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Barotropic Rossby wave radiation from a model Gulf Stream

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[1] The barotropic Rossby wave field in the North Atlantic Ocean is studied in an eddy-resolving ocean model simulation. The meandering model Gulf Stream radiates barotropic Rossby waves southward through preferred corridors defined by topographic features. The smoother region between the Bermuda Rise and the mid-Atlantic Ridge is a particularly striking corridor of barotropic wave radiation in the 20–50 day period band. Barotropic Rossby waves are also preferentially excited at higher frequencies over the Bermuda Rise, suggesting resonant excitation of topographic Rossby normal modes. The prevalence of these radiated waves suggests that they may be an important energy sink for the equilibrium state of the Gulf Stream. **Citation:** Miller, A. J., et al. (2007), Barotropic Rossby wave radiation from a model Gulf Stream, *Geophys. Res. Lett.*, *34*, L23613, doi:10.1029/2007GL031937.

1. Introduction

[2] The paths along which energy flows through the ocean fundamentally influence the structure and strength of the general circulation. As ocean general circulation models (OGCM) have become more sophisticated and simulate the general circulation in detail, the need for more information about the energy pathways has become compelling [e.g., *Wunsch and Ferrari*, 2004; *Huang*, 2004]. This is especially important for the energetics of western boundary currents (WBC), which control the bulk of climatic heat transport by the ocean.

[3] One process that remains particularly obscure in WBC dynamics is the radiation of barotropic (BT) Rossby wave (RW) energy from these unstable currents. BTRW radiation is likely to be a ubiquitous product of meandering current jets, particularly those with a meridional component of flow, but has yet to be well observed. North of the Gulf Stream (GS), topographic-Rossby waves have been identified radiating from the GS onto the continental slope [*Thompson and Luyten*, 1976; *Hogg*, 1981; *Price and Rossby*, 1982; *Welsh et al.*, 1991; *Bower and Hogg*, 1992; *Pickart*, 1995]. *Price and Rossby* [1982] and *Bower and Hogg* [1992] (hereinafter referred to as BH92) found

evidence for at least occasional southward radiation of BTRW on each side of Bermuda, respectively.

[4] The forcing of BTRW by meandering current jets has been studied extensively with analytical and numerical models over the past 30 years [*Pedlosky*, 1977; *Talley*, 1983; *Malanotte-Rizzoli*, 1984; *Miller et al.*, 1987; *Malanotte-Rizzoli et al.*, 1995; *Hogg*, 1988; *Kamenkovich and Pedlosky*, 1996; *Sheremet et al.*, 1997; *LaCasce*, 2002; *Nakamura and Kagimoto*, 2006]. The implication of these works is that radiation is a viable, perhaps significant, pathway for energy loss from the stronger components of the general circulation. Indeed, the BT energy loss may be much more important than baroclinic loss because BT variability has a high energy flux [*Rhines*, 1977] and decays more quickly than baroclinic variability [*Wunsch*, 1998].

[5] Simplified numerical models designed to study WBC dynamics, however, still frequently use flat-bottomed oceans [*Berloff*, 2005], even though BTRW are known to propagate freely into the ocean interior when the bottom is flat [*Miller et al.*, 1987] but can be trapped locally, or extinguished by friction, near the WBC when the bottom is rough [*Boning*, 1989]. Bottom roughness enhances the baroclinicity of the eddy field by reducing the energy in the BT mode, because energy of the BT mode is scattered into smaller scales that are more effectively removed by lateral friction. The difference in energy balance for the WBC is significantly altered by the roughness [*Treguier and Hua*, 1989], suggesting that radiated BTRW exert an important influence.

[6] Although the importance of BTRW radiation in the real oceans has been taken for granted for over 30 years [*Rhines*, 1977], no experiment to date has explicitly sought to observe this process. Observations of BT variability are nearly impossible with traditional instrumentation because hydrography is blind to the BT component, while current meter moorings rarely adequately resolve the BT flow. Satellite altimetry is another approach, but sea surface heights are usually dominated by baroclinic variability at sub-inertial periods [*Wunsch*, 1997] (although *Fu et al.* [2001] discovered strong excitation of 25-day period BT waves in the Argentine Basin with altimeter sea surface heights and *Warren et al.* [2002] observed a bimonthly BT wave propagating through the Mascarene Basin in both altimetric and current meter data).

