Aliasing of high-frequency variability by altimetry: Evaluation from bottom pressure recorders

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Abstract. In spectra computed from bottom pressure records, 18% to 63% of non-tidal energy is associated with frequencies greater than 1 cycle per 20 days, the approximate Nyquist frequency for the TOPEX/Poseidon (T/P) satellite. Since bottom pressure measurements are correlated with coincident sea surface height measurements from the T/P satellite, hourly bottom pressure data are used here to characterize the aliasing expected from T/P. As numerical modeling studies have also demonstrated, spectra computed from data sampled at 10-day intervals are likely to alias substantial amounts of unresolved high-frequency variability, particularly at frequencies greater than 0.2 times the Nyquist frequency.

Introduction

Recent ocean numerical modeling studies have found significant high-frequency surface pressure variability, particularly outside the tropics [*Fukumori et al.*, 1998; *Stammer et al.*, 2000; *Tierney et al.*, 2000]. For example, *Fukumori et al.* [1998] noted that in most of the ocean poleward of 30° over half of the spectral energy for sea level fluctuations in the intraseasonal band (< 180 days) occurs at frequencies greater than one cycle per 20 days and will be aliased by the 10-day sampling of sea surface height provided by the TOPEX/Poseidon (T/P) satellite and its planned successors, Jason-1 (due to launch in 2001) and Jason-2. Such high frequency signals will present a major challenge to the interpretation of satellite data from the Gravity Recovery and Climate Experiment (GRACE), which promises to measure large-scale, long-period bottom pressure changes with an accuracy equivalent to better than 1 mm of water [*Wahr et al.*, 1998]. In the models, this variability has been largely explained as a barotropic response to atmospheric pressure and wind.

In this study, we provide in situ support for model aliasing estimates by examining bottom pressure recorder (BPR) measurements from a variety of locations in the Atlantic, Indian, and Southern Oceans. The results shown here are consistent with numerical findings in predicting substantial aliasing of energy at frequencies greater than $\mathcal{N}_{TP}$, the Nyquist frequency of $\sim$ 1 cycle per 20 days for T/P-type altimetry. This paper begins by discussing the merits of using BPR data as a proxy for altimeter measurements, then examines expected spectral aliasing based on these BPR measurements, and finally considers possible strategies for working with ocean data sampled at 10-day intervals.

Paper number 2000GL012244.
0094-8276/01/2000GL012244$05.00

Altimetry and Bottom Pressure Data

Since the early 1980s, Proudman Oceanographic Laboratory and the University of Grenoble have carried out BPR measurements in the Atlantic and Southern Oceans, focusing in the 1990s on Drake Passage [*Woodworth et al.*, 1996; *Spencer and Vassie*, 1997] and the Indian Ocean [*Vassie et al.*, 1994]. Most sampled hourly, though more recent deployments have recorded every 15 minutes. Here, 7 time series deployed since 1992 (black dots in Figure 1) are compared with TOPEX altimeter measurements. An additional 16 time series of at least 150 days duration that predate T/P (open circles in Fig. 1) are also examined. For multi-year time series, BPRs were ordinarily redeployed annually, although t (called Myrtle) provided a continuous record, and Drake Passage BPRs deployed in 1994 were not recovered until 1996. Full details of the BPR records are available from the Global Undersea Pressure web site (www.pol.ac.uk/psmslh/gloup/gloup.html).

For this study, records were separately demeaned and detided using standard procedures to remove semidiurnal, diurnal, fortnightly, and monthly tides [*Bell et al.*, 1999]. Annual and semi-annual signals are retained, since not all records are sufficiently long to allow their removal. Consecutive time series from the same locations were checked for significant mismatches, and where possible series were concatenated. Table 1 summarizes the locations and durations of the BPRs used in this study.

Measurements from the 7 BPR sites monitored since the launch of T/P were compared with measurements from the nearest ascending and descending groundtracks for the TOPEX altimeter (which has lower noise levels than the Poseidon altimeter) on a point-by-point basis, with no spatial or temporal filtering. In contrast, an earlier comparison of Southern Ocean bottom pressure data and altimetry concentrated on the low-frequency signal [*Woodworth et al.*, 1996]. TOPEX data were processed by applying all standard data corrections (including inverse barometer), as discussed by *Gille et al.* [2001]. Correlation coefficients were computed between BPR measurements and the TOPEX measurement closest in time and space. Correlation coefficients ranged from 0.18 to 0.63 and were statistically significant at the 95% level at all locations except g (Marfrio). In order to

