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Study of Earth's Rotation and Geophysical Fluids Progresses

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Variations in the Earth's speed of rotation and the position and orientation of the rotation axis—known collectively as Earth orientation parameters—are observed by a variety of space geodetic techniques coordinated by the International Earth Rotation Service (IERS). Observations of Earth orientation parameters provide fundamental information about the physical properties of the Earth's interior and the variability of fluids in the atmosphere, oceans, and liquid core, and on land.

Participants at a workshop held October 14–18, 1996, at the Paris Observatory, where IERS is headquartered, called for extending IERS activities [*Reigber and Feissel*, 1997] to include the monitoring of geodetically important properties of the oceans, the liquid core, and terrestrial water to supplement current atmospheric angular momentum variation (AAM) measurements. Given the success of the IERS, expansion of its activities into other areas is not only natural for understanding the observed Earth orientation parameters, but essential for fulfilling its mission of improving the underlying space geodetic observations.

Atmospheric Angular Momentum Variation

By the early 1980s, advances in meteorological analysis and modeling made it possible to compute total atmospheric angular momentum variations every few hours or less. Comparisons of angular momentum variations with corresponding length of day time series from newly developed space geodetic techniques clearly showed that, via the conservation of the angular momentum, the atmosphere caused most changes in length of day at periods of less than a few years (as shown in Figure 1). By 1989, the IERS established a Sub-Bureau for Atmospheric Angular Momentum (SBAAM) as an auxiliary activity [*Salstein et al.*, 1993].

The SBAAM obtains the three-vector components of atmospheric angular momentum variation every six hours from the U.S. National Centers for Environmental Prediction and other centers in Europe and Japan. The widespread availability of these estimates has enabled a wealth of scientific investigations concerning the causes of variations in Earth orientation parameters and improved forecasts of these parameters, which benefits the tracking and navigation of interplanetary spacecraft and other researchers who need to know the Earth's orientation in space.

The SBAAM is strictly concerned with determining atmospheric quantities, especially those related to changes in length of day and polar motion. However, SBAAM calculations also include an estimated oceanic contribution due to inertia changes in the ocean that are forced by atmospheric pressure loading. These are based on the assumption of an isostatic ocean response to barometric pressure changes, the "inverted barometer" assumption, which is generally thought to hold at timescales exceeding several days.

SBAAM calculations also provide estimates of important atmospheric effects on nutations, which might seem surprising given their classical description as a response to external (solar, lunar, and planetary) torques. However, because of the Earth's prograde di-

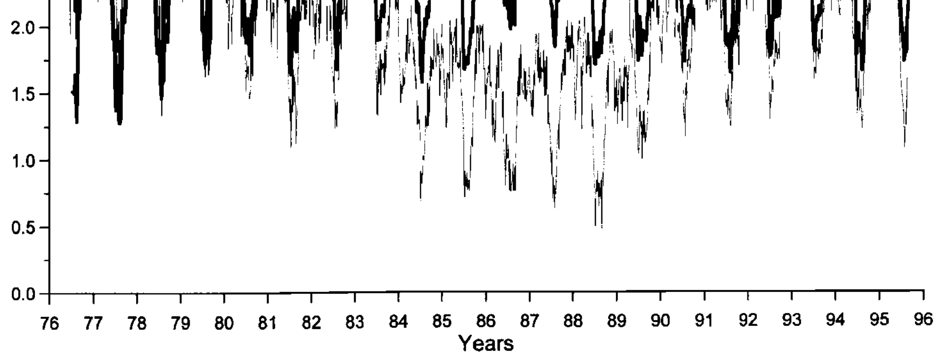

Fig. 1. Variations of length-of-day changes as deduced from atmospheric angular momentum fluctuations. Length-of-day changes deduced from space geodetic techniques are shown for the same time period. Their strong coherence on timescales shorter than several years is confirmation that length-of-day changes at near-weekly to interannual periods arise from the exchange of angular momentum between the Earth and the atmosphere. However, discrepancies on a variety of timescales are likely the effect of the other geophysical fluids.

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urnal rotation, the nutations (which are long-period as observed in inertial space) occur at nearly retrograde diurnal frequencies as observed in an Earth-fixed frame. Thus any Earth process with nearly retrograde diurnal frequencies, as observed on the Earth, such as nearly diurnal changes in atmospheric wind and pressure, can affect the nutations. The equatorial components of subdaily atmospheric angular momentum variations (or the corresponding atmospheric torques) must therefore be monitored to support the analysis of nutation observations, as well as polar motion studies.

The SBAAM takes advantage of a number of atmospheric "reanalysis" projects at various meteorological centers which employ a fixed numerical scheme and incorporate data that may have been omitted from original operational results. Operational angular momentum time series suffer from frequent algorithm and model changes, and angular momentum calculations from these reanalyses generally show improved agreement with Earth orientation time series.

