Observations of Acoustic Noise Bursts Accompanying Nonlinear Internal Gravity Waves on a Continental Shelf off New Jersey

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Key Points:

* Noise bursts are one of the strongest acoustic manifestations of internal gravity waves observed in the ocean
* The most energetic part of the noise bursts is caused by collisions of suspended sediment particles with each other, the sensor and the seafloor
* Spectrograms of the noise bursts can potentially be used to characterize near-bottom currents and sediment transport on the continental shelf

Abstract

Anomalously large, transient fluctuations of acoustical noise intensity (up to four-five orders of magnitude above the background in a wide frequency band) were observed with single-hydrophone receiver units (SHRUs) and on the L-shaped horizontal and vertical line array (HVLA) “Shark” hydrophone array (belonging to Woods Hole Oceanographic Institution) in the Shallow Water 2006 experiment. The present study investigated temporal and spatial properties of these noise bursts. The site of the experiment (the New Jersey Atlantic shelf) is characterized by strong internal gravity wave activity, including tidally generated nonlinear internal waves (NIWs). As NIWs move from the shelf break towards the coast, they form trains consisting of up to twelve separate, localized, soliton-like waves with up to 25–35 m displacement of isopycnal surfaces. The NIW trains consecutively cross the positions of five SHRUs and the HVLA Shark that are located about 5–8 km from each other along a line perpendicular to the coast. We found that the bursts of acoustic noise were observed when an NIW train passed through locations of the corresponding acoustic receivers. Turbulence of the water flow, saltation and bedload of marine sediments were the dominant causes of the acoustic noise bursts caused by NIWs at different frequency bands. On near-bottom hydrophones, the most energetic part of the observed noise bursts was generated by collisions of suspended sediment particles with each other, the sensor, and the seafloor.

1 Introduction

Internal gravity waves in the ocean create time-dependent and spatially inhomogeneous variations in temperature and sound speed profiles and are known to have a significant effect on underwater sound propagation (Simmen et al., 1997; Colosi et al., 1999; Tang et al., 2007). Especially strong variations in the sound propagation conditions and attendant fluctuations of the acoustic fields occur due to nonlinear internal waves (NIW) on continental shelves (Zhou et al., 1991; Godin et al., 2006; Apel et al., 2007). The magnitude of the acoustic effects depends on the NIW amplitude and spatial structure as well as on the azimuthal direction of the acoustical track relative to the direction of NIW propagation, which determines the dominant physical mechanism of the NIW-sound interaction. For example, on a 14 km propagation track largely along NIW wavefronts in the SWARM95 experiment in the Mid-Atlantic Bight, NIW-induced focusing and defocusing of acoustic normal modes in the horizontal plane was found to result in sound intensity fluctuations of low-frequency (20–300 Hz), with magnitudes of 7–8 dB and periods of about 10 minutes (Badiey et al., 2002, 2007). In the same experiment, for mid-frequency signals (a few kHz) on a different sound propagation track crossing the NIW wavefronts, sound intensity fluctuations of a few dB took place due to NIW-induced coupling of the acoustic normal modes (Badiey et al., 2002; Katsnelson et al., 2009). Perhaps the strongest reported NIW-induced fluctuations of the transmission loss, or frequency-dependent sound intensity, of 20–25 dB were observed in the Yellow Sea off China; these were explained in terms of the resonant Bragg scattering of sound by an NIW wave train (Zhou et al., 1991; Apel et al., 2007).

In addition to the propagation effects, NIWs were observed to change sound intensity by generating underwater acoustic noise. Currents of various nature, including NIW-induced currents, shed vortices and generate turbulent pressure fluctuations when flowing past acoustic sensors and elements of their moorings. These pressure fluctuations are observed as very low-frequency noise (typically, below a few tens of Hertz) and are known as “flow noise” (Strasberg, 1979; Webb, 1988). Measurements of NIW-induced flow noise have been described in the literature (Serebryany et al., 2008b; Yang et al., 2013). At higher frequencies, Serebryany et al. (2005, 2008a, 2008b) observed strong fluctuations of the ocean surface-generated broadband acoustic noise that accompanied passage of a strong NIW. These fluctuations were attributed to the modulation of the surface gravity and capillary-gravity wave activity on the ocean surface by NIW-induced currents. NIW-induced fluctuations of the intensity of the surface-generated noise reached 10–15 dB in deep water in the Indian ocean (Serebryany et al., 2005) and up to about 6 dB on the continental shelf in the in the Mid-Atlantic Bight (Serebryany et al., 2008b). Similar observations were made by Yang et al. in the northeast of Taiwan (Yang et al., 2013) and in the South China Sea (Yang et al., 2015), with about 10 dB variations of the acoustic noise intensity due to NIW-induced changes in the surface wave activity.

