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HIGH-FREQUENCY NONLINEAR INTERNAL WAVES AROUND THE PHILIPPINES

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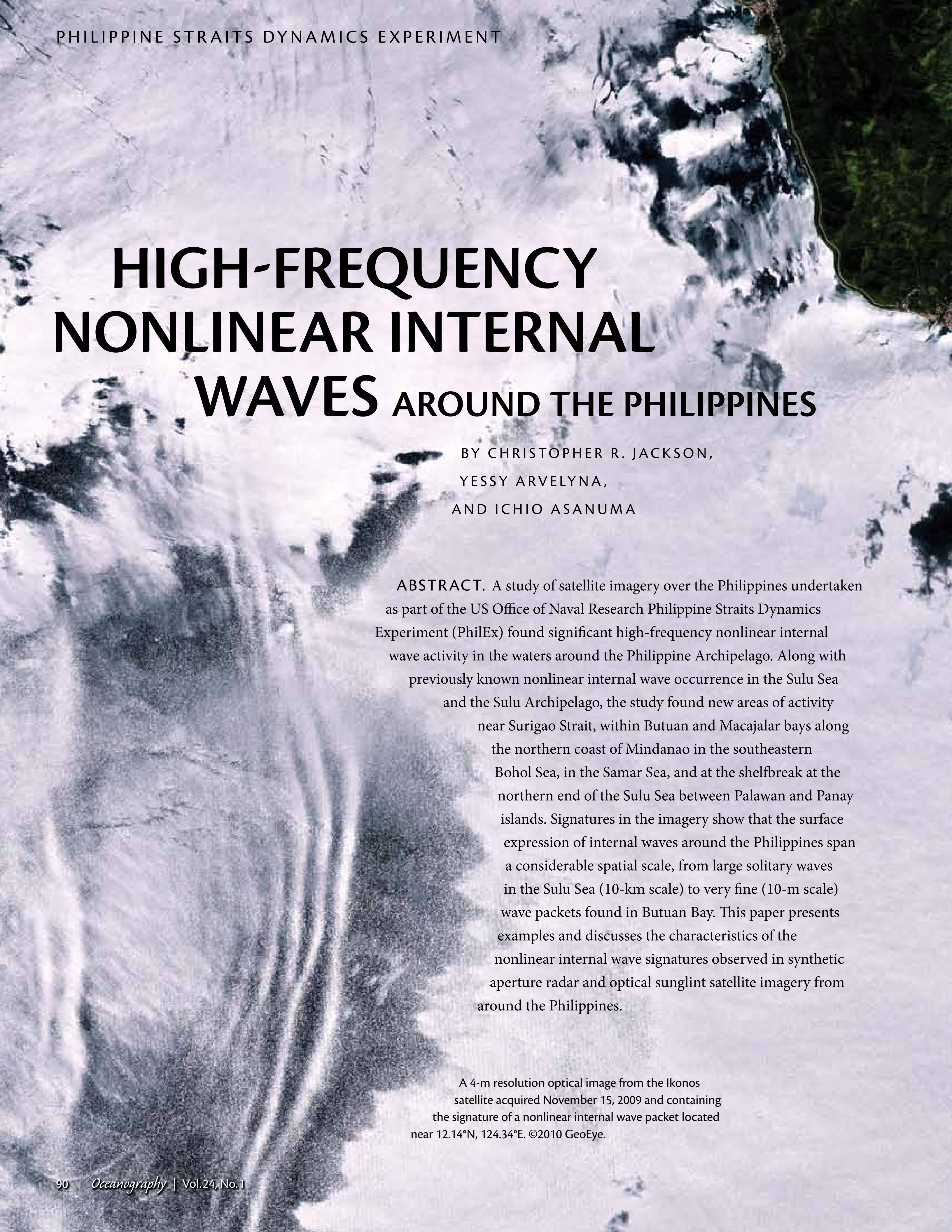
ABSTRACT. A study of satellite imagery over the Philippines undertaken as part of the US Office of Naval Research Philippine Straits Dynamics Experiment (PhilEx) found significant high-frequency nonlinear internal wave activity in the waters around the Philippine Archipelago. Along with previously known nonlinear internal wave occurrence in the Sulu Sea and the Sulu Archipelago, the study found new areas of activity near Surigao Strait, within Butuan and Macajalar bays along the northern coast of Mindanao in the southeastern Bohol Sea, in the Samar Sea, and at the shelfbreak at the northern end of the Sulu Sea between Palawan and Panay islands. Signatures in the imagery show that the surface expression of internal waves around the Philippines span a considerable spatial scale, from large solitary waves in the Sulu Sea (10-km scale) to very fine (10-m scale) wave packets found in Butuan Bay. This paper presents examples and discusses the characteristics of the nonlinear internal wave signatures observed in synthetic aperture radar and optical sunglint satellite imagery from around the Philippines.



A 4-m resolution optical image from the Ikonos satellite acquired November 15, 2009 and containing the signature of a nonlinear internal wave packet located near 12.14°N, 124.34°E. ©2010 GeoEye.

