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Rapid ice melting drives Earth's pole to the east

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[1] Space geodetic observations of polar motion show that around 2005, the average annual pole position began drifting toward the east, an abrupt departure from the drift direction seen over the past century. Satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) show that about 90% of this change is due to accelerated melting of polar ice sheets and mountain glaciers and related sea level rise. The close relationship between long-term polar motion and climate-related mass redistribution established using GRACE data indicates that accurately measured polar motion data offer an additional tool for monitoring global-scale ice melting and sea level rise and should be useful in bridging the anticipated gap between GRACE and follow-on satellite gravity missions. **Citation:** Chen, J. L., C. R. Wilson, J. C. Ries, and B. D. Tapley (2013), Rapid ice melting drives Earth's pole to the east, *Geophys. Res. Lett.*, *40*, 2625–2630, doi:10.1002/grl.50552.

1. Introduction

[2] The Earth's pole, the Northern Hemisphere point where the rotation axis intersects the surface, is in constant motion. Dominantly, the motion is circular (Figure 1), following a prograde path with a diameter of several meters, a superposition of the Chandler (~14 months) and Annual Wobbles [*Wilson and Haubrich*, 1976; *Gross et al*., 2003] maintained by the motion and redistribution of air and water. Since regular observations began in 1899, there has been an additional southward drift of the pole at a rate ~0.1m/yr along ongitude 70°W. The drift is attributed to Pleistocene deglaciation (Post Glacial Rebound, or PGR) [e.g., *Mitrovica et al*., 2006] and other sources of mass movement or redistribution in the solid Earth [e.g., *Spada et al*., 1992; *Steinberger and O'Connell*, 2002; *Doubrovine et al*., 2012; *Creveling et al*., 2012], whose time scales require treatment of the Earth as a viscoelastic body. There is also irregular motion of the pole at intermediate time scales of a few years, for which a purely elastic treatment of the Earth should be sufficient. We show here that polar motion at these intermediate time scales is likely climate related and that increased ice melting rates are the main cause of an abrupt eastward turn of the mean pole position around 2005 (Figure 2). This change has been noted previously and is the reason that the International Earth Rotation and Reference Systems Service (IERS) 2010 Conventions adopted a higher order polynomial for the definition of the mean pole [*Cheng et al*., 2011; *Petit and Luzum*, 2010]. A previous study [*Roy and Peltier*, 2011] examined similar, but relatively minor long-term rate changes in polar motion (and also a similar rate change in the degree-2 zonal gravity coefficient J2) in around 1992 and speculated a possible connection between the rate changes and polar ice sheets ice melt.

[3] Polar motion is measured relative to the mean epoch of the International Terrestrial Reference Frame using coordinates X and Y (see Figure 1), in angular units of milliseconds of arc (1 mas = ~3 cm of polar motion). Space geodetic observations of polar motion, introduced in the early 1980s, include very long baseline interferometry, satellite laser ranging (SLR), and lunar laser ranging. In the 1990s, the Global Navigation Satellite Systems (GPS and others) became a dominant contributor, and the combined space observations now yield ~0.03 mas daily pole position precision (~1 mm on the Earth surface) [*IERS Annual Report*, 2008–2009]. This is at least 2 orders of magnitude better than the precision of monthly pole position measurements made in the early twentieth century. For this reason, we restrict analysis to the post-1982 period, using time series of polar motion and polar motion excitation from ocean and atmospheric sources derived from global data-assimilating climate models.

[4] Additional data are valuable in deciphering causes of low-frequency polar motion, the most important being GRACE (Gravity Recovery and Climate Experiment) satellite gravity measurements. Since 2002, the U.S.-German jointly sponsored GRACE mission has been providing a precise survey of the Earth's time-variable gravity field, with unprecedented temporal and spatial sampling [*Tapley et al*., 2004]. GRACE time-variable gravity fields provide a means of measuring temporal and spatial variations of mass redistribution within the Earth system, from terrestrial water storage (TWS) change, ice mass change, and sea level variation, to solid Earth deformation [*Cazenave and Chen*, 2010]. GRACE data have documented accelerated ice melting rates in Greenland and Antarctica beginning about 2005 or 2006 [*Chen et al*., 2009; *Velicogna*, 2009; *Rignot et al*., 2011], roughly coincident with the abrupt change in polar motion.

