Internal wave detection using the Moderate Resolution Imaging Spectroradiometer (MODIS)

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The Moderate Resolution Imaging Spectroradiometer (MODIS), with its combined attributes of fine spatial resolution, large swath area, and near-daily global coverage, has for the first time allowed sunglint (the near-specular reflectance pattern of sunlight off the ocean surface) to be used to analyze and survey high-frequency nonlinear internal solitary wave occurrences on a near-global scale. The sunglint area within the MODIS swath is large enough to cover an entire basin, and it’s spatial resolution is fine enough to identify internal wave signatures whose wavelength is greater than a few hundred meters. This paper describes the use of MODIS for high-frequency nonlinear internal wave detection, presents the results of a survey that detected 3581 internal wave occurrences in MODIS imagery over the period between August 2002 through May 2004, and discusses ways MODIS imagery can be used to improve the study of internal waves.


1. Introduction

Since the early 1970s, high-frequency nonlinear internal waves have been distinctive features in photographs, multispectral radiometer images, and synthetic aperture radar images of the sea surface obtained by spacecraft [Jackson, 2004]. The waves manifest themselves as alternating bands of light and dark quasilinear strips that remain coherent over tens of hundreds of kilometers. Internal waves occur globally, produced by a combination of stratification, bathymetry, and current flow and are important in the energy exchange between the large-scale tides and small-scale mixing. Historically, occurrences of these waves have been noted on the continental shelves, especially during the summer months [Colosi et al., 2001; Moum et al., 2003], as well as in straits [Farmer and Armi, 1999] and in the marginal seas [Apel et al., 1985; Osborne and Burch, 1980].

The use of sunglint imagery for internal wave detection has been previously applied to astronaut photography [Apel, 1979], imagery acquired from Landsat [Apel et al., 1975; Sawyer, 1983] and the Defense Meteorological Satellite Program (DMSP) satellites [Fett et al., 1979]. More recent work by Mitnik et al. [2000] examined the similarities and differences in internal wave signatures between synthetic aperture radar (SAR) and sunglint images from SPOT. These studies demonstrated the utility of sunglint for the detection of internal waves, but each was focused on a limited geographic area for a short period of time.

The MODIS (Moderate Resolution Imaging Spectroradiometer) sensor collects data in a continuous, systematic manner at 250-m resolution on a 2300-km swath. It produces almost daily world wide coverage which results in a large volume of imagery that has for the first time, allowed the near-specular reflectance pattern of sunlight off the ocean surface (sunglint) to be used to identify high-frequency nonlinear internal solitary wave occurrences on a near-global scale. These characteristics make MODIS imagery particularly well suited for surveying and cataloging internal wave occurrences and for studying the evolution of internal wave fields.

This paper discusses the characteristics of the MODIS sensor and how high-frequency nonlinear internal waves are detected in the sunglint regions of the true-color imagery (section 2). It then presents an overview of an internal wave survey using MODIS true-color imagery covering 21 months between August 2002 and May 2004 that resulted in the detection of 3581 internal wave occurrences (section 3). Section 4 presents the analysis of internal wave signatures in MODIS images from seven areas of the world. Section 5 discusses how the imagery can be used to support internal wave studies when wave observations are made on short timescales and when a large database of observations are available.

2. MODIS (Moderate Resolution Imaging Spectroradiometer)

The MODIS sensors are onboard the National Aeronautics and Space Administration’s (NASA’s) Earth Observing System satellites Terra and Aqua. These satellites, launched in 1999 and 2002 respectively, are in Sun-synchronous orbit at approximately 700-km altitude and each MODIS sensor collects data continuously along a
2300-km wide swath providing near-global daily coverage. The MODIS data are acquired at 36 channels in the visible and infrared regions the spectrum, with a spatial resolution between 250 m and 1 km dependent on the collection wavelength [Salomonson et al., 1989] and with a geolocation accuracy of at least 60 m (1 σ) [Wolfe, 2006]. The true-color images are created from the calibrated, corrected and geolocated radiance (Level-1B) data by compositing MODIS Bands 1 (855 nm at 250 m resolution), 4 (555 nm at 500 m resolution) and 3 (466 nm at 500 m resolution) into the red, green and blue image channels respectively. Full details of the characteristics of MODIS and its associated data products are given by Qu et al. [2006] or on the NASA MODIS website (modis.gsfc.nasa.gov).

