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A no-net-rotation model of present-day surface motions

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Abstract. A significant portion of the Earth's surface consists of zones of diffuse deformation. The interior regions of these diffuse zones of deformation move at distinctly different velocities from that of adjacent plates, and, because of their complexities, have been ignored in previous no-net-rotation (NNR) models. We have calculated a new NNR model from a continuous velocity field that incorporates both rigid plate motion and velocity gradients within plate boundary zones. When compared with earlier NNR models we find significantly different angular velocities for many plates. Differences between the NNR model presented here and earlier NNR models can be attributed to the effect of including velocity gradients in diffuse plate boundary zones as well as to the actual differences between geodetically derived surface motions and geologic estimates.

1. Introduction

Accurate estimates of the motion of the lithosphere with respect to the Earth's interior (i.e., the absolute motion) provide important constraints for studies relating mantle flow with surface motions and for the quantification of driving forces acting on the lithosphere in general. Absolute plate motion estimates are defined either with respect to hotspots [*Gripp and Gordon*, 1990] or by a no-net-rotation (NNR) requirement for the lithosphere (NNR-NUVEL1 [*Argus and Gordon*, 1991]). Here we re-evaluate the NNR model, because for two reasons the current models may be incorrect. First, existing models are based on plate motion models that are average estimates over the last 3 Ma, inferred from geologic information and earthquake slip-vectors. Space-based geodetic measurements, on the other hand, now allow direct measurements of present-day plate motions. Although there is in general good agreement between the inferred present-day plate motions and the NUVEL-1A plate model [*DeMets et al.*, 1994], some significant differences between the two estimates have become apparent. Second, the NNR model depends on the values of $\mathbf{v} \times \mathbf{r}$ over the Earth's entire surface, with $\mathbf{v}$ being the horizontal surface velocity at position $\mathbf{r}$. Previous NNR models have assumed that the Earth's surface consist entirely of discontinuous plates. Yet a significant portion of the Earth's surface is covered by (diffuse) plate boundary zones, in which horizontal velocities cannot be described by one rigid body rotation. Since large regions such as central [e.g., *Holt et al.*, 2000] and southeast Asia [*Michel et al.*, 2001] are known to have significant motions with respect to adjacent plates, current NNR models will need to include such regions, and their present-day relative motions, in order to infer an accurate NNR reference frame. There is evidence, for example, that the inclusion of diffuse plate boundary zones in geodynamic models constraining plate motions improves the resolution of the model divergence and vorticity fields [e.g., *Bercovici and Wessel*, 1994].

Zhang et al. [1999] presented NNR rotation vectors for several plates, determined from the ITRF96 geodetic data set. However, they excluded velocities within plate boundary zones and used the NUVEL1A model to constrain the motions of some plates. Here we re-evaluate NNR angular velocities by using the global velocity and strain rate model presented by *Kreemer et al.* [2001].

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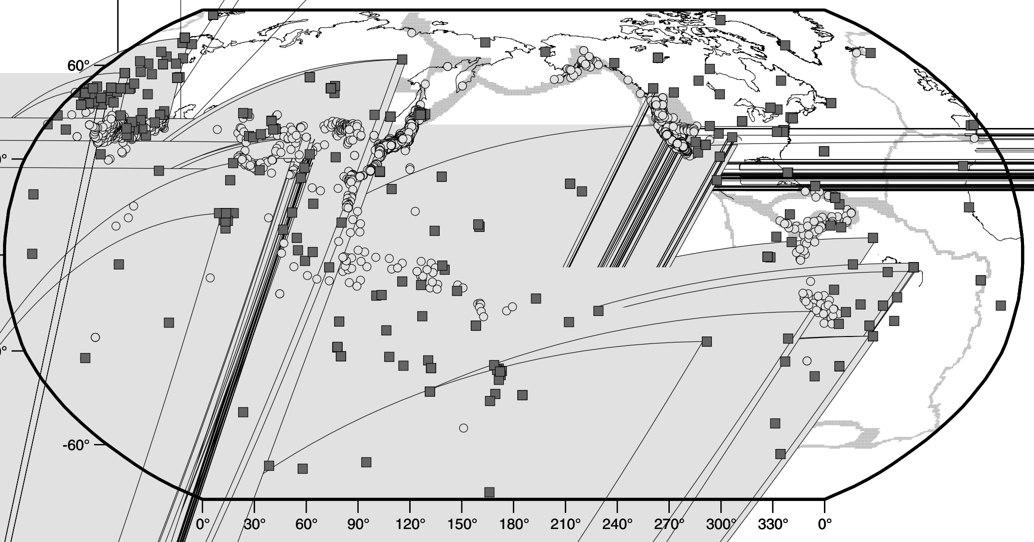
2. A global velocity field

