Mass Transport in Global Geophysical Fluids: Space Geodetic Monitoring

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Abstract

Mass transports in the atmosphere -hydrosphere - solid Earth - core system (the "global geophysical fluids") occur on all temporal and spatial scales. They produce variations in Earth's rotation, gravity field, and geocenter. Although relatively small, these global geodynamic effects have been measured by space geodetic techniques to increasing accuracy for geophysical and environmental investigations. In a sense, such techniques have become unique tools for remotely sensing large-scale mass transports not amenable to observation otherwise. New space geodetic missions and projects promise further advances in data quality in terms of accuracy, spatial resolution, and temporal resolution, opening up important new avenues of research for better understanding of global mass transport processes and the Earth's dynamic responses to these processes.

The Physical Effects

Mass transports occurring in the atmosphere - hydrosphere - solid Earth - core system (the "global geophysical fluids") are important geophysical phenomena. They occur on all temporal and spatial scales. Large-scale mass transports in the Earth system produce variations in Earth's rotation, gravity field, and geocenter (see Figure 1). Although relatively small, these global geodynamic effects have been measured by space geodetic techniques to increasing, unprecedented accuracy, opening up important new avenues of research for better understanding of global mass transport processes and the Earth's dynamic responses to these processes.

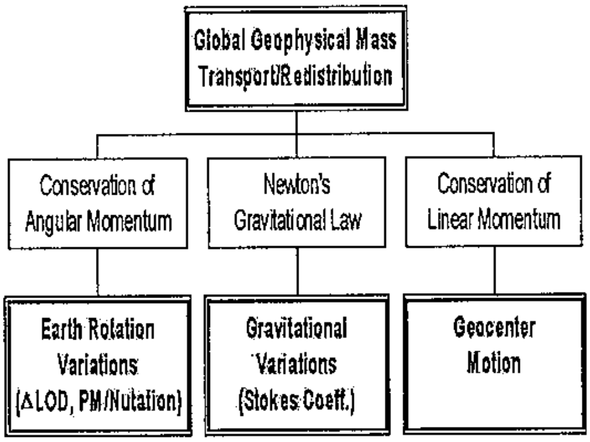

Figure 1: Global geodynamic effects caused by mass transports in the Earth system (or "geophysical fluids"), and the physical principles behind the process.

To illustrate these effects, consider a simple "solid Earth + atmosphere" system where an air mass moves across the surface of an otherwise uniformly rotating solid Earth. Regardless of its driving mechanism, this air mass transport will have certain geodynamic consequences. Via surface torques, the relative motion of the air mass imparts changes in the solid Earth's rotation, just as a circus seal does by balancing itself on a rolling ball. Furthermore, the associated redistribution of mass changes the Earth's inertia tensor and hence its rotation. A familiar analogy is a spinning ice skater changing his rotation by moving his arms -- he'd spin faster when drawing his arms closer to his body and vice versa, and he'd "wobble" if he does so in an asymmetric way. The above two effects (whose sum is what's observed) are consequences of the conservation of angular momentum, which here dictates that the total angular momentum of the Earth + atmosphere system stays constant.

A second geodynamic effect is the change in the gravity field produced by the moving air mass. In general, Newton's gravitational law states that a body produces its own gravity field around it according to the distribution of mass within the body. Therefore, a temporal change in the mass distribution will in general cause the gravity field to change with time.

Finally, the system is subject to the conservation of linear momentum, which dictates that it is the center of mass of the total Earth + atmosphere system that should always obey celestial mechanics in its translational motion around the solar system, no matter how the air mass moves relative to the solid Earth. Relative to this combined center of mass (about which satellites orbit), the solid Earth's center of mass (with which observing ground stations move) would then undergo apparent (but very slight) motion. This is referred to as the geocenter motion. A physical analogy would be two masses connected by a spring and thrown into a trajectory.

Our real Earth is of course a lot more complex, and exciting, than the above Earth + atmosphere system. See Figure 2. Any geophysical process involving fluid mass transport will have its own geodynamic effects (Figure1) depending on its spatial and temporal characteristics. The signal observed by space geodetic techniques is the sum of all the individual signals.