In the present paper, we describe our analysis of observations of very large (between 40 and 50 dB) broadband, transient increases in the noise intensity, to be referred to as noise bursts, on the continental shelf off New Jersey. By combining acoustic observations on various hydrophones with measurements of the water temperature and current velocity, we established a relationship between individual noise bursts and tidally generated, localized, soliton-like NIWs, and identified the physical mechanisms responsible for the observed acoustic manifestations of the NIWs.

The paper is organized as follows: Section 2 outlines acquisition of the data used in this study. Properties of the noise bursts are discussed in Section 3. In Section 4 we show that the observed temporal and spectral characteristics of the noise bursts can be explained in terms of three physical mechanisms of noise generation, which include turbulence of the water flow and NIW-induced sediment saltation. Section 5 puts our findings into the broader context of previous research on sediment-generated underwater noise and sediment resuspension by NIWs. The results of the work are summarized in Section 6 along with their possible application to investigation of soliton-like NIWs on the continental shelf and their possible contributions to sediment transport.

2 Experiment and Data

The data used in this study were obtained in the multi-disciplinary, multi-institutional Shallow Water 2006 experiment (SW’06). The experiment was carried out in July–September, 2006, in the Mid-Atlantic Bight on the continental shelf off New Jersey (Newhall et al., 2007; Tang et al., 2007; Lynch & Tang, 2008; Xue et al., 2014). A bathymetric map of the experiment site is shown in the lower left corner of Figure 1. Water depth in this area decreases gradually from about 120 m near the shelf break to 55–60 m 40 km from the shelf break. The summer water temperature profile was characterized by a monotone temperature decrease from the surface to the seafloor and a rather strong thermocline with about 12oC temperature drop between 10 and 25 m depths. The corresponding sound speed profile was at its minimum on the seafloor and provided a bottom-interacting guided sound propagation.

The site of the experiment is characterized by a strong internal gravity wave activity, which is well documented (Tang et al., 2007; Xue et al., 2014). Approximately twice a day, a strong NIW is generated around the shelf break as a result of interaction of tides with the bathymetry. NIWs move from the shelf break shoreward in the northwest direction, largely along the bathymetry gradient. Over the two-month duration of the experiment, tens of events were registered of NIW train passages through the instrumented site. Direction of propagation and surface structure (shape of wavefronts, the number of waves in the train, and distance between them) were obtained using satellite images (Xue et al., 2014), which show a rather narrow spread of NIW propagation directions in the horizontal plane. NIW propagation directions were nearly parallel to the across-shelf line, along which a suite of acoustic sensors, thermistor chains, and acoustic Doppler current profilers (ADCPs) was deployed (Figure 1).

Detailed information about the three-dimensional structure and temporal evolution of the NIW trains was obtained using a few tens of thermistor chains (Newhall et al., 2007; Tang et al., 2007; Lynch & Tang, 2008). These data show that the NIWs were depression waves. As it moved from the shelf break towards the shore, each NIW evolved into a wave train consisting of up to 10–12 localized, soliton-like waves (Figure 1). The isopycnal depression amplitude of the individual localized waves was largest near the leading front of the train and gradually decreased toward its back end. The observed wave trains were qualitatively similar to the D-noidal model of NIWs (Apel, 2003).

Observations of strong NIW events on the 17, 18, 19 and 22 of August, 2006, have been selected for the present study. These events had quite similar patterns of NIW movement and, in turn, similar features of noise sound field fluctuations. Consider a 12-hour time period from 08:00–20:00 GMT on August 19, 2006. The period started with the appearance of an NIW in the shelf-break area. NIW evolution process can be analyzed using temperature records from a cluster of 16 thermistor chains in a 2x2 km square-shaped area (Newhall et al., 2007). Positions of selected thermistor chains, denoted by letters SW, and of the acoustic receiving systems, single-hydrophone receiving units (SHRUs) and the L-shaped horizontal and vertical line hydrophone array (HVLA) Shark, are shown on the bathymetric map in Figure 1. SHRUs were moored with heavy anchors, with the hydrophone located about 7 m above the seafloor. HVLA Shark consisted of a 16-hydrophone vertical linear array (VLA), which extended through most of the water column, and a 450m-long, 32-hydrophone, near-bottom horizontal linear array (HLA).

Five color panels in Figure 1 show the temperature records obtained by five thermistor chains located at various distances from the shelf break. Each temperature record was 90 minutes long, corresponding to the time it took an NIW train to pass each thermistor chain. It can be seen that the NIW train was generated in the area between SW23 (where we can see the forward front of an unstructured NIW) and SW54, where NIW had developed a well-defined across-the-front structure. The distance between SW23 and SW24 was about 14 km. At SW54, the NIW contained 12 distinct, soliton-like waves (peaks of the depression of the isothermal surfaces) with amplitudes of the thermocline’s displacement from equilibrium position of up to 25–30 m (Figure 1). As the NIW train moved shoreward, it passed consecutively a set of acoustic receivers, including the HVLA Shark and five SHRUs, which were located a distance of 5–8 km from one other along a straight line. The NIW train evolved as it propagated; the amplitudes and the number of the localized waves in the train changed (Figure 1). One can estimate the speed *v* of the NIW train using distance between thermistor chains and the temporal interval between arrivals of the NIW leading front. From such an estimate we obtained *v* ~ 0.9 m/s, length of the NIW trains *L* ~ 5 km, quasi-period of the spatial structure inside the NIW train *l* ~ 250–300 m. The corresponding scale of temporal variability was 5–7 minutes.

