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Seasonal fluctuations in the mass of the Amazon River system and Earth's elastic response

Michael Bevis,[1] Douglas Alsdorf,[2] Eric Kendrick,[1] Luiz Paulo Fortes,[3] Bruce Forsberg,[4] Robert Smalley Jr.,[5] and Janet Becker[6]

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[1] A GPS station in Manaus, near the center of the Amazon basin, manifests an annual cycle of vertical displacement with a peak-to-peak amplitude of 50–75 mm. This is by far the largest crustal oscillation observed to date, and nearly 2–3 times larger than the amplitude predicted for this region. Vertical ground displacement is strongly anti-correlated with the local stage height of the Amazon river, with no detectable time lag between the two time series. This suggests that we are observing, for the first time, a purely elastic response to changes in the weight of a flowing river system. We use a simple hydrological model to relate stage height to the regional pattern of flooding, and argue that the elastic oscillations observed in Manaus are dominated by changes in water loading developed within ~200 km of the GPS station. **Citation:** Bevis, M., D. Alsdorf, E. Kendrick, L. P. Fortes, B. Forsberg, R. Smalley Jr., and J. Becker (2005), Seasonal fluctuations in the mass of the Amazon River system and Earth's elastic response, *Geophys. Res. Lett.*, *32*, L16308, doi:10.1029/2005GL023491.

1. Introduction

[2] The surface of the earth oscillates in response to seasonal fluctuations in the loads imposed on the lithosphere by the atmosphere and, more importantly, by the hydrosphere [*Van Dam et al.*, 2001; *Heki*, 2001; *Blewitt et al.*, 2001; *Dong et al.*, 2002]. This mainly vertical elastic response to environmental loading occurs at global [*Blewitt et al.*, 2001], regional [*Heki*, 2001] and local scales [*Bevis et al.*, 2004]. *Davis et al.* [2004] recently used space-based measurements of gravity change, geodetic measurements from 10 Global Positioning System (GPS) stations (none in the central Amazon basin), and a global elastic model to estimate the annual loading-induced deformation of South America. They predicted that the maximum vertical motions, with a peak-to-peak amplitude of ~26 mm, occur in the central Amazon basin. This is fairly consistent with an earlier study in which a global elastic model was subject to loads computed from hydrological databases [*Van Dam et al.*, 2001].

[1]Geodetic Science, Ohio State University, Columbus, Ohio, USA.
[2]Geological Sciences, Ohio State University, Columbus, Ohio, USA.
[3]Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil.
[4]Department of Ecology, Instituto Nacional de Pesquisas da Amazonas, Manaus, Brazil.
[5]Center for Earthquake Research and Information, University of Memphis, Memphis, Tennessee, USA.
[6]Hawaii Institute for Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii, USA.

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[3] The geodetic GPS station MANA is located in the city of Manaus (Brazil) on the northern bank of the Rio Negro, very near its confluence with the mainstem Amazon River. This geodetic station is located adjacent to a river gauge which records the stage height of the Amazon river as it cycles through its annual vertical range of 10–15 meters (Figure 1a). We present the station position time series for MANA in a reference frame which minimizes (i) the horizontal motions of 15 continuous GPS stations distributed throughout the stable core of the South American plate, and (ii) the vertical motion of 31 stations distributed throughout this and several adjacent plates. The latter group does not include any stations from the central Amazon basin. The vertical (U or up) coordinate for MANA (Figure 1b) oscillates within a total range ~75 mm, which is about 3–9 times larger than is seen at most GPS stations worldwide, and more than twice as large as the largest range of motion observed in a recent global survey of periodic vertical motions [*Dong et al.*, 2002]. The horizontal motions at MANA are an order of magnitude smaller, and they are clearly resolved only in the north (N) component of motion (Figure 1c). Note that the geodetic measurement of the east (E) component of motion (Figure 1d) is noisier than is that of the N component.