[7] The MODIS imagery collected during the daylight portion of its orbital period contain distinctive narrow silvery-gray ellipses of reflected sunlight over the oceans where angle of reflection, is within approximately 30 o of the Sun’s specular reflection point. These sunglint ellipses, located to the east of the swath center for Terra, (west for Aqua), are approximately 500 km across their minor axis and can extend for more than 45 degrees in latitude. It is in these sunglint regions, where standard ocean color products cannot be retrieved [Esaias et al., 1998], that internal wave signatures are readily detected.

[8] Cox and Munk [1954] described the relationship between sunlight reflected from the sea surface, the distribution of surface wave slopes (i.e., sea surface roughness) and wind speed. They showed that sunglint reflection is heavily biased toward the capillary and short gravity waves set up by wind roughening [Munk et al., 2000]. It is these capillary and short gravity waves, modified by the variable surface currents associated with internal waves, that allow the internal waves to be observed in satellite imagery for wind speeds of approximately 2 m/s to 10 m/s [Hennings et al., 1994; Holt, 2004]. In addition, there is a geometry dependence that will cause either the rough or smooth zones on the surface to appear either bright or dark depending on if the zones are contained in what Munk et al. [2000] describe as the inner “glitter” or outer “glitter” regions. The inner glitter regions require only a small slope on the ocean surface to satisfy the specular (or near specular) condition where in the outer glitter region, farther off the sensor nadir, requires steeper facets to produce the sunglint reflection.

[9] Nonlinear internal waves manifest themselves as either isolated wave fronts (usually called solitons) or in collections of waves, called packets, were the number of individual waves in a packet can vary from three to a few dozen, depending on their age and distance from the generation point. The internal waves appear in the imagery as alternating bands of light and dark strips that result from variations in sea surface roughness [Alpers, 1985]. The roughness variations are caused by the creation of convergent (rough) and divergent (smooth) zones set up by the internal wave currents that move across the surface in phase with wave’s subsurface crests and troughs [Munk et al., 2000]. Internal wave wavelength, here defined as the distance between two corresponding points on successive waves in a packet, varies from approximately 200 m to 15 km and the waves can have along crest lengths from a few tens to few hundred kilometers.

[10] While sunglint imagery from other optical sensors (Landsat, SPOT, ASTER, AVHRR, DMSP) can be, or has been, used for internal wave observation, these imagery all have limitations for large area internal wave surveying compared to imagery from MODIS. Higher-resolution sensors like Landsat, SPOT and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) have significantly smaller swath widths (60–100 km) and cover a correspondingly smaller portion of the world on a daily basis. Wide area coverage instruments like AVHRR (Advanced Very High Resolution Radiometer) and DMSP collect data at only 1 km and 4 km resolution respectively, from which only a limited number of very large internal wave signatures can be detected. A 500-m collection mode for DMSP provides nearly comparable sunglint imagery to MODIS but these data are not collected systematically on a worldwide basis and are not readily available.

[11] The only sensors that approach the capabilities of MODIS for large area detection and study of internal waves include MERIS (MEdium-spectral Resolution, Imaging Spectrometer) with a 1150 km swath [Curran and Steele, 2005] and the synthetic aperture radars on ENVISAT and RADSAT-1 while operating in their wide swath (or scanSAR) modes which have swath widths of 450 and 500 km respectively. Also, while SAR is independent of cloud cover and the reliance on a specific (near specular) imaging geometry, it does not acquire imagery in the same continuous, systematic near-global way acquired by MODIS.

