



Fig. 1. Geophysical fluid processes that involve large-scale mass transports and produce variations in Earth's rotation, gravity field, and geocenter.

field in terms of the Stokes coefficients of its spherical harmonic expansion.

In particular, and more pertinent to the present discussion, the precise SLR technique has detected tiny temporal variations in the low-degree gravity field, and those more than a month long can now be clearly identified. The upcoming series of space gravity missions of CHAMP and GRACE employ satellite-to-satellite tracking techniques, and GOCE will carry a gravity gradiometer (which measures local gradient of gravity). These three missions will yield gravity information at much higher precision and geographical resolution. For example, GRACE promises to be able to resolve water-level-equivalent mass changes of only a centimeter over an area of a few hundred kilometers at a temporal resolution as short as 10 days [Wahr *et al.*, 1998].

On another front, satellite-based SLR, GPS, and DORIS data are beginning to reveal geocenter motion at the centimeter level. This motion manifests itself as a translation of the ground station networks with respect to the center of mass of the whole Earth system defined by satellite orbits. Mathematically, the three components of the geocenter translation vector correspond directly to the three Stokes coefficients of spherical harmonic degree 1 of the gravity field. Although in its infancy and still beset by many technical and modeling problems, geocenter motion measurements have prompted a number of recent geophysical investigations and will undoubtedly continue to do so [IERS, 1999a].

Geophysical Fluids

The magnitude of the geodynamic effects produced by a particular mass transport is approximately proportional to the ratios of (net transported mass)/(Earth mass) and (net transport-distance)/(Earth radius). Many

processes are below the detection threshold because of the relatively small mass or short distances involved. Examples include volcanic outgassing; volcanic eruptions where most material stays in the local area; landslides and rock/mud flows, however great; thermal expansion and/or freezing of ocean water, however extensive; floating icebergs; intercontinental trade of petroleum and other commercial goods; and building of cities and the Great Wall of China. Biomass variations may be of marginal importance.

However, there are many fundamental geophysical processes involving large-scale mass transports that do cause measurable geodynamic effects (Figure 1), but even they produce signals typically no larger than 1 part in ten billion [e.g., Chao, 1994]. The most prominent are perhaps weather effects, which are originally driven by solar radiative input and related over much of the globe to the Earth's rotational Coriolis force and modified by atmosphere-ocean and atmosphere-land interactions. The meteorological pressure systems seen on weather maps indicate that different masses of air move around the planet as part of the general circulation. Thus, the winds produced show a variation of these synoptic motions on short timescales, but they are strong as well on longer scales related to intraseasonal, seasonal, and interannual oscillations. Interannual anomalies associated with El Niño/La Niña are of particular interest in this regard, especially because they are part of the system that produces very strong zonal wind anomalies across the Pacific Ocean and elsewhere from the tropics to higher latitudes [e.g., IERS, 1999b]. Remarkably, the length of day showed a very clear strong signal during the recent 1997-1998 El Niño event and in earlier ones, also.

Mass transport also occurs in the oceans. There it is mainly caused by tidal forcing,

surface wind forcing, atmospheric pressure forcing, and thermohaline fluxes. Satellite altimetry can measure changes in the sea-surface height caused by these forcing mechanisms, and GRACE (and CHAMP to a certain extent) will soon be able to infer changes in the ocean-bottom pressure. Numerical models of the oceanic general circulation allow detailed investigation of the response of the oceans to these forcing mechanisms and allow quantities such as the angular momentum associated with oceanic mass transport to be modeled and compared with Earth rotation measurements. Recent studies have shown that nontidal oceanic mass transport can measurably change the length of the day [e.g., Marcus *et al.*, 1998] and can also cause the Earth to wobble as it rotates [e.g., Ponte *et al.*, 1998].

Large mass transports/redistributions occur as tides at all tidal periods. The tides involve mass transports and angular momentum exchanges within the Earth system at periods ranging from subdaily to 18.6 years. Earth tides, ocean tides, and atmospheric tides all contribute to geodynamic variations, and all are readily observable with modern techniques. The Earth's body tide is responsible for large length-of-day variations at monthly and fortnightly periods; the ocean tides are the dominant cause of diurnal and semidiurnal variations in both rotational rate and polar motion. The geodetic measurements are stimulating improvements to all fluid and solid tidal models.

Redistribution of water mass stored on the continents occurs on a variety of time scales. Seasonal and shorter time scales involve precipitation, evaporation, and runoff, with storage of water in lakes, streams, soil, and biomass. Over longer time scales, storage variations in ice sheets and glaciers signal climate changes, while ground water storage changes take place in deeper aquifers. Some of these hydrological processes are fundamentally regulated by vegetation, but all are ultimately exchanged with and hence reflected in atmospheric water content and sea level in an intricate budget. Water mass redistribution involving these various reservoirs and mechanisms has been shown to have observable effects on Earth rotation, geocenter, and gravity field changes. However, the variety of transport mechanisms and storage reservoirs makes the task of globally monitoring water storage on land extremely challenging. Indeed, this is considered to be a first-order problem for the climate community and is being pursued at every major climate research center.

Accounting for 68% of the total mass and 89% of the moment of inertia of the entire Earth, the solid, but non-rigid, mantle is perpetually in motion as well. Some motions are caused by external forces, including tidal deformation, atmospheric and oceanic loading, and occasional meteorite impacts. For internal processes, volcanic eruptions and pre-seismic, coseismic, and post-seismic dislocations associated with an earthquake act on short time scales. On longer time scales, present-day post-glacial rebound, surface processes of soil erosion and deposition, and tectonic activity such as plate motion, orogeny, and

internal mantle convection all transport large masses over long distances. Finally, the entire solid Earth undergoes an equilibrium adjustment in response to the secular slowing down of the Earth's spin due to tidal friction.