[7] We revisit here the problem of the southward radiation of BTRW from the GS by examining a state-of-the-art eddy resolving GCM. In earlier work [*Miller et al.*, 1987] it was demonstrated that a boundary current forced by only mean winds can readily fill a simple, flat-bottomed quasi-geostrophic numerical model basin with BT energy radiated from the meandering current. Here we examine the distri-

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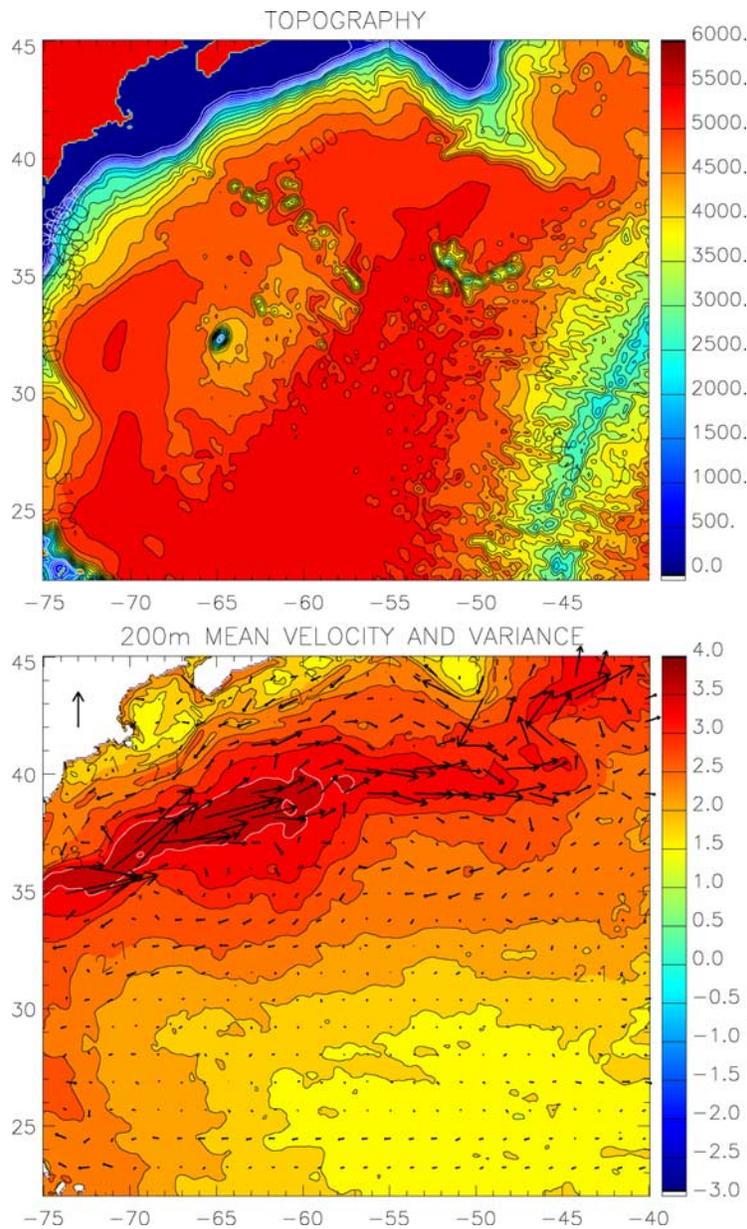
Figure 1. (top) Bathymetry of the ROMS ocean model in the region around the Gulf Stream. Contour interval is 300 m. Dark blue indicates the region of the 200 m minimum model depth. (bottom) Model mean velocity (arrows, 30 cm/s marked) and velocity variance (contours, plotted as $\log_{10}[(cm/s)^2/cpd]$) at roughly 200 m from the surface.

bution of BT velocity variance in the region near a vigorously unstable GS when realistic topography is present. We then determine if the spatial distribution is consistent with BTRW radiation from the unstable WBC of the model. Lastly, we interpret these results in the context of previous observations.

