

In due course, climate change science no doubt will provide an explanation for global dimming and brightening and enable these oscillations to be reconciled with those in global warming. What is difficult to account for is the way in which the Intergovernmental Panel on Climate Change (IPCC), charged with providing the world's governments with an overview of climate change science, has responded to this major challenge to the consensus explanation.

It is now 30 years since the publication of a paper calling attention to a large reduction in shortwave radiation measured over a 40-year interval at an isolated mountaintop desert site [Suraqui *et al.*, 1974]. This finding was followed by the more than 70 others listed in the bibliography previously cited.

No reference to these findings has appeared in the three massive IPCC assessment reports published during the past 15 years. This omission is surprising in view of the important practical consequences of changes in  $E_{g\downarrow}$  in addition to their theoretical significance for climate change. These consequences stem from the ubiquitous role of solar energy in powering the Earth's life-sustaining water, carbon, and atmospheric cycles. One such effect of global dimming already noted can be seen in the widespread reports of reductions in potential evaporation listed in the global dimming bibliography site. Another practical consequence, that of global brightening, may have already appeared in

the increased net primary production of vegetation monitored from satellites over most of the Northern Hemisphere since the early 1980s [Broun *et al.*, 2004].

The omission of reference to changes in  $E_{g\downarrow}$  in the IPCC assessments brings into question the confidence that can be placed in a top-down, 'consensus' science system that ignores such a major and significant element of climate change.

A separate and more fundamental question is whether scientific understanding of climate change is now sufficient to produce a useful consensus view. Is climate change a science or is it a trans-science, asking questions that can be stated in the language of science but that are currently beyond its ability to answer?

The cautionary note global dimming and brightening sounds for climate change scientists is not a new one; rather it strikingly vindicates the two rules of climate change set out by Peter Wright 30 years ago [Wright, 1971]. The first rule states that some feature of the atmosphere can always be found that will oscillate in accordance with your hypothesis; the second states that shortly after its discovery, the oscillation will disappear.

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## New Madrid GPS: Much Ado About Nothing?

PAGE 59

Two articles in this issue address the surprising and intriguing negative result that high-precision geodetic measurements find no compelling evidence for crustal motions in the New Madrid Seismic Zone of the central United States.

The geodetic measurements have drawn great interest because they add another puzzle to the many surrounding New Madrid. This area is the best known case of large earthquakes within the interior of the plates, in continental lithosphere. Such earthquakes are much rarer and release much less seismic energy than those at plate boundaries. Because idealized plates are perfectly rigid, these earthquakes demonstrate that deformation occurs within plates and provide a lower bound on their rigidity. Moreover, precisely because such earthquakes are rare, they pose a hazard to areas that are less well prepared for earthquakes than areas with more active ones. Assessing the hazard is further complicated by a growing sense that earthquakes within plates migrate among seismic zones that 'turn on,' remain active for some time, and then 'turn off.'

The potential hazard is illustrated by the large (magnitude 7) earthquakes that occurred in 1811 and 1812, causing shaking across much of the area. Houses collapsed in

the tiny Mississippi River town of New Madrid, Mo., and minor damage occurred in St. Louis, Mo., Louisville, Ky., and Nashville, Tenn. The smaller earthquakes that continue today, which may be aftershocks of the 1811–1812 events, are more of a nuisance than a catastrophe. For example, the largest earthquake in the past century, the 1968 (magnitude 5.5) southern Illinois earthquake, was widely felt and caused damage but no fatalities. However, large earthquakes like those of 1811–1812 would be much more destructive. Paleoseismic data suggest that these have occurred about 500 years apart in the past 1000 years and hence may recur.

Surprisingly little is known about these earthquakes. It is not clear why they occur, when they started, when, if ever, they will recur, and how large a hazard they pose. As a result, researchers looked to the new tool of GPS geodesy for new insights and were surprised by the results [Newman *et al.*, 1999].

A GPS measurement yields a site's position to a precision of millimeters, so a series of measurements over time gives its velocity. This is typically plotted as a velocity vector from the site's position, with an error ellipse about the vector's head showing the uncertainty in velocity. Ideally, the ellipse is a small region about the vector's head, showing that the velocity is well constrained. This is far from the case for sites in the New Madrid zone (Figure

1, top). The site velocities shown, which are motions with respect to the rigid North American plate, are small—less than 2 millimeters per year—and generally within their error ellipses. Hence most sites show no motion significantly different from zero. In other words, the GPS data do not require that they be moving at all, and restrict any motion to being very slow. Moreover, the vectors do not show the spatially coherent pattern typically seen in deforming seismic zones.