For the entire duration of the SW’06 experiment, acoustic pressure was continuously measured by the SHRU and HVLA Shark hydrophones. The acoustic data was recorded with the common sampling rate of 9750 Hz for all hydrophones. Measured time series *p*(*t*) of acoustic pressure *p* are used below for calculation of various characteristics of the acoustic field, including its intensity, frequency spectrum, and spectrograms. In addition, current velocity was measured using acoustic Doppler current profiles (ADCPs). The data obtained with a moored ADCP (Figure 1) that was used in this study is described in Section 3.

3 Observations of Noise Bursts

The vertical line array of HVLA Shark was collocated with thermistor chain SW54 (Figure 1) but other acoustic receivers, including SHRU1, SHRU4, and SHRU5, had no collocated temperature sensors. Figure 2 presents a diagram demonstrating the connection between NIW passage and observations of elevated noise intensity at different points across the shelf. In the top panel, the vertical axis denotes distance along the straight line through locations of the hydrophones and thermistor chains, with 0 of this axis corresponding to the position of the thermistor chain SW01. The horizontal axis represents time and covers 15 hours of observations. Temporal variation of temperature at different locations is illustrated by temperature measurements (denoted by the letter ***t***), by one thermistor at 40 m depth of each of 5 thermistor chains. Note that all positions of the forward front of NIW train in the range-time plane were located approximately along a straight line, which indicates a nearly constant speed of the NIW train of 0.9 m/s. Time series of measured sound intensity are shown for four SHRUs and one of the hydrophones (channel 40) of HVLA Shark. The parts of these records that show large, rapid increases (bursts) of the noise intensity are indicated by boxes ***a-e***. Figure 2 shows that the noise bursts were observed when the NIW train traveled past the acoustic sensor.

More detailed information about the frequency content of acoustic signals and its time dependence can be obtained using spectrograms. Spectrograms *S*(*f, t*) have been calculated in the frequency range 10-4000 Hz as follows:

 

Here *p*(*t*) is a measured time series of acoustic pressure, *f* is sound frequency, and *W*(*t–t*1) is the time window. A Kaiser window (Kaiser & Schafer, 1980) incorporating 1024 pressure samples was used. Figure 2 shows spectrograms of noise recorded when a NIW train was moving consecutively through positions of SHRU1 (panel ***a***), HVLA Shark (channel 40, hydrophone in the center of HLA, panel ***b***), and SHRUs 3, 4, 5 (panels ***c, d, e*** , respectively). HVLA Shark is represented in Figure 2 by measurements on channel 40, which was a hydrophone at the center of the horizontal line array.

In the area of NIW generation, where water depth was about 100 m, fluctuations of acoustic intensity were relatively weak, especially at frequencies above 1 kHz (see panel ***a*** in Figure 2), although there was some correlation of the intensity fluctuations with NIWs. In particular, the temporal scale of the sound variability of about 7 minutes corresponded to the time interval between separate localized waves with the NIW train. A similar situation took place on the HVLA Shark hydrophones (panel ***b***). Noise intensity was significantly weaker on the vertical part of the L-shaped array than on its horizontal part as was previously reported by Serebryany et al. (2008b).

Acoustic intensity fluctuations increased as the NIW train moved to shallower water. Panel ***d*** in Figure 2 depicts the spectrogram of noise recorded by SHRU4, which was located between thermistor chains SW03 and SW04. Comparison of the shapes of the NIW train recorded by these thermistor chains (panels ***b*** and ***c*** in Figure 1) shows that the main parameters of the NIW train – the number of individual localized waves, their amplitudes (~ 30–40 m), and the time interval between the waves (~ 7 min) – did not change significantly between SW03 and SW04. Hence, SW03 and SW04 measurements should provide a suitable representation of the NIW train at SHRU4. Comparison of the temperature record ***c*** in Figure 1 and spectrogram ***d*** in Figure 2 demonstrated a good agreement between the temporal scales (total duration of about 1 hour, the interval between peaks ~ 7 min) in the temperature and intensity measurements. The agreement between time dependencies of the temperature variations and acoustic spectra indicated a causal relation between NIWs and noise intensity fluctuations at SHRU4 and, by extension, at other locations on the continental shelf.

