Detection and Modeling of Non-Tidal Oceanic Effects on the Earth's Rotation Rate

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Sub-decadal changes in the Earth's rotation rate, and hence in the length-of-day (LOD), are largely controlled by variations in atmospheric angular momentum. Results from two oceanic general circulation models (OGCMs), forced by observed wind stress and heat flux for the years 1992-1994, show that ocean current and mass distribution changes also induce detectable LOD variations. The close similarity of axial oceanic angular momentum (OAM) results from two independent OGCMs, and their coherence with LOD, demonstrate that global ocean models can successfully capture the large-scale circulation changes that drive OAM variability on seasonal and shorter time scales.

Changes in the rotation rate of the solid Earth (that is its crust and mantle), typically yield variations in the length-of-day (LOD) of about 1 ms over several years (*1*). The Earth as a whole conserves its angular momentum (with the exception of tidal torques); LOD variations, in particular, arise largely from compensating changes in atmospheric angular momentum (AAM) carried by zonal (west-to-east) winds (*2,3*). Remaining discrepancies in the axial budget indicate that other reservoirs also store and release appreciable quantities of angular momentum on these time scales, but these have been less well resolved.

In this study we show that (i) a significant non-tidal oceanic signal can be detected in geodetic LOD series, and (ii) this contribution of oceanic angular momentum (OAM) helps to close the global budget on seasonal and shorter time scales. Because the three-dimensional observational data needed to compute OAM directly are not available, we use two OGCM simulations as a proxy for our analysis. These comparisons can provide a valuable check on the realism of the model-derived OAM, and may be used to estimate contributions from other angular momentum reservoirs, such as changes in terrestrial and atmospheric water storage.

We consider results from two OGCMs whose dynamical formulations differ considerably: the Modular Ocean Model (*4*) (MOM), based on earlier multi-level models developed at the Geophysical Fluid Dynamics Laboratory (*5*), and a multi-layer model based on an early version of the Miami Isopycnal Coordinate Ocean Model (MICOM) (*6*). Both MOM and MICOM are based on the primitive equations of fluid flow that use the Boussinesq and hydrostatic approximations. The major differences between the two models are (i) their vertical coordinate systems: MOM uses geometrical depth beneath a rigid lid, while MICOM employs a density-based coordinate with a freely-varying surface height; and (ii) their treatment of the surface mixed layer: MOM uses a Richardson-number scheme (*7*), while MICOM uses the Kraus-Turner mixed layer model (*8*). Both models have a horizontal resolution of 2° longitude by 1° latitude and comparable vertical resolution (22 and 12 layers respectively).

The OGCMs were spun up for 10 years starting from climatological temperature and salinity distributions (*9*), forced with climatological monthly wind stress (*10*) and sea surface temperature and salinity (*9*). The models were then driven with surface wind stress derived from the daily National Center for Environmental Prediction (NCEP) 1000-mb analysis from 1 January 1992 to 15 December 1994, and heat flux computed using the bulk formulation described in (*11*); the first 45 days were excluded from the analysis to eliminate transient effects. Pressure forcing by the atmosphere was not included. A shorter experiment (24 September 1992 to 14 March 1994) was also made with the MOM model using surface wind stress derived from the ERS-1 scatterometer (*12*).

The contributions to OAM variation calculated from the zonal currents simulated by each model represent changes in the relative axial angular momentum of the oceans, and are expressed in units of equivalent LOD (Fig. 1A). Both models are characterized by a net west-to-east flow which sequesters positive angular momentum, giving rise to a mean positive LOD forcing of approximately 100 microseconds (μs); for comparison the atmosphere has a mean zonal velocity of roughly 7 ms^{-1}, and would change the average LOD by about 2.5 milliseconds (ms) were its super-rotation to cease (Fig. 2A). Both current terms are characterized by drifts that are approximately linear in time but opposite in sign. Removal of these trends, which reflect the incomplete equilibration of the OGCMs during spinup, leaves relative OAM variations that are similar between the MICOM and MOM simulations (not shown); the rms magnitudes are 12.7 and 14.5 μs, respectively.