Beyond the Atmosphere: Other Geophysical Fluids

The IERS workshop developed a plan, later ratified by the directing board, that the IERS should expand its coordination efforts to include monitoring angular momentum of various geophysical fluids, in addition to the atmosphere. This recommendation was motivated by dramatic improvements in data quality in recent years, which reveal previously undetectable variations in Earth orientation parameters that are most likely forced by geophysical fluids. The following sections discuss the areas that the IERS proposes for study.

Nontidal Ocean Angular Momentum

After the atmosphere, the oceans are likely to have the next largest effect on the length of day, and, as a cause of polar motion, the oceans are probably as important as the atmosphere. Studies with oceanic general circulation models (GCM) show that both currents and mass redistribution make important contributions to polar motion and length of day, and that the oceanic contribution is much more complicated than can be predicted using the inverted barometer approximation as practiced now [e.g., *Wilson*, 1995].

Properly accounting for oceanic effects on Earth orientation parameters requires numerical integration of gridded fields from oceanic GCM analysis systems. This must be done in a manner that is analogous to the calculations from atmospheric GCMs by the SBAAM. Given that ocean GCM's are not yet fully developed, the organization of a subbureau for OAM might seem premature, but early action should provide a useful service to both the oceanographic and the Earth orientation communities.

Ocean Tidal Angular Momentum

The periodic angular momentum variations associated with ocean tidal currents and mass redistribution contribute to variations in Earth orientation parameters at tidal periods. Diurnal, semidiurnal, and other tidal terms have been observed in universal time and polar motion for a number of years. The principal source must be the ocean tides, with roughly comparable effects from both currents (relative motion) and tidal heights (inertia). With the advent of essentially continuous observations of Earth orientation parameters via a global array of GPS receivers, and plans under way for similar continuous observations through globally coordinated very long baseline interferometry programs, observations of tidal variations in Earth orientation parameters will continue to improve. At the same time, the quality of ocean tide models is increasing rapidly. Recent tide models that employ hydrodynamic calculations, coupled with Topex/Poseidon altimeter data constraints, agree with tide gauge observations within 2-3 cm in the deep oceans, representing roughly a 5 cm rms improvement over the now-classical Schwiderski results from the early 1980s. Continued refinement of tide models, particularly in shallow water, is expected using data from present and future altimetry missions. Given the rapid progress in both observations of Earth orientation parameters and ocean tide models, the IERS is likely to eventually adopt a standard ocean tidal model that gives predictions of Earth orientation parameters over a range of periods. Predictions of variations in tidal Earth orientation parameters serve as diagnostic measures of tide model performance and pave the way for further study of nontidal causes of Earth orientation parameters variations, especially those at nearly diurnal and semidiurnal frequencies.

Hydrological Angular Momentum

The few published estimates of the geodetic consequences of variations in hydrological angular momentum (HAM) associated with continental storage of water, ice, and snow suggest that there should be associated and observable polar motion, geocenter, and geodetic station coordinate changes. Again, the use of an operational hydrologic data-assimilating model to calculate variability in HAM and expected Earth orientation parameter changes would be ideal, but fully developed models are not available at present. A more complete approach, via a full climate system model with atmosphere, ocean, and land elements that are hydrologically coupled should eventually provide predictions of the effects of river runoff, snow and ice cover, vegetation mass, and groundwater storage in addition to water mass load variations for the oceans.

Fluid Core Angular Momentum

At decade timescales, length of day and geomagnetic field variations appear to be correlated, probably reflecting fluid core angular momentum transfer to the mantle. The main mechanism for this transfer may be topographic coupling, but gravitational, viscous, and electromagnetic coupling are also possible. In any case, fluid core variability is an active area of investigation within the geophysical community, as indicated by recently published numerical simulations of the geodynamo and the seismological discovery of a super-rotating inner core. Studies such as these have natural links to the observational programs of the IERS.

Other Activities Related to Geophysical Fluids

The quality of IERS results depends on the precision of the underlying space geodetic measuring systems, and it is essential to monitor and predict the influences that global geophysical fluids have on the measuring systems. These influences arise through gravitational variations, geocenter variation, and mass loading/unloading associated with the redistributed mass of the fluids. For example, using gridded GCM fields of surface pressure or ocean density, it is easy to predict the slight time variations in the gravity field (the Stokes coefficients) based on Newton's gravitational law, and thereby improve the force model for satellites such as LAGEOS, which are the basis for the laser ranging technique. Similarly, one can compute the shift in the center of mass of the solid Earth (or geocenter), which is central to the terrestrial reference system.

The studies are also desirable from the viewpoint of geophysical research, because gravitational and geocenter variations tell a story complementary to Earth rotation variations and can now be observed by laser ranging and other techniques. Further details are given by *Chao* [1994].

For more information on the modeling and monitoring of the various geophysical fluids discussed above, visit the ftp site at hpiers.obspm.fr, the web page at http://hpiers.obspm.fr/iers/ierscb.html, or send e-mail to iers@obspm.fr.

This report is based on the International Earth Rotation Service Workshop on Future Directions of the IERS, held at the Paris Observatory, October 14–18, 1996.

