



Long-term polar motion excited by ocean thermal expansion

Felix W. Landerer,^{1,2} Johann H. Jungclauss,³ and Jochem Marotzke³

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[1] Ocean warming is commonly considered unable to excite significant long-term trends in polar motion. Here, however, we argue that this assumption needs to be revised. We demonstrate that steric sea level rise leads to a distinct pattern of horizontal mass redistribution within ocean basins and hence to ocean bottom pressure changes that alter Earth's inertia tensor on decadal and longer time scales. Based on Earth system model simulations, we estimate that ocean warming leads to polar motion of 0.15 to 0.20 milli-arcseconds per one millimeter of thermal sea level rise. This is equivalent to a polar motion rate of about 0.47 milli-arcseconds per year towards 155°W to 160°W for current projections of steric sea level rise during the 21st century. The proposed polar motion signal is therefore not negligible in comparison to other decadal and secular signals, and should be accounted for in the interpretation of polar motion observations. **Citation:** Landerer, F. W., J. H. Jungclauss, and J. Marotzke (2009), Long-term polar motion excited by ocean thermal expansion, *Geophys. Res. Lett.*, 36, L17603, doi:10.1029/2009GL039692.

1. Introduction

[2] Redistribution of mass on or near Earth's surface causes changes in Earth's inertia tensor, and conservation of angular momentum implies that the position of Earth's rotation pole relative to the solid Earth adjusts accordingly [e.g., *Munk and MacDonald*, 1960; *Wahr*, 1982]. Several modes of mass redistribution in the atmosphere-ocean-land system can excite polar motion on time-scales from hours to centuries [*Munk and MacDonald*, 1960; *Lambeck*, 1980; *Ponte et al.*, 1998, 2002; *Gross*, 2007]. While observations of this polar motion provide a convenient integral constraint for global mass redistribution in the Earth system, the attribution of polar motion to underlying excitation mechanisms is ambiguous because different processes can integrate to similar polar motion. An inversion of polar motion observations for unknown geophysical properties and processes therefore needs to account for all known excitation mechanisms. One particular mechanism is related to mass exchange between the oceans and growing or melting land ice sheets, thus linking rates and sources of non-steric (mass-related) sea level change to changes of rotational parameters. However, *Munk* [2002] noted an inconsistency between twentieth century observations of rotational parameters and sea level rise (which has non-steric as well as

steric components). This so-called sea level enigma has since been at least partially resolved through an improved theory of rotational stability [*Mitrovica et al.*, 2006], but the relationship between the integral quantities sea level and Earth rotation continues to be of great interest in light of ongoing secular global climate change.

[3] In this letter, we revisit the subject of secular Earth orientation changes and focus on secular polar motion excited from steric sea level changes. Previous work focused on the effect and mechanisms related to non-steric sea level changes [e.g., *Munk and Revelle*, 1952; *Barnett*, 1990; *Munk*, 2002], which require a mass source outside of the oceans, such as melting or growing ice sheets. In contrast, steric sea level changes occur through density changes at constant ocean mass. Steric mass displacements have been assumed to be mainly vertical and small with a negligible influence on sea floor loading, and are therefore commonly not considered to excite sizable polar motion over long periods [*Munk and MacDonald*, 1960; *Lambeck*, 1980; *Peltier*, 1988; *Trupin*, 1993; *Chao*, 1994]. Notwithstanding these arguments, recent climate model simulations and a simple conceptual model have demonstrated that steric sea level rise through ocean warming leads to a specific pattern of horizontal mass redistribution within ocean basins [*Landerer et al.*, 2007a]. This pattern is strongly correlated to the ocean bathymetry: large, positive signals occur over shallow shelf areas, and smaller, mostly negative signals over abyssal ocean regions. To first order, the warming and expanding deep ocean spills over shallow shelf areas. Since steric sea level rise is a relatively slow process, it may provide an effective excitation mechanism of polar motion on decadal and longer time-scales. In what follows, we quantify the effect of steric sea level rise on polar motion using two state-of-the-art climate model projections of ocean density change over the twenty-first century.