The results are gratifying from the view of plate tectonics, in that they and sites elsewhere in eastern North America show that the plate is quite rigid, with the major deviation being vertical motion due to postglacial adjustment. Beyond this motion, there is no clear case for tectonic effects, in that the small motions could be a combination of observational and analysis errors, and small motions of the geodetic monuments. However, much faster motion had been expected because of the earthquakes. It had been suggested that the earthquakes of 1811–1812 were magnitude 8 events and occurred about every 500 years. If so, more than 5 millimeters per year of average motion during the interval between earthquakes would be needed to store up the slip for a future large earthquake (Figure 1, middle). Hence, the first inference from the slow motions was that typical large earthquakes in the area are smaller, magnitude 7, in accord with recent analysis of historic records of the intensity of shaking

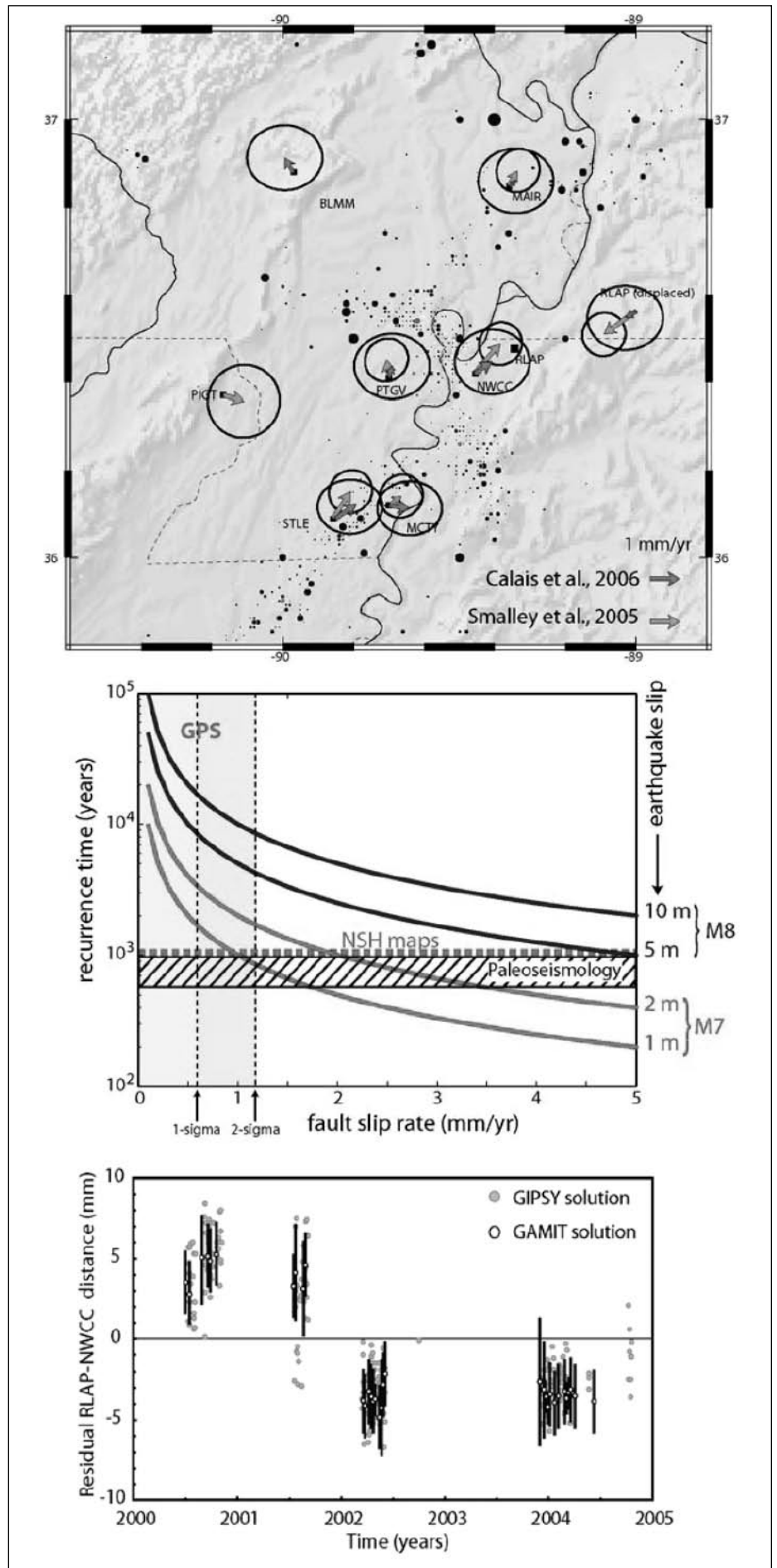
Fig. 1. GPS data and interpretations for the New Madrid Seismic Zone, after Newman et al. [1999] and Calais et al. [2005, 2006]. (top) GPS site velocities and associated uncertainties (95% confidence ellipses) from two different analyses. Larger ellipses are from Smalley et al. [2005]. Site velocities within error ellipses show no statistically significant motion. RLAP motion is plotted displaced for clarity. Small circles show regional seismicity. (middle) Slip expected in a future earthquake assuming the geodetically observed fault slip rate accumulates over a given recurrence time. Curves show range for magnitude 7 and 8 earthquakes. Horizontal lines show recurrence times assumed in National Seismic Hazard (NSH) maps and inferred from paleoseismic studies. Vertical lines show maximum slip rate from GPS data. (bottom) Time series of estimates of the distance between sites RLAP and NWCC after removal of a mean distance, derived using two different GPS data analysis software packages. Note offset between 2001 and 2002.