2. Ocean Model Hindcast

[8] The OGCM output is from a North Atlantic simulation [*Fennel et al.*, 2006] of the Regional Ocean Modeling System (ROMS), which is a generalized sigma-coordinate, hydrostatic, primitive equation model with a free surface [*Haidvogel et al.*, 2000; *Moore et al.*, 2004; *Shchepetkin and McWilliams*, 2005]. The ROMS model output consists of a 6-year run (after a 5-year spin-up using COADS wind stress) with 3-day average NCEP/DOE wind stress forcing from 1994 through 1999. The model has 30 sigma-levels, 0.1 degree resolution and south-north boundaries at 30S and 75N, respectively. The topography in the region around the GS is shown in Figure 1 (top). The output exists as 3-day averages, which allows analysis of velocity variations with periods longer than 6 days.

[9] BT velocity is frequently defined in the literature in two different ways, as the vertical integral of velocity or as the "deep" ocean velocity, far below the thermocline but above the bottom boundary layer. The vertical integral of velocity is routinely saved in ROMS and this is our definition of BT velocity. We also chose a model sigma level that was roughly 500 m off the ocean bottom in the
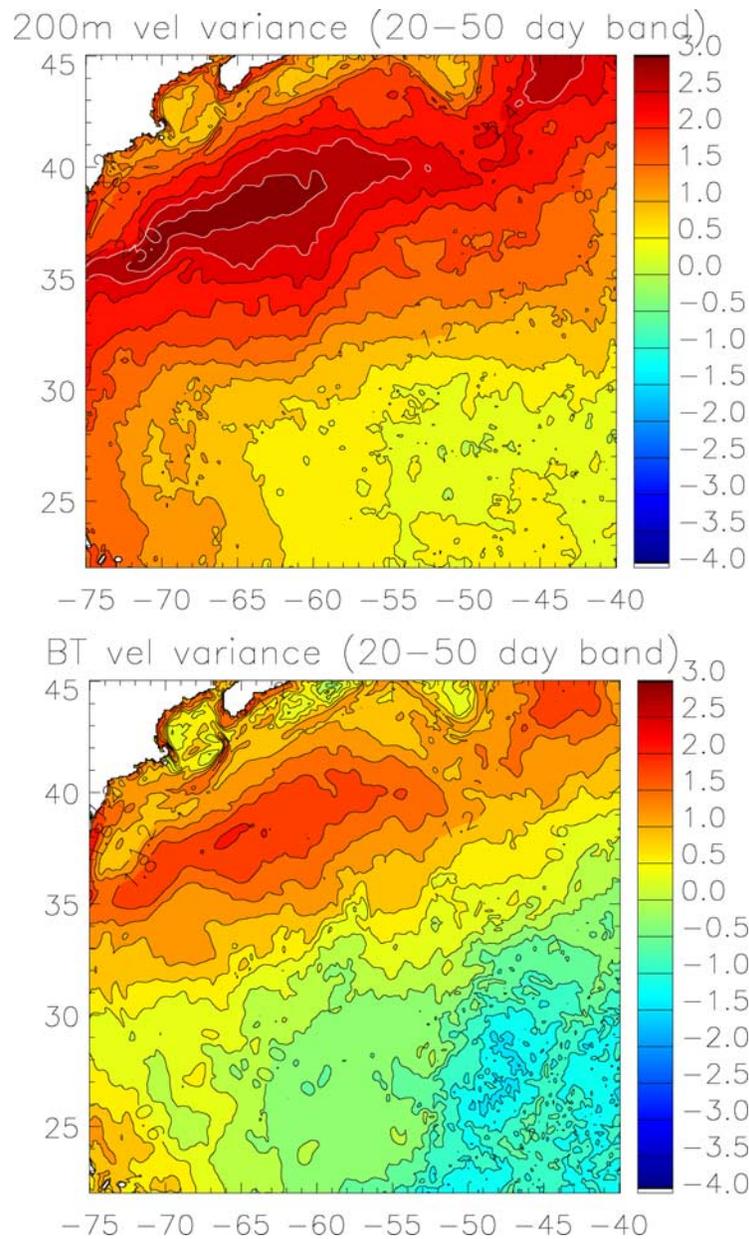
Figure 2. (top) Model near-surface velocity variance in the 20–50 day band at roughly 200 m depth. (bottom) As in Figure 2 (top), but for barotropic (vertically averaged) velocity variance. Values are $\log_{10}[(cm/s)^2/cpd]$.

deep ocean to represent "deep" currents. In the course of our analyses we found the results (away from the GS) to be remarkably similar using BT or "deep" currents. This suggests that BT velocity is well-defined by the vertical integral in the sense that topographic coupling between BT and baroclinic modes [e.g., *Rhines*, 1977] is not strong on the spatiotemporal scales of this analysis. We also show results for currents at a sigma-level at roughly 200 m depth in the deep ocean, which are meant to characterize near-surface currents that behave much differently than BT currents.

