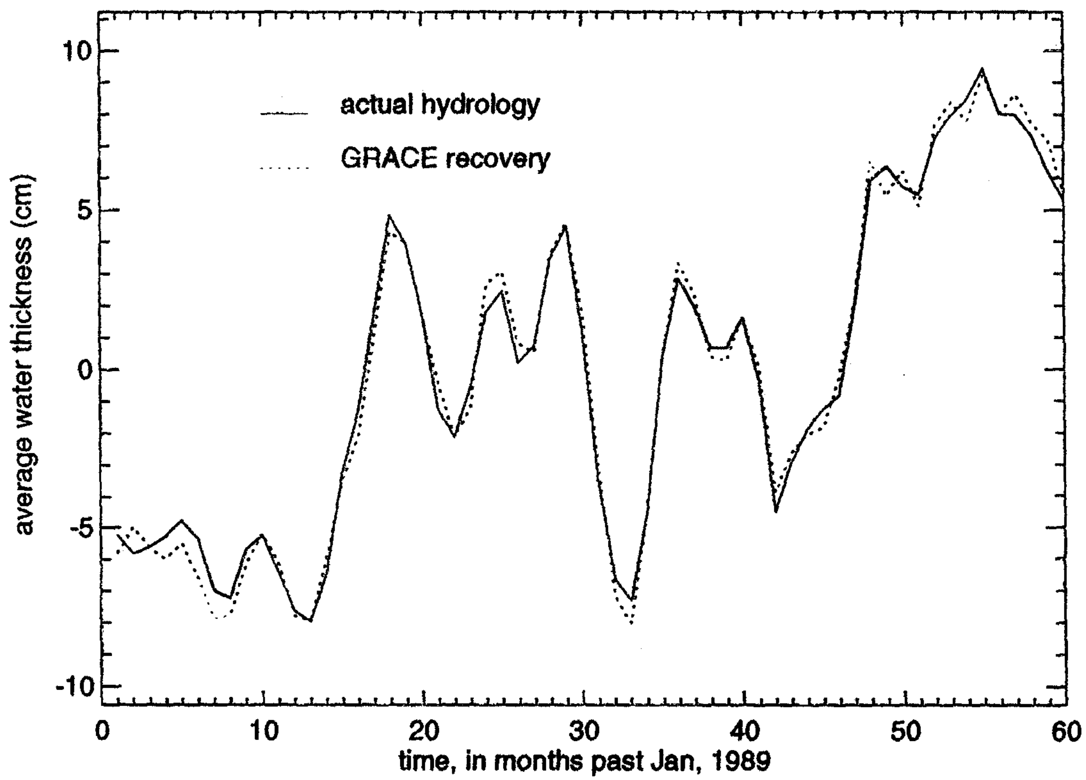
Top Panel: Groundwater in cm estimated from GRACE