Because of the background planetary rotation, changes in the oceans' moment of inertia also induce OAM variations (their effect on the relative angular momentum is orders of magnitude smaller and is neglected). Changes in the planetary terms for the two models (solid lines in Fig. 1B) again show long-term trends of opposite sign, although these are not linear and are much larger than the corresponding trends for the relative OAM. Because of the use of the Boussinesq approximation in the governing equations, both models conserve volume rather than mass. The OAM variations due to changes in the total mass content of each model (*13*) are shown by the dashed lines in Fig. 1B, and clearly account for the bulk of the long-term trends. Removal of the effects of mass non-conservation, as well as residual linear trends representing incomplete equilibration during spinup, yields time series of planetary OAM (not shown) that are similar between the MOM and MICOM results; their respective rms magnitudes are 21.2 and 22.5 μs, nearly twice that of the relative OAM variation.

The total OAM variations obtained by adding the detrended relative and planetary OAM series bear a strong resemblance over the nearly 3 years simulated by the two models with NCEP forcing (Fig. 1C), despite their distinct dynamical formulations and the differences in long-term trends following spinup. The shorter OAM series derived from the MOM model forced by ERS-1 winds resembles the NCEP-forced results over the period of overlap, although its rms magnitude is only 64% as great because of the lower variability of the ERS scatterometer winds (*12*). Thus simulations of the circulation features that contribute to the axial OAM, that is, the large-scale current systems and mass distribution (*14*), seem to be robust.

For comparison with an LOD time series, we used the Kalman-filtered SPACE96 calculation (*15*), which is sampled at daily intervals (Fig. 2A). The effects of tidal forcing on both the solid Earth and oceans has been removed from this series (*16*). We also estimated the LOD forcing due to atmospheric winds integrated from 1000 hPa to 0.3 hPa;

values below 10 hPa were computed as the averages of global wind analyses provided by the ECMWF, JMA, and the NCEP-NCAR reanalysis campaign, whereas those above 10 hPa were obtained from the BADC (*17*). Both the geodetic and atmospheric series contain a strong seasonal signal; higher-frequency variability is also clearly shared by the two time series (*18*).

In a closed two-component system consisting of the solid Earth and atmosphere the combined angular momentum would be constant, and this would be reflected by identical (although offset) shapes of the AAM and LOD series (Fig. 2A). Therefore, the nonzero residual variation shown in Fig. 2B (note the difference in vertical scale) implies that an additional angular momentum reservoir is participating in the global budget. Variations in core motions are believed to be responsible for observed decadal-scale excursions of up to several ms in LOD (*1*). As the core is only weakly coupled to the mantle on the shorter time scales considered here (*19*), we accounted for its effect by removing a least-squares-fit quadratic trend from the LOD-AAM variation. The residual LOD-AAM signal (shown in Fig. 2C) represents the missing part of the Earth's axial angular momentum budget, and has an rms magnitude of 60.5 μs.

The three-year OAM series generated by the MICOM and MOM models using NCEP forcing (Fig. 1C) have rms magnitudes of 30.7 and 30.5 μs, respectively, and thus potentially represent about half of the residual LOD variation. The MICOM series, shown in Fig. 2C with a quadratic background removed, bears a striking similarity to the LOD-AAM residual ($r^2 = 0.77$), and explains 42% of its variance; the MOM series (not shown) has a correlation coefficient of 0.72 and explains 34% of the variance. The high correlation coefficients from both models (significant at approximately the 3σ level) demonstrate the detection of a non-tidal oceanic signal in the Earth's rotation rate.

Further understanding of the oceans' effect on Earth rotation may be gained by comparing geodetic, atmospheric, and oceanic signals in the frequency domain. LOD spectra contain strong seasonal peaks, with amplitudes from ~ 0.3 to 0.4 ms (*20*). These peaks are still evident in our LOD data following removal of the wind excitation in the 1000 - 10 hPa layer (Fig. 3A), although the amplitude has been reduced by an order of magnitude. The winds above 10 hPa (carrying ~ 1% of the total atmospheric mass) make a disproportionately large contribution to the seasonal AAM cycle (*2*); removal of the excitation attributed to BADC winds (10 - 0.3 hPa) gives a particularly strong reduction in our results at the annual period, where the residual LOD amplitude is now comparable to that of the low-frequency background.

