A comparison of in situ bottom pressure array measurements with GRACE estimates in the Kuroshio Extension

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1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) mission, launched in March 2002, measures global gravity fields at monthly intervals [Tapley et al., 2004]. In the ocean, temporal changes in GRACE gravity fields arise from water mass redistribution due to atmospheric forcing, ocean currents, and net fresh water fluxes such as from evaporation, precipitation, river run-off, or ice melting. Satellite altimeters measure sea surface height which includes both steric and mass-loading components. The former are associated with subsurface temperature and salinity changes causing expansion or contraction of the water column and do not contribute to mass loading. One of the scientific objectives of the GRACE mission is to produce high-quality ocean mass-loading estimates that can be used in conjunction with altimeter sea surface height estimates to derive the steric sea surface height signal

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For this comparison study, we produced a spatially-averaged monthly-mean \( \overline{P_{\text{bot}}} \) time series over the observational domain, noted as \( \langle \overline{P_{\text{bot}}} \rangle \). In addition, we also generated monthly-mean \( P_{\text{bot}} \) time series \( \langle P_{\text{bot}} \rangle \) for each PIES to compare to GRACE. Measurement durations differed among the PIES sites due to various instrument issues. Seven sites, indicated by open triangles in Figure 1, had \( P_{\text{bot}} \) records that ended prior to September 2005 and were excluded from the point-measurement comparisons.

Quantitative comparisons were conducted for the time period November 2004 through June 2006. GRACE was temporarily in a 4-day (61-revolution) repeat cycle during July–October 2004. Due to the lack of global coverage, the monthly GRACE fields have reduced data quality during these months (http://podac.jpl.nasa.gov/grace/documentation.html). GRACE monthly fields are produced based on available data in each month, and some months (May 2004, December 2004, March 2005, June 2005, December 2005, and March 2006) have 1 to 5 missing days. We did not exclude these missing GRACE days when we produced the KESS time averages \( \langle \overline{P_{\text{bot}}} \rangle \) and \( \overline{P_{\text{bot}}} \).

3. Results

The KESS monthly-array average, \( \langle \overline{P_{\text{bot}}} \rangle \), and GRACE \( P_{\text{bot}} \) series, estimated near the center of the KESS domain at 34.5°N, 146.5°E (cross in Figure 1), track each other and in particular exhibit a consistent seasonal signal (Figure 2). Note the sharp \( P_{\text{bot}} \) decrease in winter. This is a basin-scale seasonal cycle of \( P_{\text{bot}} \), related to the seasonal cycle of wind stress change and bottom topography [Gill and Niler, 1973], and has been observed and simulated previously in the North Pacific [e.g., Bingham and Hughes, 2006]. Differences between the three GRACE products exist. For a given smoothing radius \( R \), CSR and JPL estimates show higher correlation coefficients \( (Cr \geq 0.74) \) with \( \langle \overline{P_{\text{bot}}} \rangle \) than the GFZ estimates \( (Cr \leq 0.57) \). All \( Cr \) values are statistically significant within the 95% confidence limit. With increased \( R \) from 300 to 750 km, \( Cr \) values decrease for CSR, 0.82 to 0.74 and GFZ, 0.57 to 0.51. On the other hand, JPL estimates show a small increase of the \( Cr \) from 0.82 to 0.84.

For all three \( R \) comparisons, the root-mean-squared (RMS) differences for JPL estimates show the smallest values of 1.4–1.6 cm (with explained variance of 70–62%), while those for GFZ estimates show the largest values of 2.1–2.3 cm (with explained variance of 32–14%). RMS differences between JPL and CSR differ very little with no apparent relationship to the \( R \) length. The \( Cr \) values and RMS differences demonstrate that GRACE can measure monthly water mass variations of ~600-km scale with high quality in the KESS domain. In addition, CSR and JPL products appear better than GFZ products in the KESS region.

Correlation analysis is also applied between individual in situ KESS \( P_{\text{bot}} \) and GRACE \( P_{\text{bot}} \) at each PIES site, obtained by linear 2-D interpolation from 1°-resolution monthly GRACE estimates. The spatial distribution of \( Cr \) shows a distinct spatial structure (Figure 3): high correlation along the northern and western portion of the array. Values larger than 0.6 occur in the northern side of the domain for the CSR and JPL estimates with \( R = 300 \) km. This area is
more elongated northeast-to-southwest direction for the \( R = 500 \) and 750 km products. Similar to the \( h_P \) comparisons, the GFZ estimates show the lowest \( Cr \), typically less than 0.6 for all three \( R \) comparisons.