2. Methods

[4] We compute the motion of Earth's rotation pole from the equatorial components of the effective angular momentum (EAM) functions, which can be split into two terms: a mass term, which relates the solid body rotation to ocean bottom pressure, and a motion term, which accounts for angular momentum carried by fluid motion relative to the solid Earth [*Barnes et al.*, 1983]. Here, we focus on the mass terms only. The vector $\chi_{1,2}^{mass}$ describes the motion relative to a fixed rotation axis in the standard geographic coordinate system (the components χ_1^{mass} and χ_2^{mass} point towards 0°E, and 90°E, respectively):

$$\chi_1^{mass} = -\frac{1.098R_e^2}{(\Delta I_{CA})g} \iint \Delta p \sin \theta \cos \theta \cos \lambda dS \quad (1)$$

¹Max Planck Institute for Meteorology, International Max Planck Research School on Earth System Modelling, Hamburg, Germany.

²Now at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

³Max Planck Institute for Meteorology, Hamburg, Germany.

$$\chi_2^{mass} = -\frac{1.098R_e^2}{(\Delta I_{CA})g} \iint \Delta p \sin \theta \cos \theta \sin \lambda dS \quad (2)$$

where the factor 1.098 accounts for surface-loading effects, $R_e = 6.371 \times 10^6$ m is the Earth's mean radius, dS the surface area element, $\Delta I_{CA} = 2.377 \times 10^{35}$ kg m² the difference between the polar and equatorial moments of inertia of Earth's mantle, $g = 9.81$ ms⁻² the gravitational acceleration, and Δp the surface mass anomaly.

[5] For the surface mass anomaly Δp , we use ocean bottom pressure changes that result from internal ocean mass redistribution under global warming conditions as projected by future changes of ocean temperature, salinity, and dynamic sea level in two independent coupled atmosphere-ocean general circulation models: one is ECHAM5/MPI-OM from the Max Planck Institute for Meteorology [Marsland *et al.*, 2003; Roeckner *et al.*, 2003; Jungclaus *et al.*, 2006], the other is GFDL-CM2.1 from the Geophysical Fluid Dynamics Laboratory [Griffies *et al.*, 2005; Stouffer *et al.*, 2006]. Both models are forced with observed atmospheric trace gas concentrations during the 20th century, then follow the same IPCC-A1B warming scenario [Nakicenovic and Swart, 2000] until 2100; from thereon, the forcing is held constant for another century. A land surface component in the models closes the hydrological cycle by routing river runoff to the ocean. To derive bottom pressure changes, we subtract steric sea level changes from dynamic sea level changes, taking the effects of temperature as well as salinity changes on density (steric = thermosteric + halosteric) into account. Locally, trends in the halosteric and thermosteric components can be of comparable magnitude, reflecting the significant impact of changing surface freshwater fluxes on the ocean's density structure [Landerer *et al.*, 2007a]. In the global mean, however, steric change is essentially thermosteric. Since both ocean models use the Boussinesq approximation, we add a spatially constant but time-varying correction to ensure proper ocean mass conservation [Greatbatch, 1994]. This approach is consistent with the fact that long-term changes of non-steric sea level changes from the melting of large ice sheets or glaciers are not included in either simulation. Similarly, there are no significant long-term trends in the freshwater fluxes from the atmosphere or land. Neither model includes the secondary potential from ocean loading and self-attraction, but these are expected to contribute less than 8% to Earth orientation variations [Thomas *et al.*, 2001]. All reported results are annual mean deviations relative to an unperturbed climate state from each model, and we have subtracted parallel control simulations for each model with no changes in greenhouse gas forcing to remove any small model drift that is not related to changes in the forcing. In focusing on longer periods, we apply a Butterworth low-pass filter with a cut-off period of 6 years to all time series.