The OAM time series generated by the OGCM runs also contain seasonal rotation signals, as evidenced by the pronounced decrease in the residual LOD amplitudes (red lines in Fig. 3A) at the first two annual harmonics. Removal of the oceanic excitation simulated by both models produces local amplitude minima within a bandwidth of the annual frequency, suggesting that the oceans play a significant role in the axial angular momentum budget on that timescale (*21*). At the semiannual period, both the 10 - 0.3 hPa winds and the oceanic excitation reduce the LOD residual, although the latter has a greater impact. The upper-atmospheric data apparently contain little of the LOD signal at subseasonal periods, because their incorporation into the atmospheric excitation fails to reduce the spectral amplitude relative to the 1000 - 10 hPa residual in that range. The oceanic excitation from both models, by contrast, consistently lowers the LOD residuals at frequencies up to about $(25 \text{ day})^{-1}$.

Further evidence for the presence of a rotational signal in the OGCM results can be obtained from their effect on the coherence of LOD with its excitation sources. The atmospheric data sets used in our study produce coherence with LOD significant at the 95% level for all frequencies up to $(10 \text{ day})^{-1}$; however, the addition of the 10 - 0.3 hPa winds to the 1000 - 10 hPa data yields no consistent improvement at subseasonal frequencies (Fig. 3B, black lines). By contrast, addition of the OAM data from both models to the atmospheric excitation consistently increases the coherence with LOD at frequencies up to $(25 \text{ day})^{-1}$, and generally improves the results up to $(15 \text{ day})^{-1}$. At higher frequencies the effects of incorporating the OAM series are mixed. The combined AAM and MICOM excitation gives better overall results, however, and maintains coherence with LOD significant at the 99% level for all frequencies up to (10 day)$^{-1}$.

The superior results obtained with MICOM at high frequency appear to be due to its isopycnal formulation and better treatment of the mixed layer (*22*); in particular, the density-based vertical coordinate allows a more realistic treatment of the effects of bottom topography than the "staircase" representation employed in depth-based models. The future use of in situ and satellite observations in constraining OGCMs and the incorporation of atmospheric pressure forcing will lead to an increasingly accurate picture of oceanic effects on the Earth's rotational dynamics.

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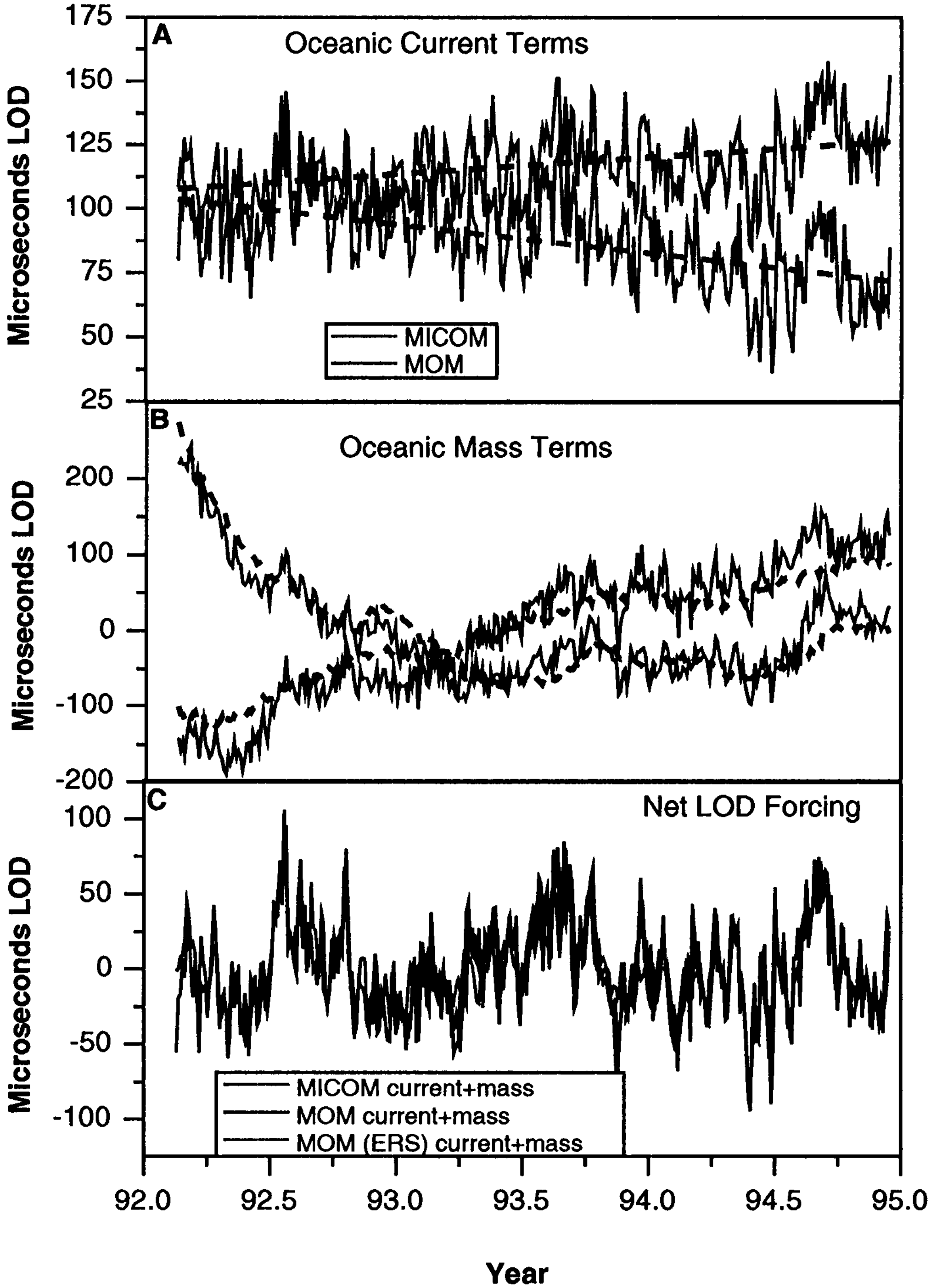
Figure Captions