[5] The main objective of this study is to understand what are the primary driving forces of the abrupt change in the mean pole position, through investigating contributions to observed polar motion from mass changes of different components of the Earth system, including polar ice sheets, mountain glaciers, land hydrology, atmosphere, and ocean, using GRACE time-variable gravity fields and estimates from advanced climate models.

Additional supporting information may be found in the online version of this article.

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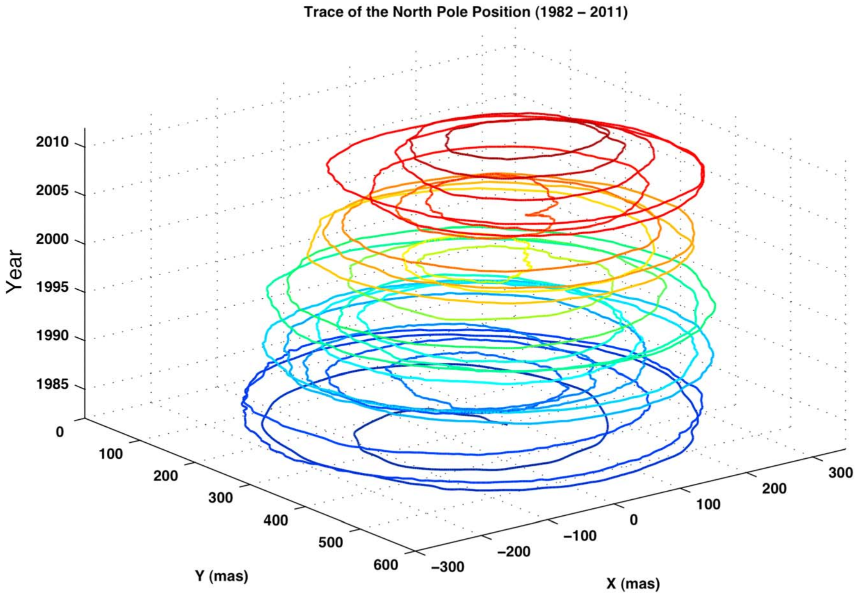


Figure 1. Daily pole positions for 1982–2011 in the left-handed (*X*, *Y*) coordinate system. The vertical axis shows time in years using color to distinguish individual years. *X* and *Y* are International Earth Rotation and Reference Systems Service (IERS) combined solutions (EOP 08 C04).

2. Data Processing

2.1. Polar Motion Observations and Excitations

[6] Polar motion (*X*, *Y*) time series are from the International Earth Rotation and Reference Systems Service (IERS) combined Earth Orientation Parameters (EOP) solutions 08 C04 (available at http://hpiers.obspm.fr/eop-pc/analysis/excitactive.html). The EOP 08 C04 daily time series cover the period 1962 to the present. The focus here is on polar motion data taken since 1982, which are based upon space geodetic observations. Prior data, mainly from optical measurements, have significantly larger uncertainty. Polar motion is excited by both redistribution of mass within the Earth system and changes in relative motion with respect to Earth-fixed coordinates, mainly due to atmospheric winds and ocean currents [e.g., *Gross et al*., 2003]. An excitation time series (χ_1, χ_2) is obtained by application of a linear filter to the two components (*X*, *Y*) of the polar motion time series. The filter removes the Earth's resonant response near the 14 month Chandler period [*Wilson*, 1985], and its transfer function approaches unity near zero frequency, so long-period variations in excitation and polar motion are