3. Results

[6] Over the simulation period, the increased concentration of anthropogenic greenhouse gases leads to a significant steric sea level rise as the oceans take up heat. Global steric sea level is projected to increase by 0.24 m in ECHAM5/MPI-OM, and 0.25 m in GFDL-CM2.1 (time

mean for 2091–2100). In both models, the main feature of the accompanying ocean loading changes is their strong correlation to the bathymetry (Figure 1). Over shallow depths (less than about 500 m), ocean bottom pressure generally increases by values that are similar to the global mean steric sea level rise. Over deeper ocean regions, ocean bottom pressure generally decreases by values which are only a fraction of the global steric sea level rise. The patterns, signs and magnitudes of these changes are consistent with a simple conceptual mass redistribution model that links a specific pattern of horizontal mass redistribution to a global steric sea level rise [Landerer *et al.*, 2007b]. To first order, the global warming signal penetrates to deeper layers below the thermocline, and the steric expansion essentially pushes water up. This process would create a sea surface height gradient, but it appears that most of this gradient is not balanced by geostrophic flows, and the expanded water instead 'spreads' over shallower shelf regions such that the sea surface height gradients reach a new equilibrium [Landerer *et al.*, 2007a]. In the process, mass is effectively redistributed horizontally, which leads to large bottom pressure changes in particular over shallow areas.

[7] Some differences in the sign of the model's loading responses emerge over the abyssal regions of the Pacific Ocean. While ECHAM5/MPI-OM projects negative changes throughout this basin, GFDL-CM2.1 has an alternating pattern of negative and positive loading changes. However, the absolute values of the loading changes in either model in this region towards the end of the 21st century are relatively small (<0.005 m). Toward the middle of the 22nd century, the sign and amplitude of loading changes in the Pacific Ocean is similar in both models (see auxiliary material).¹ Over shallow shelf regions, where the sign is consistent between the models, amplitude differences can reach several centimeters. The complex interplay between radiative forcing, surface fluxes of heat and freshwater, pressure gradients, ocean current changes, and mass transport make it difficult to attribute the differences to any one of these processes. Small differences in the spatio-temporal patterns of secular ocean heat uptake and salinity change as well as wind forcing are the most likely candidates to explain the model spread of the simulated bottom pressures. While the overall pattern of projected bottom pressure changes is very distinct, even the largest trends will likely not be directly observable in the real ocean, as bottom pressure sensors are known for their notorious drift over time.

[8] From the spatial pattern of bottom pressure changes, we compute the polar motion vector (equation (1)). For the period between years 1860 to 2000, the orientation of the polar motion vector shows no preferred direction, with excitation amplitudes that are mostly below 10 milli-arcseconds (Figure 2). Beginning in the late 20th century, in phase with distinct global steric sea level rise in both simulations, significant trends in the polar motion vector emerge out of the interannual variability. The trend in the χ_1^{mass} component in both models is larger by a factor of about 2.4 compared to χ_2^{mass} . A linear least-squares estimate for the years 2000 to 2200 yields significant polar

¹Auxiliary materials are available in the HTML. doi:10.1029/2009GL039692.

