

Geomagnetic storms could get worse than we thought

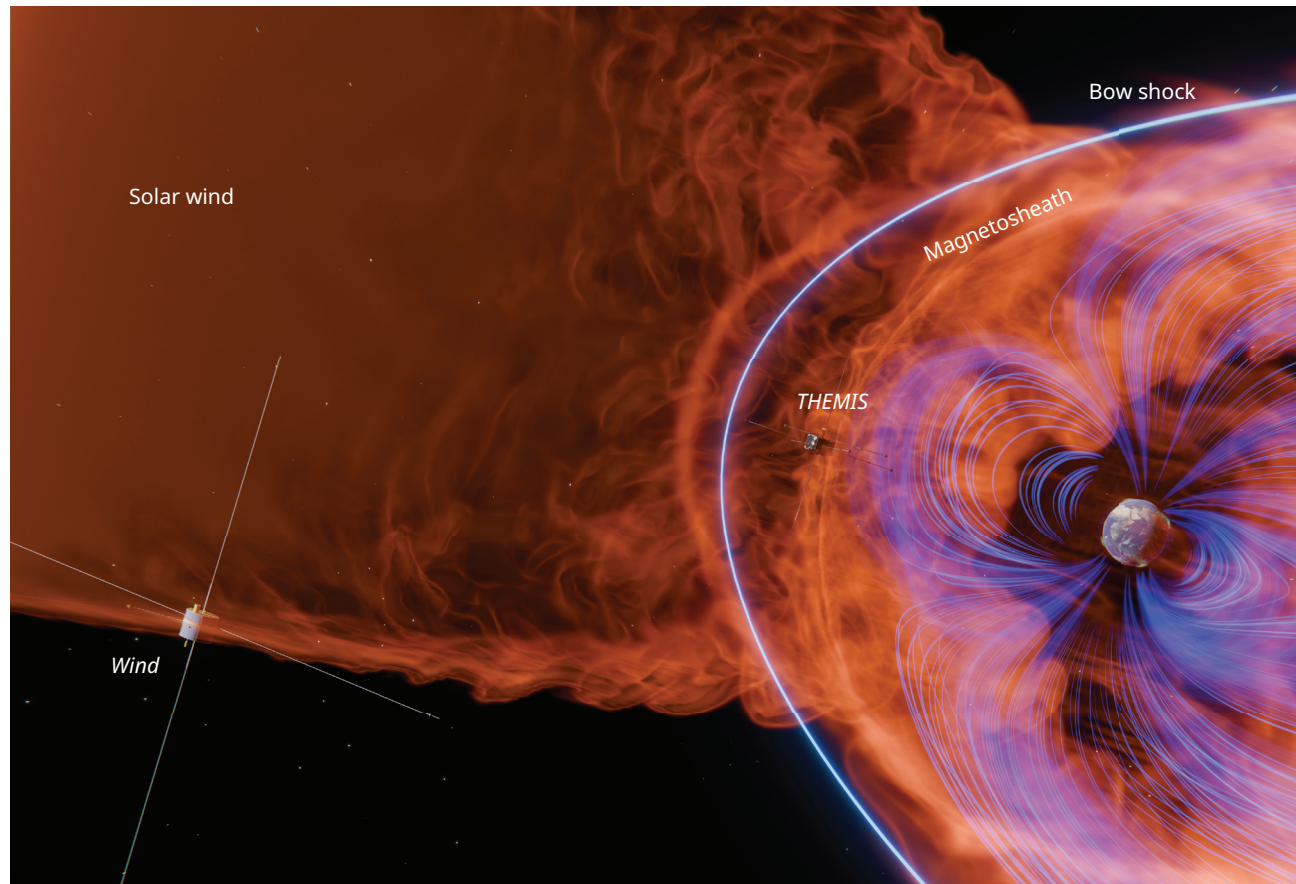
What had appeared to be an upper limit to the strength of the events is an artifact of measurement uncertainty and statistical bias. Those lessons could be relevant for data analyses in other disciplines.

By **Laura Fattaruso**

Unusually bright auroras were seen across the globe in late August and early September 1859—the light displays extended all the way to the tropics. Telegraph wires across Europe and North America failed and, in some cases, caught fire. The events were caused by the largest recorded geomagnetic storm, triggered by a coronal mass ejection colliding with Earth's magnetic field. Such a storm today could cause power grid failure, disruptions to GPS and global communication, and increased radiation exposure. The National Research Council has estimated that the damage could exceed a trillion dollars and take a decade to repair.