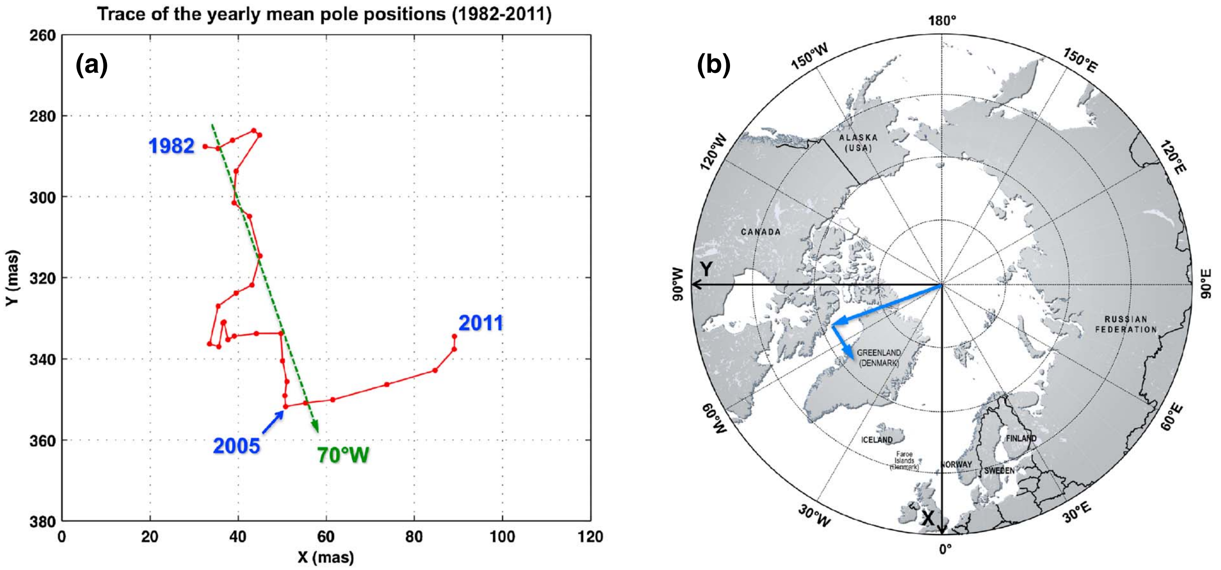


Figure 2. (a) Yearly mean pole positions (red dots, connected by lines) for 1982–2011 in the left-handed (*X*, *Y*) coordinate system. Annual variations and Chandler Wobble are first removed, before computing yearly means. The green arrow indicates the average drift direction (longitude ~70°W) of the mean pole over the last century. (b) Illustration of the mean pole drift directions on the Earth surface. The long blue arrow represents the last century long-term drift, ~70°W, and the short arrow represents the direction for the period 2006–2011.

