Interdisciplinary Space Geodesy: Links with the Earth Sciences

By

Jean O. Dickey
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109 USA
International Association of Geodesy Scientific Assembly
September 2-7, 2001
Budapest
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
Spatial and Time Scales of Geoid Variations

- Secular/Decadal
  - post-glacial rebound
  - polar ice
  - glaciers

- Interannual/Seasonal/Sub-seasonal
  - ocean mass flux
  - atmosphere
  - hydrology: surface and ground water, snow, ice

- Diurnal/Semidiurnal
  - solid earth and ocean tides
  - coastal tides

Wavelength (km)
Gravity Recovery and Climate Experiment
GRACE

Mission Objective

Produce a new model of the Earth's gravity field with unprecedented 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

November 10, 1997

John Wahr
Gravity Field: Current Status
GRACE: Expected Results

Geoid Signals and Accuracies expected from GRACE

- Mean Ocean (POCM)
- Kaula's Power Law
- EGM96
- Hydrology (Ann)
- Ocean (Ann)
- GRACE 90d, 450 km
- GRACE 90d, 300 km

Geoid Height (mm)

Half Wavelength (km)
GRACE
Predicted 5-year Geoid Signals & GRACE Errors

- Greenland
- Antarctica
- PGR, high viscosity LM
- PGR, medium viscosity LM
- 1.75 mm/yr sea level rise
- GRACE rate, 5 yr, 450 km

[Diagram showing geoid change vs. half wavelength (km)]
to increase meteorological measurements (i.e., data-poor regions). However, it would be more efficient in some cases to measure as a proxy data type in some locations.

Gravity data may serve as a proxy for ocean dynamics and hydrological constraints and improved understanding of water in soils and the ocean would benefit from reliable extended-range forecasting which would unravel the effects of the other sub-systems (such as the hydrological cycle) involved in gravity variations. Knowledge of atmospheric variation is vital to understanding the climate system.

The Dynamic Atmosphere
Infrared thermally variable deep ocean currents could be spacial scales of a few hundred km or longer and sea floor pressure variations over the world oceans at

A time-varying geoid would allow the determination of

and non-steric components of sea level variations for the separation of the time-dependent steric combinations of gravity and altimetry data will provide

an error source on these spatial scales from satellite altimetry, especially at basin scales absolute dynamic topography and surface circulation offer dramatic improvement in our knowledge of

Several mission scenarios (SCG, SST, SSI and SSE)

Ocean Dynamics and Heat Flux
Variations in soil moisture

In meteorology: these measurements reflect the

global water and energy balances
(tens of km and less) and longer scales for estimating processes at traditional hydrological length scales

In hydrology: the connection between hydrological

are important:

Gravity measurements of changes in water storage

Decline in aquifers

Valuable for monitoring secular water level

Scientific insight into hydrologic cycle

Irrigation

Likelihood of floods and the runoff available for agriculture, monitoring snow pack, assessing the

Great value in forecasting conditions for

at subcontinental length scales

be potentially measured with a high level of accuracy

Variations in groundwater and soil moisture levels can

Water and Energy Cycling
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).
Construct monthly, 1 month, synthetic geoids that include effects of:

How well can GRACE recover the hydrology signal?
GRACE errors: From Thomas & Watkins (JPL) and Benkendorf (U Texas)

over ocean.

Atmos Press Errors: Estimated as (P_{ECMWF} - P_{NCEP})/\sqrt{N} over land, set to 0 1994.

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

Water Storage: Uses global soil moisture estimates of Hahn et al. (1996)

---

GRACE errors, for 1 year of data

Atmospheric pressure errors (without Antarctica)

Oceans + Continental Water Storage *

Amplitudes of Annually-Varying Terms in the Geoid
For the United States alone, the rms difference is 7 mm.

America is 13 mm.

The rms difference between the two solutions over North

Hydrological model

Bottom Panel: Groundwater in cm from

GRACE

Top Panel: Groundwater in cm estimated from
The rms difference between the curves is 5 mm.

Rock Island, Illinois

Compared to the forward hydrological model for a ~300 Km disc centered at

Monthly Groundwater Solutions from GRACE
Solid Earth Processes
(Geoid maximum) \(-0.01\) mm/yr
(geoid minimum) \(0.14\) mm/yr

Assume sea level rise due to addition of water to the oceans.

\[
\text{Rate of change in geoid due to 1 mm/yr rise in global sea level}
\]
Network of automatic weather stations in the
continental interior
Sheets of debris accumulating around increasing perimeter of the ice
Sources of debris: differences in material composition, topography, and climate
Deposition of debris near the ice sheet

Improving calculations of mass input to ice sheet
Comparison with satellite altimetry

Viscosity (provided by the gravity mission)
Modeling of rebound with improved mantle
numerical models of rebound
Network of GPS receivers on land, numerical
signals

Complementary information important in separation of

Effect of atmospheric pressure trends
Internal and external stability of snowfall
Post-glacial rebound
Secular changes in ice-sheet mass

Phenomena include:

Greenland and Antarctica is complex issue.
The measurement and interpretation of changes in
large numbers of glaciers and ice caps
Drainage systems and regions characterized by
regional discharge rates (such as mass balance of individual
monitoring of glacial change at both global and
provide unique insights through the continental
redistribution of the continental; gravity can

Most of the likely mechanisms involve mass
(last century) not well understood
Sources of global sea-level rise (1.0 to 2.5 mm/yr over

Sea Level Change

JPL