The SW3 and SW4 temperature records (panels ***b*** and ***c*** in Figure 1) have 12 large peaks, which corresponded to individual localized internal waves. Amplitude of the waves tended to decrease toward the tail of the NIW train. The data from acoustic sensors SHRU 3 and SHRU4, which were located between the thermistor chains SW3 and SW4 (Figure 1), showed fewer peaks in the spectrograms. There are six strong, broadband noise bursts in SHRU3 data in panel ***c*** in Figure 2. Water depth was about 68 m and 82 m at SHRU4 and SHRU3 locations respectively. For SHRU4, which was located in shallower water of 68 m depth, panel ***d*** in Figure 2 shows 10 strong, broadband noise bursts. We relate the observed difference in the number of noise bursts to the difference in the speed of the near-bottom currents induced by NIWs at the two sites. As discussed in Section 4, speed of the near-bottom currents increased with increasing wave amplitude and decreasing water depth (see Eq. ). The change in the number of noise bursts at frequencies above a few hundred Hertz suggests that acoustic noise generation has a threshold character. Weaker NIWs within the wave train were below the threshold, and larger NIW amplitudes are required in deeper water to reach the threshold.

The value of the threshold can be estimated by combining the noise intensity and water temperature measurements with current velocity data. Current velocity was not measured at acoustic sensor locations. We used the velocity data obtained with an acoustic Doppler current profiler, which was collocated with the thermistor chain SW30. Figure 3 compares the ADCP measurements with simultaneous measurements of the water temperature profile by thermistor chains SW07 and SW30 and acoustic observations at SHRU3. In the direction across the NIW wavefront, SW30 and ADCP preceded SHRU3 by about 700 m, and SW07 was behind SHRU3 by about 500 m (Figure 1). This geometry was responsible for the 10–15 minutes shifts of the respective temperature and current velocity manifestations of an NIW wave train (Figure 3b–d) from its acoustic manifestations (Figure 3a). The wave train evolved as it propagated. Isothermal depressions had five and seven strong peaks following the leading front of the NIW train at SW07 and at SW30, respectively (Figure 3b, c). It is reasonable to assume that there were six strong peaks at SHRU3, which is located between SW07 and at SW30. Figure 3a shows six strong, broadband noise bursts following the leading front of the NIW train.

Horizontal velocity of the water flow caused by the NIW train reached its maximum when the isothermal depression was at maximum (Figure 3c, d). Observed velocities reached – and for the strongest peaks exceeded – 60 cm/s below the thermocline. Velocity magnitude gradually declined with depth below the thermocline and decreased by a factor of about 1.5 near the bottom (Figure 3d). Comparison of the spectrogram of acoustic noise with the ADCP measurements indicated that strong, broadband noise bursts occurred when the NIW-induced near-bottom current exceeded a threshold value of about 40 cm/s.

These results suggest that the noise bursts occurred around the time when a peak of isothermal depression passed the observation point. A more precise relation between the phase of the isothermal displacement and acoustic noise can be obtained using the HVLA Shark data, since SW54 thermistors were attached to the vertical part of the hydrophone array. Figure 4 compares simultaneous, collocated measurements of the water temperature profile and sound intensity on the lowest hydrophone on the vertical part of the array. The figure demonstrates that maximum noise intensity was observed when the NIW-induced displacement of isothermal surface was at maximum. The time-dependent acoustic intensity *I* and intensity level *IL* were calculated as follows:

 

 

Here ∆*t* = 1 s is the average time, *ρ* and *c* are the density and sound speed in water, and *I*0 is the reference intensity, corresponding to the root mean square acoustic pressure of 1 μPa. Each point of noise intensity is calculated with 1024 points of pressure without overlap.

The noise generated by NIWs on near-bottom hydrophones was as strong as, if not stronger, than any signal received or noise of a different origin. This is illustrated in Figure 5, which shows the time dependence of acoustic intensity recorded by SHRU5 during a full day. A number of sound generation mechanisms contributed to the observed acoustic field. For instance, from 04:00 to 17:00 there were prominent signals from the research sources (Newhall et al., 2007; Lynch & Tang, 2008), which were towed through the experiment site. Strong low-frequency noise, presumably due to shipping and/or a storm, was present from about 10:00-14:00. This noise was superimposed on and overshadows signals from the research sources. NIW-induced noise intensity bursts appeared as a sequence of high and narrow, quasi-periodic intensity peaks in the 16:30-17:30 time interval. Intensity of the noise bursts reached 150-155 dB re 1 μPa. It exceeded the background noise intensity of 110-115 dB re 1 μPa by 40 dB, or four orders of magnitude.