[Hough et al., 2000]. Beyond this, debate has continued, focusing on two broad questions that are explored by the articles here.

The first question is whether the GPS data show any motion. The motions are so slow that minor differences in the length of data used, the processing method, or assumptions in the error analysis can lead to different interpretations (Figure 1, top). *Smalley et al.* [2005] conclude that significant motion occurs at two sites, RLAP and NWCC on opposite sides of the scarp thought to have been part of the fault break in 1811–1812. In contrast, *Calais et al.* [2005, 2006] find that none of the sites shows significant motion and that the inferred motion between RLAP and NWCC is due to a puzzling offset in the time series, suggestive of problems in the data or analysis rather than tectonic motion (Figure 1, bottom). *Newman* [this issue] explores a related issue, showing that reporting small motions as strains—differences between small motions at two sites divided by the distance between them—can be misleading.

The second question is what the small or nil motions imply for past and future earthquakes. Analyses to date have explored the implications of the slow motions for the time and magnitude of future large earthquakes. Another possibility is that the motions are nil, perhaps implying that the seismic zone is shutting down and will not generate future large earthquakes. Alternatively, *Rydelek* [this issue] shows that the motions may be transient effects from the 1811–1812 earthquakes and thus give no direct information about future earthquakes.

The two articles here illustrate the complexity of the issues, which will likely be debated for many years. GPS velocity issues will eventually be resolved because the precision of velocity estimates increases with time. Hence the estimated motion will either continue shrinking closer to zero or climb above the uncertainties to show significant motion. However, the tectonic issues and their implications for seismic hazard policy may take



much longer—hundred of years or more—to resolve. This situation would have delighted Mark Twain, who piloted steamboats through the area only 50 years after the 1811–1812 earthquakes. In his words, “There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.”

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## Earthquake Risk From Strain Rates on Slipping Faults

PAGE 60

Discrete geodetic measurements made near active faults may capture only small bits of a relatively complex field of deformation surrounding a fault, making it difficult to accurately describe the nature of ongoing activity along the fault. This difficulty is compounded when geodetic measurements are reported as strain rates, which involve differences in the displacement between two or more sites over time. As a result, very low displacement rates can be quoted as very high strain rates, which may lead to incorrectly inferring high seismic risk. As an example, I look at a recent deformation study across the New Madrid Seismic Zone (NMSZ). The NMSZ, located in east central United States and away from rapidly deforming plate boundaries, is best known for its series of three large earthquakes ( $M > 7$ ) in the early 1800s, and continues today with numerous small earthquakes (Figure 1).

A recent study by Smalley *et al.* [2005] used two GPS sites within a larger continuous network to identify rapid strain accumulation across the central thrust segment of the NMSZ. Using the limited subset of data, Smalley *et al.* [2005] inferred that the strain rate measured at the NMSZ is comparable to rates along the San Andreas and other active faults, in apparent contrast to an earlier campaign GPS study that showed less than 2 millimeter per year of overall deformation [Newman *et al.*, 1999]. It has been argued that the new results do not require motion statistically different from zero, reflecting differences in processing techniques and random noise [Calais *et al.*, 2005]. However, here I consider a separate larger and more general issue. This is the validity of using simple strain measurements across a fault for implying earthquake recurrence and seismic hazards. The difficulty is that the small displacement rates can be quoted as high strain rates.