[12] GRACE measurements can potentially determine deep currents through geostrophy. Following a reviewer’s suggestion, we tested correlations between CPIES- and GRACE-derived deep currents. However, we found the deep currents were not correlated with statistical significance. Since the horizontal scale of seasonal \( P_{bot} \) change is large, the horizontal gradient of \( P_{bot} \) eliminates the dominant seasonal signal, which seems to result in no significant correlations.

[13] KESS \( P_{bot} \) measurements near the southeastern area centered at site G4 have almost no correlations with any GRACE products (Figure 3). This low \( Cr \) here is not related to bottom topography because KESS region is located in relatively flat topography. In fact note the relatively high correlations found near seamount complexes adjacent to sites B1-C1-C2 or E2-F2-F1.

[14] Figures 2d and 2e plot the individual monthly time series of in situ \( P_{bot} \) and GRACE \( P_{bot} \) with \( R = 500 \) km at sites B2 and G4. Site B2 shows good agreement with GRACE \( P_{bots} \) while site G4 shows poor agreement. Furthermore, the G4 \( P_{bot} \) seems to contain mesoscale components large enough to obscure the seasonal signal which is prominent in \( P_{bot} \).

[15] We can compute spatial correlations between PIEEs to determine a domain-wide distribution of characteristic length scale, unlike the above-mentioned previous GRACE evaluation studies using pointwise \( P_{bot} \) measurements. At each PIEE we computed spatial correlations between all \( P_{bot} \).
pairs, and then those were least-squares-fitted to a Gaussian curve $G(r) = e^{-r^2/2r_0^2}$, where spatial lag $r$ is horizontal distance and $r_0$ is e-folding scale fit to the spatial correlations. A clear spatial structure emerges. Figure 4a maps the $r_0$ values computed at each PIES site (recall that we excluded 7 short PIES records). The western and northeastern areas have long $r_0$ values (>300 km), while the middle area of northern half and southeastern area have short $r_0$ values (<300 km). Site G4 has the shortest $r_0$ of 140 km. Two correlation functions are shown for the two extrema in the spatial correlation in Figure 4b. Site B2 exhibits high correlations with many PIES sites in the array, while site G4 shows a quick drop of correlations when the distances become longer than about 150 km.

[16] A region of high eddy kinetic energy (EKE) coincides with the region of short $r_0$. We computed EKE using optimally interpolated (OI) deep current maps (Figure 4c). OI maps are constructed with a 100 km Gaussian correlation function and the OI grid has 10-km resolution. Short-wavelength $P_{bot}$ components, small $r_0$, are closely associated with deep mesoscale eddies energetic under the first quasi-stationary meander trough of the Kuroshio Extension, where the RMS variability of $P_{bot}$ is large (Figure 4d). The $r_0$ and EKE maps show a remarkably similar pattern to the $Cr$ maps in Figure 3. Low $Cr$ area coincides with short $r_0$/high EKE area and high $Cr$ area coincide with long $r_0$/low EKE area. This result demonstrates that short-wavelength mesoscale $P_{bot}$ components in the KESS region cause low correlation between in situ $P_{bot}$ and GRACE $P_{bot}$.

4. Conclusion

[17] Due to the lack of available $P_{bot}$ measurements, all previous validations of GRACE in the ocean have used pointwise in situ $P_{bot}$ measurements for the comparisons. This study compared in situ $P_{bot}$ measurements from a wide array covering 600 km × 600 km area with GRACE $P_{bot}$ estimates in the Kuroshio Extension. Domain-averaged in situ $P_{bot}$ measurements, ($\overline{P}_{bot}$), revealed good agreement with the GRACE $P_{bot}$ estimates from both CSR and JPL gravity products, and relatively poor agreement with those from GFZ. The large-scale seasonal cycle dominates the monthly and spatially averaged mass variability in this region [Bingham and Hughes, 2006]. The correlation analyses with ($\overline{P}_{bot}$) was insensitive to the choice of $R$ length (300–750 km) applied to GRACE estimates. This study demonstrates that GRACE mission yields high-quality large-scale averages of monthly-mean $P_{bot}$ fluctuations in the Kuroshio Extension region.

[18] Individual comparisons between in situ $P_{bot}$ and GRACE estimates at each PIES site reveal a spatially-varying pattern of correlations. Munekane [2007] shows that pointwise $P_{bot}$ and GRACE estimates may differ due to two factors—artificial leakage from the mass variations on land and filtering of short spatial-scale oceanographic components. From our $P_{bot}$ array measurements, we show that when short-wavelength mesoscale $P_{bot}$ components dominate the monthly-averaged records, the comparisons between pointwise in situ $P_{bot}$ measurements and GRACE estimates can result in low correlations.

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References


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