The Global Geophysical Fluids Center (GGFC) of the International Earth Rotation and Reference Systems Service

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Abstract: The International Earth Rotation Service established a Global Geophysical Fluids Center (GGFC) in 1998, as one if its product centers. The purpose is to better support, facilitate, and provide services to the worldwide research community, in areas related to the variations in Earth rotation, gravity field and geocenter that are caused by mass transport in the geophysical fluids including the atmosphere, ocean, solid Earth, and core, and geophysical processes associated with tides, mass loading, and hydrological cycles. These services are administered through GGFC's Special Bureaus (SB). Today there are eight SBs worldwide; they are SB Atmosphere, SB Oceans, SB Tides, SB Hydrology, SB Mantle, SB Core, SB Gravity/Geocenter, and SB Loading. They maintain individual data archive and services.

1 Overview

Established in 1998 by the International Earth Rotation Service (IERS, an organization sponsored jointly by the International Union of Geodesy & Geophysics and the International Astronomical Union), the GGFC is headed by Ben Chao, and located at the Laboratory for Terrestrial Physics of NASA's Goddard Space Flight Center. Under GGFC, eight Special Bureaus (SB) were selected worldwide, each to be responsible for facilitating research activities relating to a specific Earth component or aspect of the geophysical fluids of the Earth system (Chao et al., 2000). They are SB Atmosphere, SB Oceans, SB Tides, SB Hydrology, SB Mantle, SB Core, SB Gravity/Geocenter, and SB Loading.

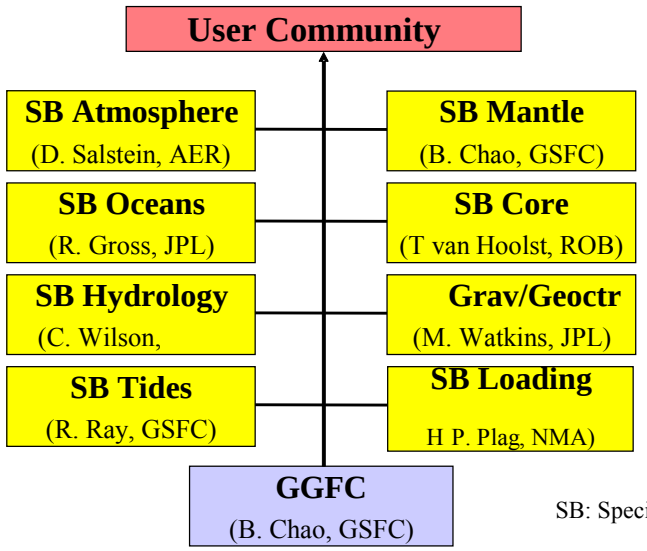
The GGFC/SBs have the responsibility of supporting, facilitating, and providing services to the scientific research community, in areas related to the variations in Earth rotation, gravity field, geocenter, and surface deformations that are caused by mass transport in the atmosphere-hydrosphere-solid Earth-core system, or the global geophysical fluids. Under GGFC/SBs, the "value-added" data of the time variation of angular momenta and the related torques, gravitational coefficients, geocenter shift, and global mass loading will be computed for all geophysical fluids based on global observational data, and/or products from state-of-the-art models some of which assimilate such data. The computed quantities, algorithm and data formats are standardized (an IERS Technical Note for GGFC is in preparation), and results are documented, archived and made available to the public on dedicated individual SB websites via Internet. In addition, GGFC has been actively conducting scientific symposia, special sessions, and business meetings at international conferences.

The GGFC is fundamentally interdisciplinary in terms of NASA's Earth Science mission strategy and goals. The data products involved include:

- Geodetic measurements of temporal variations of Earth's rotation vector, gravity field in Stokes coefficients, geocenter, and surface deformations;
- Global geophysical fluids data directly related to the above, including pressure fields of atmosphere and oceans, wind and current fields, tides, and temperature/salinity profiles derived from atmospheric and oceanic general circulation models (GCM);
- Observed and/or modeled data sets for land water and snow/ice mass distribution, mass flow fields in the fluid core, and solid-Earth surface deformations due to tides, seismicity, tectonics, post-glacial rebound, environmental mass loading, and anthropogenic effects;
- Ancillary data products from satellite missions (some are assimilated into the GCMs in (2)), including ocean altimetry, (future) laser altimetry, ocean scatterometer, and geomagnetic field.

GGFC and the SBs are strictly scientific services supported by the individual hosting institutions or organizations, for which IERS assumes no financial responsibilities. GGFC's functions widely support and conform to the goals defined in the newly-released comprehensive report of NASA Solid Earth Science Working Group (SESWG) in a substantial way. Its work is tightly linked to the success of new space missions including GRACE, JASON, ICESat and planned future missions relying on precise geodesy. Its measure of success is dictated by the ever-stringent requirements on the precision and accuracy of observations and the definition of the fundamental terrestrial reference frame, as well as the ultimate impacts in geophysical interpretation of the observations.

