Detection of the Earth rotation response to a rapid fluctuation of Southern Ocean circulation in November 2009

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[1] At seasonal and shorter periods the solid Earth and its overlying geophysical fluids form a closed dynamical system, which (except for tidal forcing) conserves its total angular momentum. While atmospheric effects dominate changes in the Earth's rate of rotation and hence length-of-day (LOD) on these time scales, the addition of oceanic angular momentum (OAM) estimates has been shown to improve closure of the LOD budget in a statistical sense. Here we demonstrate, for the first time, the signature of a specific, sub-monthly ocean current fluctuation on the Earth's rotation rate, coinciding with recently-reported anomalies which developed in southeast Pacific surface temperature and bottom pressure fields during late 2009. Our results show that concurrent variations in the Antarctic Circumpolar Current (ACC), which saw a sharp drop and recovery in zonal transport during a two-week period in November, were strong enough to cause a detectable change in LOD following the removal of atmospheric angular momentum (AAM) computed from the Modern Era Retrospective Analysis for Research and Applications (MERRA) database. The strong OAM variations driving the LOD-AAM changes were diagnosed from ocean state estimates of the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO) and involved roughly equal contributions from the current and pressure terms, with in situ confirmation for the latter provided by tide-corrected bottom pressure recorder data from the South Drake Passage site of the Antarctic Circumpolar Current Levels by Altimetry and Island Measurements (ACCLAIM) network. **Citation:** Marcus, S. L., J. O. Dickey, I. Fukumori, and O. de Viron (2012), Detection of the Earth rotation response to a rapid fluctuation of Southern Ocean circulation in November 2009, *Geophys. Res. Lett.*, *39*, L04605, doi:10.1029/2011GL050671.

1. Introduction

[2] Angular momentum in the total Earth system (aside from tidal effects) is conserved, with exchanges between the main reservoirs (liquid outer core, solid crust and mantle, and fluid atmosphere, oceans, and land hydrology) dominating on different time scales. At periods of a few years or less changes in the solid Earth's rotation rate, and hence the length-of-day (LOD), are forced mainly by the atmosphere [cf. *Hide and Dickey*, 1991, and references therein]; indeed this relationship is strong enough that specific changes in LOD have been attributed by earlier investigators to localized atmospheric forcing events [e.g., *Salstein and Rosen*, 1994]. For some time it has been known that oceanic angular momentum (OAM) also makes a detectable contribution to LOD changes on seasonal and shorter time scales [e.g., *Marcus et al.*, 1998; *Johnson et al.*, 1999; *Ponte and Stammer*, 2000; *Ponte and Ali*, 2002; *Dickey et al.*, 2010], with OAM series calculated from numerical models showing a significant reduction in statistical measures of residual LOD variations after removal of the stronger atmospheric effects. Here we establish, for the first time, a link between a specific, short-period (14-day) fluctuation in OAM and its rotational signature in LOD with atmospheric effects removed, using oceanic state estimates of the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO [cf. *Fukumori*, 2002]). The data employed in this study are outlined in Section 2, and the time-domain aspects of the global OAM signal and its forcing are presented in Section 3. In Section 4 the Southern Ocean origins of the OAM signal are examined, and its geodetic signature is reviewed in Section 5. A summary and discussion of the results, and of their relationship with earlier findings regarding the Southeast Pacific Ocean anomaly of late 2009, are provided in Section 6.

2. Data Employed

[3] Earth rotation measurements were taken from the SPACE2009 data set, produced at JPL by combining retrievals from the space-geodetic techniques of lunar and satellite laser ranging, very long baseline interferometry and GPS in a Kalman filter [*Ratcliff and Gross*, 2010]; here the daily tide-corrected geodetic values of LOD archived at 12Z were accessed for the period 1 January 2009 – 28 May 2010. The formal (1-σ) error for the series over the time period studied here is 0.01 msec or less. Atmospheric angular momentum (AAM) was calculated from the NASA Global Modeling and Assimilation Office (GMAO) Modern Era Retrospective Analysis for Research and Applications (MERRA [cf. *Rienecker et al.*, 2011]) archive, using daily-averaged zonal winds integrated from the surface to 1 hPa and hydrostatic pressure effects computed using the inverted barometer (IB) assumption.