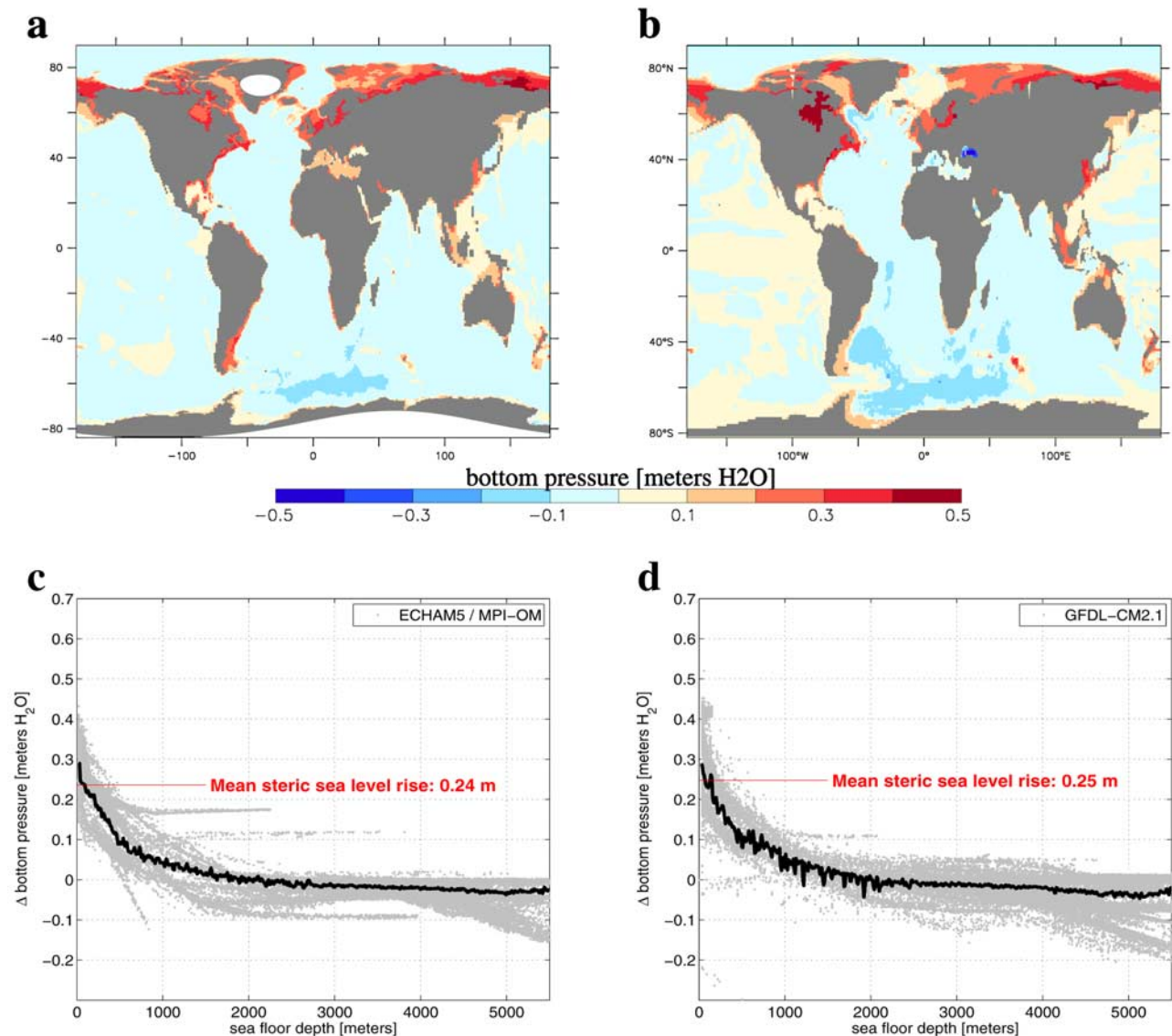


Figure 1. Ocean loading anomalies due to internal ocean mass redistribution. Pattern of simulated sea floor loading changes (time mean 2090–2099, relative to an unperturbed climate) for (a) ECHAM5/MPI-OM and (b) GFDL-CM2.1. Sea floor loading changes (time mean 2090–2099) as they occur for different depths (grey), and global mean loading changes for each depth (black) for (c) ECHAM5/MPI-OM and (d) GFDL-CM2.1. For the global mean loading changes in c and d, the grid-point anomalies have been binned into 10 meter depth intervals according to the model bathymetry.

motion rates of 0.45 milli-arcseconds per year (mas/a) for ECHAM5/MPI-OM, and 0.48 mas/a for GFDL-CM2.1. The trace of this trend is, to a very good approximation, linearly polarized towards 160°W in ECHAM5/MPI-OM, and towards 155°W in GFDL-CM2.1. As explained above, polar motion can also be excited from ocean current changes [Barnes *et al.*, 1983]. When we include this motion term in our analysis, the projected polar motion rates from the oceans are slightly reduced to 0.42 mas/a, and the direction is slightly changed towards 150°W (these values are from the ECHAM5/MPI-OM simulation). In comparison, contemporary polar motion is dominated by a secular trend towards 79°W at an average rate of about 3.5 mas/a as a consequence of the ongoing viscoelastic glacial isostatic adjustment (GIA) since the large continental ice sheets