Kreemer et al. [2001] presented a global strain rate and velocity model, which is an updated version of the model by *Kreemer et al.* [2000]. The updated model includes 2933 (mainly) published geodetic velocities, both measured on stable plates and within plate boundary zones, as well as some observed strain rates inferred from Quaternary fault slip rates in Asia. The velocity and strain rate fields are obtained through a bi-cubic Bessel interpolation of geodetic velocities (GPS, VLBI, DORIS) and observed strain rates [e.g., *Beavan and Haines*, 2001]. The modeling was done using a continuous grid in longitudinal direction that covers all areas between 80°N and 80°S. Each grid area is 0.6° by 0.5° in dimension. The model grid includes 25 rigid spherical caps and all remaining grid areas were assumed to constitute the plate boundary zones. The reader is referred to *Kreemer et al.* [2000; 2001] for a detailed explanation of the global strain rate and velocity model.

The 2933 geodetic velocities used in the model are taken from 50 different studies (Figure 1). We solve for the frames of reference for each geodetic study that enable a best-fit with the model velocity field. Table 1 lists the weighted root-mean-square (WRMS) between observed and model velocities for each plate (the total global WRMS is 1.00). We do not show results for the Caroline, Capricorn, Juan de Fuca, Rivera, and Scotia plates, because the motions of these plates are not directly constrained by geodetic measurements.

Our results confirm some of the significant discrepancies between present-day plate motions and the NUVEL-



perimposed are site locations for which
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sia in previous NNR models.

otation model

ation model for the lithosphere is satis-
e integral of $\mathbf{v} \times \mathbf{r}$ over the Earth's surface
. Under certain conditions, a no-net-rotation
frame would satisfy a case of no-net-torque
xerted on the lithosphere as a whole [*Solomon*
leep, 1974]. The most important condition under
ch the NNR model would be analogous to a no-net-
rque model is that basal drag between the mantle and
lithosphere is laterally uniform. The assumption of uniform basal drag is a first order approximation since drag underneath oceans is likely to be different from continents, and asthenospheric flow may not be parallel to plate motion directions, both of which would result in
al torques. As noted before [e.g., *Solomon and*
1974; *Harper*, 1986; *Argus and Gordon*, 1991], the
epancy that seems to exist between models based
the NNR condition and models with a hotspot-fixed
eference frame points at a differential motion between the lithosphere and the deep mantle. This, in turn, indicates that the assumption of uniform drag may be false. Therefore, to allow further investigation into plate-mantle interactions, it is important that an accurate NNR model is established.

The no-net-rotation requirement can be written as

$$\int_{Earth} [(\mathbf{W}(\widehat{\mathbf{r}}) \times \widehat{\mathbf{r}}) \times \widehat{\mathbf{r}}] dA =$$

$$\int_{Earth} [(\widehat{\mathbf{r}} \cdot \mathbf{W}(\widehat{\mathbf{r}}))\widehat{\mathbf{r}} - (\widehat{\mathbf{r}} \cdot \widehat{\mathbf{r}})\mathbf{W}(\widehat{\mathbf{r}})] dA = 0, \qquad (1)$$

where dA is an area element. The NNR angular velocity $\mathbf{W}(\widehat{\mathbf{r}})$ is a continuous function of the position vector, $\widehat{\mathbf{r}}$, on a unit sphere. $\mathbf{W}(\widehat{\mathbf{r}})$ can be written as the sum of $\mathbf{W}_{\mathrm{p}}(\widehat{\mathbf{r}}) + \boldsymbol{\omega}_{\mathrm{pa}}$, where $\mathbf{W}_{\mathrm{p}}(\widehat{\mathbf{r}})$ is the model angular velocity for any point p with respect to our model reference frame (being the Pacific plate (pa)), and ω_{pa} is the NNR angular velocity for the Pacific plate. In the modeling of *Kreemer et al.* [2000; 2001] $\mathbf{W}_{\mathrm{p}}(\widehat{\mathbf{r}})$ is solved for at the corner points of the 0.6° by 0.5° grid areas and $\mathbf{W}_{\mathrm{p}}(\widehat{\mathbf{r}})$ is defined continuously in between points through the bi-cubic Bessel interpolation [e.g., *Beavan and Haines*, 2001]. Note that for plates and microplates $\mathbf{W}(\widehat{\mathbf{r}})$ is a constant, and is simply the angular velocity of the given plate. From (1) it can be shown that