[4] Time series of OAM were obtained from run KF080 of the ECCO model, which employed a near-global (75°N–75°S) grid with $1° \times 1°$ resolution in the extratropics and 46 vertical levels. The model was spun up for 10 years from climatological values and then forced by momentum, heat and freshwater fluxes from the NCEP reanalysis [*Kalnay et al.*, 1996] starting in 1993, with subsurface temperature and altimetric sea surface height assimilated into the ocean state estimates [*Fukumori*, 2002]. The daily OAM was derived

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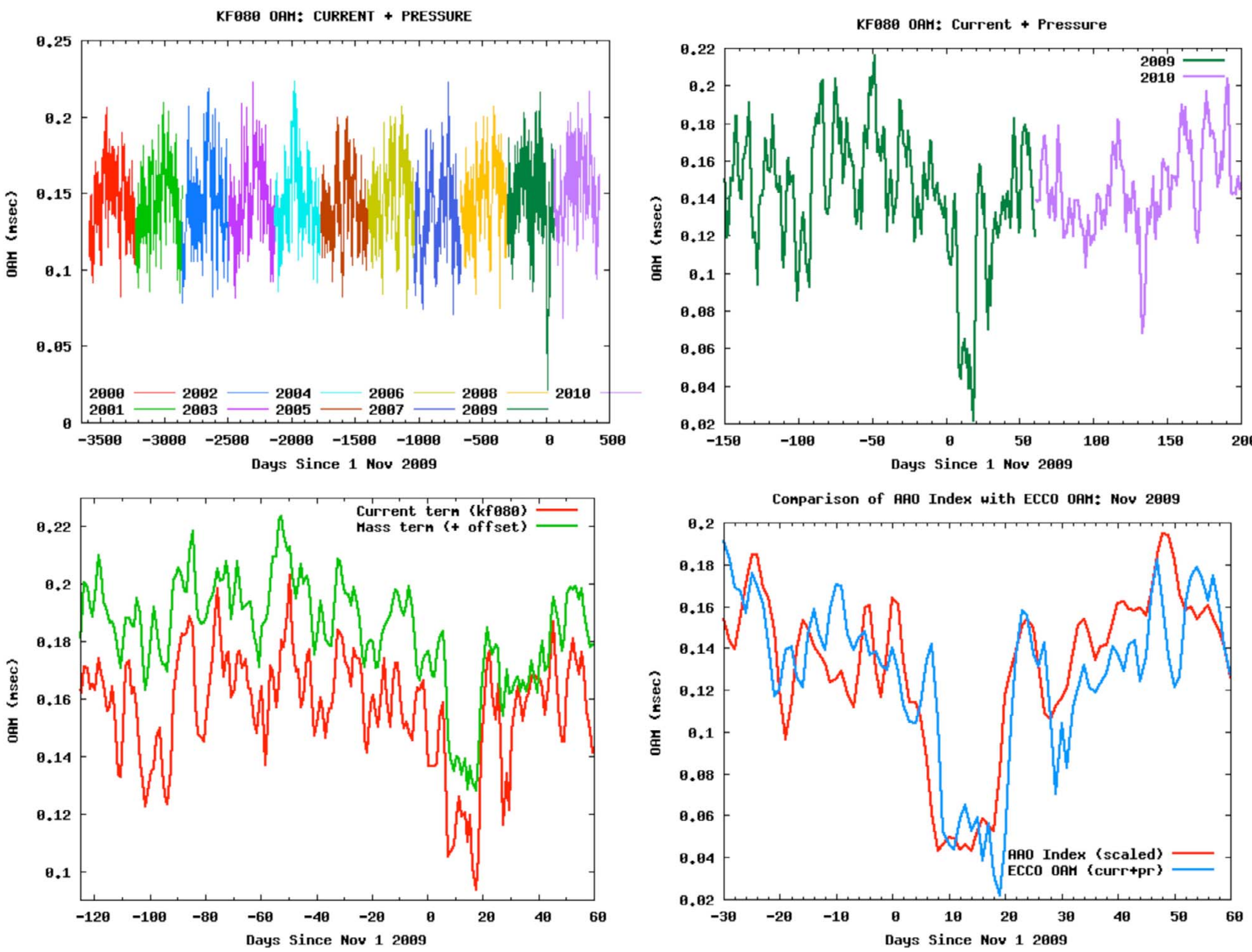