IERS Global Geophysical Fluids Center (GGFC)

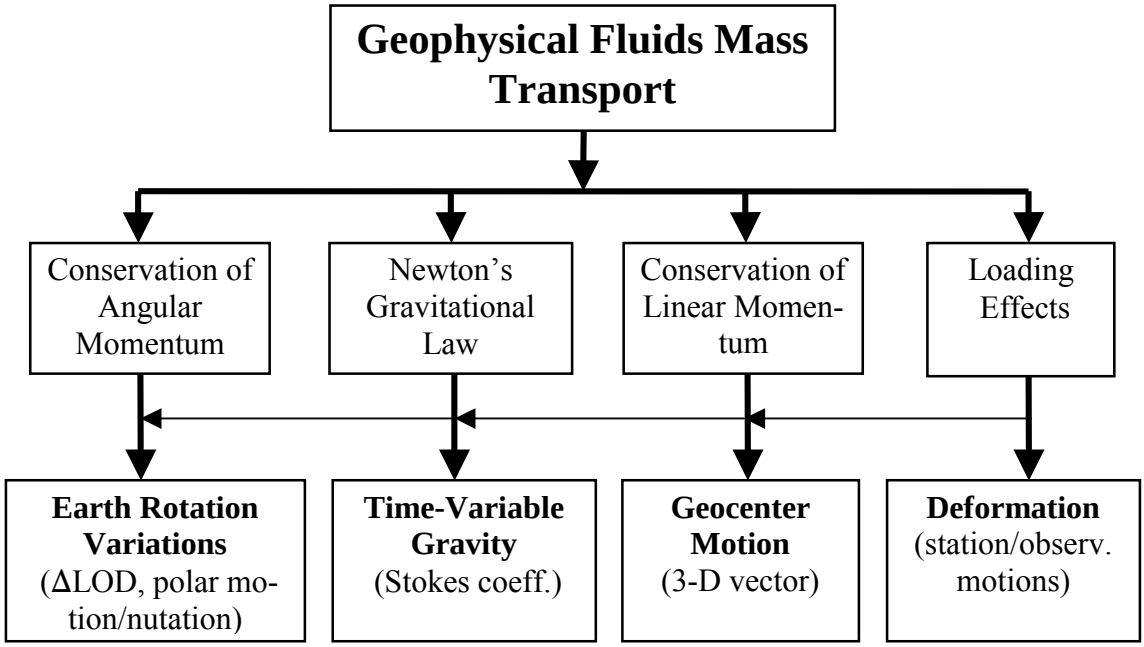


SB: Special Bureau

2 Mass Transports and Their Geodynamic Effects

Mass transport is a fundamental process in the climatic, environmental, and geophysical variability, which is becoming observable by various space geodetic techniques, acting as remote-sensing tools, with ever increasing precision/accuracy and temporal/spatial resolution. Mass transports will cause the following geodynamic effects in the geophysical fluids on a broad time scale: (1) variations in the solid Earth's rotation (in length-of-day/universal time and polar motion/nutation) via the conservation of angular momentum and effected by torques at the fluid-solid Earth interfaces; (2) changes in the gravity field according to Newton's gravitational law; (3) motion in the center of mass of the solid Earth relative to that of the whole Earth ("geocenter") via the conservation of linear momentum; and (4) mass loading effects normally manifested in surface deformations and movements. Any geophysical process involving fluid mass transport will have its own geodynamic effects depending on its spatial distribution and temporal behaviour modified by loading effects. The sum of all the individual signals, with their spatial and temporal characteristics, is what's observed.

Geodynamic Effects of Mass Transport in Geophysical Fluids



The magnitude of the geodynamic effects produced by a particular mass transport is approximately proportional to the ratios (net transported mass)/(Earth mass) and (net transport-distance)/(Earth radius). Many fundamental geophysical processes do involve large-scale mass transports that cause measurable geodynamic effects – even then they still only produce signals typically no larger than 1 part in 10^{10}. The most prominent are perhaps weather effects, driven originally by solar radiation 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 appearing on weather maps indicate that different masses of air move around the planet as part of the general circulation. The wind thus

produced shows a variation on short timescales of these synoptic motions, but they are strong as well on longer scales related to intra-seasonal, seasonal, and interannual oscillations. Interannual anomalies associated with El Nino/ La Nina 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. Remarkably, the length of day showed a very clear strong signal during the recent 1997–98 El Nino event and in earlier ones as well.