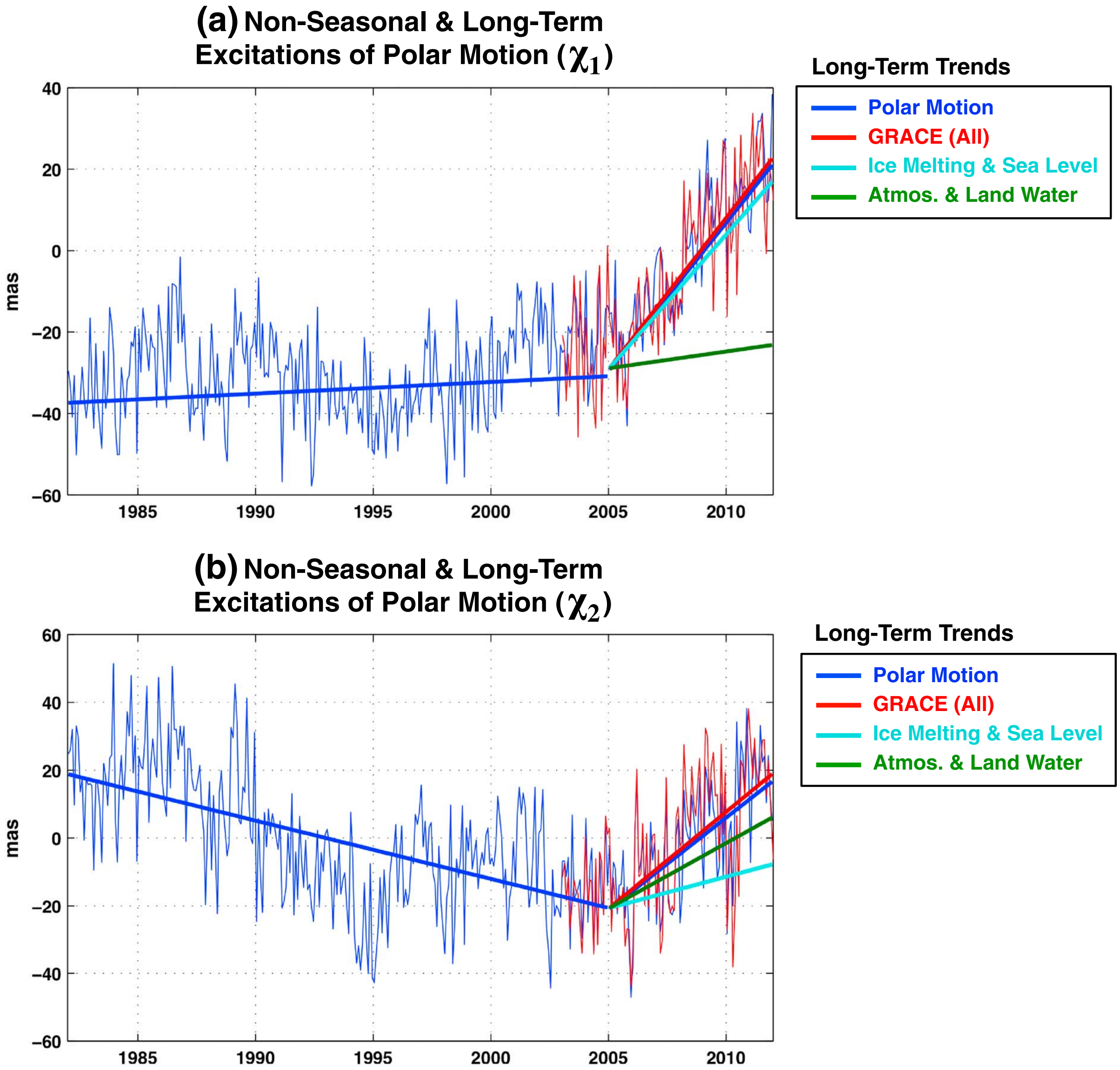


Figure 3. (a) and (b) Monthly non-seasonal and long-term mass-term excitations [in units of milliarcsecond (mas)] derived from observed polar motion excitations χ_1 and χ_2 (blue curves, with wind and current contributions removed), superimposed by climate contributions observed by GRACE (red curves, which include contributions from the atmosphere, ocean, land hydrology, and ice melting). Annual and semiannual variations have been removed using a least-squares fit. Long-term trends for the two periods 1982.01–2004.12 and 2005.01–2011.12, estimated from least squares fit are shown in thick straight lines for comparison. GRACE trends (red for all, cyan for ice melting and sea level rise, and green for atmosphere and land water) are only provided for the period 2005.01–2011.12.

essentially the same. Observed polar motion excitations χ_1 and χ_2 are provided by the IERS online conversion tool (available at http://hpiers.obspm.fr/eop-pc/analysis/excitactive.html), and the linear transfer function for doing this uses a Chandler period of 433 days and a quality factor of 175 applied to the EOP 08 C04 time series.