Figure 1. Variations of total oceanic angular momentum estimated by altimeter-assimilated run KF080 of the ECCO model, on different time scales: (top left) over the last decade – note the unique size and strength of the negative OAM anomaly in late 2009, the subject of this study; (top right) over the last half of 2009 and first half of 2010 – note the sharp drop and recovery of the OAM over a 2-week period encompassing the anomaly; (bottom left) over the last half of 2009 – note the near equality of the global pressure and current terms, consistent with the close geostrophic balance expected at high latitudes (see auxiliary material); (bottom right) over 90 days surrounding the anomaly – note the close similarity of the Antarctic Oscillation Index (AAO – arbitrary units) to the OAM, which follows it at a lag of about 2 days.

from vertically-integrated zonal currents and bottom pressure, with corrections applied to the planetary angular momentum to account for non-physical changes in total ocean mass [cf. *Marcus et al.*, 1998] and the elastic response of the solid Earth, and expressed in units of equivalent length-of-day [*Gross et al.*, 2004]. In addition the full model states were saved as non-overlapping 10-day averages for each year of the run, and the values for 2009 were accessed to compute the diagnostic quantities used in Section 4 to investigate the geographic origins of the global OAM anomaly.

[5] Bottom pressure recorder (BPR) data were obtained from the South Drake site (60° 51′ S, 54° 43′ W, depth 989 m) maintained by the Antarctic Circumpolar Current Levels by Altimetry and Island Measurements (ACCLAIM) program, at 15-minute intervals for the period 25 June 2009 (following a discontinuity in the data) through 25 November 2009 (when the South Drake BPR series ends). The data were averaged to hourly values and then passed through the 39-point Doodson X0 filter provided by the ACCLAIM website to remove short-period tides; the fortnightly (Mf and Mt) tides were subsequently removed by least-square fitting a mean and harmonics to the hourly filtered series at the corresponding frequencies. Finally, daily values of the Antarctic Oscillation (or Southern Annular Mode) index, representing the time-varying amplitude of the first EOF of the 700 hPa height anomaly field poleward of 20°S, were obtained from the Climate Prediction Center.

3. Global OAM Signal

[6] Figure 1 (top left) shows a time series of the axial component of the total (current + mass) global OAM for the years 2000–2010, diagnosed as a daily average of hourly output from the ECCO estimate. A sharp minimum, by far the largest anomaly during this portion of the run, is visible in late 2009. Figure 1 (top right), showing the axial OAM from mid-2009 to mid-2010, indicates that the OAM entered the anomaly abruptly during November 8, and recovered almost as rapidly on November 20–21 2009, having a duration of no more than two weeks. Remarkably the pressure and current terms made nearly equal contributions to the anomaly (Figure 1, bottom left), consistent with a close

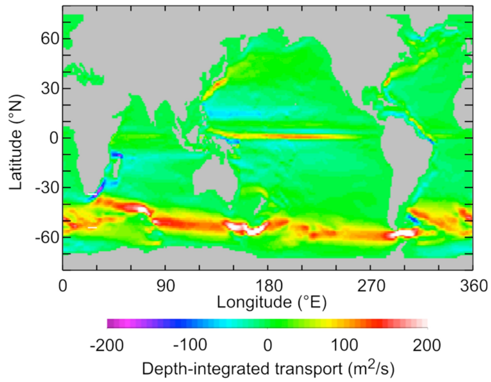

Figure 2. The time-mean, depth-integrated volume transport per unit meridional distance and time (m^2/sec) for 1993–2010, taken from ECCO run KF080. Note that the flow around the Southern Ocean has a broader and generally more northward latitudinal extent than current through the Drake Passage, thereby increasing its contribution to global OAM anomalies.

geostrophic balance between the motion and mass fields (see auxiliary material).[1]

[7] Interestingly, the timing of the OAM anomaly coincided closely with a dip in the Antarctic Oscillation (AAO) index, also known as the Southern Annular Mode (SAM [cf. *Thompson and Wallace*, 2000; *Hughes et al.*, 2003]), with the OAM following the AAO drop and recovery at a lag of approximately two days (Figure 1, bottom right). *Webb and de Cuevas* [2007] found a similar two-day lag between applied wind stress and the response of the Antarctic Circumpolar Current (ACC) in numerical experiments using the OCCAM global ocean model, with a largely barotropic response facilitating rapid transfer of the surface wind forcing to the underlying topography. This is consistent with our results for the November 2009 case, suggesting that the global OAM anomaly shown in Figure 1 was largely driven by mass and current changes associated with the ACC, with concomitant changes in the Earth's rotation forced by anomalous torques on the bottom topography.