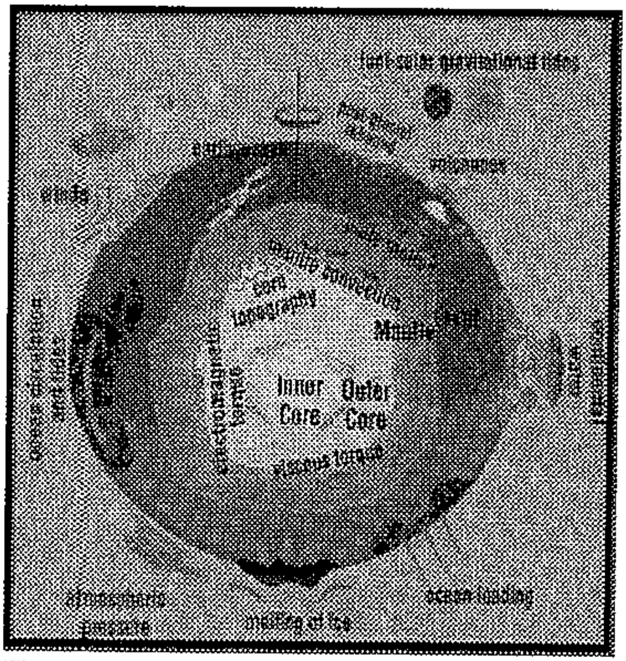

Figure 2: Cartoon showing the important geophysical processes that produce large-scale mass transports in the geophysical fluids.

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 processes are below the detection threshold because of the relatively small mass and/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 (seasonal or otherwise) may be of marginal importance.

However, there are many fundamental geophysical processes involving large-scale mass transports that do cause measurable geodynamic effects (Figure 2) -- although even they produce signals typically no larger than 1 part in 10^{10} [e.g., *Chao, 1994*]. The most prominent are perhaps weather effects, driven originally by 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 showing 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 intraseasonal, 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 too (Figure 3; see also *IERS*, 1999a).

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 (see below) will soon be able to measure changes in the ocean-bottom pressure. Numerical models of the oceanic general circulation allow the response of the oceans to these forcing mechanisms to be investigated in detail, 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.

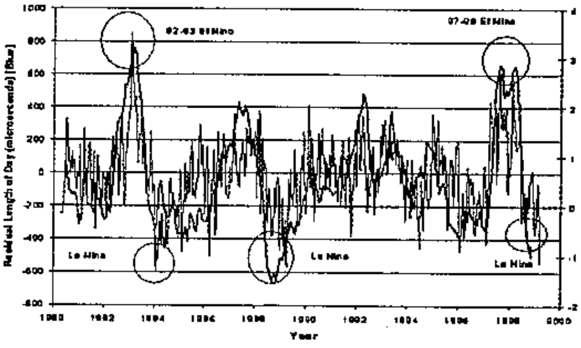

Figure 3: Interannual length-of-day variations (in milliseconds in excess of 24 hours, the lighter curve) are mostly caused by ENSO and hence closely follow the Southern Oscillation Index (the darker curve), especially during El Nino and La Nina periods (circles). (Courtesy of T. Clark and D. MacMillan).

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, 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 variety of transport mechanisms and storage reservoirs makes the task of globally monitoring water storage on land 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, but non-rigid, Earth is perpetually in motion as well. There are motions 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 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 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; (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 which 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 timescale under which the effect in question applies.

Space Geodetic Measurements

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 if relative to inertial space, or polar motion if relative to an Earth-fixed frame). 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 use of the Global Positioning System (GPS) data especially for higher temporal resolution, and radio tracking data from the DORIS system (Doppler Orbitography and Radio positioning Integrated by Satellite). Sub-milliarcsecond precisions (corresponding to sub-centimeter precision 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 continuous, hourly measurements with even higher precision.

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 average gravity field in terms of the Stokes coefficients of its spherical harmonic expansion. The GPS tracking of the 8 mini-satellites of the COSMIC/ROCSAT-3 (to be launched in 2003, see *Kuo et al.*, 1999) is expected to contribute significantly to further improvements in the gravity model, especially in long wavelengths. In particular, and more pertinent to the present discussion, the precise SLR technique has detected tiny temporal variations in the low-degree gravity field. Variations longer than monthly can now be clearly identified. The upcoming series of space gravity missions of CHAMP and GRACE 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 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 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 (*IERS*, 1999b).

Epilogue

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. In 1998, the International Earth Rotation Service (IERS), the organization that monitors the rotational motions of the Earth and related properties, created the Global Geophysical Fluids Center (GGFC, see *Chao et al.*, 2000, and website at <http://bowie.gsfc.nasa.gov/ggfc/>). GGFC is to serve as a link between the space geodesy community with the "global Change" research community, taking full advantage of all the advances mentioned above in meteorological, oceanographic, hydrological, and geophysical modeling and data acquisition, and those in the space geodetic techniques and measurements. One looks to many more exciting years to come in this line of research.

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