Deeper in the solid Earth, the fluid outer core is constantly turning and churning in association with the geodynamo's generation of the magnetic field. The variation of the core angular momentum can evidently be inferred from surface observations of the geomagnetic field or modeled by physical hypotheses and the equations of motion that drive and govern the geodynamo and hence the core flow. This core angular momentum has been compared to the observed variations of the length-of-day at decadal time scales, while torques at the core-mantle and inner core boundaries have been evaluated. The recent seismological finding of a differential rotation of the solid inner core is also under evaluation in this context.

In this sense, the entire Earth system consists of several geophysical fluid components. Various types of torques acting on the boundaries between the geophysical fluids exchange angular momentum among the fluids, thus exciting Earth rotational variations. These torques include (i) frictional torque, in the form of wind stress over land and ocean surfaces, ocean bottom drag, and viscous stress at the core-mantle and inner core boundaries; (ii) pressure torque acting across topography that exists between atmosphere-land, ocean-land, and core-mantle boundaries; (iii) gravitational torque acting on density anomalies at distance; and (iv) magnetic torque generated by the geodynamo that acts on the core-mantle and inner core boundaries.

In addition, subtler interactions exist among the geophysical fluid components that would modify the Earth's response. Notable examples include mantle elastic/inelastic yielding under surface loading, the ocean's inverted-barometer behavior (or the departure from it), and the extent of coupling at the core-mantle and inner core boundaries. They are, in general, functions of the time scale under which the effect in question applies.

GGFC Organization and Functions

Philosophically, the GGFC provides a link between two user communities. On the one hand is the geodetic measurement community, who wants to better understand their measurements, to further develop measurement requirements and strategies, and to be able to better predict and quantify the variabilities. On the other hand, the geophysical modelers

want to interpret the geodetic measurements in terms of various geophysical processes based on models and/or observations. They may want to better model the geophysical fluid processes by utilizing the independent information and constraints provided by the space geodetic measurements and infer Earth's properties by examining its dynamic responses and behavior.

Established in January 1, 1998, of the IERS's 10th anniversary, the GGFC is coordinated from NASA Goddard Space Flight Center's Laboratory for Terrestrial Physics. The GGFC is responsible for promoting related science and outreach activities, including collective publications, dedicated symposia and special sessions at professional meetings, and assistance in coordinating and supporting various international projects and observational campaigns. The actual functions of the GGFC reside in its seven Special Bureaus (SBs) that were also established in 1998. Each SB is responsible for activities related to a certain fluid component or aspect of the Earth system. The primary functions of the SBs are data and information acquisition, archiving, and dissemination; intercomparison and assessment of data products; recommending conventions and standards; and providing a forum for professional exchanges and discussions.

Building on three decades of development and advances, modern space geodesy has matured and become an effective tool for remote sensing of a variety of global geophysical processes. At the heart of it is the unique capability of remote sensing of global mass transports that constantly occur in all parts of geophysical fluids. The IERS's GGFC and its SBs are well situated to support and provide services to the research community in this new interdisciplinary field.

Individual SB Web sites have been developed as the major mechanism for data dissemination and communication. The GGFC coordinating center has a portal Web site at <http://bowie.gsfc.nasa.gov/ggfc/>. The SB Web sites are:

- Atmosphere: <http://www.aer.com/groups/diag/sb.html>
- Oceans: <http://euler.jpl.nasa.gov/sbo/>
- Hydrology: <http://www.csr.utexas.edu/research/ggfc/>
- Tides: <http://bowie.gsfc.nasa.gov/ggfc/tides/index.html>
- Mantle: <http://bowie.gsfc.nasa.gov/ggfc/mantle.html>
- Core: <http://www.astro.oma.be/SBC/main.html>
- Gravity/Geocenter: (under construction)

Two mirror Web sites have also been established to enable easier access from different parts of the world: <http://ggfc.u-strasbg.fr> at Strasbourg, France (courtesy of P.Gegout), and <http://www.miz.nao.ac.jp> at Mizusawa, Japan (courtesy of Y.Tamura).

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References

- Chao, B. F., The Geoid and Earth Rotation, in *Geophysical Interpretations of Geoid*, edited by P. Vanicek and N. Christou, CRC Press, Boca Raton, Fla., 1994.
- Dehant, V., C. R. Wilson, D. A. Salstein, B. F. Chao, R. S. Gross, Ch. LeProvost, and R. M. Ponte, Study of Earth's rotation and geophysical fluids progresses, *Eos, Trans. AGU*, 78, 357–360, 1997.
- IERS, *IERS analysis campaign to investigate motions of the geocenter*, IERS Tech. Note #25, edited by J. Ray, 1999a.
- IERS, *The impact of El Niño and other low-frequency signals on Earth rotation and global Earth system parameters*, IERS Tech. Note #26, edited by D. A. Salstein, B. Kolaczek, and D. Gambis, 1999b.
- Marcus, S. L., Y. Chao, J. O. Dickey, and P. Gegout, Detection and modeling of nontidal oceanic effects on Earth's rotation rate, *Science*, 281, 1656–1659, 1998.
- Ponte, R. M., D. Stammer, and J. Marshall, Oceanic signals in observed motions of the Earth's pole of rotation, *Nature*, 391, 476–479, 1998.
- Salstein, D. A., D. M. Kann, A. J. Miller, and R. D. Rosen, The sub-bureau for Atmospheric Angular Momentum of the International Earth Rotation Service: A meteorological data center with geodetic applications, *Bull. Am. Meteorol. Soc.*, 74, 67–80, 1993.
- Wahr, J., M. Molenaar, and F. Bryan, Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, 103, 30,205–30,230, 1998.

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