Bottom Panel: : Groundwater in cm from hydrological model

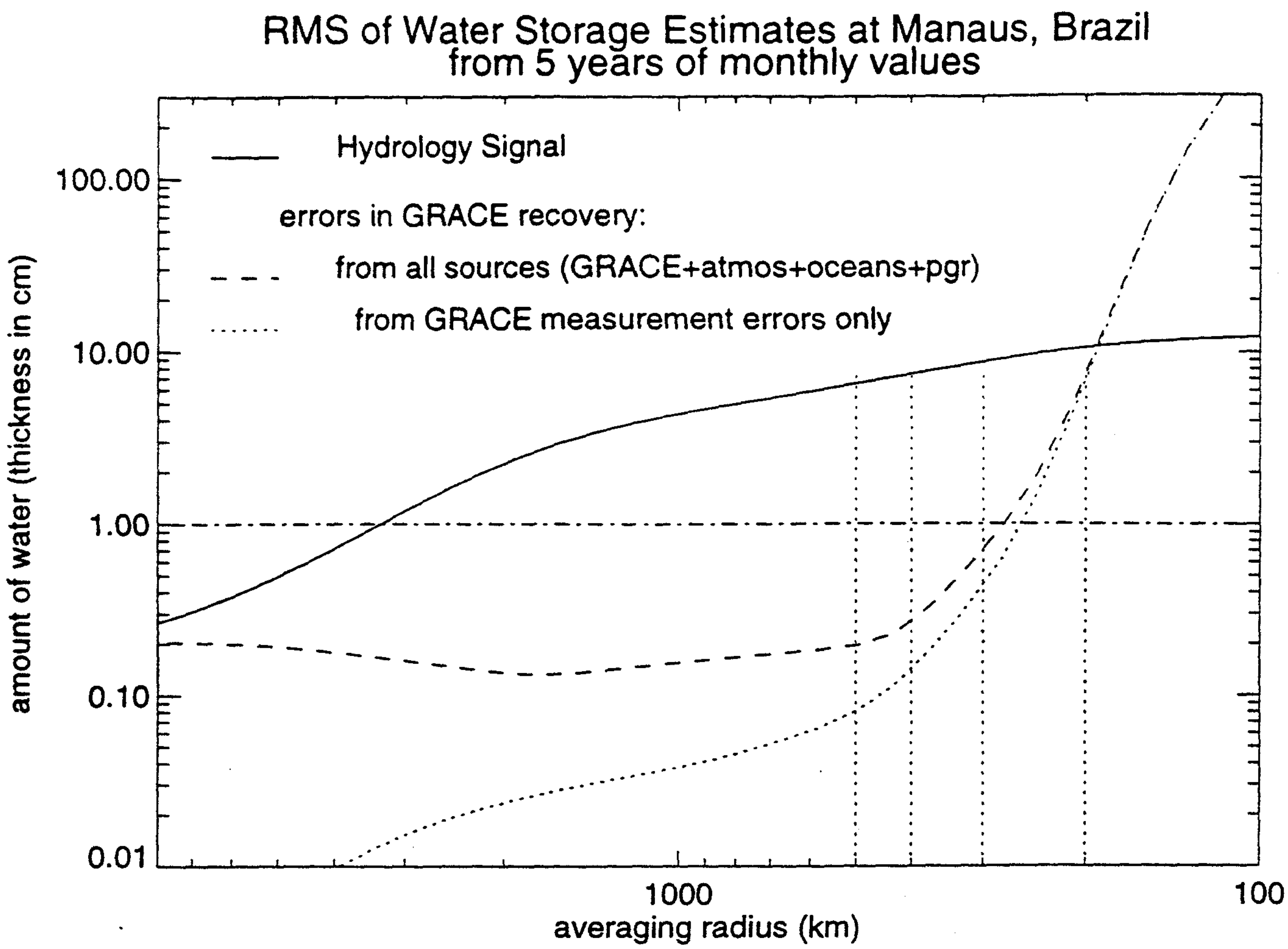
- The rms difference between the two solutions over North America is 13 mm.
- For The United States alone, the rms difference is 7 mm.