[4] The U component of motion at MANA is strongly anti-correlated with the stage height of the Amazon river in Manaus (Figure 1a). That is, the down (D = −U) component of ground motion is positively correlated with the local height of the Amazon river and therefore with the load that the river system locally imposes on the ground. We have computed the cross correlation between the stage height time series, H(t), and the vertical ground deflection, D(t + τ), that occurs after some time lag τ with a step size or resolution of 1 day (Figure 2). We find that the maximum correlation occurs when $\tau = 0 \pm 1$ day. This implies that the solid earth is responding essentially instantaneously to the hydrological loading cycle. This is consistent with other studies that have found that the lithosphere and the underlying mantle behave as a perfect elastic, or very nearly so, for forcing periods of one year or less [*Ray et al.*, 2001; *Wahr et al.*, 2003; *Bevis et al.*, 2004]. We can find no comparable relationship between U(t) and local rainfall, or integrated rainfall, suggesting that soil expansion does not contribute significantly to surface motion.

[5] As the stage height of the Amazon River increases, the total area of flooding also increases (Figure 3), which means that the local volume and mass of river water is not simply related to stage height. In order to compute the loading changes associated with seasonal changes in stage height it is necessary to develop a hydrological model for

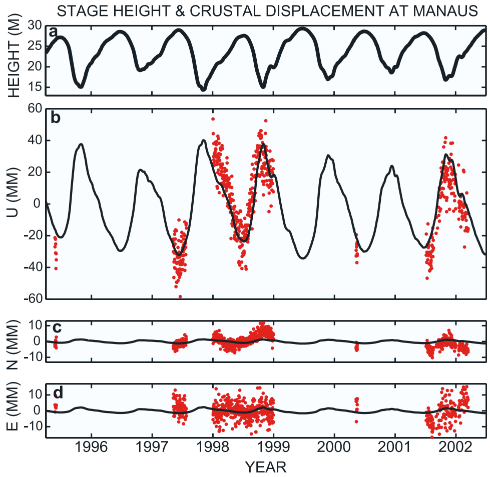

Figure 1. (a) Stage height time series H(t) observed in Manaus, (b) daily solutions for the upwards component of displacement U(t) at GPS station MANA (red dots), and the model prediction (solid curve), (c) and (d) geodetic measurements (red dots) and model predictions (solid curves) for the north and east components of displacement.

the river system near Manaus. Accurate regional models for the distribution of river water within the Amazon basin are not yet available, because very few river gauges have been deployed in a vast area characterized by a complicated pattern of inundation and drainage. However, it is possible to produce a simple model [*Richey et al.*, 1989] for a river system in the immediate vicinity of a river gauge. The implied surface loads can be used to drive an elastic model so as to predict the surface displacement at any given point.

2. The Hydrological Model

[6] We developed a simple model that fills the 3 arc second cells in the Shuttle Radar Topography Mission digital elevation model (SRTM DEM) with water elevations extrapolated along a sloping plane emanating from the Manaus stream gauge. Ideally, this simple model would incorporate measurements from the few surrounding stream gauges, but no data are available for the time period

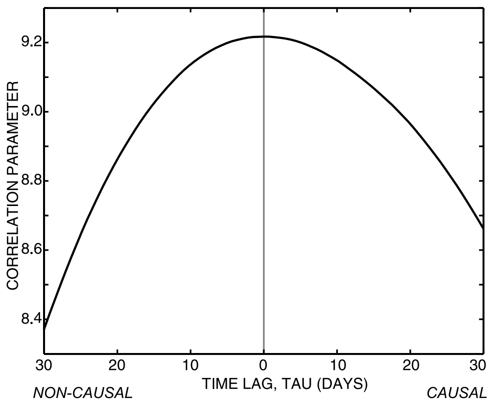

Figure 2. The strength of the correlation between stage height H(t) and downwards crustal displacement D(t + τ) as a function of the time lag τ. No time lag is detected.