3. MODIS Internal Wave Survey

[12] The previous work by Apel et al. [1975], Fett et al. [1979], and Sawyer [1983] using sunglint to study internal waves motivated the examination of MODIS sunglint imagery to identify internal wave occurrences to support the development of an Atlas of Internal Solitary-like Waves [Jackson, 2004] (www.internalwaveatlas.com). The survey relied on MODIS true color images on the NASA MODIS Rapid Response System web site (rapidfire.sci.gsfc.nasa.gov) which posts daily, near-real-time imagery to support active fire detection [Descloi
tres et al., 2002]. Imagery on the Rapid web site includes 20-km resolution thumbnails that were used to identify images that contained sunglint and direct links to the 250-m imagery allowed the finer resolution imagery to be examined relatively quickly. While it is possible to detect the internal wave signatures in 1-km resolution images in a few areas of the world, the 250-m imagery was required to identify the majority of internal wave signatures found in the survey.

[13] Beginning with August 2002, MODIS 250-m true-color sunglint imagery were examined for internal wave packets or isolated soliton signatures. Figure 1 shows the location of 3581 internal wave occurrences noted in the imagery during 21 months from 1 August 2002 through 16 May 2004 (excluding January 2003). The survey was done entirely “by eye,” and did not count individual wave packets but rather distinct regions of wave activity visible in any given image. For example, wave packets visible in a particular image that were generated on subsequent phases of the tide but which originated at the same location were considered to be a single occurrence. The internal wave
Figure 1. Location of internal waves observed in MODIS imagery from August 2002 through May 2004 along with the geographic boundary for the 15 regions listed in Table 1. The survey identified a total number of 3581 wave occurrences which combine to create 2774 distinct region, area, and date occurrences. Well-known occurrence sites are shown in gray, new areas of activity are shown in red, and areas of geographically expanded activity are shown in blue.
occurrences were noted on 589 of the 621 days examined. Although limited to times of light cloud cover and the proper location of the sunglint ellipse, it was found that up to a dozen internal wave occurrences could be identified on a given day. It should be noted, that NASA’s Rapid website is not a comprehensive archive of MODIS imagery and so the survey represents a lower limit on the number of internal waves detectable by MODIS over the survey period.

Table 1 presents a summary of the survey results for the top 15 regions of wave activity, representing 76% of the internal waves observed in the MODIS survey. The regional break down was chosen to take into account both historically reported locations of wave activity and to group similar occurrences within a geographic area. Some regions therefore have one or more or subregions of unique internal wave activity. Table 1 list the number of subregions contained in each region along with the total number of internal waves observed over the region and the total number of distinct region, subregion, and occurrence date combinations. The survey identified a total number of 3581 wave occurrences which combine to create 2774 distinct region, subregion and date combinations.

In addition to their geographic delineation, the internal wave occurrences can be divided into three categories based on how well the occurrences in a particular region/subregion have been previously studied. In the first category are regions where internal waves have been previously reported and their characteristics well documented. In the second category are regions where internal wave activity has been reported, usually from in situ measurements or individual remote sensing images (like an astronaut photograph), but the full extent of the activity (geographically or temporally) and the characteristics of the waves have not been determined. In the third category are regions in which the MODIS survey found a significant amount of internal wave activity where little or no activity had been previously reported. This categorization of wave types is reflected by the colors in Figure 1 where waves from category 1 are presented as dark gray, category 2 as blue and category 3 as red.

Figure 1 highlights that high-frequency nonlinear waves are ubiquitous in many areas of the world. The waves are present throughout many of the marginal seas (Andaman, Sulu, Celebes as well as almost all the seas of Indonesia), occupy much of the Equatorial Indian Ocean, are spread across the Central Atlantic (between Brazil and West Africa) and cover a large area in Eastern Equatorial Pacific (from the coast of Central America to south of the Galapagos Islands) with more localized occurrences in the eastern Caribbean, the Persian Gulf, south of Japan among the Bonin Islands and in the Tasman Sea west of New Zealand. Section 4 will discuss several of these areas in detail.