melted about 10000 years ago [Gross and Vondrak, 1999; Peltier, 1998]. Superimposed on this rebound signal are irregular low-frequency wobbles of Earth's rotation pole that reach maximum amplitudes of 1 mas/a, but whose causes remain enigmatic [Gross, 2007]. The amplitude and direction of the projected polar motion reported here are markedly different from an earlier study by Ponte *et al.* [2002] (hereinafter referred to as PRG02), who used a similar forcing scenario but found no distinct polar motion trends. We conjecture that the main reason lies in the more accurate formulation of model physics and boundary conditions for the ocean models used here: ocean model resolution of the present study is $1\text{--}1.5^{\circ}$ vs. $2.5\text{--}3.75^{\circ}$ from PRG02, the models used here employ the more accurate free-surface formulation for sea surface height vs.

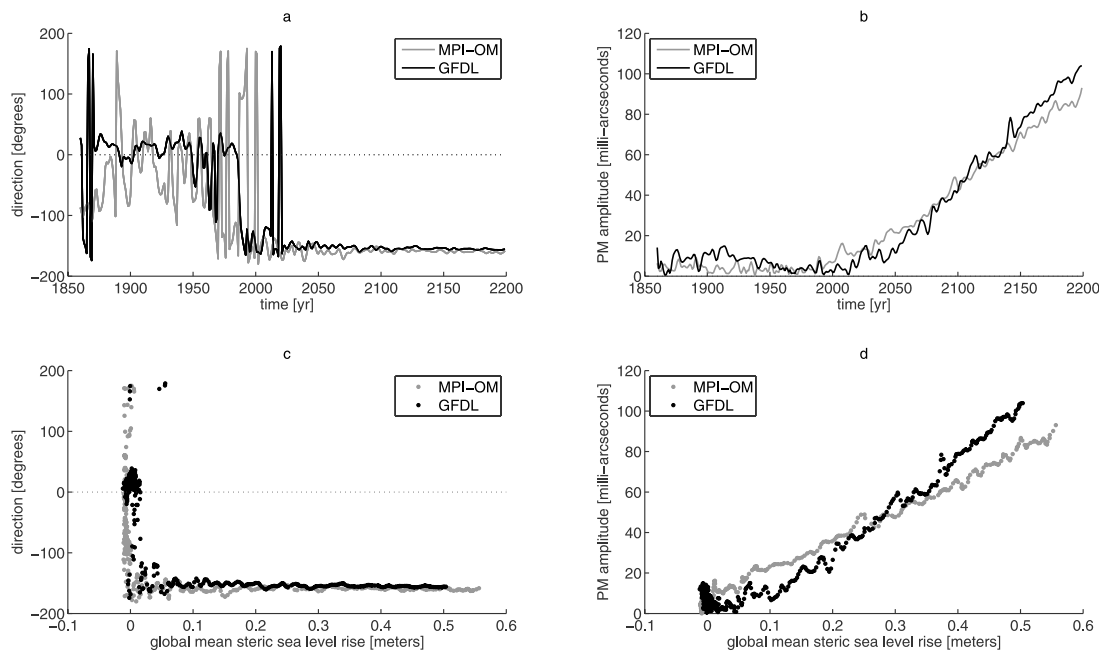


Figure 2. Polar motion induced by internal ocean mass redistribution, and its relation to global thermal sea level rise. (a) Direction and (b) the amplitude of the simulated polar motion excitation as a function of time; (c) direction and (d) amplitude of polar motion excitation as a function of global steric sea level rise. The data are filtered with a low-pass filter with a cut-off period of 6 years.

the less accurate rigid-lid formulation by PRG02, and the ocean model in PRG02 also required artificial flux adjustments. These aspects likely lead to the different patterns of simulated ocean bottom pressure changes and horizontal mass redistribution.