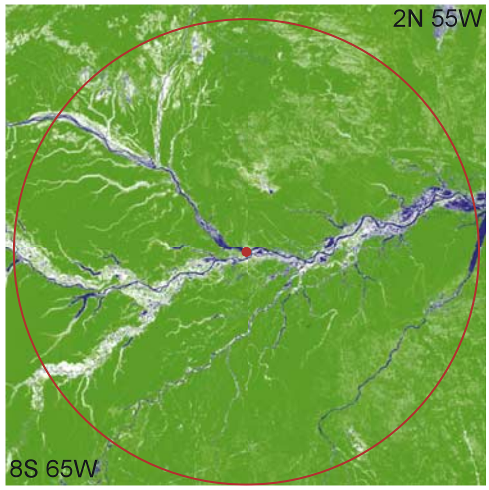

Figure 3. The patterns of flooding in a 10° by 10° section of the central Amazon basin nearly centered on the GPS station MANA in Manaus (red dot). This is an overlay of two mosaics constructed by the Global Rain Forest Mapping project using JERS-1 L-band SAR images over the entire Amazon Basin [*Rosenqvist et al.*, 2000]. One mosaic was acquired during the low-water period of late 1995 and the second during peak stage in 1996. Dark blue indicates channels that always contain water, white depicts floodplains that seasonally flood and drain; green represents non-flooded areas [*Hess et al.*, 2003].

matching GPS acquisitions. To ensure reasonable approximation to continuity, we summed volumes from cells falling within the regional areas used in the continuity approach of *Richey et al.* [1989] and adjusted the slope on the plane emanating from Manaus until a match was found. The resulting slope of 3.0 cm/km is within the expected range [*Birkett et al.*, 2002]. The 10° $\times$ 10° study location was divided into channel, floodplain, and non-flooded regions using the Synthetic Aperture Radar (SAR) based classification of *Hess et al.* [2003]. Channel volumes are constrained by annual averages from stream gauges located on the Amazon and Negro rivers. The volumes from the much smaller tributaries draining non-flooded areas are unknown. Floodplain volumes are poorly constrained by *Richey et al.* [1989] such that *Alsdorf* [2003] integrated spaceborne interferometric SAR measurements of water level changes [*Alsdorf et al.*, 2000] and suggested an error of 30%. Therefore, in the load modeling we used 100% of the channel volumes found in our simple hydrologic model, 70% of the floodplain volumes and none of the volumes for the small tributaries draining non-flooded regions. This simple hydrologic model is designed to provide first-order relationships between water volumes and mass loading. Further refinements require additional hydraulic measurements not currently available [*Alsdorf and Lettenmaier*, 2003].

3. The Elastic Model

[7] In surface loading problems the lateral scale of the load sets the vertical scale for deformation within the half space. For example, if a uniform downwards pressure is exerted on the surface of a homogeneous elastic half space within a circular loading area with radius R, then half of the

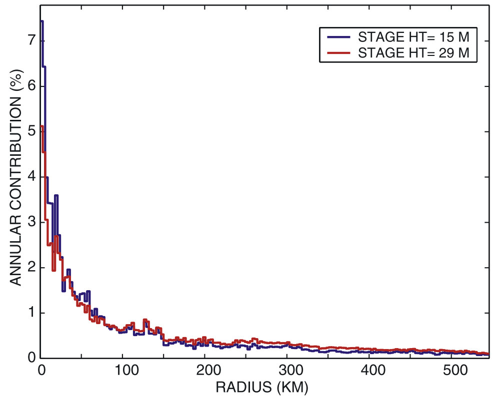

Figure 4. The contribution of the water loads in each of a series of concentric annuli, centred on GPS station MANA, to the total vertical displacement predicted for MANA by the coupled hydrological and elastic models. The two curves indicate the radial or annular influence functions for low (15 m) and high (29 m) stage heights. The extent of the outermost annulus is shown by the dotted ring in Figure 3, which indicates that part of our model domain (near the four corners) lies beyond the outer annulus.

resulting elastic strain energy stored in the entire half space resides in the cylindrical volume with radius 1.5 R and depth 1.25 R which immediately underlies and is centered on the surface load.