4. Southern Ocean Flow Fields

[8] The ACC forms the largest continuous circulation in the global ocean [e.g., *Zlotnicki et al.*, 2007, and references therein], with climatological transport estimated between 120 and 160 Sv (1 Sverdrup = 10^6 m^3/sec). For a zonally continuous ring of current at the latitude of the Drake Passage the contribution of the transport term to LOD is approximately 1.4 μsec / Sv [*Dickey et al.*, 1993], giving a mean source from currents of about 0.2 msec; note that the associated geostrophic pressure term contributes in the same sense to the OAM [cf. *Ponte and Stammer*, 2000], since an eastward current is accompanied by a south-to-north pressure gradient (in the Southern Hemisphere), such that the associated equatorward displacement of mass increases the ocean's axial moment of inertia and hence its planetary angular momentum.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050671.

[9] The time-mean, depth-integrated zonal transport computed from the ECCO estimate (Figure 2) illustrates that the ACC, bounded to the north by Africa, Australia and New Zealand, has a broader latitudinal extent than that defined by the Drake Passage [see also *Sokolov and Rintoul*, 2009, Figure 1]. The climatological angular momentum contribution of the ECCO currents per degree of latitude at each of the four passages is shown in Figure 3 (top left; lines with symbols), along with the anomalous transport computed for a ten-day period centered on 11 November 2009, covering the initial phase of the OAM anomaly (lines without symbols). The zonal current is evidently weaker than the mean during the OAM anomaly at all four locations, with some indication of a poleward shift in the net transport in the two widest passages (Africa and Australia), where the transport reduction is largest on the northern flank of the current. A comparison of 10-day average cross sections of the transport through the Drake Passage, spanning the time of the anomaly (Figure 3, top right), shows that the November 7–16 mean had the lowest value of the six 10-day periods considered at all latitudes, with some indication of local minima near 58.5°S and 62.5°S. The second-lowest transport occurs during the November 17–26 period, overlapping the last half of the global OAM anomaly, with minima at the same latitudes.

[10] A climatological cross-section of zonally-averaged Southern Ocean current angular momentum from the ECCO estimate is shown in Figure 3 (bottom left; red line); the mean OAM-weighted latitude for the eastward flow (green line) is found near 51°S, or approximately 8° equatorward of the Drake Passage. Interestingly the global OAM current-term anomaly, as seen in the 10-day averages spanning the event (Figure 3, bottom right; green line), closely resembles that which would be generated by the estimated transport through the Drake passage if it extended uniformly around the globe at the mean ACC latitude of 51°S (red line); a similar result is obtained by summing the zonal OAM across latitudes 40°S-70°S (blue line). Note that the sizes of the OAM anomalies due to currents are somewhat attenuated by the 10-day averaging of the gridded transport fields in the model output, showing an amplitude of about 0.03 msec here compared to roughly 0.06 msec for the daily-averaged global series in Figure 1 (bottom left). The modeled Drake Passage transport anomaly reaches approximately 17 Sv in magnitude during the November 7–16 averaging period (not shown), amounting to ∼13% of the mean ECCO transport (∼130 Sv) over the last decade.