$$\int_{Earth} [(\delta_{ij} - x_i x_j)\mathbf{W}_{\mathrm{p}}(\widehat{\mathbf{r}})] \mathrm{dA} = (\frac{-8\pi}{3})\boldsymbol{\omega}_{\mathrm{pa}}, \qquad (2)$$

where δ_{ij} is the Kronecker delta, and x_i are the Cartesian components of $\widehat{\mathbf{r}}$. Since $\mathbf{W}_{\mathrm{p}}(\widehat{\mathbf{r}})$ is known everywhere (we define the area south of 80°S to be part of the Antarctic plate, and that the area north of 80°N is part of either Eurasia or North America) we numerically

Table 1. Fit Between Plate Model Velocities and Geodetic Velocities, No-Net-Rotation Euler Vector, 1-σ Error Ellipse, RMS Velocity, and Euler Vector Difference Between our Model (I), NNR-NUVEL-1A (II), and a Model Combining NNR-NUVEL-1A Plate Geometries with our Velocity Field Model (III).

	Fit to obs. velocities			NNR Euler Vector			1-σ error ellipse					I vs. II		I vs. III		II vs. III	
Plate	Nvel	Nsites	WRMS	Latitude °N	Longitude °E	$\dot{\omega}$ ° Myr^{-1}	σ_{max}	σ_{min}	ζ_{max}	σ_{ω}	V$_{RMS}$	Δ(%)	α(°)	Δ(%)	α(°)	Δ(%)	α(°)
Amurian	7	6	0.92	62.3	-107.9	0.301	0.8	0.3	-34	0.005	29.9	--	--	--	--	--	--
Anatolia	10	9	0.94	41.9	27.2	1.410	10.7	0.5	57	0.104	18.4	--	--	--	--	--	--
Antarctica	7	6	0.87	63.2	-120.7	0.232	0.5	0.4	20	0.007	14.2	2.0	1.9	9.7	7.0	7.0	8.8
Arabia	2	2	2.35	49.6	-45.2	0.378	3.4	0.6	35	0.007	40.1	43.0	27.5	0.4	5.7	43.6	29.5
Australia	34	24	0.92	33.8	36.1	0.623	0.6	0.2	-49	0.003	61.6	3.0	2.3	0.5	3.4	3.6	5.3
Caribbean	7	3	0.63	36.6	-91.9	0.291	3.0	0.6	-22	0.020	15.0	26.5	12.6	2.3	7.2	28.2	17.0
Cocos	1	1	1.05	10.5	-101.6	2.529	13.2	0.7	16	0.102	48.2	40.3	19.4	0.0	0.8	40.3	18.6
Eurasia	110	63	1.05	56.3	-98.6	0.273	0.3	0.2	74	0.002	24.9	14.9	10.9	5.7	6.9	19.4	9.1
India	19	14	1.25	52.7	-13.6	0.482	1.6	0.5	12	0.005	52.0	12.2	11.5	0.4	4.4	12.7	14.2
Nazca	11	6	1.02	44.3	-98.6	0.639	2.1	0.7	8	0.009	64.0	16.0	3.5	1.7	3.2	14.1	2.2
N. America	57	39	1.00	0.8	-82.8	0.208	0.3	0.2	-3	0.002	20.1	0.3	5.8	5.0	10.1	4.9	10.8
Nubia	7	7	1.08	54.5	-86.2	0.280	0.6	0.3	84	0.003	28.2	3.0	8.1	4.0	7.1	1.0	15.2
Okhotsk	10	10	0.75	-21.7	-57.9	0.390	3.0	0.6	-57	0.030	26.8	--	--	--	--	--	--
Pacific	18	15	1.36	-64.6	106.6	0.640	0.4	0.3	56	0.003	63.2	0.6	1.5	1.4	3.3	2.1	1.9
Phil. Sea	4	3	1.97	-40.9	-36.7	1.030	6.0	1.5	-47	0.037	49.6	11.7	3.4	3.5	0.6	8.6	3.9
Somalia	2	2	0.52	54.6	-85.3	0.292	1.4	0.7	47	0.008	26.6	--	--	--	--	--	--
S. America	30	19	0.86	-15.9	-121.7	0.113	0.9	0.3	-41	0.003	11.8	6.5	11.0	6.7	18.1	0.1	23.5
S. China	4	4	1.13	73.5	-159.6	0.401	2.3	0.4	-19	0.009	40.3	--	--	--	--	--	--
Sunda	9	9	1.62	47.3	-90.9	0.386	1.6	0.4	-17	0.006	36.0	--	--	--	--	--	--
Tarim	8	8	0.95	-13.1	-87.1	0.637	3.6	0.4	6	0.031	32.7	--	--	--	--	--	--