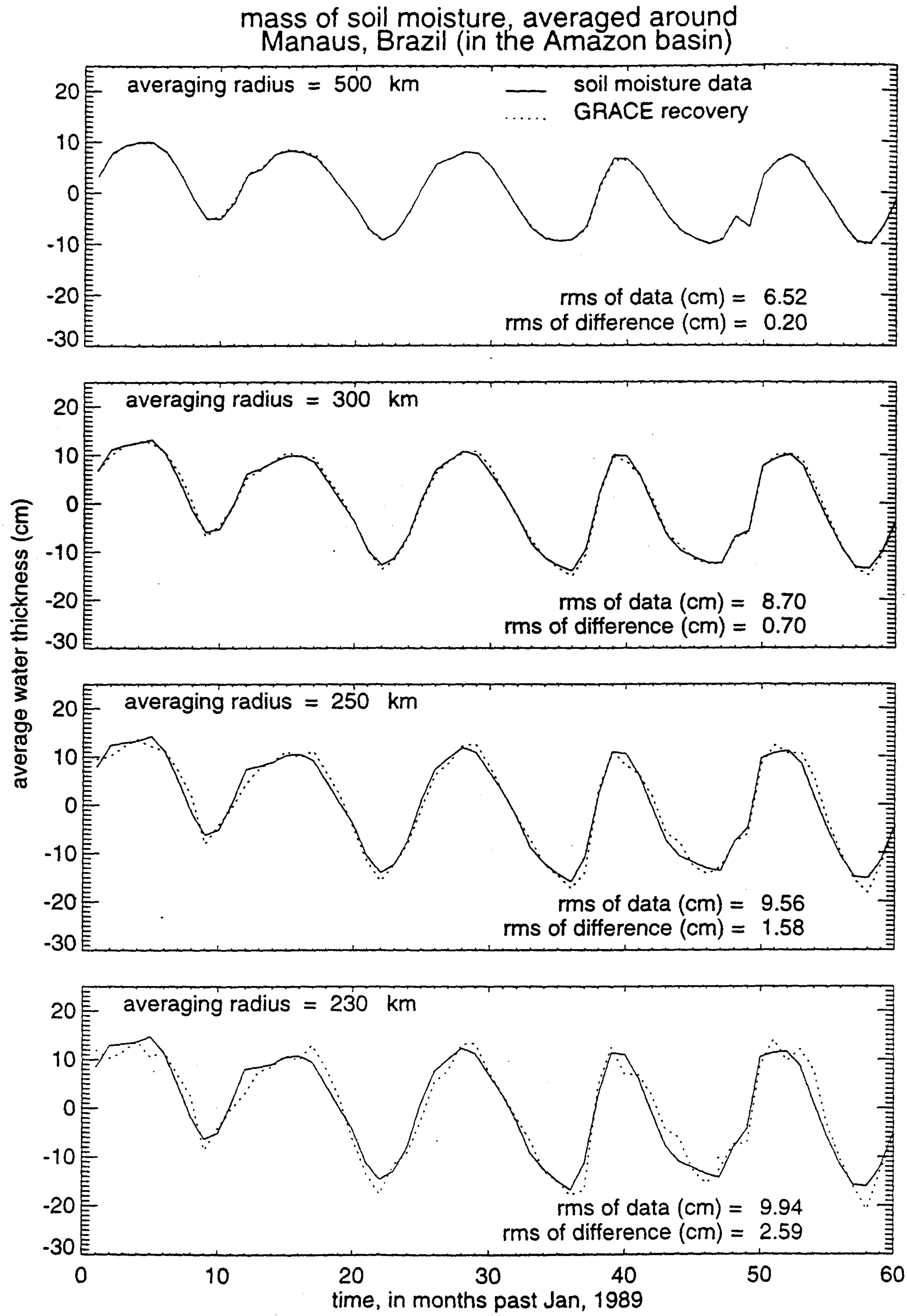
Monthly Groundwater Solutions from GRACE



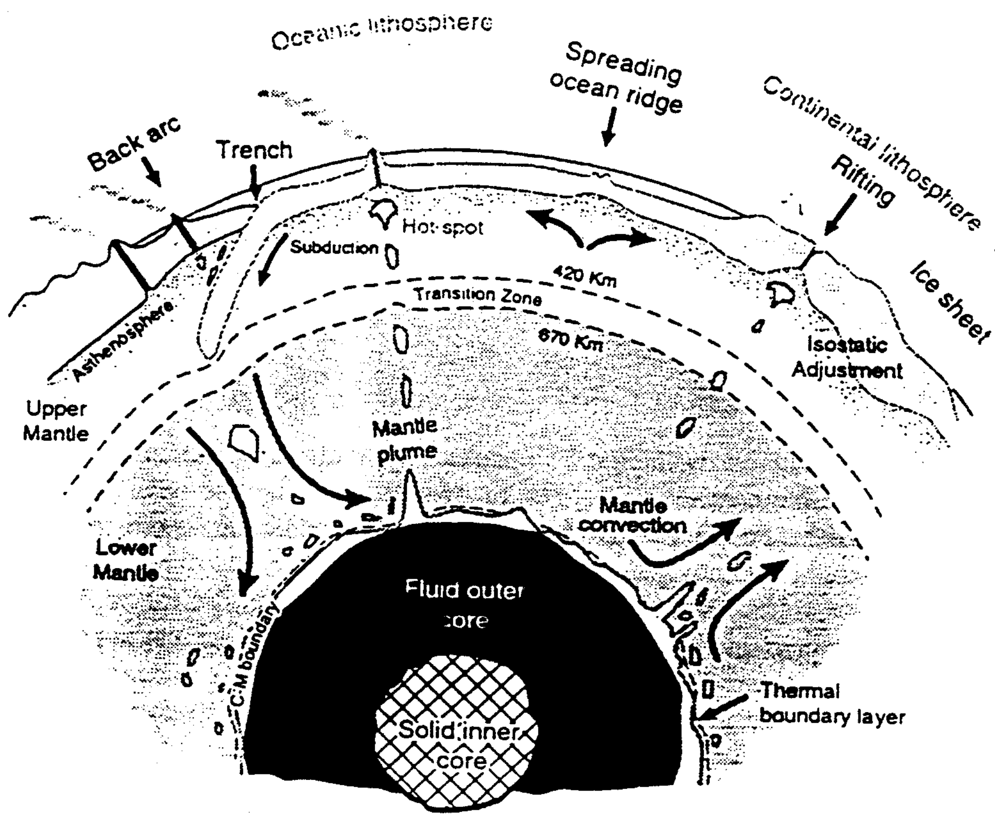
- Compared to the forward hydrological model for a ~300 km disc centered at Rock Island, Illinois
- The rms difference between the curves is 5 mm