INTRODUCTION

Oceanic nonlinear internal waves are common in those parts of the world's ocean where strong currents displace highly stratified water over locations with significant bathymetric variation. These conditions are regularly found in archipelago systems at low to mid latitudes like the Philippines and Indonesia. As their name implies, internal waves propagate inside the body of the ocean along a pycnocline layer (the portion of the water column with a sharp change in density). The internal waves are considered nonlinear when forces are present that counteract the force of dispersion, allowing the waves to retain their form as they propagate tens to hundreds of kilometers away from their generation site over time periods lasting up to several days. Internal waves are commonly generated by displacement of the pycnocline over a bathymetric feature such as a shelfbreak or interisland sill, with the restoring force of the displaced water parcel causing it to oscillate at the local buoyancy frequency, generating a new wave on each oscillation. (An analogous restoration of a displaced water parcel, but one that lacks nonlinearity, is observed when an object is dropped through the water's surface and the restoring force produces the concentric rings of ripples on the surface.) In situ measurements show that the amplitude of a nonlinear internal wave (measured as a displacement of the pycnocline) can range from just a few meters to in excess of 100 m.

The conditions necessary for the generation of high-frequency nonlinear internal waves are present in many locations around the world (Jackson, 2004, 2007), including continental shelves (Apel et al., 1975; Stanton and Ostrovsky, 1998), straits (Farmer and Armi, 1999; Susanto et al., 2005), and marginal seas (Osbourne and Burch, 1980; Apel et al., 1985). The waves represent an important energy transfer mechanism between large-scale tides and small-scale turbulence and mixing (MacKinnon and Gregg, 2003; Moum et al., 2003; St. Laurent, 2008; Shroyer et al., 2010), affect the transport of momentum, and impact biological processes through redistribution of nutrients in the water column (Apel et al., 2007).

The signatures of nonlinear internal waves have characteristics that make them distinct features in both synthetic aperture radar (SAR) and optical sunglint satellite imagery. The signatures appear in the imagery as a pattern of alternating light and dark quasilinear bands that are the result of overall surface roughness variations (Alpers, 1985). The roughness variations are created by currents within the internal wave that produce convergent (rough) and divergent (smooth) zones on the surface that move in phase with the internal wave's subsurface crests and troughs (Munk et al., 2000). With the waves remaining coherent for up to several days, the signatures of several individual solitary waves (solitons) or several compact groupings (packets) produced on successive generation cycles (usually tidal) can, in many instances, be found on the same satellite image (see Figures 2a and 4). The distance between leading waves from successive generation cycles can vary from just a few kilometers to more than 100 km, depending on the phase speed of the waves and its stage of evolution. In situ observations have shown that phase speeds for oceanic nonlinear internal waves can vary from less than 0.3 m s^{-1} to more than 3 m s^{-1}, with the speed determined to first order by water depth and the sharpness of the density change at the pycnocline. Interwave spacing (the distance between individual waves in a packet) can vary from just a few tens or few hundreds of meters to more than 10 km, with the examples from around the Philippines covering this range. Many packets show a rank ordering, with the largest wave signatures (in terms of overall width of the roughness band and the along-crest length) at the front and the smallest at the rear. The imagery shows that the wave packets lengthen over time, both front to back and in the along-crest direction, as the packets evolve. It is in the context of these wave packets, consisting of multiple individual "solitary" waves, that the traditional definitions of frequency and period are maintained in regard to nonlinear internal waves.

As part of the Office of Naval Research (ONR) Philippine Straits Dynamics Experiment (PhilEx), historical SAR satellite imagery from the European Space Agency's (ESA) ERS-1 and ERS-2 satellites and the Advanced SAR (ASAR) instrument on ESA's Envisat satellite, along with sunglint imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument and meter-scale resolution optical satellites, were examined to identify the types and locations of the signatures from various oceanographic and atmospheric phenomena present around the Philippine Archipelago. This historical imagery was supplemented by contemporary satellite collections obtained between 2007 and 2009 in