[8] We shall show that the vertical response at MANA is dominated by surface loads with a horizontal scale of $\sim 10^2$ km. As a result, the associated surface displacements are sensitive to the elastic structure of the crust and lithospheric mantle, and to a lesser extent to that of the asthenosphere, but are insensitive to the elastic structure of the mesosphere and lower mantle. Unfortunately the shallow elastic structure of the earth beneath Manaus is not well known. If we could observe the displacements at say 5–10 GPS stations located at different distances from the Amazon and Rio Negro, we could adopt a multilayered elastic model for the area, and attempt to infer the properties of these layers based on the observed response to annual loading cycles. But our displacement observations are confined to a single point and only the vertical component of displacement is very well resolved. Instead we adopt a simple model based on a uniform elastic half space [*Becker and Bevis*, 2004]. The loading response of this model is completely determined by two elastic parameters: Young's Modulus, Y, and Poisson's ratio, ν. If ν is restricted to the geophysically plausible range of 0.25–0.30, then the key control on the model response is the value assigned to Y [*Bevis et al.*, 2004]. The elastic structure of the crust and uppermost mantle vary with depth, and so the elastic constants we adopt for our uniform half space model must represent a spatial average of these values over the depth range in which most of elastic support of the time-varying river load is actually achieved. We would expect this nominally uniform or *effective* value of Y to fall in the range 60–160 GPa, as discussed below.

4. Results and Discussion

[9] We assume that $\nu = 0.25$ and select the value of Y so as to produce the maximum agreement with the geodetic time series U(t). The best fit to the data, which is obtained when Y = 137.3 GPa, is shown by the continuous curves in Figures 1b–1d. The model curve for U explains more than half of the variability apparent in the geodetic time series. Most, but not all, of the residual scatter in U (which has an RMS value of 11.8 mm) can be accounted for by daily positioning error. We can change the value assigned to ν and recover identical fits by making small adjustments to the value of Y. For example, if ν is assigned a value of 0.3, then Y = 133.3 GPa. Predicted vertical displacement is so insensitive to the effective value of ν that the model curve in Figure 1b is practically achieved with a single degree of freedom.

[10] In order to assess whether or not we are modeling the hydrologic load over a wide enough aperture to properly account for the loads inducing the displacement at Manaus, we consider two extreme values of stage height (15 m and 29 m), and determine what percentage of the total U displacement at MANA is contributed by those cells whose centers are located between R − 1.5 km and R + 1.5 km from MANA, for various values of R (Figure 4). We can see that the cells near the edge of our basin model are making a small but not negligible contribution to the predicted value for U. Accordingly we have slightly underestimated the load producing the vertical displacement at MANA, and so we have slightly overestimated Y. The annular influence functions (Figure 4) indicate that at low stage (H = 15 m) the water loads producing half the displacement at MANA are located within 52 km of MANA, and during the high stage (H = 29 m) the corresponding radius is 88 km.

[11] The radially symmetric earth model PREM [*Dziewonski and Anderson*, 1981] indicates that the value of Y in mantle above the 220 km discontinuity falls in the range 168–173 GPa. This whole earth model is believed to