[9] As described above, the bathymetry-following bottom pressure changes are related to the global mean thermosteric sea level rise, which through equation (1) provides the argument for a causal relationship between global steric change and excitation of polar motion. For the time period between the years 1860 and 2200, a linear least-squares fit yields an excitation power of about 0.15 mas per 1 mm of steric sea level rise for ECHAM5/MPI-OM, and a somewhat higher rate of about 0.20 mas per 1 mm of steric sea level rise for GFDL-CM2.1 (Figure 2). The larger polar motion rate in GFDL-CM2.1 might be related to differences in the pattern of steric changes and circulation adjustments, which lead to slightly different patterns of horizontal ocean mass redistribution as discussed above. As a caveat, we note that the proposed relationship of polar motion and steric sea level change does not have to be linear: the pattern and rates of bottom pressure changes may vary over time even if the rate of global steric sea level rise remains constant. For the range of steric changes projected here, a linear dependence seems reasonable (Figure 2). In Figures 2c and 2d it is evident that polar motion can also be excited by purely dynamic ocean-internal mass redistribution with little or no change in global steric sea level (less than about 5 cm). When the steric change is below 5 cm, the root-mean square variability of the polar motion amplitudes in both models is 13 mas, which we take as an estimate of the background variability of the simulated ocean excitation of polar motion. For ECHAM5/MPI-OM, polar motion amplitudes cross this threshold once steric sea level has risen about 5.5 cm,

while for GFDL-CM2.1 the cross over occurs at about 13 cm.

[10] How big is the induced polar motion from steric relative to non-steric sea level rise? For non-steric sea level changes, the direction and rate depends mainly on the geographic position of the non-steric sea level source [Lambeck, 1980]. A globally uniform 1 mm sea level rise from Greenland melting corresponds to an excitation of about 3.4 mas towards 36°W , whereas a similar sea level rise from Antarctica melting moves the pole 0.74 mas towards 89°W . Therefore, non-steric sea level changes have an excitation power that can be larger by an order of magnitude compared to steric sea level change. Note, however, that over the time period from 1993 to 2003, the estimated non-steric sea level contributions from melting of Greenland (0.21 ± 0.07 mm/year) and Antarctica (0.21 ± 0.35 mm/year) are considerably smaller than the steric sea level rate (1.6 ± 0.5 mm/year) [Bindoff *et al.*, 2007], which would partly compensate for the higher excitation potential.

[11] As observations exist of global steric sea level rise and polar motion over the last 50 years, we use the regression coefficients derived above to assess the impact of this excitation mechanism over the observational period. The rate of thermal expansion of the global oceans during the last 50 years is estimated to lie between 0.3–0.7 mm/a [Cazenave and Nerem, 2004]. Taking a central value of 0.5 mm/a for the steric sea level change, and a mean regression slope of 0.17 mas/mm as inferred from the two climate model simulations, the warming signal during the last 50 years would have resulted in an average polar motion excitation of about 0.085 mas/a, which is roughly an order of magnitude less than observed decadal polar motion amplitudes. Evidently, thermal sea level rise over the last 50 years was too small to explain the observed decadal

fluctuations of polar motion. This also implies that polar motion excited by steric change does little towards solving any remaining sea level enigma as mentioned above.

4. Summary

[12] Our results demonstrate that horizontal mass redistribution from ocean warming and steric sea level rise has the potential to excite considerable polar motion on decadal to centennial time scales, contrary to conventional wisdom. The pertinent point of the polar motion excitation mechanism presented here is that it occurs at constant ocean mass, and therefore does not require ocean-external (non-steric) sources for sea level changes such as melting of high-latitude ice sheets or subpolar glaciers. While other excitation mechanisms played a more important role for decadal polar motion during the last 50 years, we conjecture that long-term polar motion will be increasingly influenced by a global steric sea level rise; the relative importance of the mechanism presented here depends on non-steric sea level rates from the melting of ice-sheets, which are still highly uncertain. The conclusion of our results is that polar motion excited by steric sea level change should be taken into account when long-period observations of polar motion are inverted to deduce geophysical parameters and other mass redistribution processes. On a more speculative note, polar motion observations may be able to provide an independent constraint on steric sea level change, but this requires that other trend sources can be accurately accounted for.

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J. H. Jungclauss and J. Marotzke, Max Planck Institute for Meteorology, Bundesstrasse 53, D-20146 Hamburg, Germany.

F. W. Landerer, Jet Propulsion Laboratory, California Institute of Technology, MS 238-600, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. (felix.w.landerer@jpl.nasa.gov)