Figure 1 also highlights some of the limitations the of the MODIS sunglint survey. In general, Figure 1 shows only a limited number of internal wave detections over the deep ocean. This is due to limitations on the imagery available from the MODIS Rapid website and not limitations on the coverage by the MODIS sensor. Unlike data from other sensors, MODIS imagery over the central ocean is resident in the Level 1 and Atmosphere Archive and Distribution System (LAADS) archive and can be processed and examined to support internal wave detection in the open ocean. Figure 1 also shows that internal waves were only detected between 45°S and 55°N, close to the maximal extent of the sunglint that occurs at the summer and winter solstices, (the termination at 45°S is not due to sunglint limitations but detectable internal wave activity). The variation in the latitude of internal wave detections over the course of the year is shown in Figure 2 and results from the shifting location of the sunglint region. Figure 2 shows that sunglint portions of the MODIS imagery have the advantage of

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of Subregions</th>
<th>Total Number of Occurrences (Region, Subregion, Date)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>14</td>
<td>465</td>
</tr>
<tr>
<td>South China Sea</td>
<td>8</td>
<td>278</td>
</tr>
<tr>
<td>Western Equatorial Indian</td>
<td>1</td>
<td>324</td>
</tr>
<tr>
<td>Pacific Central America</td>
<td>5</td>
<td>234</td>
</tr>
<tr>
<td>Andaman Sea</td>
<td>3</td>
<td>213</td>
</tr>
<tr>
<td>West Central Africa</td>
<td>3</td>
<td>192</td>
</tr>
<tr>
<td>Sulu Sea</td>
<td>2</td>
<td>142</td>
</tr>
<tr>
<td>Western Equatorial Atlantic</td>
<td>1</td>
<td>180</td>
</tr>
<tr>
<td>Eastern Equatorial Indian</td>
<td>1</td>
<td>123</td>
</tr>
<tr>
<td>Southwest Africa</td>
<td>2</td>
<td>110</td>
</tr>
<tr>
<td>Australia-NW</td>
<td>1</td>
<td>112</td>
</tr>
<tr>
<td>Eastern Equatorial Pacific</td>
<td>1</td>
<td>104</td>
</tr>
<tr>
<td>Gulf of California</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>Northwest South</td>
<td>1</td>
<td>83</td>
</tr>
<tr>
<td>America</td>
<td>1</td>
<td>69</td>
</tr>
<tr>
<td>Celebes Sea</td>
<td>1</td>
<td>69</td>
</tr>
</tbody>
</table>

*These regions represent 76% of the observed occurrences. The table shows the number of subregions contained in each region along with the total number of internal waves observed in the region and the total number of distinct region, subregion, and occurrence date combinations.

Figure 2. Latitude of internal wave observations observed in MODIS imagery as a function of day of year. The latitude range of detections follows the movement of the changing location of the sunglint pattern.
Figure 3. True-color MODIS image of the Banda Sea acquired on 24 February 2004 at 5:05 UTC. Four groups of internal waves are visible in the central sea radiating from a generation point in the Ombai Strait. Imaged area is approximately 450 km × 600 km.
tracking in phase with the seasonal heating of the ocean’s upper layer that provides the stratification necessary for internal wave creation.

4. Internal Wave Occurrence Regions

This section examines seven regions of significant nonlinear internal wave activity that were found during the MODIS survey. A image showing the wave signatures in each region is presented along with a short description of the wave characteristics that could be derived from the MODIS true-color imagery.