4 Mechanisms of Noise Generation

Noise intensity, its time dependence, and the spectral content of the noise showed significant variability depending on hydrophone position and position of NIW train. Three distinct types of acoustic noise that accompanied the passage of NIWs can be identified, which combined to explain the bulk of observations (see Figure 6). These types are (i) low-frequency noise, which is illustrated in Figures 6a and 6b, (ii) noise spikes of ~1 s duration with spectral peaks located below approximately 1 kHz (Figure 5c), and (iii) more frequent, shorter-duration spikes with prominent high-frequency content above 3 kHz, which subsequently merged to become a continuous signal of a few minutes in duration (Figure 6d).

The low-frequency noise was most pronounced at infrasonic frequencies below 10 Hz (Figure 6b). It was observed almost continuously as each soliton-like wave in the NIW train passed the acoustic receiver. Acoustic intensity increased rapidly with the magnitude of pycnocline depression (see the time dependence of noise spectral density at frequencies below 10 Hz in Figure 6b). The low-frequency noise was clearly observed on all SHRUs and on VLA hydrophones, where noise intensity was only weakly dependent on the hydrophone depth.

We interpret the low-frequency noise that was observed as flow noise (Strasberg, 1979; Webb, 1988; Bassett et al., 2014). Flow noise, also known as pseudosound, results from advection of pressure fluctuations in a turbulent flow past the sensor. Pressure fluctuations include ambient fluctuations in a turbulent flow as well as pressure pulsations due to eddy shedding when the flow interacts with the sensor and the entire mooring. Intensity of flow noise is known to increase with decreasing frequency (Strasberg, 1979; Webb, 1988; Bassett et al., 2014). Interpretation of the low-frequency noise as flow noise is supported by the apparent absence of such noise in signals on HLA hydrophones, which lie on the seafloor. The representative frequency of pseudosound is due to eddy shedding, by flowing past a cylinder of diameter *d* is *fe* = *St u/d*, where *St* ~ 0.2 is the Strouhal number and *u* is flow velocity (Strasberg, 1979; Webb, 1988). With NIW-induced currents of ~0.5 m/s (Serebryany et al., 2008b; see also Figure 3d), the observed upper frequency of 10 Hz is consistent with the eddy shedding by a mooring wire with *d* ~ 1 cm. The hydrophone and pressure housing have larger dimensions and contribute to lower-frequency pseudosound.

The observed strong correlation between intensity of low-frequency noise and pycnocline depression in NIWs (Figure 4) can be understood within the following simple model of NIW currents. Consider a progressive NIW with a linear wavefront, which moves with speed *c* along horizontal coordinate *x* in an ocean, where potential density jumps across a narrow pycnocline and remains constant below it. Let the water depth, unperturbed pycnocline depth, and pycnocline depression due to NIW be *H*(*x*), *h*(*x*), and *η*(*x – ct*). The flow is stationary in the reference frame moving with NIW. In the long-wave approximation (Apel et al., 2007), it follows then from the continuity equation that flow velocity *u*(*x, t*) below the pycnocline is

 

The minus sign in the numerator in Eq. indicates that near the seafloor, water flows in the direction opposite to the direction of NIW propagation. Note that magnitude |*u*| of the flow velocity rapidly increases with increasing pycnocline depression and, for fixed *η*, is inversely proportional to the distance from the perturbed pycnocline to the seafloor. For example, in the vicinity of SHRU3 the water depth was *H ≈* 80 m, thickness of thermocline *h ≈* 20 m and the pycnocline depression *η* ≈ 20 m, and Eq. (4) gives |*u*| = *c*/2~ 0.5 m/s. This estimate agrees well with the ADCP measurements shown in Figure 3d.

The key to understanding the origin of the second noise type, illustrated in Figure 6c, is the fact that it was observed only on HLA hydrophones and was not present on either VLA hydrophones or SHRUs. HLA hydrophones lay on the seafloor, while the VLA and SHRU hydrophones were located at least 6 m above it. Moreover, the type-two noise was at maximum on hydrophones in the middle of the HLA, and no noise of this type was observed on the hydrophones at both ends of the array, which were fixed by heavy anchors (Newhall et al., 2007). All the observed features of type-two noise are consistent with hydrophones being dragged along the seafloor by NIW-induced near-bottom currents, with the stronger noise caused by the bigger displacements that occurred away from the anchors. This interpretation was proposed by Serebryany et al. (2008a, 2008b), who were the first to report observations of NIW-associated noise on several HLA hydrophones in the middle of the array.

The third and most intense type of observed noise is illustrated in Figure 6d, which uses the SHRU5 data. We interpret this noise type as the noise generated by moving sediments that had been mobilized by the NIW-induced near-bottom currents. After sediment particles leave the seafloor, they generate acoustic waves (noise) by colliding with each other and with the stationary seabed as well as with near-bottom acoustic sensors and/or their housing. Mobilization of sediments and dynamics of the suspended sediment particles are controlled by the composition of surficial sediments and the near-bottom current, but are not expected to depend on the causes of the current itself.