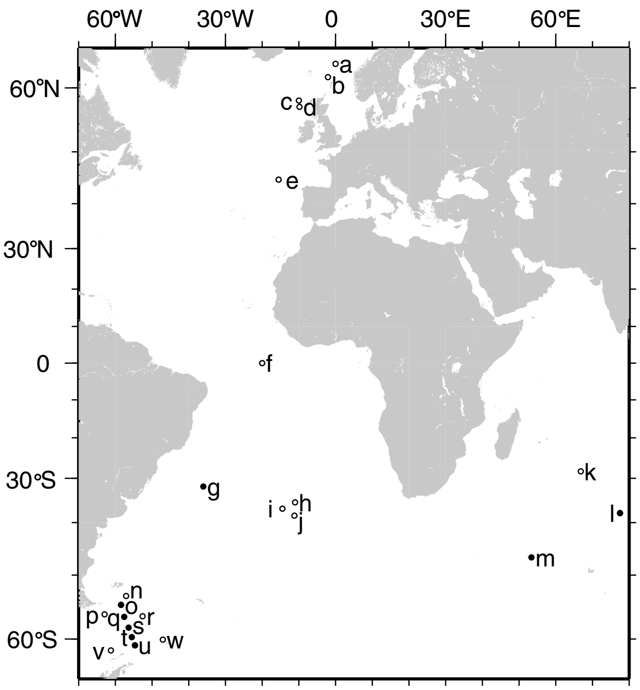

Figure 1. Locations of bottom pressure records used in this study.

emphasize fast response barotropic variations, we also computed correlation coefficients of differences between consecutive measurements. This process acted as a high pass filter, and the resulting correlation coefficients were greater, ranging from 0.25 to 0.78, and were all significant at the 95% level. In many cases higher correlation coefficients occurred for BPR and TOPEX pairs that were slightly separated in time or space. Maximum correlation coefficients for measurements separated by up to ± 5 days and $\pm 1^\circ$ ranged from 0.34 up to 0.74 (or 0.45 to 0.82 for differences). Baroclinic effects, such as instability, may be responsible for displacements between surface and deep ocean. However our results indicate no statistically significant pattern of time lags or spatial shifts between surface and deep measurements. On the basis of our correlation coefficient calculations, we will assume that information about aliasing inferred from BPRs is also likely to be applicable to altimetry.

Spectra from Bottom Pressure

Figure 2 shows spectra for eight selected time series. BPR time series were separated into between 3 and 27 overlapping segments, a Hamming window was applied, spectra were computed for each segment, and these spectra were averaged to produce the plotted quantities. Also shown are 95% confidence limits. Time segments of 64-days duration were used for records less than 250 days in length; time segments of 128-days duration for records between 250 and 650 days, and time segments of 256 days for records longer than 650 days. Thus frequencies from one cycle per 64, 128, or 256 days up to 1 cycle per 2 hours are resolved. Black dots in Figure 2 indicate spectra computed from BPRs, subsampled every 10 days, to correspond to the TOPEX sampling frequency. Like the original hourly records, subsampled data were also divided into overlapping segments and Hamming filtered before spectra were computed. The calculation was repeated for subsampled time series each offset by one time step, and the resulting spectra were averaged to produce the plotted quantities. Spectra from subsampled data are biased positive relative to the original spectra, because high-frequency variability is aliased into the resolved frequency range.

Figure 3 shows the fraction of energy in spectra computed from the subsampled records that is due to aliasing of high-frequency variability. While the degree of aliasing varies in different locations, at frequencies greater than 0.5 $\mathcal{N}_{TP}$, aliased energy exceeds resolved energy for all BPRs outside Drake Passage and for BPRs o and u within Drake Passage. For frequencies less than 0.2 $\mathcal{N}_{TP}$, the fraction of energy due to aliasing is less than a half everywhere except BPRs d and m. Although BPRs d and m show substantial aliasing even at lowest resolved frequencies, elsewhere there is little difference between the spectra from the original hourly data and the spectra from the subsampled data at low frequencies. These results indicate that although the bottom pressure spectra are red, the spectral slope is not steep enough in the frequency range from 1 cycle per 20 days to 1 cycle per 2 days to prevent unresolved energy from being aliased into the spectra.

