Times Standard

Not My Fault: The Sea is Not Level

Lori Dengler for the Times-Standard
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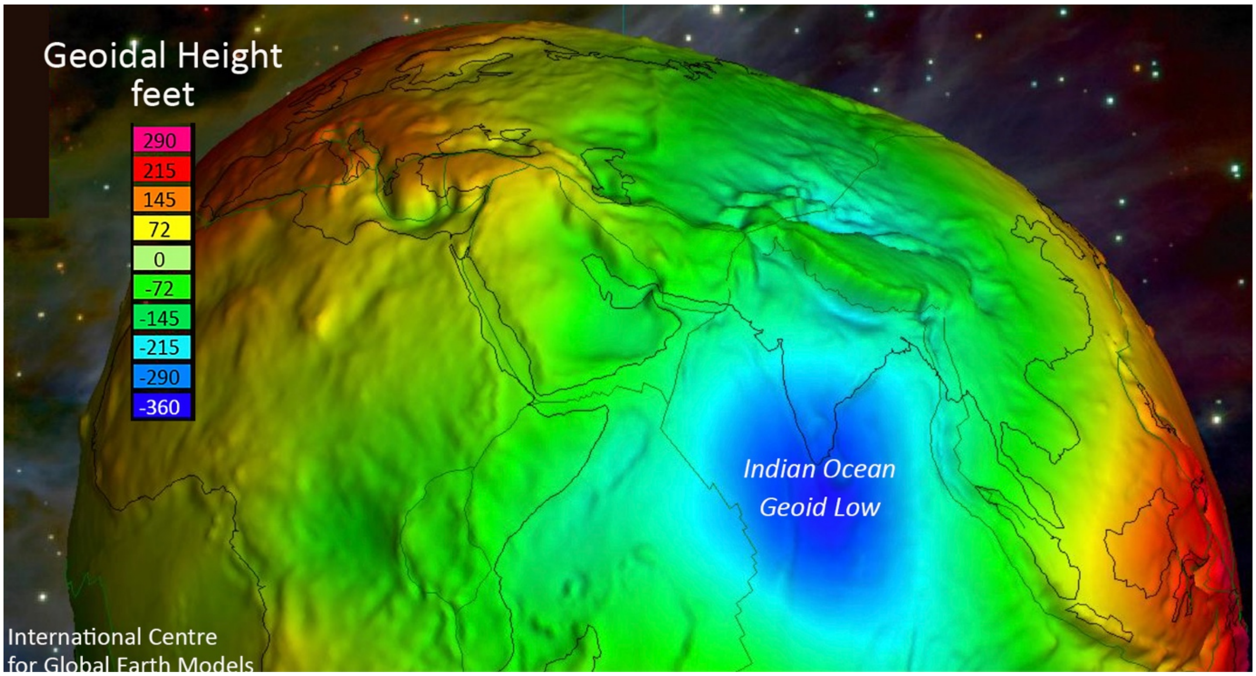

Gravity variations over the earth's surface as reflected by the geoid, the surface corresponding to mean sea level. The highs and lows relative to this surface are greatly exaggerated. Warm tones represent areas where this surface is higher than the average, greens close to average, and blues below average. The largest anomaly on the planet is in the Indian ocean where the geoidal height is nearly 360 feet below the reference surface. Map adapted from the International Centre for Global Earth Models https://icgem.gfz.de/vis3d/longtime.

The ocean surface is definitely not flat. It is constantly changing as wind waves and swells produce surface undulations, daily tidal fluctuations raise and lower the average height. It changes slowly over time with the amount of water locked up on land in glaciers and ice caps. Plate motion continuously changes the size and shape of ocean basins and the distribution of continental land masses. One factor affecting ocean heights might be unfamiliar, the distribution of mass in the deep earth far below the ocean causes undulations in its surface.

I've been wanting to write a column about these undulations ever since a paper was published in 2023 by two scientists from the Indian Institute of Science in Bangalor who teamed up with the GFZ German Research Centre to understand the largest gravity anomaly on the planet, but earthquakes and tsunamis kept leaping into the news and distracting me. 2026 has gotten off to a much quieter start with no earthquakes to reach magnitude 7 and only two earthquake fatalities (caused by a M5.6 earthquake in Pakistan). Valentines Day seemed like the perfect time to focus on cool science and no deaths or destruction.

To understand the work of Pal and Ghosh, I need to backtrack into the world of gravity measurements and the shape of the earth. One of the first phrases I learned in introductory French was “la terre est ronde et c’est vrai” (the earth is round and that is true). But it isn’t. To a good first approximation, the earth is an oblate spheroid, wider at the equator than at the poles. It’s not enough to easily see on photos taken from space, but the equatorial radius is about 13 miles longer than the polar radius.