5. Geodetic and Observational Validation

[11] Figure 4 (top) shows a comparison of the LOD-AAM residual (green line) with OAM derived from the ECCO model (blue line), for a period of 201 days encompassing the November 2009 anomaly. Removal of a best-fitting mean and trend from both series reveals good agreement between the two data types, with a correlation coefficient of r = 0.60 over the time interval shown, significant at the 99% level assuming that the 14-day period of the anomaly corresponds to one temporal degree of freedom. If the 2-week OAM anomaly is replaced by constant values (dotted line), the correlation coefficient for the full 201-day period drops to r = 0.36, still significant at the 90% level but considerably reduced. Also plotted (with arbitrary vertical offset and

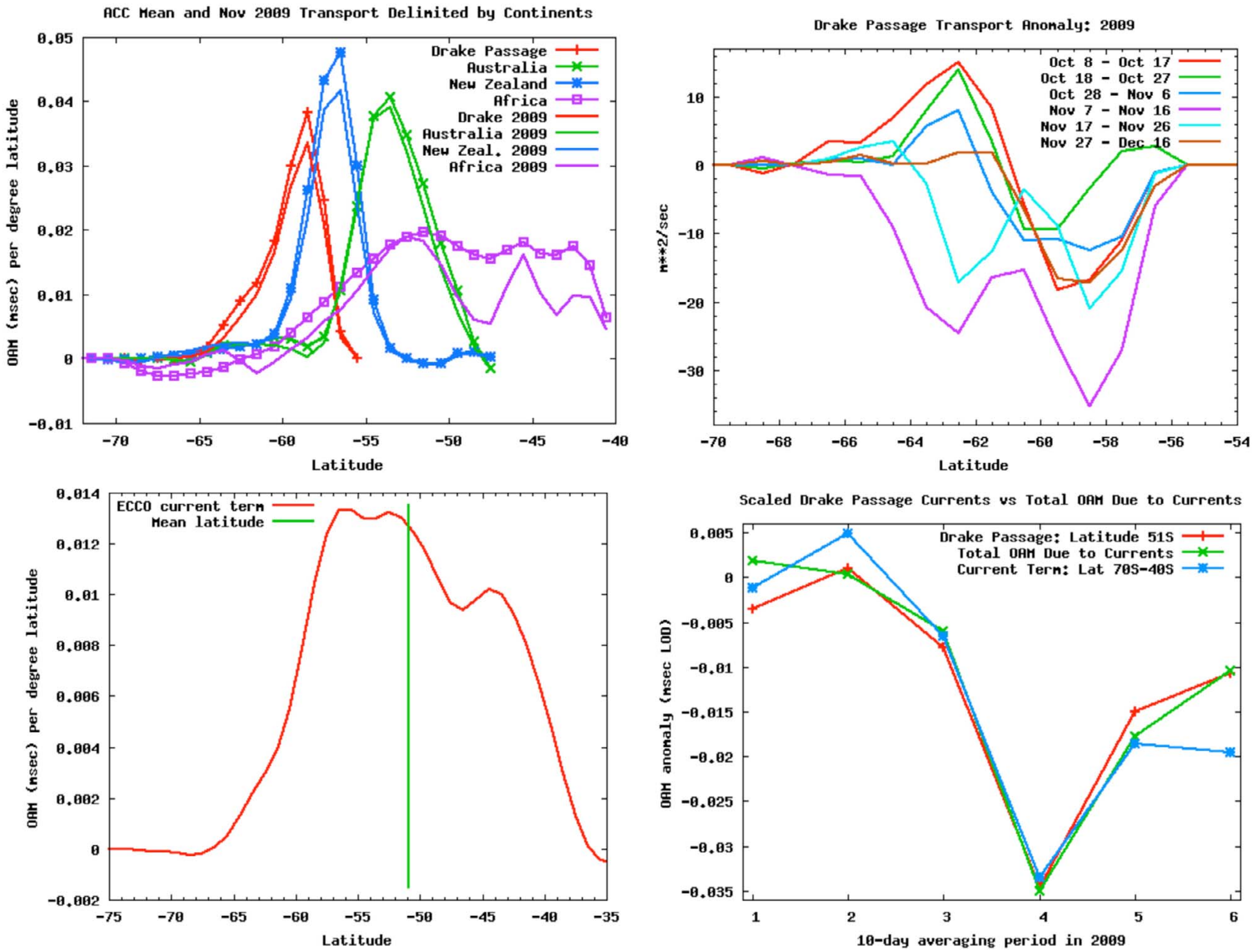

Figure 3. Variations of zonal transport simulated by the ECCO model: (top left) climatological transport at longitudes corresponding to the southernmost extensions of land surfaces bounding the ACC (lines with symbols), and the transport values averaged over the period 7–16 November 2009 (lines without symbols); (top right) transport anomaly at the longitude of the Drake passage, for six 10-day periods encompassing the November 8–21 anomaly; (bottom left) zonally-averaged current contribution to the climatological OAM from the Southern Ocean in the ECCO model per degree of latitude, with the mean OAM-weighted latitude indicated near 51°S; (bottom right) time series of six 10-day ECCO transport averages encompassing the anomaly (November 7–16 = period 4), for all currents (green), for currents south of 40°S (blue), and for Drake passage currents (red) assuming the transport takes place at the mean latitude (51°S) of the zonally-averaged ACC.