4.1. Indonesia

The survey identified the largest number of wave occurrences in the Indonesian Seas. Waves were noted in 14 distinct subregions around Indonesia including the Bali Sea, Banda Sea, Cream Sea, Flores Sea, Halmahera Sea, Molucca Sea, Savu Sea, the Sumba Strait and north and south of the Lombok Strait. The profusion of waves in this region is due to the large number of shallow interisland sills that separate deeper basins and which are accompanied by the strong currents of the Indonesian throughflow between the Pacific and Indian Oceans. The survey indicates that wave occurrences take place all year round in the Indonesia region. Figure 3 is a true-color MODIS sunglint image acquired on 24 February 2004 at 5:05 UTC that shows internal wave signatures in the Banda Sea. Four groups of solitary-like internal waves are visible as dark bands against the silver-gray sunglint which covers almost the entire sea surface area visible in the image. The waves appear to originate in the Ombai Strait between the islands of Alor and Wetar and persist for more than 500 km into the Banda Sea from their generation point. Modeling of the M2 baroclinic tide in this area has shown that the Ombai Strait has some of the strongest internal tidal flow in Indonesia [Robertson and Ffield, 2005]. The strong current in combination with a small sill in the strait would cause the necessary displacement of the pycnocline for the generation of internal waves in a manner similar to that of the Sulu Sea. A finer-scale packet of internal waves is also visible immediately north of Timor propagating eastward. Figure 3 is one of a pair of images collected over the Banda Sea on 24 February 2004. Figure 3 combined with

Figure 4. A contrast enhanced true-color MODIS image over the southwestern South China Sea acquired on 6 March 2003 at 3:20 UTC. More than ten internal wave packets are visible northeast of the Natuna Bessar Island. The packets are finescale (approximately 500 m wavelength) propagating primarily to southwest and aligned with the local bathymetry are typical of continental shelf generated internal waves. Imaged area is approximately 223 km × 223 km.
its corresponding Terra image acquired at 2:15 UTC, indicates the waves propagated a distance of between 25 to 30 km (depending on the packet) with an average propagation velocity for the leading soliton of between 2.5 and 3.0 m/s.

4.2. Southwestern South China Sea

[20] Internal wave occurrences have been well documented in the northern portion of the South China Sea between the Luzon Strait and the Dongsha Coral Reef [Hsu and Liu, 2000]. However, the MODIS survey also identified significant nonlinear internal wave activity all along the coast of Vietnam and in the southwestern portion of the South China Sea on the continental shelf between Vietnam and Borneo. Figure 4 is a true-color MODIS sunglint image acquired over the southwestern South China Sea on 6 March 2003 at 3:20 UTC. More than ten internal wave packets are visible northeast of Natuna Bessar Island. The packets are finescale, approximately 500-m wavelength, propagating primarily to southwest and are aligned with the local bathymetry. The separation distance between packets of 25 to 30 km indicates a propagation speed of approximately 0.6 m/s, assuming a semidiurnal generation period. The characteristics of these wave signatures are typical of continental shelf generated internal waves observed in other areas of the world.

4.3. Celebes Sea

[21] The MODIS survey found significant internal wave activity from February through December in the Celebes Sea. The waves manifest themselves as isolated solitary wave fronts or as groups of 3 to 5 waves that propagate across the sea to the southeast and the west. The southeast propagating waves originate in (or near) the Sulu Archipelago and western propagating waves originate at the eastern edge of the sea, most likely near the Sangi Islands. Figure 5 is a true-color MODIS sunglint image acquired over the Celebes Sea on 6 March 2006 at 5:25 UTC showing both kinds of wave occurrences. Five groups of internal waves are visible in western half of the sea, two propagating west toward Borneo, two propagating southwest toward Celebes, and the partial signature of a fifth group visible immediately adjacent to the coast of Celebes. Imaged area is approximately 555 km \( \times \) 445 km.

Figure 5. True-color MODIS image of the Celebes Sea acquired on 6 March 2006 at 5:25 UTC. Five groups of internal waves are visible in western half of the sea, two propagating west toward Borneo, two wave groups propagating southeast toward Celebes, and the partial signature of a fifth group visible immediately adjacent to the coast of Celebes. Imaged area is approximately 555 km \( \times \) 445 km.
east toward Celebes and the partial signature of a fifth group is visible immediately adjacent to the coast of Celebes. The separation distances between the leading waves suggest that both types are generated semidiurnally with propagation velocities of approximately 3.0 m/s across the deep basin.