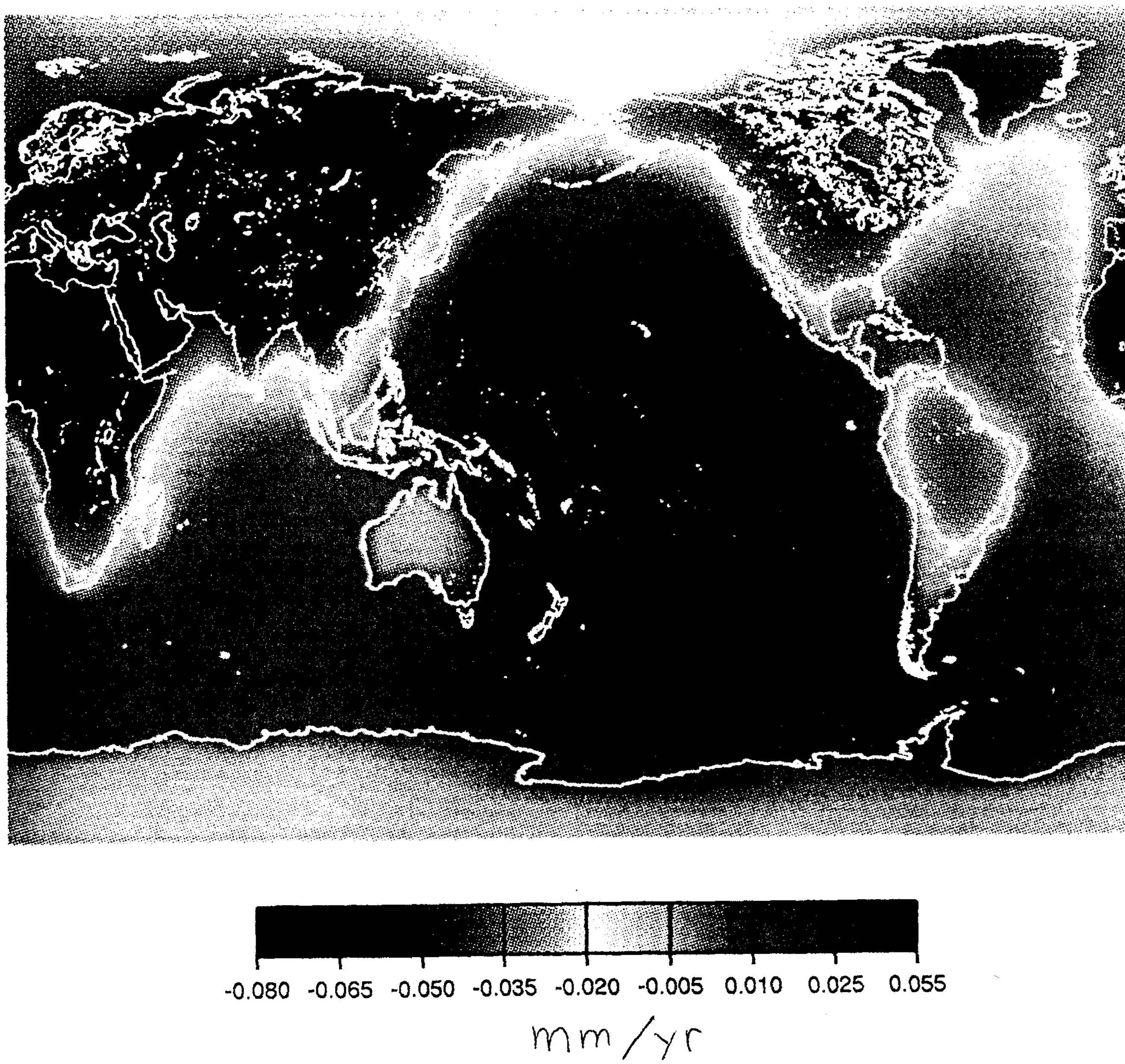
RMS of Water Storage Estimates at Manaus, Brazil
from 5 years of monthly values
Hydrology Signal
errors in GRACE recovery:
from all sources (GRACE+atmos+oceans+pgr)
from GRACE measurement errors only
amount of water (thickness in cm)
100.00
10.00
1.00
0.10
0.01
1000
100
averaging radius (km)