The sixth column in Table 1 indicates the fraction of spectral energy at periods longer than one cycle per 20 days. If the spectra were strongly red, very little energy would lie at frequencies greater than one cycle per 20 days, and these

Table 1. Bottom Pressure Gauges in This Study

BPR	Length (days)	Location	Depth (m)	Std Dev. (mb)	% Vari. $< \mathcal{N}$
a	164	63.1°N 0.0°W	1579	5.5	39
b	163	61.4°N 2.1°W	1025	4.6	37
c	153	58.2°N 10.0°W	1870	4.1	48
d	294	57.3°N 9.9°W	2004	3.4	38
e	218	44.9°N 15.6°W	3164	3.2	66
f	600	0.0°S 20.0°W	2700	1.9	46
g	449	32.0°S 36.0°W	2604	4.2	57
h	1065	35.5°S 11.0°W	4080	3.4	47
i	358	37.0°S 14.5°W	3505	2.8	48
j	671	38.5°S 11.1°W	3435	3.0	47
k	204	28.3°S 66.8°E	3650	2.6	60
l	2351	37.9°S 77.6°E	350	6.1	80
m	358	46.9°S 53.5°W	3600	4.3	42
n	1440	53.5°S 57.0°W	2803	3.7	42
o	1840	54.9°S 58.4°W	1052	3.4	53
p	320	56.5°S 63.0°W	3925	9.6	79
q	357	56.8°S 57.5°W	2096	4.6	82
r	724	56.7°S 52.5°W	3150	4.9	73
s	730	58.4°S 56.4°W	3776	5.9	77
t	1467	59.7°S 55.5°W	3690	6.1	74
u	1869	60.8°S 54.7°W	1040	5.1	61
v	320	61.5°S 61.3°W	3946	3.4	64
w	1101	60.0°S 47.1°W	2180	4.1	56

Summary of BPR duration (used for this study), position, depth, standard deviation of bottom pressure, and fraction of variability at frequencies less than 1 cycle/20 days. With the exception of BPR t, multi-year records were redeployed annually and may have data gaps and changes in location between years. Depths and positions shown are initial values.

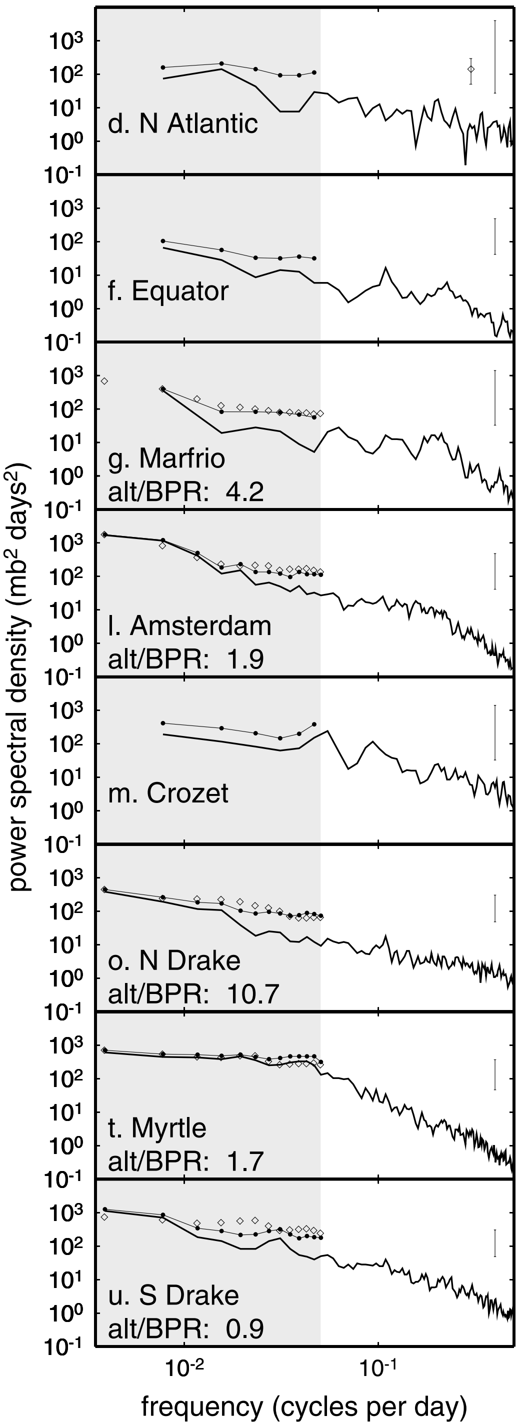

Figure 2. Bottom pressure spectra and error bars for the locations identified in Figure 1. Gray regions indicate the portion of the frequency spectrum resolved by the 9.9156-day sampling of the TOPEX/Poseidon altimeter. Black dots indicate spectra computed for data that has been subsampled at the TOPEX sampling frequency. Open diamonds indicate mean spectra computed from TOPEX data along the nearest ascending and descending groundtracks. Spectra are averaged over $\pm 1.1^\circ$ from the point on the ground track closest to the BPR, and the error bar is indicated in the top panel. Error bars are estimated conservatively, assuming that geographically separated TOPEX measurements are not independent measurements. TOPEX spectra are scaled for comparison with BPRs, as indicated by the ratios in the figure.

numbers would be close to 100%. This is not the case, and the fraction of resolved energy varies from 37% to 82%, with a mean of 57%. This means that 18% to 63% of apparent spectral energy results from aliasing of high frequency signals. As *Fukumori et al.*'s [1998] model predicted, aliasing is lower for the Drake Passage BPRs (n-w) than elsewhere.