[7] Before comparing observed polar motion excitations with GRACE-observed mass excitations, we need to remove wind and ocean current contributions. Daily wind excitations are computed from the National Centers for Environmental Prediction (NCEP) reanalysis wind fields integrated from the surface to 10 mbar levels of the atmosphere. The ECCO ocean current excitations are derived from a combination of the 50 year ECCO simulation (1949–2002; available at http://euler.jpl.nasa.gov/sbo/sbo_data.html) [*Gross et al.*, 2003] and the ECCO kf080 assimilation (1993–2012). The two time series are combined after removing a mean difference for the overlapping period (1993–2002). Possible inconsistency between the two ECCO models will not affect the present study, as our focus is the period since 2002 where a comparison with GRACE observations is possible. All excitation time series (daily polar motion observations, daily NCEP wind, and 10 day ECCO current) are averaged into monthly intervals for comparisons.

[8] The observed mass excitations contain other long-term effects from the solid Earth, including PGR effects, after the removal of the ice load since the Last Glacial Maximum [*Peltier*, 2009]. These effects require treatment of the Earth as viscoelastic, whereas the focus here is on time scales of a few years where an elastic assumption should be adequate.

Table 1. Mass-Term Polar Motion Excitation Rates (in mas/yr) for χ_1 and χ_2 From Polar Motion Observations and GRACE Estimates for the Entire Geophysical Fluids System (noted as "GRACE (All)", From ice Melting of Polar Ice Sheets and Mountain Glaciers and Corresponding Sea Level Rise (Noted as "GRACE Ice and Sea Level"), and From Atmospheric Pressure and Land Water Storage (Noted as "GRACE Atmos. and Water")

	χ_1 Rate (mas/yr)		χ_2 Rate (mas/yr)	
Mass Excitations	(1982–2004)	(2005–2011)	(1982–2004)	(2005–2011)
Polar Motion	0.28 ± 0.06	7.26 ± 0.17	-1.71 ± 0.08	5.45 ± 0.25
GRACE (All)		7.45 ± 0.64		5.71 ± 1.53
GRACE Ice and Sea Level		6.62 ± 0.52		1.87 ± 1.30
GRACE Atmos. and Water		0.83 ± 0.66		3.86 ± 0.35

Two separate rates (for periods1982–2004 and 2005–2011) are provided for polar motion observations, and GRACE rates are only estimated for the 2005–2011 period.

We remove PGR effects on χ_1 and χ_2 (of~0.33 and -1.73 mas/yr, respectively) using a PGR model [*Geruo et al.*, 2013], which is an updated version of the *Paulson et al.* [2007] model. The same PGR model [*Geruo et al.*, 2013] is also used to remove PGR effects in the GRACE estimates. PGR model error will affect the estimated long-term trends of GRACE and polar motion, but as the same linear PGR trends are removed from both GRACE and polar motion, PGR model error will not affect the GRACE-polar motion comparisons and conclusions of the present study. Furthermore, the rate changes discussed here are independent of PGR model error, which is considered a linear signal in the studied time scales.