mass of soil moisture, averaged around
Manaus, Brazil (in the Amazon basin)
averaging radius = 500 km
soil moisture data
GRACE recovery
rms of data (cm) = 6.52
rms of difference (cm) = 0.20
averaging radius = 300 km
rms of data (cm) = 8.70
rms of difference (cm) = 0.70
averaging radius = 250 km
rms of data (cm) = 9.56
rms of difference (cm) = 1.58
averaging radius = 230 km
rms of data (cm) = 9.94
rms of difference (cm) = 2.59
average water thickness (cm)
time, in months past Jan, 1989
20
10
0
-10
-20
-30
0
10
20
30
40
50
60

Solid Earth Processes



Rate of change in geoid due to 1 mm/yr rise in global sea level



Assumes sea level rise is due to addition of water to the oceans.

(Geoid maximum) - (geoid minimum) = 0.14 mm/yr

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Sea Level Change

- Sources of global sea-level rise (1.0 to 2.5 mm/yr over last century) not well understood
  - Most of the likely mechanisms involve mass redistribution from the continents; gravity can provide unique insights through the continual monitoring of geoid changes both globally and regionally (such as mass balance of individual drainage system and regions characterized by large numbers of glaciers and ice caps
- The measurement and interpretation of changes in Greenland and Antarctica is complex issue; phenomena include:
  - Secular changes in ice-sheet mass
  - Post glacial rebound
  - Interannual variability of snowfall
  - Effect of atmospheric pressure trends
- Complimentary information important in separation of signals
  - Network of GPS receivers on land, numerical models of rebound with improved mantle viscosity (provided by the gravity mission), comparison with satellite altimetry
  - Improving calculations of mass input to ice-sheet surfaces from measurements of moisture-flux divergence around increasing perimeter of the ice sheets
  - Network of automatic weather stations in the continent interior

FUTURE: WHAT'S NEXT?

- GEODESY PROVIDES AN INFRASTRUCTURE THAT IS FUNDAMENTAL NOT ONLY FOR GEODESY BUT ALSO FOR SISTER DISCIPLINES (GIGGOS, RUMMEL)
  - REFERENCE FRAME
  - EARTH ROTATION
  - POSITIONING
  - GRAVITY
- GEODESY IS BECOMING MORE & MORE INTERDISCIPLINARY

GEODESY → POSITIONING → CRUSTAL DEFORMATION → TECTONICS

GEODESY → POSITIONING/ALTIMETRY → SEA LEVEL + SEA SURFACE HEIGHTS → OCEANOGRAPHY

GEODESY → GRAVITY → STATIC → SOLID EARTH

→ TIME VARYING GRAVITY → PGR, OCEANS, ICE GROUND

- EARTH ROTATION – FUNDAMENTAL INTEGRAL QUANTITY

  CONSTRAINTS

  SYNERGISTIC APPROACH