Are the BPR results representative of altimeter measurements? Open diamonds in Fig. 2 show spectra from TOPEX altimeter data, scaled to match the BPR spectra at the lowest resolved frequency. TOPEX spectra were computed for measurements within a $\pm 1.1^\circ$ window along the four ascending and descending tracks nearest the BPR location. Scaling factors identified in the lower right of Fig. 2 show the ratio of altimeter energy to BPR energy, after altimeter measurements have been converted to pressure units. These values are typically about 2, but range from 0.9 up to 10.7; values vary, because background energy can vary within the geographic region used for TOPEX spectral analysis. The TOPEX spectra have about the same slopes as the 10-day BPR spectra. If this is also the case for the unresolved high frequencies, then spectra from TOPEX will alias as much high frequency variability as the subsampled BPR records.

Summary and Discussion

These results from bottom pressure gauges suggest that spectra computed from TOPEX measurements are likely to be representative only for frequencies less than about $0.2\mathcal{N}_{TP}$. Other missions with different sampling intervals may show different aliasing characteristics. We expect that frequencies closer to $\mathcal{N}_{TP}$ may be contaminated by unresolved variability in the frequency range between 1 cycle per 20 days and about 1 cycle per 2 days. The magnitude of aliasing varies at different locations, depending on how flat the spectrum is.

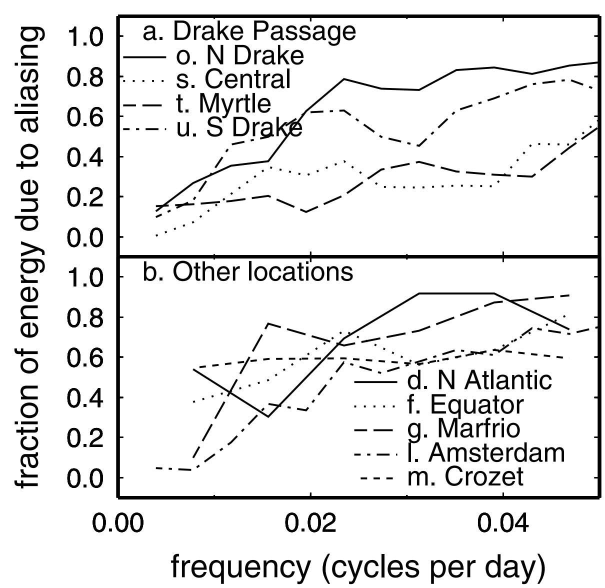

Figure 3. Fraction of energy due to aliasing in spectra computed from 10-day samples of bottom pressure data. Plotted quantity is 1 minus the ratio of the spectral energy computed from the full data set to the spectral energy computed from subsampled data. Spectra were computed after all fortnightly tidal energy had been removed from the data.

Aliasing will have no impact on analysis of altimeter data in a limited number of cases where no interpolation in time or space is required, such as direct comparisons between coincident altimeter and in situ records. For most studies, however, aliasing is likely to pose a challenge. Depending on the nature of the analysis to be carried out using altimeter (or gravity) sampling, aliasing effects may be minimized using a number of different techniques. Numerical studies have suggested using model results to de-alias altimeter signals; results from coarse-resolution models forced by realistic winds have significantly reduced the variance in altimeter observations [*Stammer et al.*, 2000; *Tierney et al.*, 2000]. However, analysis by *Gille et al.* [2001] has indicated that in state-of-the-art eddy-resolving models the barotropic response of the ocean to wind forcing may be too fast, and work by *Huang and Jin* [2000] has indicated that bottom pressure may be unreliable in Boussinesq models. For this reason, caution is advised in de-aliasing altimeter measurements using numerical models.

In other cases alternative strategies may be used to minimize the high-frequency aliasing of altimeter sampling. For analyses of the mesoscale, spatial high-pass filtering can be used to remove large-scale barotropic modes. And for analyses of low-frequency processes, filtering out TOPEX energy at frequencies above about $0.2\mathcal{N}_{\mathcal{TP}}$ will reduce most aliasing.

Acknowledgments. K. Rubython and P. Woodworth have made bottom pressure data available for this study, both in preliminary form and through the Proudman Oceanographic Laboratory web site. Comments from the reviewers and from P. Woodworth have helped to improve the text. This work was supported by JPL contract 960875 for the TOPEX/Poseidon Extended Mission.

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(Received August 23, 2000; revised January 11, 2001; accepted January 30, 2001.)