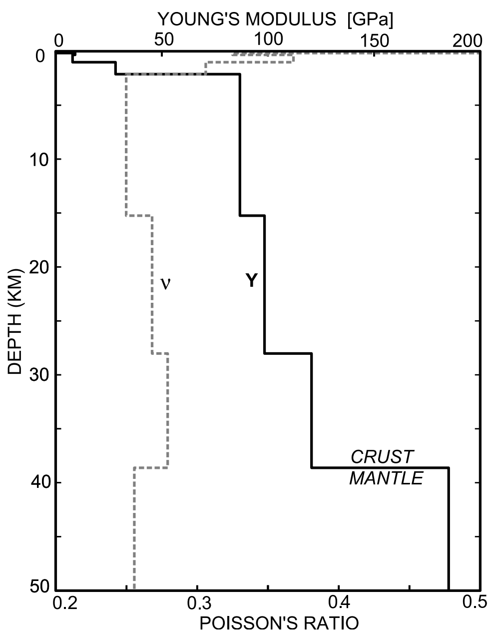

Figure 5. Vertical profiles showing Young's modulus (Y) and Poisson's ratio (ν) versus depth for a 'typical' continental setting. These curves were computed from a layered model for P wave velocity, S wave velocity, and density [*Mooney et al.*, 1998].

be accurate to within 5% at depths near 200 km (where Y = 168 GPa), but it becomes increasingly inaccurate as one approaches the surface. PREM is not accurate in the earth's outermost 50 km, because the uppermost mantle and especially the crust are extremely heterogeneous. There are better crustal models, based largely on seismic refraction surveys [*Mooney et al.*, 1998], which can be used to construct vertical profiles of Y and ν in the upper 50 km, but such surveys do not exist in the Amazon Basin. Nevertheless we present a 'typical' profile for continental crust in Figure 5, to provide a very general idea of how Y might vary with depth. Uniform half space analyses of loads that receive significant elastic support from both the continental crust and the mantle should find effective values for Y in the range 60–160 GPa. Accordingly, it is quite reasonable that the effective value for Y in our loading problem is less than but not greatly less than about 137 GPa.

5. Concluding Remarks

[12] The GPS station MANA is, in effect, weighing a local portion of the Amazon river system. We have obtained a fairly good fit to the displacement history at MANA using a uniform half-space model (UHM). Obviously we could obtain a better fit with a layered half-space model (LHM) since it would enjoy more degrees of freedom. Since the effective value for Y inferred from the UHM lies between those values thought typical for the uppermost crust and the uppermost mantle, it is also obvious that we could construct a LHM in which Y varies between these values in some plausible way, and achieves an improved fit to the surface response field. The looming problem, of course, is non-uniqueness. Given observations at a single point, very many plausible models would fit the data with nearly equal success. Improving our understanding of actual subsurface structure will require additional observational constraints. We hope to build additional GPS stations in the vicinity of Manaus to determine the spatial structure of loading response.

[13] The constraints imposed by in situ crustal motion measurements will complement the synoptic but spatially blurry constraints imposed by satellite measurements of hydrologically-induced gravity fluctuations such as those being made by the GRACE mission. The insights obtained by jointly analyzing flooding cycles, surface displacement and gravity change should be of interest to geophysicists as well as hydrologists. A better knowledge of crustal elastic structure has implications for the earthquake deformation cycle, for example, as well as enabling us to better calibrate geodetic constraints on regional hydrological cycles.

[14] The simple flooding and elastic models employed in this study suggest that the oscillations observed at MANA are dominated by water loading developed within ~200 km of the GPS station. This crustal flexure must propagate downstream in conjunction with the annual Amazon floodwave.

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D. Alsdorf, Geological Sciences, Ohio State University, Columbus, OH 43210, USA.

J. Becker, Hawaii Institute for Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822, USA.

M. Bevis and E. Kendrick, Geodetic Science, Ohio State University, 2070 Neil Avenue, Columbus, OH 43210, USA. (mbevis@osu.edu)

B. Forsberg, Department of Ecology, Instituto Nacional de Pesquisas da Amazonas, Manaus, Brazil.

L. P. Fortes, Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil.

R. Smalley Jr., Center for Earthquake Research and Information, University of Memphis, Memphis, TN 38152, USA.