The difference is caused by several billion years of centrifugal force that has flattened the earth just a wee bit. Rotation has pushed the equatorial regions outwards, just like the forces you experience on a spinning Fun House ride. Those lucky enough to get to the center can perch on the axis all day, but at the edge you will be quickly thrown off. That centripetal acceleration has two results – flattening the planet so you are further away from the earth’s center and exerting a force in the opposite direction of gravity. A 200-pound person will weigh nearly two pounds less on the equator than at the poles. The equatorial bulge is only earth’s most noticeable deviation from a perfect sphere. There are many more lumps and bumps in our planet’s shape. Geodesy is the discipline that focuses on the earth’s shape and gravity distribution and as an undergrad in geophysics at Berkeley, I was required to take a course in it.

Geodesy is a very old field of study, arguably going back thousands of years to Babylonia and Egypt. Over 2200 years ago, the Greek polymath Eratosthenes developed a clever way to measure the earth’s circumference using trigonometry, an estimate that is less than 5% of modern values. Many Europeans did spend a few centuries stuck in flat earth mode, but Islamic scholars continued to make measurements and refine the spherical shape of the earth in the 9th through 12th centuries.

By the 18th century, geodesy was fully back in vogue. Lectures at geographic societies were popular entertainment and debates about earth’s shape were featured at many geographic societies. Isaac Newton and Jacques Cassini engaged in a very public argument over whether the earth bulged at the equator or was more elongated along the polar axis. No surprise that Newton, who’s arguments were based on physics, was shown to be correct when an expedition to Peru definitively measured a greater equatorial radius than sites near to the poles.

Further advances in instrumentation propelled geodesy in the late 19th and early 20th centuries. Gravimeters, instruments that directly measure the acceleration of gravity, could detect even small changes due to regional geology, and tide gauges could provide precise measurement of average sea level. Gravity mapping proved to be valuable in mineral exploration, helping to pinpoint the location of economically valuable ore bodies, but it was the water-level measurements that contributed the most to a better understanding of global shape, what we now call the geoid.

To visualize what the geoid is, imagine a uniform spherical earth completely covered with water. In the absence of rotation, wind, or tidal forces, that surface will also be a perfect sphere because the gravitational force is the same everywhere. Fluids like water have no ability to resist lateral forces so that water surface will always be perpendicular to the direction of gravity.

The real earth is not uniform and it’s not just the equatorial bulge. The surface is differentiated into continents and oceans, and plate tectonics continuously shifts these about causing small variations in gravity values. The ocean surface will undulate in response to these lateral variation. If there were no frictional resistance in water, we could move over it, even as it varies in height, without ever having to work against gravity. It's what we call an equipotential surface.

Our planet is not covered with oceans, but mathematically, we can extend the equipotential surface corresponding to the mean ocean heights onto land. That's the geoid, an imaginary surface corresponding to mean sea level that does a very god job of describing the large-scale shape of the earth and was first theorized in the 1870s. The first geoidal map, determined by mathematically removing the equatorial bulge, was published in 1957, showing how high the imagined ocean surface was above of below a smooth reference shape.

The advent of satellites made it much easier to map the geoid because their orbits must conform to gravity variations in the planet below them. Our modern geoid has changed much since the late 20th century when satellite orbits crisscrossed every part of earth's surface. The result is lumpy indeed, if you exaggerate the elevation differences. The greatest deviation above the reference sphere is in Iceland where the geoidal height is nearly 280 feet higher. The low is in the Indian Ocean where the largest anomaly on the planet reaches a whopping 351 feet.

The Indian Ocean low was first recognized by Dutch geophysicist Vening Meinesz in 1948. His pioneering work in measuring gravity at sea would eventually become one of the underpinnings of modern plate tectonic theory. The gravity low is a monstrous feature, covering over a million square miles, depressing the sea level surface. Geoidal lows mean the gravitational force is weaker, so the equipotential surface dips down, closer to the earth's center.

Many of the variations in the geoid are relatively easily explained. Iceland where the largest high occurs, is caused by the excess mass being dumped in the area by the hotspot. There is a smaller but similar geoidal high over the Hawaiian-Emperor seamount chain. But the hole in the Indian Ocean has remained a 70-year puzzle.

Pal and Ghosh in their 2023 paper used computer modeling of the possible crustal and upper mantle density changes as the Indian subcontinent slowly moved north. About 100 million years ago, India began to move away from the Australia, South America, Antarctica, and Africa supercontinent (Gondwanaland). That process profoundly changed the ancient seabed it traversed. The movement triggered slow convection in the mantle, with lower density mantle plume material infilling the wake left by the passage of India.

Everyone agrees there is a mass deficit in the Indian Ocean but not everyone has jumped on the low-density plume bandwagon. The work has offered the first solid hypothesis as to what caused it and now needs further research to support it. That's what's fun about science. Check out https://geodesy.science/2020/a-brief-history-of-geodesy/ for a short video introduction to geodesy.

Lori Dengler is an emeritus professor of geology at Cal Poly Humboldt, and an expert in tsunami and earthquake hazards. The opinions expressed are hers and not the Times--Standard's. All Not My Fault columns are archived online at https://kamome.humboldt.edu/taxonomy/term/5 and may be reused for educational purposes. Leave a message at (707) 826-6019 or email Kamome@humboldt.edu for questions and comments about this column or to request copies of the preparedness magazine "Living on Shaky Ground."