2.2. Polar Motion Excitations From GRACE and Climate Models

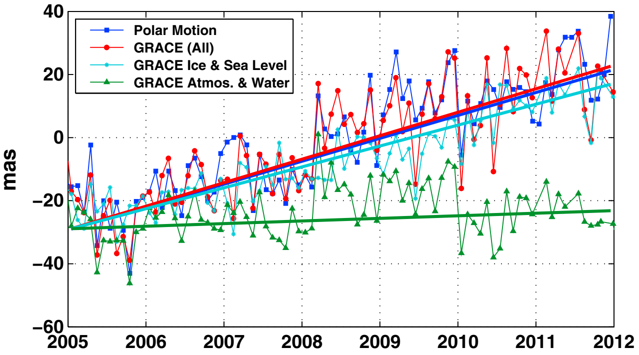
[9] We use GRACE Release-05 (RL05) monthly gravity solutions provided by the Center for Space Research (CSR), The University of Texas at Austin. The gravity solutions cover the period January 2003 to December 2011. We have replaced the degree-2 harmonic (Stokes) coefficients (C21, C22, S21, S22, and C20) by the SLR estimates provided by CSR [*Cheng and Ries*, 2012]. GRACE estimates of surface mass redistribution have limited spatial resolution reflected by the maximum degree and order 60 of the RL05 spherical harmonic expansion, with additional loss of resolution from filtering to suppress error sources (high-degree and high-order noise and longitudinal stripes) [*Wahr et al.*, 2006; *Chen et al.*, 2007]. Polar motion excitations due to mass change over polar ice sheets, mountain glaciers, TWS, and sea level change can be computed from GRACE-derived surface mass change. However, a major challenge is the leakage effect between land (especially coastal ice) and ocean signals and how to reduce the leakage effect and better separate and quantify different contributions.

[10] The forward modeling method has been proved to be successful in effectively reducing leakage effect on regional studies [e.g., *Chen et al.*, 2006, 2009; *Wouters et al.*, 2008]. Here we extend the forward modeling method from regional to global scales and apply it to GRACE monthly gravity solutions to derived surface mass change grids, which are expected to contain less leakage, or improved recovery of ice loss signals. Full details of the forward modeling approach and related computations are provided in the online supporting information). A brief synopsis is the following.

[11] 1. On a global 1° × 1° grid, we first assign initial trial mass changes (e.g., GRACE apparent mass changes after filtering and smoothing) to each grid point over land and ocean. The trial mass grid is converted into spherical harmonics (with the same resolution as GRACE data).

[12] 2. We then convert the spherical harmonics of the trial mass grid back to a spatial grid after applying GRACE data processing procedures to the spherical harmonic

(a) Non–seasonal χ_1 from Polar Motion and GRACE



(b) Non–seasonal χ_2 from Polar Motion and GRACE

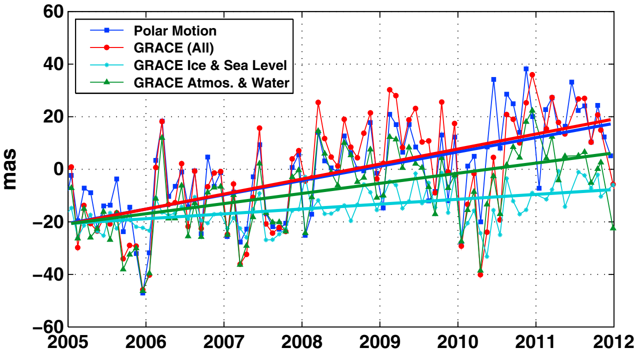


Figure 4. (a) and (b) Monthly non-seasonal and long-term mass-term excitations [in units of milliarcsecond (mas)] derived from observed polar motion excitations χ_1 and χ_2 (blue curves, with wind and current contributions removed), superimposed by climate contributions observed by GRACE for the 7-years period 2005.01–2011.12 (red for all, cyan for ice melting and sea level rise, and green for atmosphere and land water). Annual and semi-annual variations have been removed using least-squares fit. The long-term trend (for each curve), estimated from a least-squares fit is shown in thick straight line for comparison (in the same color as the fitted curve). The estimated rates and uncertainties of these long-term trends are listed in Table 1.

representation of the trial mass field (including truncation and smoothing).

[13] 3. We compare the processed trial spatial grid with the GRACE apparent mass grid and adjust the trial mass rates accordingly. Steps 1–3 are repeated iteratively, until the processed trial mass grid matches the GRACE apparent mass grid.