Fig. 1. LOD excitation computed from the OGCM results. Both models were forced with surface wind stress and heat flux computed from daily NCEP analyses; pressure forcing by the atmosphere was not considered. (**A**) Relative oceanic angular momentum (OAM) contained in zonal currents (solid lines); positive LOD forcing corresponds to a net west-to-east flow. The dashed lines indicate least-squares-fit linear trends for each model series. (**B**) Planetary OAM changes for the two OGCM simulations (solid); the time mean has been removed from each series. Dashed lines indicate the change due to variations in the total mass content of each model (see text for details). (**C**) Sum of relative and planetary OAM changes for each model, following removal of linear trends and the effects of mass non-conservation. The detrended OAM is also shown for a shorter experiment with the MOM model forced by ERS-1 winds.

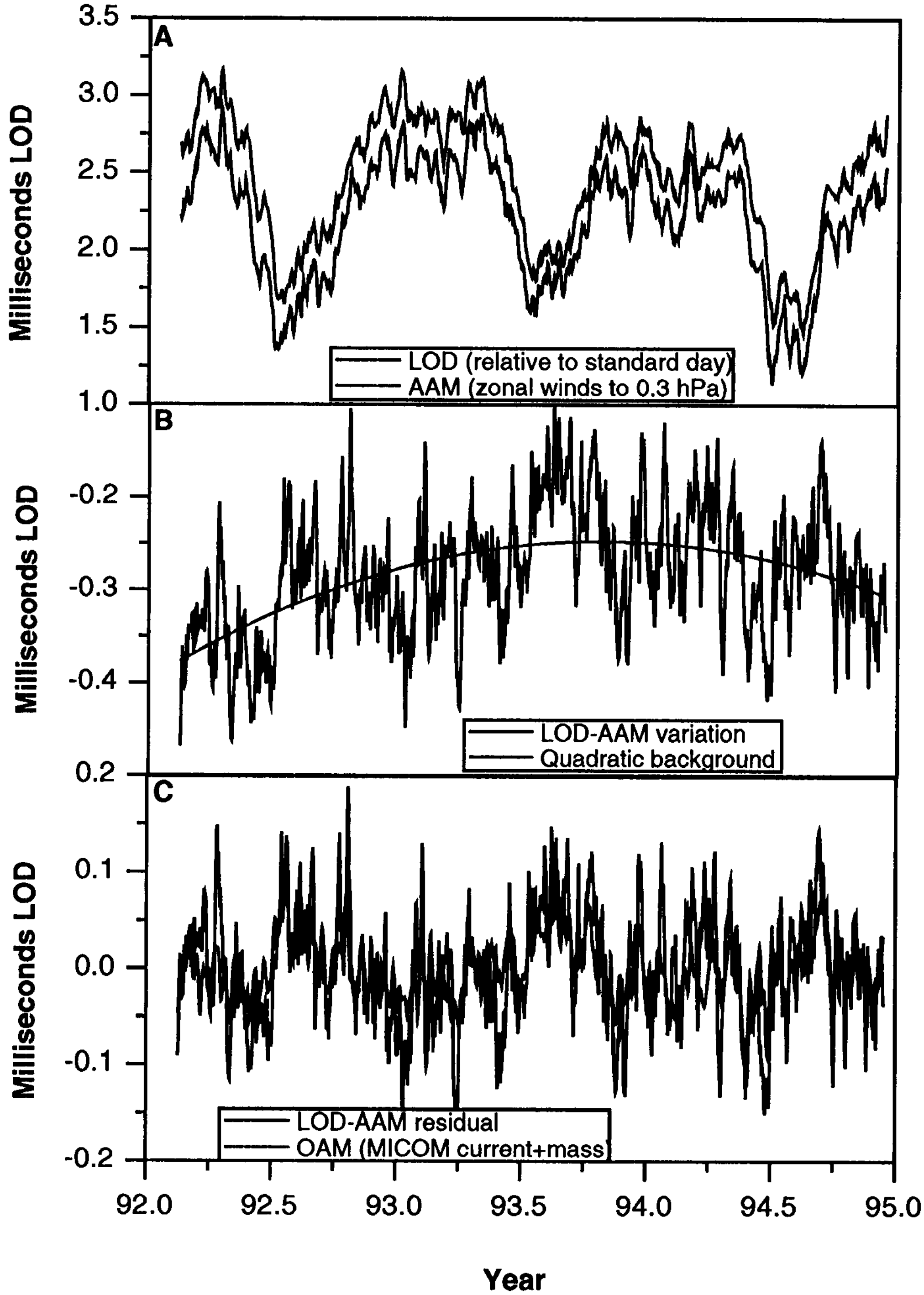
Fig. 2. (**A**) Comparison of observed LOD with atmospheric forcing, computed from zonal winds integrated from 1000 to 0.3 hPa. Since the LOD is defined with respect to an arbitrary reference value, its vertical offset has no physical significance. (**B**) The difference