scaling) are the 10-day average ECCO-simulated transport through the Drake Passage during 2009 (purple line with symbols), and the tide-corrected ocean bottom pressure (red line, with sign reversed) from the South Drake BPR site (available only through 25 November 2009). The residual LOD series clearly reflects the signature of the 8–21 November 2009 anomaly in calculated OAM and Drake Passage transport, with the BPR data giving additional observational confirmation of the reduced geostrophic ACC transport simulated by the ECCO model.

[12] In addition to correlations over the full 201-day period, we also examined the geodetic impact of the OAM fluctuations in localized time intervals. After removing the atmospheric forcing by subtracting the MERRA AAM, the variance of the daily LOD residual was tabulated in a series of moving windows of length 31 days, following removal of a best-fitting mean and trend computed separately for each window. The same computation was then performed for the LOD-AAM residual after removing ocean effects by subtracting the ECCO OAM series, and the difference – that is, the additional LOD variance accounted for by the ECCO-modeled OAM – was plotted as a function of time (i.e., at the center-point of each window) in Figure 4 (bottom). The large peak in the explained variance coinciding with the observed and modeled oceanic anomalies serves to confirm the unique rotational signature of the short-period OAM fluctuation associated with this event.

6. Summary and Discussion

[13] We have examined a strong and short-lived fluctuation in oceanic angular momentum (OAM) as estimated by an ECCO solution (KF080) constrained by altimeter data. The sharp decline and recovery of OAM is unprecedented for the last decade of the ECCO simulation (Figure 1). The proportional contributions of the current and pressure terms to the anomaly suggest a close geostrophic balance (see auxiliary material), as would be expected for extratropical