To our knowledge, NIW-induced sediment generated noise (SGN) has not been previously described. However, there is extensive literature on SGN produced by other kinds of currents such as river flow, orbital velocities in surface gravity waves, and tidal currents (Bassett, 2013; Thorne, 2014). SGN has been measured using underwater sensors and seismometers on dry land (Roth et al., 2016). SGN properties have been studied in laboratory experiments (Thorne, 1986), in rivers (Roth et al., 2016; Geay et al., 2017; Petrut et al., 2018) as well as in straits (Thorne, 1986, Bassett, 2013) and the surf zone at sea (Voulgarist et al., 1999). Bassett et al. (2013) investigated SGN caused by currents in a tidal channel in Puget Sound. They found that a near-bottom current velocity above a critical value of 50–60 cm/s was necessary to produce SGN and that the shape of the SGN spectrum depended on sediment grain size. SGN was typically most pronounced above 2 kHz with a maximum spectral density at frequencies of 10­–15 kHz.

The threshold character, frequency content, and the value of the current velocity threshold (Section 3) of the type-three NIW-induced noise are consistent with the previously observed SGN due to tidal currents in the ocean, which supports our interpretation of the mechanisms of the type-three noise. The difference in the current velocity thresholds (~40 cm/s vs. 50–60 cm/s) can be attributed to a difference in the sediment grain sizes at the experiment sites on the New Jersey shelf and in Puget Sound.

Figure 7 compares power spectra and intensity of the NIW-induced noise on three hydrophones, where one of the three noise types dominates. We used the data obtained with SHRU5, one VLA hydrophone, and one HLA hydrophone. These are the same sensors that were used in Figure 6 to illustrate the differences between the three noise types. Power spectra of the background ambient noise are usually modeled using the well-known Wenz curves (Wenz, 1962). When there were no NIWs in the vicinity of the sensors, all three hydrophones recorded signals with rather similar spectra at all frequencies above 10 Hz (Figure 7a). The measured spectra were close to the Wenz curve if contributions of the spectral peaks due to linear frequency modulated signals around 300 Hz and 500 Hz and other signals emitted by known research sound sources are excluded (Newhall et al., 2007; Lynch & Tang, 2008).

In the presence of an NIW train (Figure 7b), the spectrum of the acoustic pressure on the VLA hydrophone did not change appreciably, except at frequencies below 10 Hz. This is consistent with the flow noise properties. Signals from the research sources could still be clearly seen above the noise background. In contrast, very strong, broadband increase of noise level (Figure 7b) occurred on HLA, which was dragged along the seafloor by the NIW-induced current. The spectrum retained manifestations of the research sources in the 300–1000 Hz frequency band. At SHRU5, where the velocity of the NIW-induced near-bottom current exceeded the threshold for type-three noise generation, there was a broadband increase of the spectral level of about 30 dB between 10 Hz and 2 kHz and a rather sharp increase of the spectral level (up to ~ 40-50 dB relative to the background noise level) at frequencies above 2 kHz (Figure 7b). The spectral maximum occurred at frequencies above the highest frequency that can be resolved with the 9750 Hz sampling rate of the SHRU5 measurements, as expected for sediment generated noise (Thorne, 1986; Bassett et al., 2013; Petrut et al., 2018). At SHRU5, NIW-induced SGN surpassed contributions of all other sources of sound at every frequency.

5 Discussion

SGN is an acoustic manifestation of sediment mobilization by water flow. While NIW-induced SGN apparently has not been studied previously, there exists a large body of work on the effects that NIWs have on marine sediments on the continental shelf, and there is no doubt that sediment mobilization by NIWs does occur. It is known that the boundary layer at the footprint of NIW can became hydrodynamically unstable, and this instability results in an increase of the sediment resuspension rate (Carr & Davies, 2006). Moreover, any increase in the turbulent energy due to the hydrodynamic instability can maintain a higher sediment concentration in the water column. Bogucki et al. (1997) reported observations and analysis of the sediment resuspension/saltation produced by NIWs on the Californian continental shelf. Quaresma et al. (2007) studied sediment resuspension by NIWs using data obtained on the Portuguese continental shelf, where the bathymetry and sound speed profile are similar to those at the SW’06 site. It was shown that water turbidity and the concentration of entrained sediment particles in the water changed synchronously with the thermocline displacement. During the maximum thermocline displacement near the leading front of an NIW train, sediment grains were found at far as 35 m from the seafloor. Another example of strong variations in water turbidity due to sediment resuspension by NIWs and formation of an intermediate nepheloid layer were reported by Masunaga et al. (2015). Observations of NIW-induced sediment resuspension are supported by theory and by the results of numerical simulations (Cacchione & Southard, 1974; Bogucki & Redekopp, 1999; Stastna & Lamb, 2008; Olsthoorn & Stastna, 2014; Bourgault et al., 2014).