[10] The mean zonal and meridional currents were first inspected for verisimilitude. As observed, the model GS detaches near Cape Hatteras and progresses northeastward (Figure 1, bottom). Velocity anomalies were calculated by removing the annual mean, since there was no significant seasonal cycle. Maximum velocity variance is aligned along the axis of the model GS as expected (Figure 1, bottom).

3. Results

[11] The zonal and meridional velocity components were partitioned into frequency bands using FFT's to help elucidate the dynamical controls on the spatial patterns. Following the analysis of BH92, we chose to analyze frequency bands of 51-275d, 20-50d, 11-20d and 8-11d.

[12] Current variance at 200 m in the 20–50 day band shows relatively monotonic southward decay from the axis of the GS at all longitudes (Figure 2, top). The decay of BT current variance in this band, however, is much less uniform (Figure 2, bottom) due to apparent blockage, trapping or scattering by features associated with the Bermuda Rise and
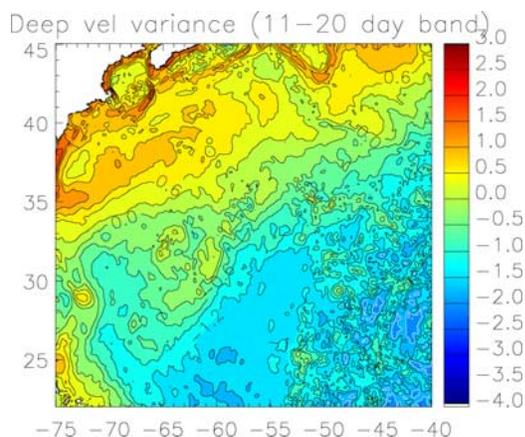
Figure 3. Model deep velocity variance in the $11-20$ day band at roughly 500 m off the bottom. Values plotted are $\log_{10}[(\mathrm{cm/s})^2/\mathrm{cpd}]$.

Mid-Atlantic Ridge. The rate of southward decay of the BT variance (Figure 2, bottom) is smallest in the "corridor" between the Rise and the Ridge (centered on $\sim$55W), and in another less-distinct corridor to the west of the Rise (centered on about $\sim$69W). The implication is that the BT variability is more effective at exiting the GS region there, presumably due to the preponderance of free BTRW that can propagate energy southward in these regions of less complicated topography. Very similar results prevail for "deep" current variance and for BT kinetic energy density (not shown).

[13] The two corridors of somewhat monotonic, southward decay of BT current variance on either side of the Rise (along $\sim$55W and $\sim$69W, between $\sim$30–38N) are remarkable. They lie to the west and to the east of a region of small BT variability centered at about $\sim$58W, $\sim$28–33N. The central corridor suggests that there is a relatively unimpeded region through which RW energy is channeled southward. This is the region where BH92 found the best (albeit weak) evidence for southward radiation in their deep current fields. Yet this region does not have "smooth" topography. Rather, the bottom is covered with abyssal hills of several hundred meters amplitude, which are reasonably well represented in the topography used in ROMS (Figure 1, top). Not until the abyssal hills are substantially larger (eastward of 53W) does the scattering effect noted by *Boning* [1989] and others appear to predominate.

[14] The features of the BT variance distribution in Figure 2 (bottom), i.e., high variance corridors along 55W and 69W, and low variance over the Ridge and the Rise are also found in the longest period band of $50-244$ days. In contrast, the two shorter period bands (stretching from 7.8 days to 20 days) exhibit a remarkably different behavior with strongest amplitudes occurring over the Bermuda Rise (Figure 3), which becomes an "island" of maximum energy extending the reach of BT wave activity hundreds of km further southward. Apparently, energy at these shorter periods is channeled, trapped and enhanced over the Rise, as BT Rossby-topographic normal modes [e.g., *Rhines and Bretherton*, 1973; *Miller et al.*, 1996; *Pierini*, 1996; *Fu et al.*, 2001; *Weijer*, 2005].