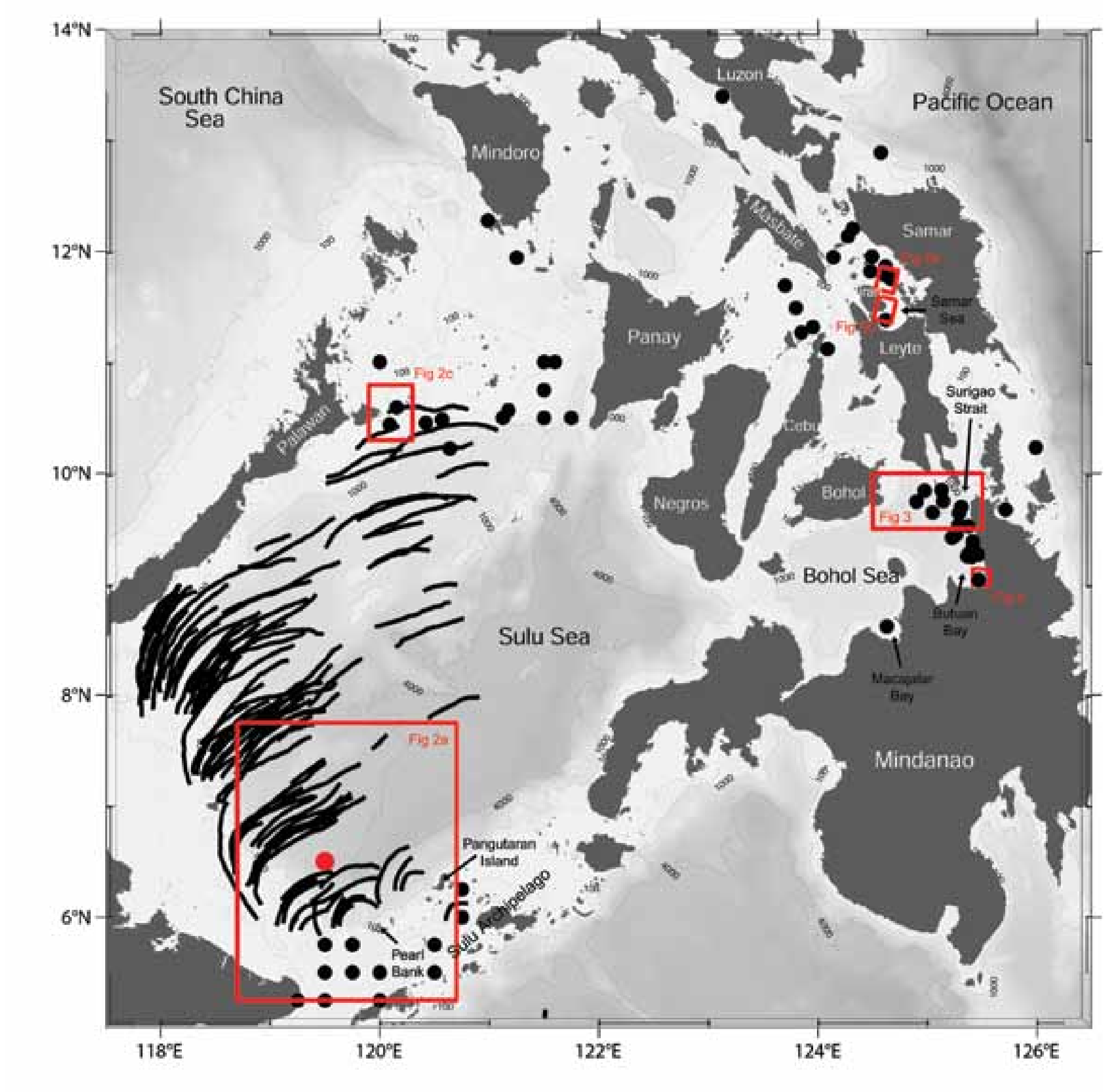


Figure 1. Map showing the distribution of nonlinear internal wave signatures around the Philippine Archipelago. Individual internal wave signatures are represented by black dots with the larger solitary wave signatures from the Sulu Sea represented by black lines that correspond to the leading wave in a wave packet. Boxes outline image locations for Figures 2–5, and the red dot shows the position of R/V *Melville* during its encounter with two solitary wave packets on March 11–12, 2009.

support of the Intensive Observational Periods conducted during the four PhilEx cruises. The contemporary collections included SAR imagery from ERS-2 and Envisat, imagery from the Phased Array type L-band Synthetic Aperture Radar (PALSAR) on the Japanese Aerospace Exploration Agency's (JAXA) Advanced Land Observing Satellite (ALOS), and optical data from the ALOS Advanced Visible and Near Infrared Radiometer (AVNIR). While many of the images were dominated by the strong wind signatures of northeast and southwest monsoons, which can easily mask the signatures of ocean phenomena, the imagery nevertheless revealed complex current and flow signatures in the major straits of Mindoro/Tablas, San Bernardino, and Surigao as well as the signatures of surface slicks, eddies, and a wide variety of nonlinear internal wave occurrences around the archipelago.

Figure 1 shows the locations of internal wave signatures found in satellite imagery of the Philippines. Black dots mark the locations of individual internal wave or wave packet signatures identified predominantly from imagery with a resolution between 25 and 250 m. The large solitary waves in the Sulu Sea are represented by black lines that correspond to leading wave fronts of individual packets observed in 32 MODIS

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250-m-resolution sunglint images.

In addition to the well-known solitary wave occurrences in the Sulu Sea (Apel et al., 1985) and the Sulu Archipelago (Jackson, 2004), the study found concentrations of nonlinear internal wave activity on the shelf region at the northern end of the Sulu Sea between Palawan and Panay islands, in the Samar Sea, at Surigao Strait, within Butuan and Macajalar Bays along the northern coast of Mindanao in the southeastern Bohol Sea, and other isolated occurrences at a variety of disparate locations. The internal wave signatures found in the Philippines imagery show that the wave's surface expressions span a considerable range of spatial scale, from the large solitary wave groups in the Sulu Sea (10-km scale) to the very fine (10-m scale) packets found in Butuan/Macajalar Bay. Table 1 presents the dimensions associated with several internal wave characteristics derived from the satellite imagery at five locations around the Philippines.

Example images from each of these regions around the Philippines are presented in Figures 2–5 and discussed in the following sections. The investigation also benefitted from the use of very-high-resolution (< 2 m) optical imagery over several of the Philippines' interior waters, which allowed for the identification of additional fine-scale nonlinear internal wave signatures. Further investigation using very-high-resolution imagery is expected to reveal additional locations of internal wave activity. Complete characterization of nonlinear internal waves around the Philippines will need to be accomplished via in situ observations, which provide the only way to accurately measure the in-water properties (such as amplitude and current strength) of the internal waves and confirm the results derived from the imagery.