SGN theory is based on a model of collisions between two sediment particles or between a particle with a slab (obstacle) (Thorne & Foden, 1988; Bassett et al., 2013; Thorne, 2014). The spectrum of the radiated sound has a maximum, and the centroid frequency of SGN  where *D* is an effective diameter of sediment particles and *C* is a function of their material properties; for instance, *fr ≈* 15 kHz for basalt particles with *D* = 2.5 mm. Acoustic intensity of SGN increases with current velocity and was found to be an acceptable proxy for bedload transport (Thorne, 2014). SGN theory, modeling, and experimental data are reviewed by Bassett et al. (2013) and Thorne (2014).

Recording and analyzing SGN can serve as minimally invasive, continuous means of measurement for sediment transport and for estimating dimensions of mobile particles (Thorne, 2014). This approach was applied to study sediment transport by various types of water flow, including rivers, tidal currents in straits, and surface gravity wave-induced flows in the surf zone (Thorne, 1986; Mason et al., 2007; Thorne, 2014; Geay et al., 2017; Petrut et al., 2018). Results of SGN analysis, including estimates of grain size distribution, agree well with the direct sampling methods (Petrut et al., 2018). Observations of NIW-induced noise bursts and identification of SGN as a dominant contribution to their intensity on near-bottom sensors, raise the possibility of extending the passive acoustic measurements of sediment transport to the sediment mobilization by strong NIWs on continental shelves. The inherent ability of the technique to provide long term series of autonomous observations is even more important on continental shelves than for measurements in rivers or in the surf zone. Moreover, measurements of the noise bursts with autonomous, moored, single-hydrophone receivers can potentially contribute to improved quantitative understanding of NIW-induced near-bottom currents as well as NIW amplitudes and their temporal and spatial variability on the continental shelf.

Sediment-generated noise has an ambient component, which results from sediment particles’ collisions with each other and the seabed, as well as a sensor-related component due to particle impacts on the acoustic sensor or its housing. Observations of sediment transport in rivers with sensors on dry land (Roth et al., 2016) offer clear evidence of the ambient component of SGN. On the other hand, sensors are routinely augmented by pipes and plates to increase particle impacts for the purposes of measuring coarse gravel transport (Thorne, 2014). Further research is needed to quantify the relative weight of the ambient and sensor-related components of SGN in the NIW-generated noise bursts and the variation of the weight with distance to the seafloor.

Given its high intensity, NIW-induced SGN may present significant challenges for the continuous operation of near-bottom acoustic sensors deployed for underwater communication, detection and tracking of biological or man-made sound sources, or remote sensing of the water column and seabed properties. SGN would be equally detrimental whether ambient or sensor-related. Spectral and spatial characteristics of the NIW-induced noise need to be understood and considered during design and deployment of acoustic systems on continental shelves.

6 Conclusions

In this study, we used a network of temperature, current velocity, and acoustic sensors deployed on the continental shelf off of New Jersey to relate the occurrence of large, transient increases in acoustic noise intensity (noise bursts) to trains of strongly nonlinear internal waves and, more specifically, to individual localized, soliton-like waves that form the trains. The noise bursts occurred in sequences of 60–80 minutes, the duration of which equals the time it took an NIW train to travel past an observation point on the New Jersey shelf. Individual noise bursts lasted for 5–7 minutes and coincided in time with passage of a single soliton-like internal wave past the hydrophone. Very large increases in the spectral density and broadband intensity of noise, of up to 50 dB relative to background, were observed on hydrophones located 6–7 m above the seafloor. The peak acoustic intensity and the spectral content of the noise bursts were controlled by the amplitude of individual soliton-like internal waves and were most directly related to the velocity of the NIW-induced near-bottom currents.

The noise burst emergence and observed variations in their intensity and spectral content with water depth, hydrophone elevation above the seafloor, and NIW amplitude have been explained in terms of three noise generation mechanisms. The low-frequency (below a few tens of Hertz) component of the noise bursts represents the flow noise that occurs due to advection of turbulent pressure pulsations past an acoustic sensor. Hydrophones lying on the seafloor recorded broadband noise, which resulted from the hydrophones being dragged along the seafloor by NIW-induced currents. The strongest noise bursts were associated with sediment-generated noise (SGN). Acoustic waves are generated when sediment is mobilized by NIW currents, and sediment particles collide with each other, with the stationary seabed, and with acoustic sensors. SGN was most pronounced at frequencies above 2 kHz. A distinctive feature of SGN is its threshold character. NIW-induced near-bottom currents stronger than about 40 cm/s were found to be necessary to initiate SGN. Compared to previously described oceanic observations of SGN in tidal channels and the near-shore surf zone, NIW-induced SGN occurs on the continental shelf at significantly larger water depths and drastically increases the extent of the seafloor area, where SGN occurrence should be expected.