[15] Following BH92, we use an estimate of the ellipse orientation of the deep currents to determine the phase propagation direction (which is perpendicular to the axis of the nearly geostrophic Rossby wave currents), and then the direction of energy propagation from the Rossby wave dispersion relation. Unlike BH92, we use the rotary coherence phase to determine the current axis because it is insensitive to the choice of coordinate axes [*Mooers*, 1982].

[16] Figure 4 displays the rotary coherence amplitude and the ellipse orientations of the ROMS BT currents in the 20–50 day band. Warm colors indicate a current axis oriented roughly northeast-southwest, being more meridionally oriented for redder colors. These current orientations generally correspond to phase propagations with a northwestward component, and thus generally southward energy propagation (with eastward or westward tendencies), given wavelengths under a thousand km. The actual energy propagation direction will depend on the specific bottom slope for each region. In the central "corridor," we find a region of warm colors indicating energy propagation consistently away from the GS. We estimated wavenumbers from the deep currents in this region and have confirmed that they are consistent with energy propagation away from the GS, given a dispersion relation based on the large-scale slope of the bottom.

[17] The pattern of ellipse orientations in the $11-20$ day band is very similar to Figure 4. At the longest periods, 50–244 days, the ellipse orientations are more variable in the corridors, although still exhibiting broad patterns of the appropriate orientations for generally southward radiation. The increased variability may indicate increased scattering, since the longer periods are likely associated with shorter wavelengths. The spatial variability in these ellipse orientation figures explains why BH92 found such variable results in their Reynolds stresses south of the GS, especially since they averaged the Reynolds stresses from a variety of mooring deployments within each of their $2° \times 5°$ boxes.

[18] Calculation of coherence functions between the deep ROMS currents and atmospheric winds yielded only weak coherence amplitudes (not shown), along the lines of what was observed in FASINEX by *Brink* [1989]. Thus, there may be a small amount of directly wind-driven BT variability "contaminating" the deep ROMS currents. But this effect definitely does not dominate the deep currents, considering the relatively small wavelengths (under 1000 km) we find in the eastern corridor, compared to expected wavelengths for atmospherically forced variability of several thousand km or more [*Chave et al.*, 1992] that result from the large scales of the atmospheric forcing. Even with the apparent weakness of the atmospherically forced variability, additional simulations with only seasonal cycle atmospheric forcing are clearly needed to definitively discriminate the wind-forced versus the radiatively generated BT wave field.

4. Discussion

[19] An eddy-resolving general circulation model of the North Atlantic reveals the existence of barotropic (BT) Rossby waves (RW) radiating southward from the Gulf Stream. The Bermuda Rise and the mid-Atlantic Ridge form barriers that effectively channel the energy, resulting in a corridor of southward BTRW energy transmission between
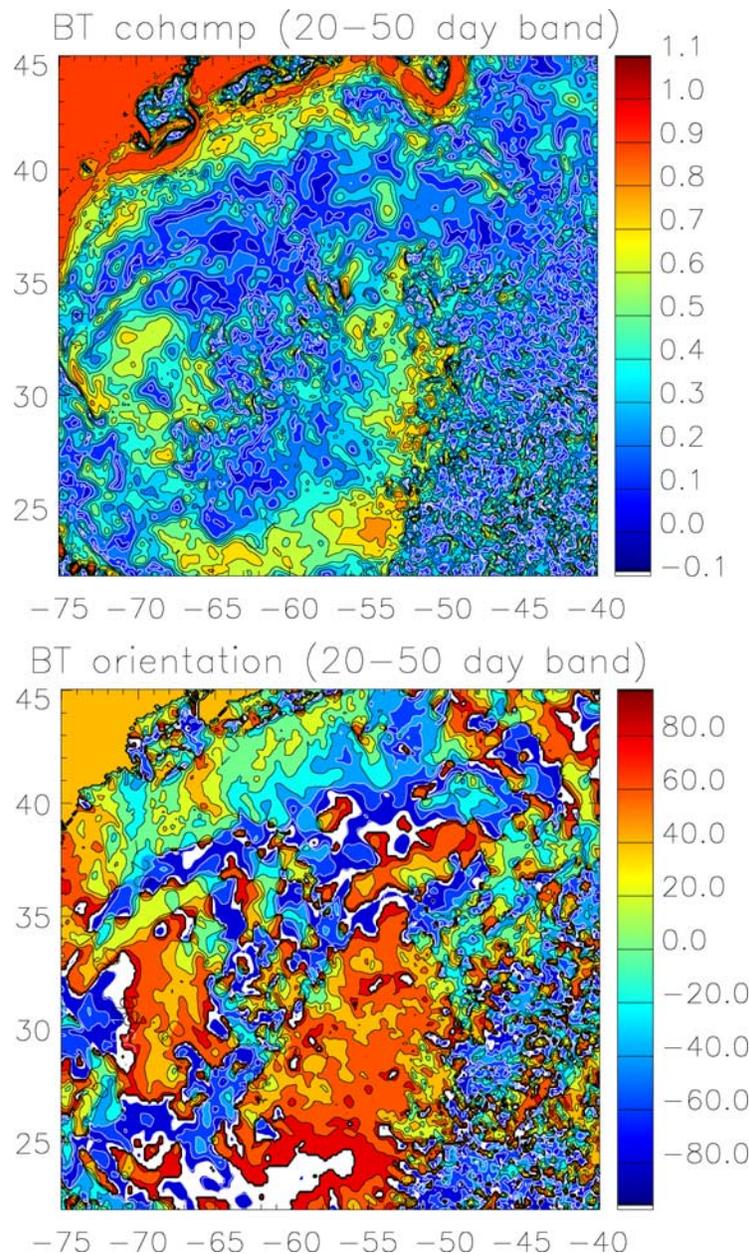
Figure 4. (top) Rotary coherence amplitude between the cyclonic and anticyclonic barotropic currents in the 20–50 day band. (bottom) Orientation (based on rotary coherence phase) of the major axis of the barotropic current ellipses in the 20–50 day band. The angles range from $-90°$ to $90°$, where the angle is measured from east, with positive being counter-clockwise from east. Warm colors indicate southward energy flux.