Mass transport also occurs in the oceans where 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 the GRACE mission will soon be able to measure changes in the ocean-bottom pressure. Numerical models of the oceanic general circulation enable detail investigations 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 modelled and compared with Earth rotation measurements. Recent studies have shown that non-tidal oceanic mass transport can measurably change the length of the day, and can also cause the Earth to wobble as it rotates.

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 timescales. Seasonal and shorter time scales involve precipitation, evaporation, and runoff, with storage of water in lakes, streams, artificial reservoirs, soil, and biomass. Over longer timescales, storage variations in ice sheets and glaciers signal climate change, 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 diversity of transport mechanisms and storage reservoirs makes the task of monitoring land water storage globally an extremely challenging task. Indeed, this is considered to be a first order problem for the climate community, and is being pursued at every major climate research center.

The solid, non-rigid Earth is perpetually in motion as well. There are motions caused by external forces, including tidal deformation, atmospheric and hydrospheric 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 timescales. On longer timescales, 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 timescales, while torques at the core-mantle and inner core boundaries have been estimated. The recent seismological finding of a differential rotation of the solid inner core is also under evaluation in this context.

Subtler but significant interactions exist among the geophysical fluid components which would modify the Earth's response to mass transports. Most notable are the elastic and anelastic mass loading effects as a result of the solid Earth's non-rigidity. The loading effects occur at every solid-fluid interface – atmospheric loading, oceanic and tidal loading, hydrological loading, and even pressure loading at the core-mantle boundary, and also at the atmosphere-ocean interface manifesting as the so-called dynamic inverted-barometer effect.

Another dynamic effect to consider is the extent of coupling at the core-mantle and inner core boundaries, which determines, for example, how "willing" the core is in participating in Earth rotation excitations exerted from the surface, or how much angular momentum the core can exchange with outside. In this regard, various types of torques acting on the boundaries between the geophysical fluids exchange angular momentum among the fluids. 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 across boundaries; (iv) electromagnetic torque generated by the geodynamo that acts on the core-mantle and inner core boundaries. These effects are in general functions of the timescale under which the torque in question applies.

3 Geodetic Measurements

These minute geodynamic signals have been observed by various space geodetic techniques with ever increasing precision/accuracy and temporal/spatial resolution. In this sense, space geodetic technologies have become an effective remote sensing tool for monitoring global mass transports.

The Earth's rotation can be represented by a 3-D vector whose components consist of the rotational speed which determines the length-of-day, and the orientation of the rotational axis (variations of which are called nutations relative to inertial space, or polar motion relative to an Earth-fixed frame). It is a superposition of a very complex suite of phenomena. For over three decades, space geodetic measurement precision has improved at the rate of one order of magnitude per decade (something of a "Moore's law"). Satellite laser ranging (SLR) and very-long-baseline interferometry (VLBI) have been the workhorse in measuring Earth's rotation. Recent years have seen an increasing application of the Global Positioning System (GPS) data especially for higher temporal resolution, and radio tracking data from the DORIS (Doppler Orbitography and Radio positioning Integrated by Satellite) system. Sub-milliarcsecond (mas) precisions (1 mas corresponding to 3 cm if projected to the Earth's surface) are now routinely achieved in daily Earth orientation measurements, and a new VLBI project called CORE is being implemented in phases, which promises even higher precision, high-temporal resolution and continuous measurements.

Measuring Earth's global gravity field and its temporal variation requires special consideration. An external observer can sense gravity only if he is not "in orbit", i.e., not in free-fall, as is an orbiting satellite – a satellite cannot directly "feel" the gravity (that's why a space-borne gravimeter is useless). However, a (near-Earth) satellite's detailed orbital trajectory does reflect the gravity field through which it traverses. Decades of precise orbit tracking data of many geodetic satellites have led to generations of increasingly refined models for the Earth's static gravity field in terms of the Stokes coefficients of its spherical harmonic expansion. The precise SLR technique has detected minute temporal variations in the low-degree gravity field. Variations longer than monthly can now be clearly identified. The space gravity missions of CHAMP and GRACE now in orbit employing satellite-to-satellite tracking techniques, and GOCE that will carry a gravity gradiometer (which measures local gradient of gravity), 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 30 days.

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 3 degree-1 Stokes coefficients 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.

For more details and updated information, see:

Chao, B. F., V. Dehant, R. S. Gross, R. D. Ray, D. A. Salstein, M. M. Watkins, and C. R. Wilson, Space geodesy monitors mass transports in global geophysical fluids, *EOS, Trans. Amer. Geophys. Union, 81,* 247–250, 2000,

or, URL <http://bowie.gsfc.nasa.gov/ggfc/>.