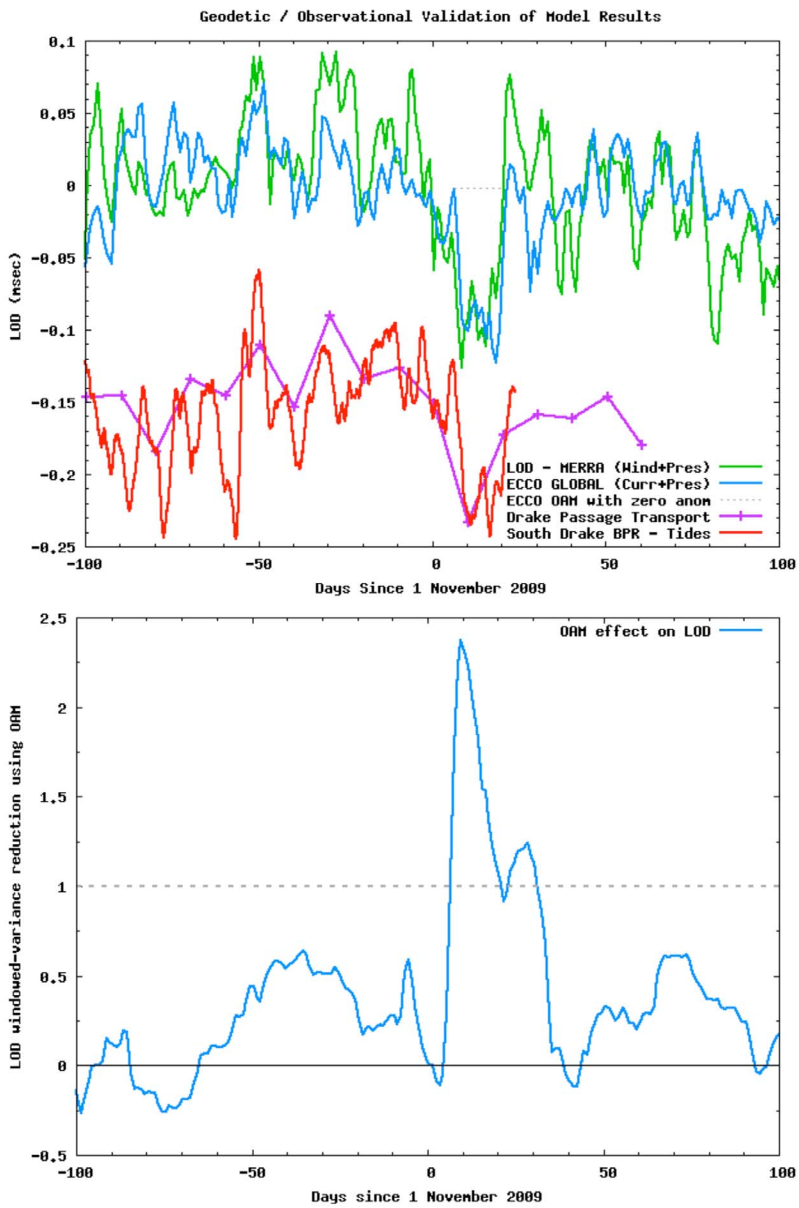

Figure 4. (top) Comparison of LOD after removing AAM computed from MERRA winds and IB pressure (green line), with the total (current plus pressure) global OAM calculated from the ECCO estimate (blue line) – units milliseconds of LOD, with mean and trend removed; also shown (with arbitrary vertical offset and scaling) are the ten-day averaged Drake passage transport for year 2009 from ECCO (purple line with symbols centered in the averaging intervals), and the bottom pressure recorder data from the South Drake passage (red line – available through 25 November 2009), with sign reversed and short-period (fortnightly and less) tidal effects removed. (bottom) Variance reduction for the AAM-adjusted LOD series detrended in moving monthly (31-day) windows, after applying the OAM correction. Units: μsec^2 LOD; negative values indicate increased variance after removing the OAM from the residual LOD.

flow anomalies; support for a Southern Ocean origin of the OAM anomaly is provided by its close resemblance to a fluctuation in the Antarctic Oscillation Index, at a lag of approximately two days. The transport at the Drake Passage was a minimum at all latitudes during a 10-day averaging segment (November 7–16) falling within the anomaly period, compared with five surrounding 10-day segments (Figure 3); furthermore, the angular momentum of a zonal current ring generated by the simulated Drake Passage transport, calculated for the effective latitude of the ACC (51°S), closely matches the global current-generated OAM averaged over the same ten-day segments. The clear signature of the OAM anomaly in the residual LOD-AAM data and variance explained during the November 2009 anomaly (Figure 4) validates the ECCO results, and documents the robustness of the atmospheric modeling and assimilation system used to adjust the LOD series.

[14] While the simulated OAM anomaly correlates well with modeled variations in the ACC and with the observed Antarctic Oscillation Index at a short lag, similar variability in the AAO (or SAM) in other years (not shown) failed to generate such large OAM anomalies. The development of

this large response may have originated in the unusual conditions which prevailed upstream of the Drake Passage in late 2009, as reported by *Lee et al.* [2010] and *Boening et al.* [2011]. They document the development of surface wind stress, sea surface temperature, sea surface height and ocean bottom pressure anomalies which maximized in November 2009 in an area bounded by 35°–55°S, 90°–150°W, possibly related to a strong mid-Pacific El Niño occurring in that time frame [*Lee et al.*, 2010]. That study also documented record high SST anomalies in the Bellingshausen Sea during the subsequent austral summer and their possible connection with regional surface wind forcing anomalies. Recent studies have also suggested that eddy mixing within the ACC may be anti-correlated with the jet intensity [*Ferrari and Nikurashin*, 2010; *Naveira Garabato et al.*, 2011], so that the drop in ACC transport noted in our results could also be linked to the enhanced poleward mixing of heat. In view of the inverse relationship between oceanic heat transport and ice sheet stability in the Antarctic [cf. *Joughin and Alley*, 2011], further elucidation of the causes and consequences of the late 2009 anomaly documented here and in previous studies could shed light on the ongoing response of the southern ocean-atmosphere-ice system to climate variability and change.

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