them and another corridor west of the Rise. At higher frequencies, the Bermuda Rise supports fast, large-scale topographic Rossby modes that carry energetic BT signals even further southward.

[20] In an effort to find observational evidence for BT wave radiation from the GS, *Bower and Hogg* [1992] examined 607 historical time series from deep current meters. Only records from deeper than 2000 m and with durations greater than 128 days were considered (the deep variability was assumed to be dominated by the BT mode). The approach was to calculate statistics such as eddy kinetic energies and Reynolds stresses averaged over $2° \times 5°$ boxes. The sign and magnitude of the Reynolds stress is an indicator

of the magnitude and direction of wave radiation. The results confirmed BT radiation northward from the GS.

[21] However, BH92 found ambiguous evidence for southward radiation. Their two boxes just to the east of Bermuda have Reynolds stresses, which, though weak, are most consistent with southward radiation (see BH92, their Figure 8). Due to the ambiguity of their statistics, BH92 concluded: "we suspect that energy does radiate outward to the south. However, the associated velocity fluctuations may be difficult to detect due to the scattering of RW by small-scale bathymetric features, and/or due to the overwhelming presence of other eddy generating processes such as baroclinic instability [in the GS's recirculation]."

[22] Our results are consistent with BH92's results in that we found tremendous spatial inhomogeneity in the distribution of velocity covariance, which gives a cautionary new perspective to their attempt at identifying southward RW radiation. Our results also support the renewed interest in topography-catalyzed diapycnal mixing as the means for maintaining the abyssal stratification [*Munk and Wunsch*, 1998] because BT variability becomes a means to stir boundary-mixed products into the deep interior ocean and is one of many potential energy sources for the near-boundary diapycnal mixing itself. The rate of dissipation of radiated BT energy, that is, whether the waves lose their energy rather quickly (e.g., through interaction with bottom topography near their source) or whether they propagate long distances before dissipating, has implications for not only how far from the source the energy may propagate (and thus how much of the ocean basins will be affected by this source) but also for the rate of dissipation of the general circulation [*Wunsch*, 1998] and for the spatial distribution of topography-catalyzed abyssal diapycnal mixing.

[23] Given the theoretical work pointing to the importance of BTRW wave radiation and, most importantly, given the observational evidence to date that is supported by our initial analyses of the ROMS output, we suggest that BTRW wave radiation from the GS is a significant contributor to the energy in the deep ocean south of the GS recirculation. This phenomenon needs to be studied with additional ocean model experiments specifically designed to elucidate its characteristics, followed by a targeted observational program.

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