### 4.4. Eastern Equatorial Indian Ocean

The survey identified a significant amount of internal wave activity from February to November in the Eastern Equatorial Indian Ocean between the Nicobar Islands and Sri Lanka. Figure 6 is a true-color MODIS sunglint image showing the symmetric generation of internal waves around the Nicobar Islands at the eastern edge of the Indian Ocean. The image was acquired on 6 April 2004 at 4:25 UTC and shows finescale internal waves with 500 to 800 m wavelength. Packets 1, 2 and 3 appear to the west of the islands and these packets propagate across the eastern equatorial Indian Ocean and shoal near Sri Lanka. Packets 1 and 2 will eventually merge into a single packet similar to packet 3, which was generated on the previous tidal cycle. The separation distance between packets 2 and 3 of 90 km gives a propagation speed of approximately 2.0 m/s, assuming a semidiurnal generation period. The waves on the east side of the islands (Packets 4 and 5) develop into the well-known internal waves that propagate across the southern portion of the Andaman Sea.

**Figure 6.** True-color MODIS image acquired on 6 April 2004 at 4:25 UTC showing the symmetric generation of internal waves around the Nicobar Islands. Packets on the west of the islands (1, 2, and 3) propagate across the eastern equatorial Indian Ocean and shoal near Sri Lanka. The packets on the east side of the islands (packets 4 and 5) develop into the well-known internal waves in the southern part of the Andaman Sea. Imaged area is approximately 260 km × 165 km.

### 4.5. West Central Africa

The survey identified wave occurrences in three areas off the Atlantic coast of Africa between the equator and 20°N. Slightly more than half (54%) of the wave activity occurred offshore as finescale waves from the area of the Cape Verde Islands south to the Sierra Leone rise. The remaining wave activity was primarily shoreward propagating continental shelf generated waves, concentrated on the wide shelf between 7°N to 15°N. However, the survey also identified 20 occurrences of seaward propagating internal waves just south of this wide shelf area. Figure 7 shows a true-color MODIS image acquired on 27 October 2002 at 11:45 UTC containing these seaward propagating waves. Two distinct wave packets (1 and 2) are visible in the upper right quadrant of the image propagating to the southwest. Near the image center is also the strong signature of a packet (3) with 4 waves amid a large number of more irregularly spaced wave signatures. The generation mechanism for these seaward propagating wave packets is not yet understood. A packet separation distance of 50 to 55 km gives a propagation speed of approximately 1.1 m/s, assuming a semidiurnal generation period.
4.6. Western Equatorial Atlantic

Internal waves in the Atlantic Ocean near the mouth of the Amazon have been reported by Ivanov et al. [1993] and more recently by Brandt et al. [2002], who detected three large-amplitude internal solitary waves of unknown origin propagating toward the north-northeast at 44°W between 4.5°N and 6°N. The MODIS survey showed that the internal wave activity in this region extends over a wide geographic area (Figure 1) from at least March through December.

Figure 8 is a true-color MODIS image acquired on 13 August 2003 at 16:05 UTC showing pulse-like internal solitary wave signatures beginning approximately 500 km from the mouth of the Amazon River and extending more than 700 km into the Atlantic. Isolated wave fronts in the lower half of the image change into irregularly organized packets in the upper half. A reduced resolution MERIS image, acquired on 13 August 2003 at 13:21 UTC, contains the signature of the southern most solitary wave visible in the MODIS image and indicates the wave traveled approximately 33 km in the time between images yielding an average propagation speed of 3.3 m/s. This speed is consistent with the separation distance of 135 km to the next solitary wave to the north given a semidiurnal generation period. The actual generation location and mechanism for large solitary waves in this region is still not known but the regularity in generation, and nearly year round occurrences of the waves points to a tidal origin.