Though we've known that an 1859-scale event could happen again, some comfort could be found in evidence that suggested that the amount of energy that solar wind could transfer to Earth's ionosphere has an upper limit, which corresponds to a limit on the intensity of geomagnetic storms. When the strength of solar wind is relatively low, Earth's geomagnetic

▼ **Figure 1.** Solar wind intensity is measured by the *Wind* spacecraft roughly 1.5 million km upstream from where solar wind hits Earth's magnetosphere. Measurements collected closer to Earth by spacecraft such as *THEMIS* (Time History of Events and Macroscale Interactions during Substorms) were used in a recent study to evaluate the uncertainty of the solar wind intensity measurements from *Wind*. (Figure courtesy of Nithin Sivadas, NASA's Goddard Space Flight Center.)



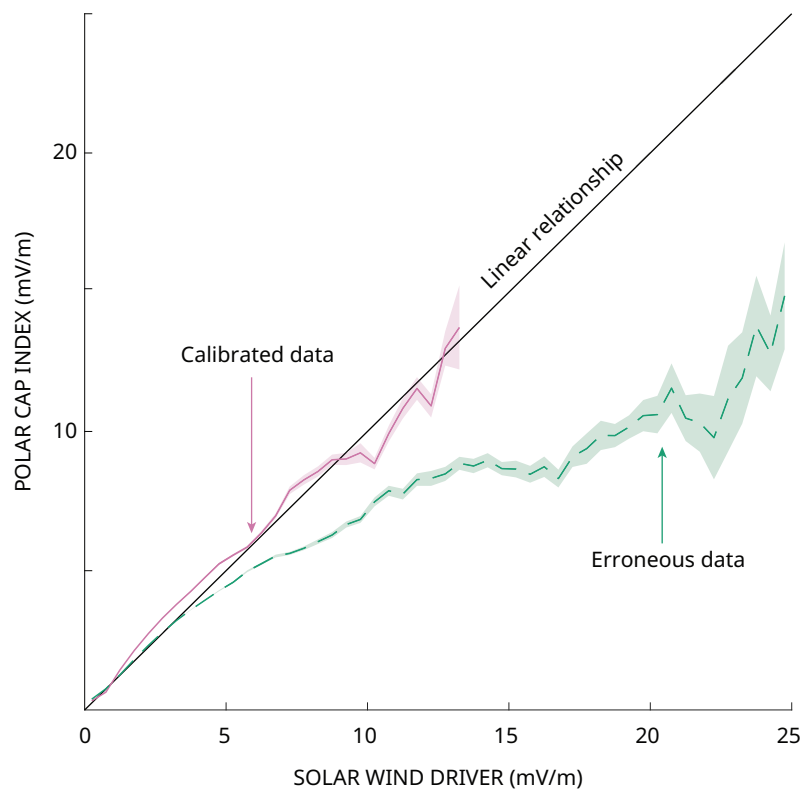


Figure 2. An analysis of uncertainty in solar wind data reveals that an apparent upper limit to the polar cap index, a measure of geomagnetic activity, was a statistical illusion. Calibrated data show that solar wind and geomagnetic activity have a linear relationship and that, under extreme conditions, geomagnetic storms could be roughly twice as intense as previously thought. (Figure adapted from ref. 1.)

response is linear. It seemed, though, that at higher solar wind intensities, the geomagnetic response would reach a saturation limit, and the resulting geomagnetic storm would be weaker than predicted by a linear relationship. Researchers have put forth nearly a dozen ideas for physical mechanisms that could explain the saturation effect, but they've not reached a consensus.

Now research by Nithin Sivadas of NASA's Goddard Space Flight Center and colleagues shows that uncertainty in the measurements of solar wind has created the illusion of an upper limit.¹ The errors stem largely from the position of the solar wind intensity measurements, which, as shown in figure 1, are collected by NASA's *Wind* spacecraft about 230 Earth radii upstream from where the solar wind interacts with the ionosphere.