THE SULU SEA AND THE SULU ARCHIPELAGO

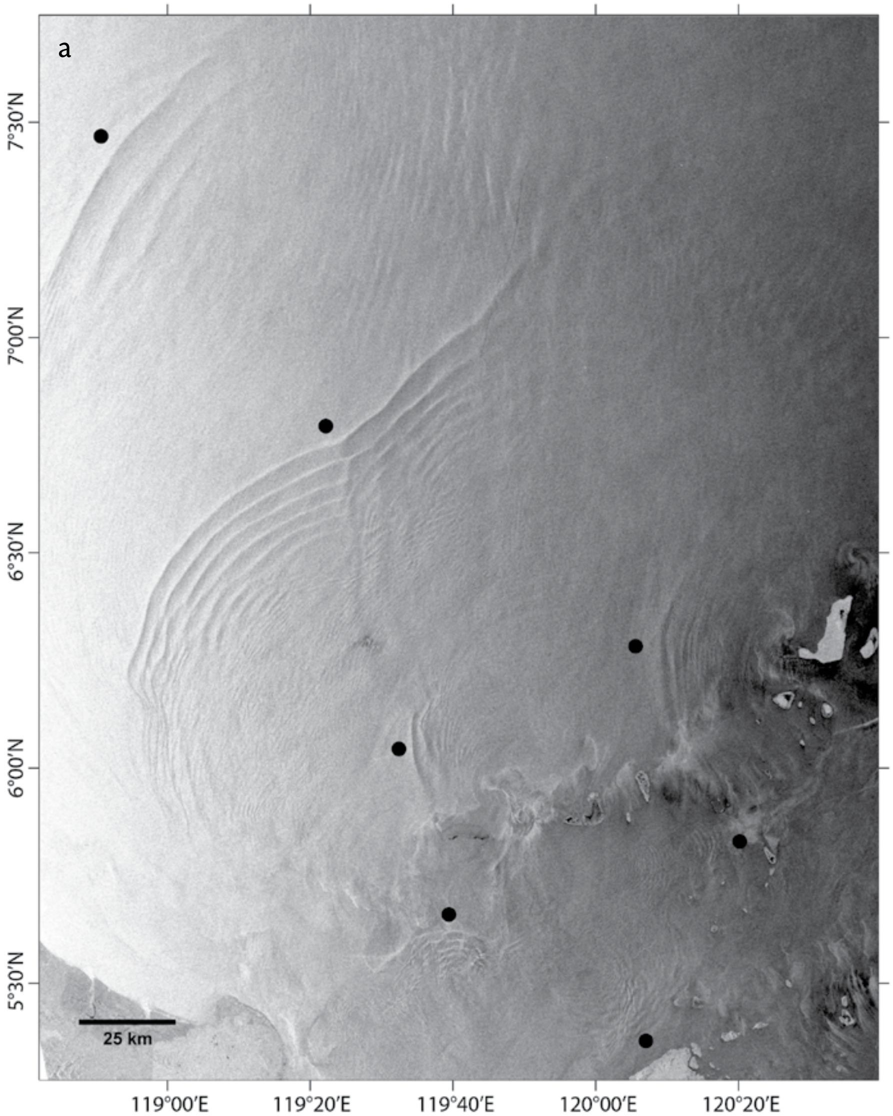
Around the Philippines, the most well-characterized internal wave occurrences are the groups of large solitary waves in the Sulu Sea. These waves originate at several locations in the Sulu Archipelago (east and west of Pearl Bank and between North Ubian and Pangutaran islands), propagate toward the northwest along the western side of the sea, and, after traveling for more than 2.5 days, dissipate against the southern coast of Palawan Island and on the shallower shelf region at the northern end of the Sulu Sea between Palawan and Panay.

The strong surface signatures of the solitary waves in the Sulu Sea (similar to those shown in Figure 2a) were first noted in 1-km-resolution sunglint images acquired from the Defense Meteorological Satellite Program (DMSP) in the early 1970s. This imagery helped motivate a field program in 1980 that collected the first in situ measurements of the Sulu Sea's packets of internal solitary waves during different portions of their evolution (Apel, 1985). The data showed that the characteristics of the Sulu Sea solitary waves included amplitudes of up to 90 m, phase speeds around 2 m s^{-1}, interpacket spacing of approximately 85 km, and interwave spacing up to 16 km with periods approaching an hour.

Figure 2a is a 150-m-resolution SAR image acquired on March 7, 2004, at 14:09 UTC from Envisat that shows the well-defined signatures of several packets of internal waves in the southern portion of the Sulu Sea and within the Sulu Archipelago. The internal solitary waves in the Sulu Sea are generated by the strong (> 3 m s^{-1}) currents in the Sulu Archipelago (Apel, 1985) where there are mixed semidiurnal and diurnal tides, with a strong fortnightly modulation that affects wave generation. Each wave packet in Figure 2a was generated on a semidiurnal turn of the tide, so the image shows the waves that were generated late on March 6 and early on March 7, 2004. The complex tidal currents that generate the solitary waves that emerge into the Sulu Sea are also believed to be responsible for the packets of smaller nonlinear internal waves that propagate within the Sulu Archipelago (Figure 2a). The Sulu Archipelago packet signatures have intrawave spacing of around a kilometer and along-crest lengths of roughly 20 km. There are no known in situ measurements of internal waves in the Sulu Archipelago, but

Table 1. Characteristics of internal wave signatures observed in satellite imagery of the Philippines