NIW-generated noise bursts are one of the strongest reported acoustic effects of internal waves in the ocean. The noise bursts may present challenges to continuous acoustic communication and acoustic monitoring of the ocean using near-bottom sensors. On the other hand, measurements of the noise bursts with autonomous, single-hydrophone receivers can potentially contribute to improved quantitative understanding of NIW-induced near-bottom currents and sediment transport by internal waves on the continental shelf. Further research is needed to fully characterize the spectrum of NIW-induced acoustic noise, its depth-dependence, relative contributions of the ambient and sensor-related components of sediment generated noise as well as the directivity and correlation properties of the ambient component of the NIW-generated acoustic noise.

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**Figure 1**. The figure caption should begin with an overall descriptive statement of the figure followed by additional text. They should be immediately after each figure. Figure parts are indicated with lower-case letters (**a, b, c…**). For initial submission, please place both the figures and captions in the text near where they are cited rather than at the end of the file (not both). At revision, captions should be placed at the end of the file, and figures should be uploaded separately. Each figure should be one complete file (please do not upload sub-figures in separate files).

**Figure 1**. Evolution of a train of nonlinear internal waves over the site of the Shallow Water 2006 (SW’06) experiment. Positions of thermistor chains SW01, SW03, SW04, SW07, SW23, SW 24, SW30, SW54, single-hydrophone acoustic receivers SHRU1, SHRU 2, SHRU3, SHRU4, SHRU5 and hydrophone array HVLA Shark as well as wave fronts (dashed lines) and the direction of propagation (arrow) of an internal wave train are indicated in the map in the lower left corner. Bathymetry is shown along the straight line through SW01 and SW24. ADCP is located at the SW30. Depth dependence of water temperature as measured by SW01 (**a**), SW03 (**b**), SW04 (**c**), SW54 (**d**), and SW23 (**e**) is shown from 07:00 to 21:00 GMT on 19 August 2006 when a train of nonlinear internal waves propagated shoreward from SW23 past SW01. Time (GMT) on 19 August 2006 is shown in hours and minutes.

**Figure 2**. Time histories of water temperature and acoustic intensity at various points along the path of propagating internal wave train. Temperature records of thermistors at the depth of 40 m are denoted by letter T and depicted in red for thermistor chains SW23, SW54, SW04, SW03, and SW01. Time intervals of appearance of the NIW train are denoted t1, t2, t3, t4 for the last four chains (SW23 does not show NIWs) and boxed. Sound intensity records by SHRUs 1, 3, 4, and 5 and hydrophone 40 of HVLA Shark are depicted in blue. For visibility, the time dependencies recorded by individual sensors are shifted vertically in proportion to the distance from the sensor to SW01. Time intervals with strong fluctuations of acoustic pressure are boxed and marked ***a*** for SHRU1, ***b*** for HVLA Shark, ***c*** for SHRU3, ***d*** SHRU4, and *e* SHRU5. Time (GMT) on 19 August 2006 is shown in hours and minutes. Five color panels in the lower part of the figure show the spectrograms corresponding to the sound intensity records in boxes ***a***–***e***.

**Figure 3**. Temperature, current velocity, and acoustic manifestations of an NIW train in the vicinity of the acoustic receiver SHRU3. (**a**) Spectrogram of acoustic noise recorded by SHRU3. (**b**) Time history of the water temperature on the thermistor chain SW07. (**c**) Time history of the water temperature on the thermistor chain SW30. (**d**) Time-dependence of the horizontal current velocity at three depths. Time (GMT) on 19 August 2006 is shown in hours and minutes.

**Figure 4**. Temporal variations of the temperature depth dependence measured by thermistor chain SW54 (upper panel) and noise intensity on a collocated hydrophone (lower panel). Time (GMT) on 19 August 2006 is shown in hours and minutes.

**Figure 5**. Temporal variation of the acoustic intensity measured by SHRU5. Time (GMT) on 19 August 2006 is shown in hours and minutes. The insert shows the spectrogram of a nine-minute section of the pressure record and illustrates contributions of research sound sources. Color shows power spectral density of total acoustic field in dB re 1 μPa2/Hz.

**Figure 6**. Spectrograms of acoustic field recorded by hydrophones on vertical (VLA) and horizontal (HLA) arrays during passage of a train of nonlinear internal waves. Spectrograms are shown of acoustic pressure on a VLA hydrophone at depth of 62 m (**a**); low-frequency part of the acoustic pressure on the same hydrophone (**b**); on a hydrophone in the middle of HLA (**c**); and on single-hydrophone receiver SHRU5 (**d**). Time (GMT) on 19 August 2006 is shown in hours minutes, and seconds.

**Figure 7**. Power spectra of acoustic pressure recorded by SHRU5 and hydrophones on vertical and horizontal arrays when nonlinear internal waves are absent (**a**) or present (**b**). The power spectra are calculated for the same hydrophones as in Figure 6.