4.7. Pacific Coast of Central America

The survey revealed an unexpectedly large amount of finescale internal wave activity year round over a large area from the Pacific coast of Central America extending down to the equator (Eastern Equatorial Pacific). Figure 9 shows a true-color MODIS image acquired on 22 March 2003 at 16:30 UTC that shows these finescale internal waves signatures southwest of Central America. Visible throughout the image are packets of waves with wavelengths between 600 and 1200 m propagating primarily northwest, parallel to the shore. Packet separation distances are between 35 and 50 km which produce a propagation speed of 0.8 to 1.2 m/s with semidiurnal generation. The wave signatures in Figure 9 are located to the seaward side of the continental shelf and cover a region with very little
Figure 8. True-color MODIS image of the western equatorial Atlantic acquired 13 August 2004 at 16:05 UTC. The image showing pulse-like internal solitary wave signatures beginning approximately 500 km from the mouth of the Amazon River and extending more than 700 km into the Atlantic. Individual solitary waves in the lower half of the image change into irregularly organized packets in the upper half. Imaged area is approximately 555 km × 670 km.
Figure 9. A contrast enhanced true-color MODIS image of the Pacific southwest of Central America acquired on 22 March 2003 at 16:30 UTC. Finescale internal waves signatures are visible throughout the image two propagating toward the northwest. Imaged area is approximately 334 km × 556 km.
topographic variation. It is not currently understood how such a large number of waves in the region are generated.

5. Applications for Internal Wave Field Studies

The ability to collect large amounts of imagery over a region and to obtain both high temporal and spatial resolution data by combining data from Aqua and Terra, or combining MODIS imagery with imagery acquired from MERIS and wide swath SAR imagery, has important applications for the study of internal wave field evolution and the broader study of ocean characteristics.

Internal wave velocity is to first order determined by the internal wave wavelength, the ocean depth and the density profile of the water column. By using pairs of MODIS/MODIS, MODIS/MERIS or MODIS/SAR images separated in time by only a few minutes to a few hours it is possible to estimate the propagation speed of individual wave packets more accurately than by computing a velocity from the distance between packets with assumptions about generation time. With better internal wave velocity estimates, there are now new opportunities to use internal wave observations to derive the ocean properties of mix layer depth, Brunt-Väisälä frequency and heat storage originally put forth by Li et al. [2000], Porter and Thompson [1999], Jones [1995] and Mollo-Christensen and Mascarenhas [1979].

The ability to collect large amounts of imagery over a particular area of wave activity at many different phases of the tidal cycle and varying environmental conditions provides another way to study internal wave field evolution and potentially estimate changes in the water column characteristics. By building up a database of internal wave locations throughout the phases of the tidal cycle, it becomes possible to estimate a “mean” propagation time (image acquisition time minus the wave generation time) to all points throughout the area of internal wave activity. This can be done by either averaging the calculated propagation time at various locations throughout a region or by fitting a simple model (e.g., wave velocity as a function of depth) to the observations. The difference between the mean travel times and observations to derive the ocean properties of mix layer depth, Brunt-Väisälä frequency and heat storage originally put forth by Li et al. [2000], Porter and Thompson [1999], Jones [1995] and Mollo-Christensen and Mascarenhas [1979].

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The ability to use MODIS imagery, particularly in combination with other sensors has important applications in the study of internal wave field evolution and the broader study of ocean characteristics. By using pairs of images separated in time by a few minutes to a few hours it is possible to estimate the propagation speed of individual wave packets more accurately and then apply established techniques to estimate oceanic mix layer depth or heat storage.

The ability to use MODIS to compile a large database of internal wave observations over a particular area of wave activity provides another way to determine if a particular factor (year, season, month, etc.) or combinations of factors (each associated with a change in environmental conditions) significantly effects internal wave propagation times in a region. Work on the examination of MODIS imagery for internal wave signatures is ongoing.

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References