	Sulu Sea	Sulu Archipelago	Surigao Strait	Samar Sea	Butuan Bay
Interwave Spacing (km)	3–12	0.8–1.75	0.6–1.5	0.1–0.35	0.06–0.09
Packet Spacing (km)	80–90	N/A	N/A	~ 10	1–1.5
Along-Crest Length (km)	100–150	20–30	40–80	20–30	1–3



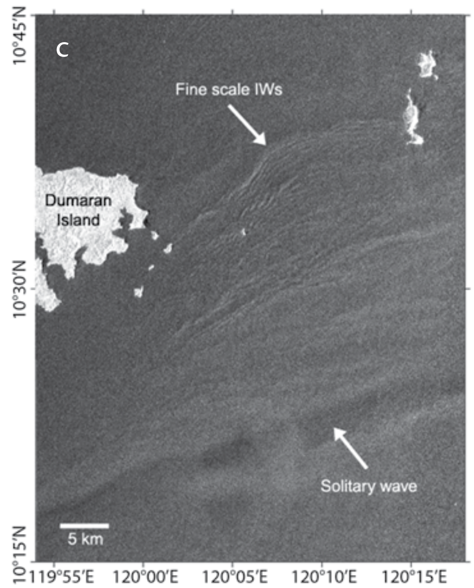


Figure 2. (a) A 150-m-resolution Envisat SAR image acquired March 7, 2004, at 14:09 UTC. The image contains the signatures of four packets (two mature and two nascent) of large solitary waves in the Sulu Sea and three smaller-scale internal wave packets in the Sulu Archipelago. Black dots are located near the leading wave fronts of individual packets. *Data provided by the European Space Agency. Original SAR image ©2004 ESA* (b) Whitecaps associated with the roughness band of a passing internal solitary wave in the Sulu Sea. The photograph was acquired from the deck of R/V *Melville* on March 12, 2009, about 18:30 UTC, while the ship was on station at 6°30′N, 119°30′E. *Photograph courtesy of Debra Tillinger* (c) Internal wave signatures near the northeast end of Palawan Island in a 100-m-resolution ALOS PALSAR image acquired on September 14, 2007, at 02:17 UTC. As individual solitary waves from the Sulu Sea shoal in this shallow shelf region, they split and transform into groups of finer-scale internal waves. *ALOS PALSAR data provided by JAXA*

the signatures observed in the satellite imagery are similar in size to the signatures of internal waves observed in the New York Bight that have amplitudes on the order of 10 to 20 m.

The March 2009 PhilEx cruise included an excursion into the Sulu Sea to acquire the first in situ measurements of solitary waves collected there since 1980. On March 11, 2009, R/V *Melville* occupied a station in the southern Sulu Sea (at 6°30'N, 119°30'E; see Figure 1) approximately 80 km from the generation site near Pearl Bank (and very close to one of the

1980 study's mooring locations). The ship remained at this position for more than 24 hours acquiring several full-depth conductivity-temperature-depth (CTD) profiles of the water column as well as continuous measurements from the hull-mounted acoustic Doppler current profilers (ADCPs) and from an in-water ADCP placed at 150-m depth (Gordon, 2009).

During the time on station, two packets of solitary waves were recorded, the first on March 11, 2010, at 18:30 UTC, and the second approximately a semidiurnal tidal cycle later on March 12, 2010, at 07:30 UTC. Both packets were detected by the ship's radar, with a band of surface whitecaps observed during the passing of the second packet (Figure 2b). The conditions at the time of these observations showed the water column to be well stratified, with a slab of water within the main thermocline at 150- to 200-m depth, moving to the southwest. On March 12 and 13, as the ship headed north along 119°30'E longitude, the second solitary wave packet observed while on station in the southern Sulu Sea was encountered at least four more times. Between 6°30'N and 8°30'N latitude, the ship caught up to the wave packet, and was then passed by the packet while the ship was stopped at other station locations. At each encounter, the wave packet displayed a distinct zone of whitecaps, with changes in the surface currents of around 1 m s^{-1} (Gordon, 2009). Analyses of the PhilEx Sulu Sea solitary wave data are currently ongoing.

After propagating more than 2.5 days, the solitary waves rapidly dissipate as they encounter the sharp shelfbreak along the southern edge of Palawan Island where their occurrence has been coupled to harbor seiche (a standing wave in an enclosed or partly enclosed body of water) activity (Giese et al., 1998). At the northeastern end of Palawan Island, the solitary waves from the Sulu Sea encounter the shelf region where the change in bottom depth is more gradual. As the individual solitary waves shoal in this shelf region, their amplitudes are reduced and they fission into sets of finer-scale internal waves (Djordevic and Redekopp, 1978). This transformation can be observed in a 100-m resolution SAR image acquired by the Japanese ALOS PALSAR on September 14, 2007, at 02:17 UTC (see Figure 2c). A large individual late-stage solitary wave visible near the bottom of the image transforms into more irregular sets of finer-scale waves closer to Palawan. Similar patterns have also been observed on the shelf between Cuyo and Panay islands.