[14] We then compute polar motion excitations from different components of the climate system (e.g., Antarctica, Greenland, mountain glaciers, TWS, and sea level) using the GRACE-derived global mass fields from forward modeling. Atmospheric and oceanic effects have been removed from GRACE gravity solutions during the GRACE de aliasing process, so GRACE mass changes over land account for terrestrial hydrology and ice mass change. To compute atmospheric and oceanic contributions, we use the supplementary GAC data product provided by the GRACE project (see supporting information for more information).

3. Results and Discussions

[15] After removing wind and ocean current contributions from the observed polar motion, the residual excitations of χ_1 and χ_2 for 1982–2011 are shown in Figures 3a and 3b, respectively. Seasonal (annual and semi-annual sinusoidal) variations have been removed using unweighted least squares fit. Both χ_1 and χ_2 residuals show a clear change in direction around 2005–2006, similar to that in yearly average pole coordinates (X, Y) (Figure 2a). Figure 3 shows the unweighted least squares fit linear trends (in blue) to residual (χ_1, χ_2) series computed separately for 1982–2004 and 2005–2011 with numerical values of slopes given in Table 1. Figures 3a and 3b also show (in red) monthly time series of polar motion excitation predicted from GRACE, for the period 2003–2011, after removing seasonal variations. Because GRACE monthly gravity field solutions provide surface mass changes for the entire Earth, it is possible to compute contributions from individual sources. Figures 3a and 3b also show the least squares fit linear trends for 2005–2011 due to: atmosphere plus water storage on land (Atmos. and Water); the sum of ice melting plus sea level change (Ice and Sea Level); and the total GRACE prediction (GRACE All). There is excellent agreement between polar motion excitation and GRACE predictions, indicating that the change in the drift of the pole around 2005 is due to mass variations in the climate system. Additional details with monthly time series of separate GRACE contributions are shown in Figures 4a and 4b. Linear rates in Figures 4a and 4b are given in Table 1. Figures 3 and 4 show that melting from polar ice sheets and mountain glaciers, and related sea level rise change, dominate changes in χ_1 (or long period variations in X), accounting for over 90% of the observed long-term rate (6.62 ± 0.52 versus 7.26 ± 0.17 mas/yr; see Table 1). Atmospheric and terrestrial water storage changes make a minor contribution to X, but are more important than ice and sea level for Y.

[16] This study shows that accelerated ice melting combined with resulted speed-up of sea level rise in recent years is the dominated driving force of the observed east-bound drift of the mean pole position. At long-term time scales, polar motion X (or excitation χ_1) is particularly sensitive to mass redistribution in the cryosphere and ocean. This study has not only confirmed the close connection between observed polar wander and long-term mass change in the climate system and successfully explained the observed change of polar wander direction (since around 2005 or 2006) but also reaffirmed the acceleration of ice melting over polar ice sheets and mountain glaciers in recent years.

[17] Polar motion is one of the most accurately determined geodetic quantities derived from a multi-technique observing program of international scope (with an accuracy reaching ~0.03 mas over variations of up to few hundred mas). Uncertainties of the observed mean pole positions are mostly negligible. The significantly larger east-bound drift rate of ~9 mas/yr (combining χ_1 and χ_2) during the period 2005 to 2011 compared to less than 2 mas/yr over the previous 23 years (1982–2005) clearly represents true signal driven by mass redistribution in the Earth system. Uncertainties in wind and ocean current excitations estimated from atmospheric and oceanic models will affect the observed mass-term polar motion excitations (as shown in Figure 3), but those uncertainties will not likely change the main conclusion of the present study (because at long-term time scales, wind and ocean current only play a minor role in polar motion excitations than that from mass terms). As mass movement in the solid Earth occurs at much longer time scales, the observed speed-up of east-bound polar wander provides an independent observational constraint to ice melting and sea level rise, two key monitors of global warming and the Earth climate system. The direct connection between long-period polar motion and climate-related mass redistribution demonstrated here also offers some promise that climate system changes can be monitored by geodetic methods through the several years gap that is likely prior to the launch of a GRACE follow-on mission.

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