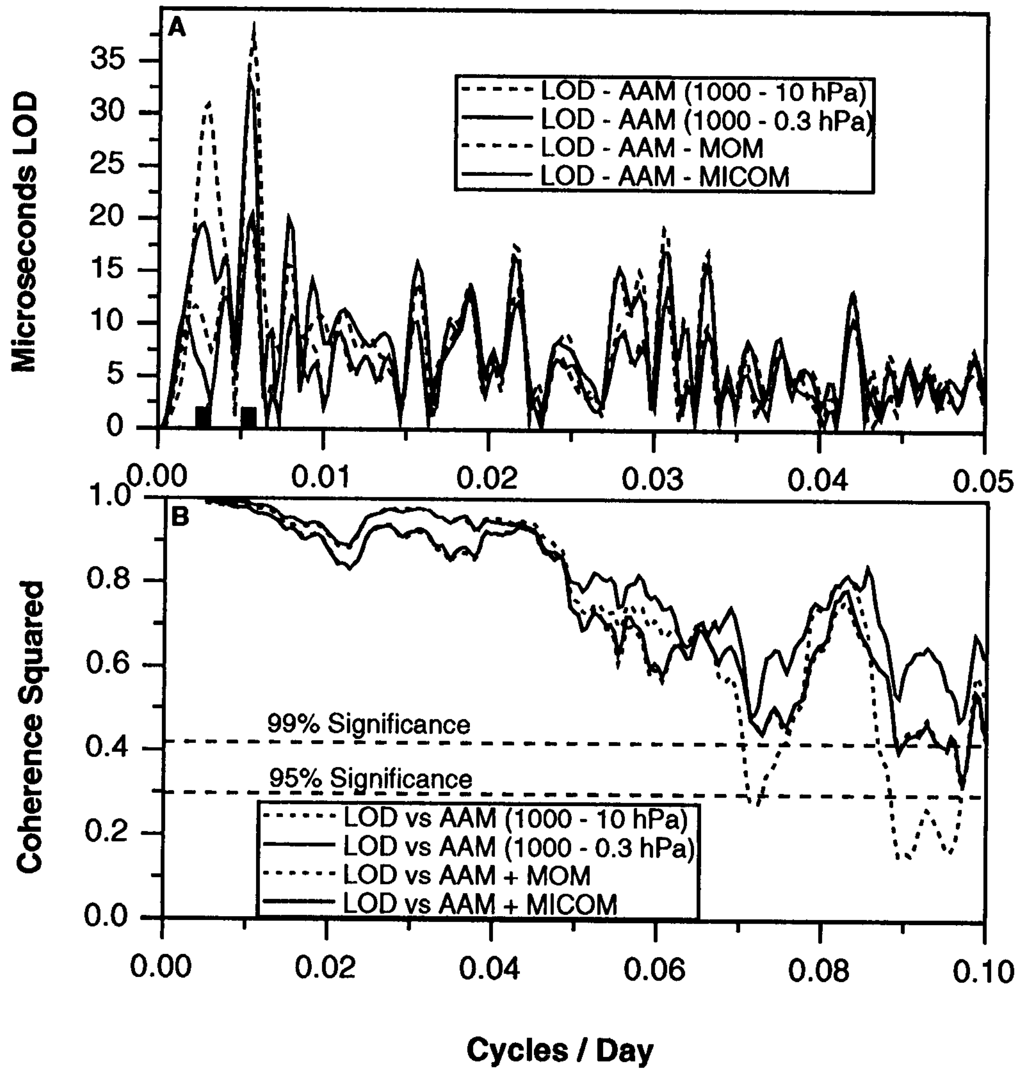
between the LOD and AAM curves plotted in frame (A), compared with a least-squares-fit second-order polynomial used to represent the effects of core-mantle coupling. (**C**) The difference between the LOD-AAM and quadratic terms plotted in frame (B), compared with the total OAM computed from the MICOM simulation.

Fig. 3. (**A**) Amplitude spectra of LOD residuals after subtraction of atmospheric and oceanic excitation. AAM was computed from winds supplied by the ECMWF and JMA analysis and NCEP reanalysis campaigns for the 1000 - 10 hPa layer, and from BADC winds for the 10 - 0.3 hPa layer; the full (1000 - 0.3 hPa) AAM was used in combination with the OAM computed from the MOM and MICOM results. Spectral bandwidth is given by the width of the blue bars, which are centered on the abscissa at the annual and semiannual frequencies. (**B**) Coherence squared of LOD with atmospheric and combined atmopheric and oceanic excitation sources (note difference in the frequency scale).



A
Oceanic Current Terms
MICOM
MOM
B
Oceanic Mass Terms
C
Net LOD Forcing
MICOM current+mass
MOM current+mass
MOM (ERS) current+mass
Microseconds LOD
175
150
125
100
75
50
25
200
100
0
-100
-200
100
50
0
-50
-100
92.0
92.5
93.0
93.5
94.0
94.5
95.0
Year


A
B
C
LOD (relative to standard day)
AAM (zonal winds to 0.3 hPa)
LOD-AAM variation
Quadratic background
LOD-AAM residual
OAM (MICOM current+mass)
Milliseconds LOD
Milliseconds LOD
Milliseconds LOD
3.5
3.0
2.5
2.0
1.5
1.0
-0.2
-0.3
-0.4
0.2
0.1
0.0
-0.1
-0.2
92.0
92.5
93.0
93.5
94.0
94.5
95.0
Year


A
Microseconds LOD
35
30
25
20
15
10
5
0
LOD - AAM (1000 - 10 hPa)
LOD - AAM (1000 - 0.3 hPa)
LOD - AAM - MOM
LOD - AAM - MICOM
0.00
0.01
0.02
0.03
0.04
0.05
B
Coherence Squared
1.0
0.8
0.6
0.4
0.2
0.0
99% Significance
95% Significance
LOD vs AAM (1000 - 10 hPa)
LOD vs AAM (1000 - 0.3 hPa)
LOD vs AAM + MOM
LOD vs AAM + MICOM
0.00
0.02
0.04
0.06
0.08
0.10
Cycles / Day