SURIGAO STRAIT AND THE BOHOL SEA

The PhilEx study identified two types of internal wave activity in the eastern Bohol Sea. At Surigao Strait, well-defined 1-km-scale wave packets propagate southwest from the strait into the Bohol Sea. Surigao Strait separates the islands of Leyte and Mindanao and is one of two openings on the eastern side of the Philippines that link Philippine waters to those of the western Pacific Ocean. (The other opening is at San Bernardino Strait between the islands of Samar and Luzon further to the north.) Pacific water works its way through Surigao Strait and feeds into the surface layer of the Bohol Sea (Gordon, 2009). Strong tidal currents in Surigao Strait and a shallow sill (near 50-m depth) at its western edge are believed to be the sources of the internal wave packets that radiate from Surigao Strait into the Bohol Sea. Figure 3 is a MODIS 250-m resolution true color optical image acquired on June 9, 2005, at 02:15 UTC; it shows the well-defined signature of a nonlinear internal wave packet roughly 45 km from Surigao Strait, composed of more than five individual waves. The internal waves emanating from Surigao Strait are smaller in physical dimension than those of the Sulu Sea, with the distance of roughly 1 km between the leading waves in the Surigao packet, compared to roughly 10 km for the packets in the Sulu Sea. In December 2007, during PhilEx's Joint US/Philippines Cruise, an internal wave near Surigao Strait was observed with the ship's echosounder and was found to have an amplitude of approximately 20 m (James Girton, University of Washington, *pers. comm.*, 2009).

In addition to the internal waves from Surigao Strait, multiple wave-packet signatures have been discovered in the southeastern Bohol Sea along the northern coast of Mindanao in and around Butuan and Macajalar bays. These signatures, found in high-resolution (< 25 m) SAR imagery from ESA's ERS satellites and very-high-resolution (< 2 m) commercial optical imagery, form complex patterns on the ocean surface as multiple wave packets propagating over a wide range of directions overlap and interact with one another. Examples of these complex patterns can be seen in Figure 4, which is a 1.65-m-resolution optical sunglint image from the GeoEye-1 satellite acquired May 19, 2009, at 02:17 UTC that covers a portion of Butuan Bay. The image contains the signatures of more than three dozen unique internal wave packets. These signatures are of much finer scale then the signatures west of Surigao Strait, with the distance between the leading waves in the Butuan Bay packets between 60 and 90 m and with their interpacket separations between 1 km and 1.5 km.

The number of wave packets observed in Butuan Bay, their location in close proximity to the coast, and the wide variety of propagation directions suggests that the waves are generated by river outflow plumes. Six rivers empty into Butuan Bay, including the Agusan River in the southeastern corner of the bay, which is the third largest river basin in the Philippines in terms of drainage area. Internal waves generated from river plumes have been previously documented at the Columbia River outflow in Oregon (Nash and Moum, 2005; Nash et al., 2009). The generation of internal waves from a river outflow results from the displacement of the pycnocline by the outflow plume's water as well as the plume's higher horizontal velocity relative to the ambient water. Pycnocline displacement and restoration are responsible for internal wave generation at the plume's leading edge, but the velocity of the outflow plume can also initially be faster than the internal wave's inherent phase speed, so the wave remains trapped at the plume front. As the propagation speed of the plume decreases below the internal wave's phase speed, the internal wave separates from the plume front and radiates away as a freely propagating wave.

THE SAMAR SEA

The Samar Sea is an interior sea located in the northeastern Philippines along the western side of Samar Island. It is connected to the Pacific Ocean via San Bernardino Strait and surrounds Biliran Island. Internal wave signatures in the Samar Sea were found in high-resolution (< 25 m) SAR imagery and in very-high-resolution (< 2 m) optical imagery. The internal wave packet signatures are on the spatial scale of 100 m, smaller than those in the Sulu Sea and