Nvel, number of geodetic velocities on plate; Nsites, number of site locations on plate; WRMS, weighted root-mean-square between observed and geodetic velocities; 1-σ error ellipse axes are in degrees, and ζ_{max} is azimuth of maximum axis in degrees; V$_{RMS}$, root-mean-square velocity (in mm yr^{-1}) relative to no-net-rotation frame; $\Delta = \frac{|\omega_I - \omega_{II}|}{\omega_I}$; $\alpha = \cos^{-1}\frac{\boldsymbol{\omega}_I \cdot \boldsymbol{\omega}_{II}}{\omega_I \omega_{II}}$

integrate (2) to solve for ω_{pa} and subsequently determine the NNR rotation vector for each plate (Table 1). Our result for ω_{pa} is 0.640° Myr^{-1} about 64.57°S and 106.59°E. We have also calculated the RMS velocities (v_{rms}) for each plate and plate boundary zone with respect to the NNR reference frame (Table 1 and 2).

4. Discussion and conclusions

The global v_{rms} of the lithosphere is 37 mm yr^{-1} (Table 2), close to the 39 mm yr^{-1} obtained by *Argus and Gordon* [1991]. However, for individual plates some significant differences in v_{rms} exist. Differences between our NNR angular velocities and the NNR-NUVEL1 angular velocities can be explained by differences between geodetic and geologic plate motion estimates, by differences in assumed plate geometries, or by the fact that our NNR model accounts for diffuse deformation zones that involve velocity fields quite distinct from adjacent plates. A combination of the these sources of discrepancy is possible as well. To distinguish between the different possibilities we have calculated angular velocities for a NNR-A model, which uses the angular velocities of the plates calculated by *Kreemer et al.* [2001] but incorporates the plate geometries presented by *Argus and Gordon* [1991]. We have determined the differences in angular velocities between the NNR, NNR-A, and NNR-NUVEL1A models (Table 1). Disagreement between the NNR-A and NNR-NUVEL1A results are due exclusively to differences between present-day angular velocities of the plates, inferred primarily from GPS, and those inferred from geologic estimates [*DeMets et al.*, 1994]. Discrepancies between NNR and NNR-A, on the other hand, are due exclusively to the use of different plate geometries and the inclusion of plate boundary deformation in the calculation of the NNR frame. For the Indian, Arabian, Nazca, Cocos, Philippine Sea and Caribbean plates the differences between NNR and NNR-NUVEL1A angular velocities are mainly determined by the disagreement between the present-day and NUVEL-1A motion of these plates (Table 1). For the Antarctic and North American plates the disagreement between the NNR and NNR-NUVEL1A angular velocities is not significant, but differences between NNR and NNR-A, and NNR-A and NNR-NUVEL1A are signif-

Table 2. Fit Between Model Velocities and Geodetic Velocities, and WRMS Velocities for Selected Diffuse Plate Boundary Zones and Entire Earth

	Fit to obs. velocities			NNR-model
Boundary Zone	Nvel	Nsites	WRMS	V$_{RMS}$
Andes	98	93	0.69	25.9
Asia	269	265	0.92	38.3
E. African Rift	4	3	0.96	26.1
Indian Ocean	6	5	0.58	58.1
Mediterranean	188	172	0.96	25.2
Middle East	45	45	0.55	32.4
W. N. America	853	752	1.28	26.3
TOTAL EARTH	2933	2682	1.00	37.1

See Table 1 for explanations

icant for these same plates. For the Eurasian plate we find a significantly different angular velocity for the NNR-A model compared to NNR-NUVEL1A, indicating a discrepancy between Eurasia's present-day and geologic motion. For the Eurasian plate there is also a difference between the NNR and NNR-A Euler vectors. The NNR-A model includes the entire Mediterranean, Middle East, and central and southeast Asia deformation zones in the definition for the Eurasian plate, whereas in the NNR model we have solved for the motions within these deformation zones, as well as for the motions of microplates. Both deforming Asia as

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