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New Radar Technology May Improve Flash Flood Forecasting

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Between rain and hail lies the story.

Recognizing the difference between the two forms of precipitation could provide more accurate—and possibly earlier—warnings of flash floods, such as those that have plagued parts of the U.S. West this summer.

The NEXRAD, or WSR-88D, Doppler National Weather Service (NWS) radars, which measure only the horizontal polarity of the precipitation, cannot distinguish between the two. But an experimental type of radar with dual-polarimetry technology can tell the rain from the hail. While this polarimetric technology is no magic pill for protecting people and property from flash floods, it could make a big difference, according to some weather experts. Scientists currently are conducting field tests of the devices, and hope to convince federal funding agencies that the technology offers social and economic benefits significant enough to justify retrofitting NWS radars within a few years.

"The difference between saying eight and four inches of rain will fall in a couple of hours is the difference between some people getting wet and street flooding and a major catastrophe," says Richard Carbone, lead scientist with the U.S. Weather Research Program, which receives support from the National Oceanic and Atmospheric Administration and other agencies. Carbone says that forecasting quantitative precipitation, which includes flash floods, is a high priority for his program.

Flash flooding is the second biggest cause of deaths from non-temperature related meteorological hazards in the U.S., according to NWS. From 1989 to 1995, the mean death toll was 64 per year, while the toll from lightning was 65. However, Frank Richards, head of NWS' hydrologic information center, says that about half of the flash flood deaths could be attributed to people ignoring warnings, rather than limitations in the forecasting system.

Richards cautions that while the polarimetric radar may provide more accurate information, funding it could remove resources from other important weather programs.

Whether polarimetric radars, or any technical fix, could have saved lives and property involved in an Amtrak train derailment and the inundation of the Havasupai Indian Reservation in Arizona in early August is uncertain. Nor is it clear that the device could have forecast the flash flood that drowned 11 hikers beneath a fast-moving 11-foot wall of water in a narrow canyon in northern Arizona on August 12; reports indicate that at least some of the hikers may have ignored warnings.

However, a flash flood that caused extensive damage to Fort Collins, Colorado in late July could provide some head-to-head evidence about how the polarimetric device stands up against a WSR-88D.

Steve Rutledge, a professor of atmospheric science at Colorado State University in Fort Collins, says that while the impact of the flood on the community was enormous, one of the half-dozen polarimetric radars in the U.S. happened to be trained on the storm and analyzed it. "Ordinary people affected by the flood don't really care much about polarimetric upgrades. But scientifically, this is an opportunity to demonstrate a radar capability that doesn't come along very often," he says.

According to Rutledge, one rain gage measured 10 inches of rainfall in five hours, while the polarimetric radar that he oversees picked up a close reading of between 8 ½ - 9 inches of rain in some areas. Rutledge says he will compare these results with a WSR-88D Weather Service radar in Denver, when the data is available in about six weeks.

Other U.S. agencies field-testing polarimetric radars include the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. NCAR scientists aimed the center's radar on a July 12 rainstorm that swamped Buffalo Creek southwest of Denver and caused two deaths. The device differentiated between that rainstorm and nearby hail, which Denver's Doppler radar could not do. The National Severe Storms Laboratory (NSSL)in Norman, Oklahoma, a leader in developing the radar, currently is retrofitting a WSR-88D donated by NWS, its bureaucratic cousin.

Early weather radars became popular after World War II, and following the landfall of several major hurricanes along the east coast during the 1950s, Congress funded a network of long-range WSR-57 weather surveillance radars. The development of minicomputers in the 1970s made it practical to analyze digital information from Doppler radars. A network of about 120 WSR-88Ds was installed across the country beginning in the early 1990s, with the last one set up earlier this summer.

WSR-88Ds are horizontally polarized and measure precipitation based on its size and on the reflectivity of radar beams that are bounced back to the device. However, when the reflectivity rate passes a certain threshold, the radar becomes "confused." The radar reads the higher amount as hail and truncates the amount of precipitation it classifies as rain. Though hail sometimes causes the higher reflectivity, in other instances soaking rain is the culprit. This distinction matters. Hail contains less water than does rain, and does not present a flash flood hazard. WSR-88Ds sometimes can underestimate by 75% the amount of rainfall actually falling, according to NSSL meteorologist Harold Brooks.

Carbone says that because the polarimetric technology measures both horizontal and vertical polarization and can tell the difference between rain and hail, it offers several benefits. "Warning time may be greater, the data will be much more certain, the errors will be smaller, and the estimation of rainfall will be more accurate," he says. "There will be fewer false alarms, and it will catch some [flood] cases that would have been missed entirely."

Jim Wilson, a senior scientist at NCAR, says the polarimetric device "is almost like having two radars in one because of the return power from the horizontally and vertically polarized waves."

In addition to the polarimetric radar, some agencies also are exploring other techniques to improve flash flood forecasts and communicate potential hazards. They range from hydrology studies to improved satellite systems, to working with psychologists on how to best communicate weather information to the public.—*Randy Showstack*