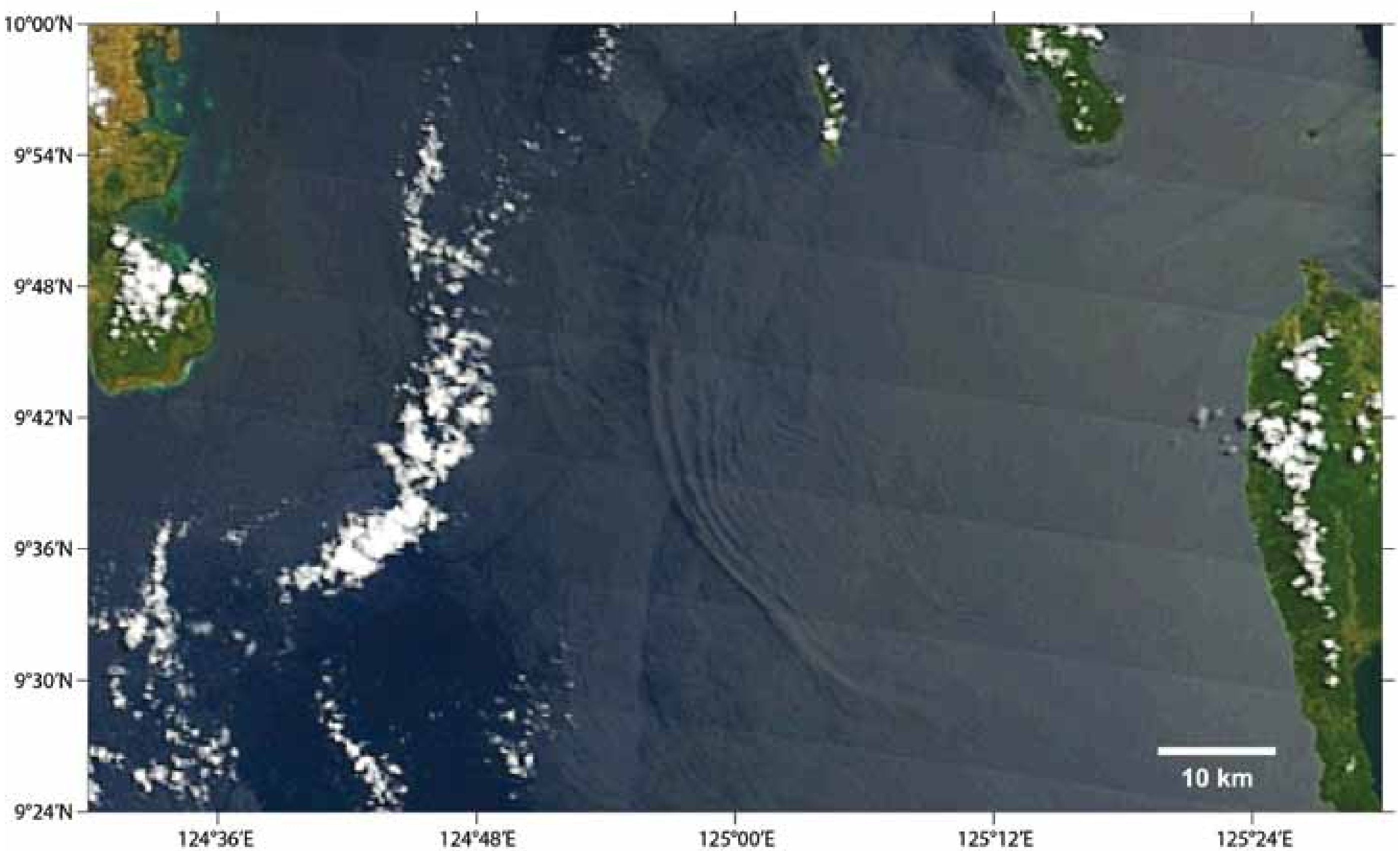


Figure 3. A 250-m-resolution MODIS true color optical image of an internal wave packet propagating from Surigao Strait acquired on June 9, 2005, at 02:15 UTC. The image shows a well-defined wave packet signature roughly 45 km from Surigao Strait; the largest inter-wave spacing is between 1 and 1.25 km.

Figure 4. A 1.65-m-resolution optical image from the GeoEye-1 satellite of internal waves in Butuan Bay acquired May 19, 2009, at 02:17 UTC. The image shows more than 36 fine-scale internal wave packet signatures propagating in a variety of directions (both seaward and shoreward). Black dots located near the leading wave fronts of individual packets help highlight the number of distinct wave packets. The waves are believed to be generated by outflow plumes of six rivers that empty into the bay. Imaged area is approximately 8.3 km x 8.9 km and is centered near 9°5'N, 125°30'E. *Image ©2010 GeoEye*

Surigao Strait but larger than those observed in Butuan and Macajalar bays.

In March 1996, SAR images from ESA's ERS-1 and ERS-2 spacecraft were acquired on sequential days (March 10 and 11) over the same geographic area of the southern Samar Sea. Each of these 100 km x 100 km images contained internal wave signatures at two locations in the Samar Sea: northeast of Biliran Island and in the southern portion of the sea near Leyte Island. These two images are nearly identical in terms of the size, shape, position, and orientation of the internal wave signatures they contain.

The presence of these nearly identical internal wave signature patterns in two images acquired 24 hours apart covering the same geographic region supports the idea that the wave generation process is repeatable and thus is associated with a tidal origin.

Figure 5a and 5b shows examples of the internal wave signatures in the Samar Sea, northeast of Biliran Island and in the southern portion of the sea near Leyte. Figure 5a is a portion of the ERS-2 image acquired on March 11, 1996, at 02:09 UTC that shows six internal wave packets northeast of Biliran Island, propagating to the east and northeast. The shape of the wave fronts and the presence of interaction signatures between packets suggest that there are at least two generation sites for the waves, most likely at the sills between the various small islands in the central Samar Sea. The easternmost wave packet has an along-crest length of more than 30 km and stretches the entire distance between Samar and Biliran islands. Figure 5b is a portion of the ERS-1 SAR image acquired on March 10, 1996, at 02:09 UTC that shows a wave packet in the southern Samar Sea near Leyte Island, propagating