Of the eight sites in a network surrounding the NMSZ, Smalley *et al.* [2005] found that only two sites, which were 11 kilometers apart, showed potentially significant deformation of

$2.7 \pm 1.6$  millimeters per year (Figure 1). Using the simple linear relation for strain rate,

$$\epsilon = \frac{\Delta u}{l}$$

where  $\Delta u$  is the change in velocity over the distance  $l$  between measurements, they find a strain rate of approximately  $10^{-7}$  per year. Unfortunately, this resultant strain rate alone does not yield useful information about the true strain accumulation across a slipping fault. That is because for a given

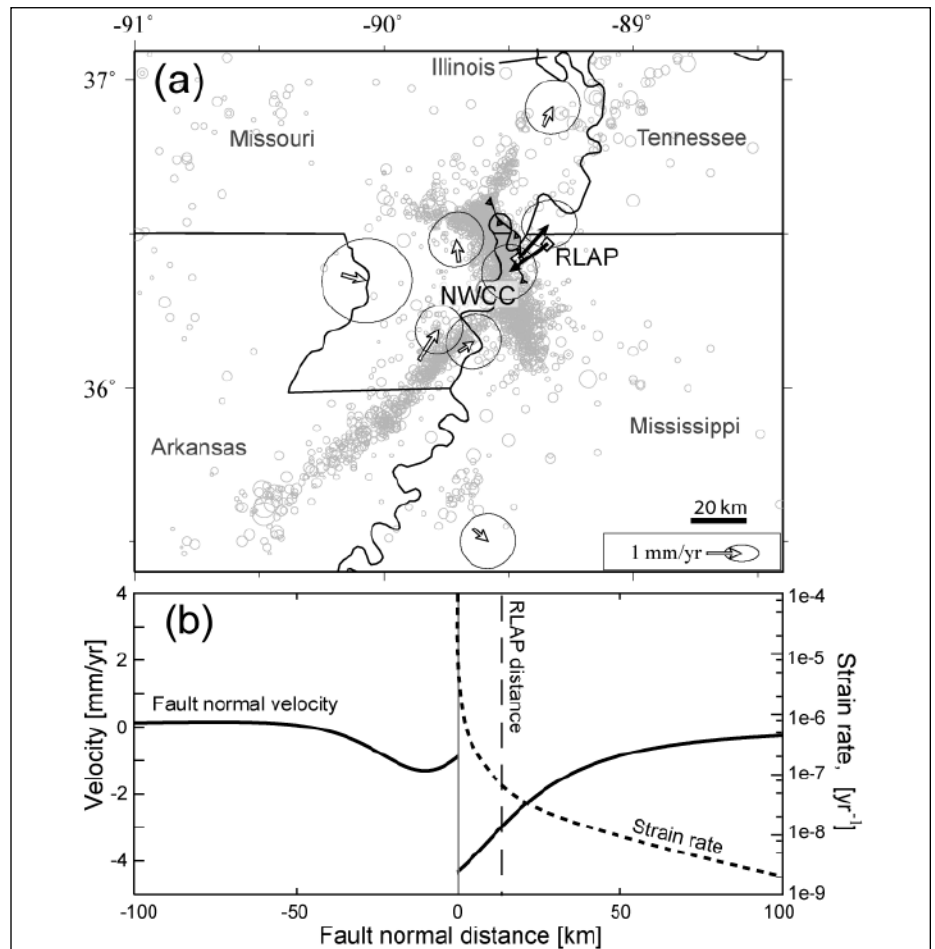


Fig. 1. (a) New Madrid seismicity since 1974 (grey circles), GPS horizontal site velocities and  $2\sigma$  errors (arrows and ellipses [Smalley *et al.*, 2005]), and approximate surface location of the Reelfoot thrust fault (thick toothed line). Solid arrows are site velocities nearest the thrust and were used to infer strain rates of  $10^{-7}$  per year at the distance of site RLAP. (b) Predicted fault-normal displacements and strain rates (thick dark solid and dashed lines) for ongoing slip across a simple thrust assuming a 60-kilometer-long,  $70^\circ$  west dipping fault extending to 20 kilometer depth (approximating the Reelfoot thrust) using the analytic model of Mansinha and Smylie [1971]. Slip is scaled to approximate that reported by Smalley *et al.* [2005], 11 kilometers from the fault (thin vertical dashed line). The resulting strain rate is not constant, but instead increases rapidly near the fault.