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Tracking oceanic nonlinear internal waves in the Indonesian seas from geostationary orbit

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ABSTRACT

Nonlinear Internal Waves (NLIWs) in the ocean are observable from passive satellite radiometers. The surface manifestations of these internally propagating waves are curvilinear bands demarcating relatively smooth and rough surface waters, providing a means for their detection via observations of sunglint. Typical horizontal scales of NLIWs are such that traditionally only high resolution (< 1 km pixel) sensors aboard polar orbiting satellites could resolve them. The launch on 28 October 2014 of the Japanese Meteorological Agency's Himawari-8 geostationary satellite and its Advanced Himawari Imager (AHI) opens up possibilities to study the spatio-temporal change of these relatively small scale NLIW features from geostationary orbit. Himawari-8 provides 500-m resolution visible imagery every 10 min over a hemispheric field of regard centered at 140.7° E longitude. These spatial and temporal resolutions allow for not only the identification of NLIWs over the low-latitude regions such as the Indonesian Seas, but also the ability to track the evolution of these waves in real time. Here, we present examples of NLIWs as viewed from Himawari-8/AHI and calculate a few basic wave quantities, including wavelength and propagation speed. These quantities were found to be consistent with previous observations and model simulations of NLIWs, but observations from AHI provide the ability to calculate wave propagation speeds in the same locations over multiple times a day for multiple days, which is impossible with polar-orbiting satellite data. Geostationary observations will augment the existing database of observed NLIWs and help to better quantify their spatial and temporal attributes.

1. Introduction

Nonlinear internal waves (NLIWs) in the ocean, also known as internal solitons or solitary internal waves, form between two layers of the stably stratified ocean and occur commonly in coastal regions in association with bathymetric features, and in the presence of tidal and wind forcings. They are important mechanisms for the transport of energy over large distances, enhanced mixing and turbulence (e.g. Ferrari and Wunsch, 2009; Alford et al., 2015), and providing an elevated nutrient supply to euphotic zones and thereby biological productivity (e.g. Sandstrom and Elliott, 1984). Classic Korteweg-de Vries (KdV) theory (Korteweg and de Vries, 1895; Benny, 1966; Benjamin, 1966) first predicted fundamental dynamics underlying the waves in stratified water and has been used to understand basic characteristics of oceanic NLIWs. They have been studied in many locations and observed ubiquitously, but the details of their generation, propagation, rapid evolutionary processes, and dissipation are not always clear due to the difficulty of observations with sufficient resolutions in both space and time.

Satellite remote sensing offers a means to observe the spatial structure of surface manifestation of NLIWs with sufficient horizontal resolution, which is not possible from in situ measurements of subsurface temperature at a fixed mooring location. NLIWs manifest at the ocean surface as patterns of roughened and calm waters associated with the convergent and divergent motions induced by the waves, respectively. In areas of sunglint, corresponding to the region of near-mirror reflectance angle off the ocean surface for a given sun/satellite viewing geometry, characteristics of the ocean surface roughness can be inferred (e.g., Jackson and Alpers, 2010; Kudryavtsev et al., 2012). The glint signal is strongest over calm waters at the point of specular reflection (Bowley et al., 1969), but in most cases wind-roughened seas can extend far beyond the specular region, causing a diffuse brightening of what would otherwise have appeared as a dark ocean surface in visible band satellite imagery. Passive sensor satellite radiometers can therefore be used in regions of sunglint to detect the patterns associated with NLIWs. The technique has been demonstrated for NLIW detection

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during the day (e.g., Apel et al., 1975; Fett and Rabe, 1977; Jackson, 2007) and also night, using moon glint (Miller et al., 2013).

The grand majority NLIW studies using passive radiometers have come from instruments aboard polar-orbiting satellites. Spatial resolutions on the order a few hundred meters in the visible portion of the spectrum are necessary to adequately resolve the horizontal scales of the waves, making instruments such as the MODerate-resolution Imaging Spectroradiometer (MODIS) ideal for their detection. A disadvantage of polar orbiters is that each satellite typically only provides at most one daytime view every 24 h, although it is possible for one polar orbiting satellite to provide a ~5-minute time series using multiple cameras (Matthews and Awaji, 2010). Occasionally a pair of images from different satellites occurring near in time over the same region might be used to infer NLIW motion, but these observations are relatively rare. Another disadvantage of polar observations is that the viewing geometry (i.e., sensor zenith and azimuth angle at each pixel location) changes significantly during the course of a satellite pass (Thompson and Gasparovic, 1986). Turiel et al. (2007) introduced the possibility of tracking oceanic internal waves using the Meteosat-5 geostationary satellite, but its imager provided visible data at 2.5-km resolution every 30 min, limiting the ability to fully resolve the horizontal scales of the waves (typical maximum wavelengths range from 100 to 1000 m; Jackson, 2004). The most common NLIWs are known to be generated at tidal (semidiurnal and diurnal) frequencies and propagate at a few meters per second while experiencing significant evolution, modification, and dissipation as well as refraction/reflection/diffraction over the course of the wave's lifetime. Owing to recent technological improvements in geostationary satellite remote sensing, it has become possible to resolve and track the ocean surface features induced by NLIWs in a continuous manner, e.g., every 10 min, which allows the calculation of accurate wave propagation speeds over time scales from 20 to ~150 min, during which the viewing angle changes very little.