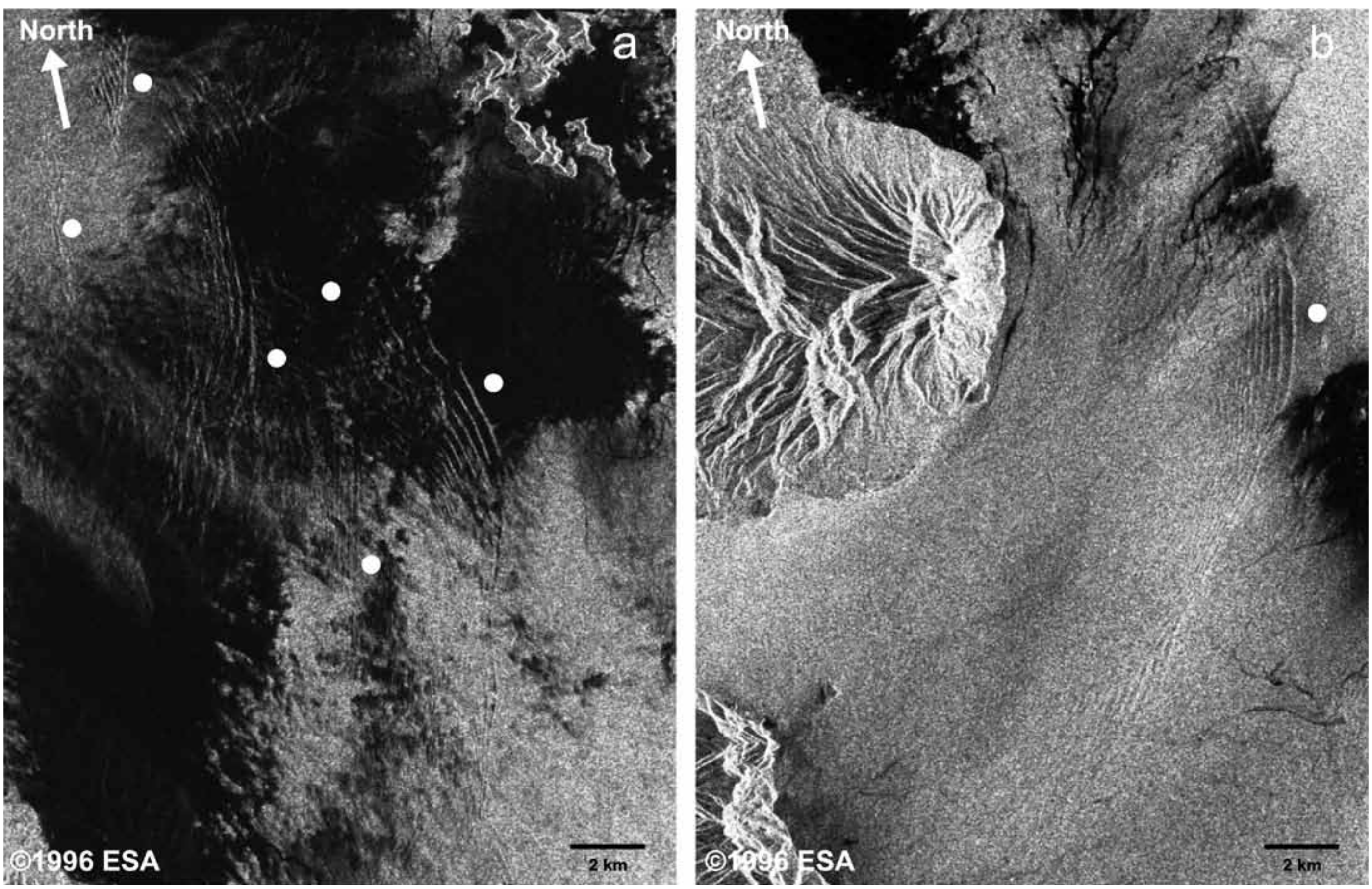


Figure 5. ERS SAR imagery collected over the Samar Sea. (a) Six intermediate-scale wave packets northeast of Biliran Island. The image was acquired by ERS-2 on March 11, 1996, at 02:09 UTC and is centered at 11°29'N, 124°37'E. (b) An internal wave packet propagating east-southeast from Biliran Strait. The image was acquired by ERS-1 on March 10, 1996, at 02:09 UTC and is centered near 11°46'N, 124°37'E. White dots are located near the leading wave fronts of individual wave packets. Internal wave signatures were present at both geographic locations on March 10 and 11, 1996, with the signatures appearing nearly identically in size, shape, position and orientation. The best example from each day is shown. Imaged area for each image is 23 km x 18 km. *Data provided by the European Space Agency. Original SAR imagery ©ESA 1996*

east-southeast from Biliran Strait (located between Biliran and Leyte islands). The packet has an along-crest length of around 20 km and the interwave spacing varies from approximately 350 m for the leading waves in the packet to around 100 m at the packet's trailing end.

SUMMARY

The Philippines, with a variety of seas, intricate geometry of islands, and complex flow through straits, exhibits a variety of nonlinear internal wave activity. A study of satellite imagery of the Philippines region undertaken as part of ONR's PhilEx yielded evidence of significant nonlinear internal wave activity in the Samar Sea, Surigao Strait, and Butuan Bay in addition to the more well-known regions of activity in the Sulu Sea and Sulu Archipelago. Signatures in the imagery show that surface expressions of Philippines internal waves span a considerable range of spatial scale, with the large solitary wave groups in the Sulu Sea at 10-km scale, the packets in the Sulu Archipelago and Surigao Strait at 1-km scale, the Samar Sea waves at 100-m scale, and the very fine scale packets in Butuan and Macajalar bays at 10-m scale. Much of this internal wave generation is due to pycnocline displacement from tide-topography interaction, but there is also evidence for generation by river plumes for the internal waves found along the northern coast of Mindanao in and around Butuan and Macajalar bays. The investigation also benefitted from the use of very-high-resolution (< 2 m) optical imagery that allowed for the identification of additional fine-scale nonlinear internal wave signatures in several of the Philippines interior seas. In situ observations are needed to fully characterize the in-water properties of the nonlinear internal waves around the Philippines (such as amplitude) and confirm the results derived from the imagery.

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