Unknown bias

The illusion of the saturation effect, the researchers found, was caused by regression to the mean—a phenomenon in which measurement of an extreme value is likely to be followed by a near-average value. A common example is seen in pain treatment. One explanation for the placebo effect is that after reporting extreme pain, patients are statistically more likely to have a closer-to-average amount of pain the next time it is measured. “Usually, people think random error is harmless because we can average it off. You take enough readings, and all the overestimates and underestimates

cancel each other out,” says Sivadas. “But this is not always the case.”

The *Wind* spacecraft, launched in 1994, sits at a point where the gravitational forces of Earth and the Sun are balanced. That position in space enables continuous data collection from a point roughly stationary relative to Earth, whereas data collection by satellites closer to Earth is affected by their orbits around the planet. But the distance between the measurement and interaction points creates substantial uncertainty about the intensity of the solar wind that is actually reaching the ionosphere. Between the position of the *Wind* measurements and Earth's ionosphere, interaction with Earth's magnetosphere causes solar wind to slow and form a bow shock. Though that doesn't lower the strength of the wind's electric field—the primary relevant factor for geomagnetic storms—variability in the solar wind's propagation time, turbulence, and orientation all contribute to the uncertainty.

Sivadas and colleagues used solar wind data collected closer to Earth, by spacecraft such as *THEMIS* (*Time History of Events and Macroscale Interactions during Substorms*, launched in 2007), to estimate the uncertainty and create an error model. They found that the highest intensities measured by *Wind* were not representative of the intensity of solar wind that interacts with the ionosphere; because of regression to the mean, the true values were lower. After correcting the data, they found a linear relationship between solar wind strength and the polar cap index,

a measure of geomagnetic activity, as shown in figure 2. The implication is that if the solar wind that reaches the ionosphere is as intense as some of the high measurements from *Wind*, then the resulting geomagnetic storms could be nearly twice as intense as researchers had previously thought.

Wider implications

In addition to data from *THEMIS*, the researchers used measurements from other near-Earth satellites, including ones from the Double Star, Cluster II, and Magnetospheric Multiscale missions. To account for the variable positions of orbiting satellites, they used machine learning to classify the positions of data points relative to the magnetosphere, which significantly increased the number of measurements available for the analysis.

“It’s nice that we have such long-term datasets,” says Sarah Vines, a lead scientist in the space science division at the Southwest Research Institute in San Antonio, Texas. “Now we’ve got multiple measurement points spread around, so we can actually look at the consistency between those.” She says that more work

is needed to unpack the complex interactions between solar wind and the magnetosphere and that the many physical models aimed at explaining the saturation effect may still contain relevant physics.

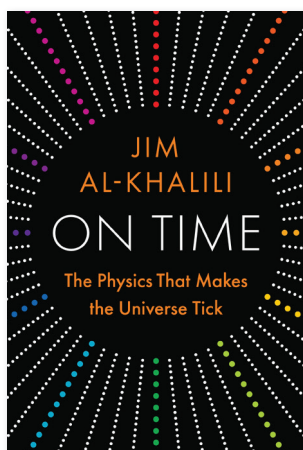
The study demonstrates that unrecognized regression to the mean can be easily misinterpreted as non-linear physics, Sivadas says. And he says it is especially important to consider when studying climate change, earthquakes, and other topics where extreme events are of interest. He notes that AI analyses could be especially susceptible.

Solar wind activity has been high over the past few years; the 11-year solar cycle reached its peak near the end of 2024. In 2022, SpaceX’s Starlink lost 38 of 49 satellites during a launch because of a geomagnetic storm that increased atmospheric drag and caused the satellites to fall out of orbit—just one example of the many types of hazards posed by the storms. **PT**

Reference

1. N. Sivadas et al., “Regression to the mean can explain saturation of geomagnetic storms,” *Nature* **655**, 1143 (2026).

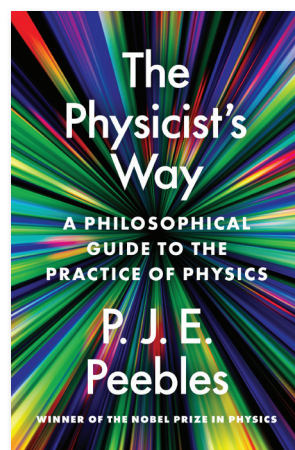
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