Here we consider potential applications of the ability to track NLIWs using the imager aboard the Japanese Meteorological Agency's (JMA) Himawari-8 geostationary satellite. The focus area is in and around the Indonesian Seas, where the generation of NLIWs is favored by strong tidal currents, well-stratified seawater, and complex coastline geometry and bathymetry with narrow passages. Section 2 will describe the new observations of NLIWs, including some discussion of sunglint, and Section 3 will summarize the findings.

2. Himawari observations of NLIWs in and around the Indonesian seas

The Indonesian Seas support abundant NLIWs, particularly north and south of the Lombok Strait between Bali and Lombok islands and the Sulu and Celebes (Sulawesi) Seas north of Makassar Strait (Liu et al., 1985; Susanto et al., 2005; Kartadikaria et al., 2011; Matthews et al., 2011). The NLIWs are generally well-observed in straits where strong (often tidal) currents interact with topographic features to generate the NLIWs, such as cases including Gibraltar Strait (e.g., Armi and Farmer, 1988), Luzon Strait (e.g., Buijsman et al., 2010), and Korea Strait (e.g., Nam and Park, 2008). Susanto et al. (2005) reported high (> 100 m) amplitude NLIWs generated by the interaction of tidal and background (i.e., Indonesian throughflow; ITF) currents and rough bottom topography in the Lombok Strait. The Internal Wave Atlas (Jackson, 2004) provides a database of a large number of NLIW observations from both the Indonesian Seas and other areas across the globe. The next generation of geostationary satellites currently coming online provides an opportunity to augment this Atlas to capture rapid changes in NLIW wavelength and propagation speed, which in turn may help with better understanding and effective monitoring of NLIWs. Below we first explain the necessary solar conditions for NLIW observations, then discuss a number of individual examples.

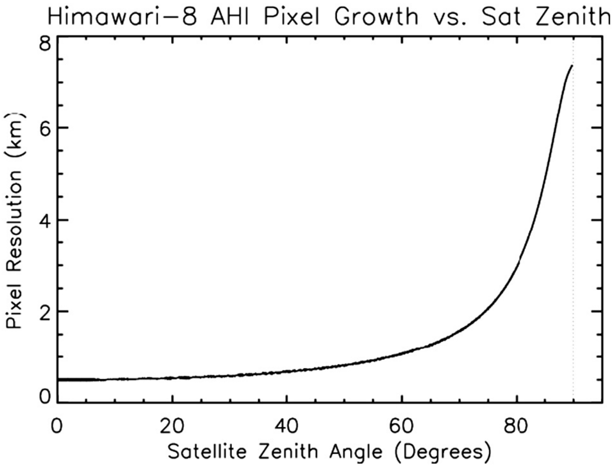

Fig. 1. Pixel spacing (km) of Himawari-8's 0.64 μm band 3 with increasing satellite zenith angle (degrees).

2.1. Sunglint coverage

Himawari-8 was launched in October 2014 by JMA and placed in a geostationary orbit at 140.7° E longitude. Its principal payload, the Advanced Himawari Imager (AHI; Bessho et al., 2016), includes multiple narrow-bandwidth visible channels, including a 500 m resolution visible channel at 0.64 μm (in the red portion of the visible spectrum). Pixel spacing in this band is 500 m only at nadir (0° N 140.7°E), and increases away from nadir as satellite zenith angle increases (Fig. 1; the orange line in Fig. 3a shows sample values of the satellite zenith angle moving outward from nadir). Pixel spacing exceeds 1 km for solar zenith angles larger than about 55°, which is well outside of the areas examined in this study. Other spectral bands are available in the visible portion of the spectrum, but since most of them are only available at 1 km resolution, here we focus on the higher resolution 0.64 μm band since it offers the best ability to resolve the horizontal scales associated with NLIWs. The satellite takes full disk hemispheric scans every 10 min, in addition to 2.5-minute scans over four mesoscale domains. Those domains are typically selected over either Japan, active typhoons, or the Kamchatka Peninsula to monitor volcanic activity. For our purpose, continuous 10-minute imagery over several hours is sufficient to be able to track NLIWs, and calculate rather instantaneous propagation speeds.

Regions of satellite-observed sunglint, corresponding to the angle of specular reflection of the water surface, change as a function of surface roughness, as well as diurnally and seasonally per the sun/sensor geometry. The detailed three-dimensional geometry describing specular reflection off a randomly oriented surface facet has been well-documented (Cox and Munk, 1954; Zeisse, 1995; Jackson and Alpers, 2010; Zhang and Wang, 2010). For the purposes of this study, we take a simple geometric/empirical approach to identifying a region where a glint signal may be observed.

At each pixel in the satellite image, we calculate two 3-D unit vectors as shown in Fig. 2. The first vector (L_{sat}) points from that pixel's location on the surface of the Earth to the satellite. The second vector (L_g) points in the direction of solar specular reflection from a flat surface located at that same pixel location on the Earth's surface. We define the θ_D as the angle formed between these two vectors:

$$\cos(\theta_D) = L_{sat} \bullet L_g \tag{1}$$

where the two vectors coincide, corresponding to $\theta_D = 0°$, the satellite is viewing along the direction of solar specular reflection for this flat surface. In nature, the surface of the ocean typically is not perfectly smooth but instead is wind-roughened, producing a distribution of tilted facets that allow the specular condition to be met at geometries