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研究課題名（英文） SURFACE CURRENT MAPPING IN COASTAL ZONES USING HIGH SPATIAL RESOLUTION SATELLITE DATA

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研究成果の概要（和文）：本研究では、2011年3月11日の津波から1週間以内に発生した、福島第一原発に隣接した沿岸域の表層流と浮遊がれきの分布を、衛星画像により総観規模でマッピングすることを行った。現場観測が存在しなかったため、複数の衛星画像を比較することでマッピングを行った。3月14日のデータから、（沿岸域の複雑な）表層流速を高精度に特定し、また発電所から津波により流出したと思われるがれきの漂流をコントロールする要因を特定するなど興味深い結果を得ることに成功した。複数の広域衛星データを活用することで、漂流するがれきが海表面の粗度を小さくすることで表層風速分布を変化させることを、本研究により初めて示すことに成功した。

研究成果の概要（英文）：This research focused on the synoptic mapping of surface currents and floating debris motions in the coastal zone adjacent to the Fukushima Daiichi nuclear power station that developed within one week of the tsunami of 11 March 2011. In the general absence of in situ data, a technique based on inter-satellite comparison has been used to perform this mapping. Good results were obtained for 14 March 2011, both in terms of surface current determinations (which revealed the complexity of the oceanic movements in the near-coastal zone) and in terms of identifying the factors controlling the evolution of floating debris clusters, some of which were likely drawn from the power-station complex by the retreating tsunami waters. As a result of unique satellite-data coverage, this project yielded the first open-ocean evidence of a restructuring of the wind profile in the vicinity of zones of strong surface-roughness suppression that develop in association with floating-debris dispersal trails.

研究分野： Satellite Oceanography

キーワード： Inter-satellite mapping　Surface currents　Marine debris　Fukushima Daiichi

１．研究開始当初の背景

The goal of making fine-scale surface current measurements from space is being actively pursued in many research institutions in both Europe and the US. In oceanographic monitoring, it is clear that traditional *in situ* measurement techniques based on ships and buoys are unable to deliver the synoptic coverage required for coastal zone and ocean-wide assessments of currents in this era of natural disasters and climate change. As a result, there is considerable emphasis on space-based methodologies, which in principle should provide the means of tracking water and floating-debris motions and of determining the transport of heat and nutrients on an inclusive year-by year basis. Such wide-view information is required if we are to successfully monitor the effects of natural disasters and, on the other hand, follow the mechanisms underpinning the evolution of our climate system.

２．研究の目的

Well-validated optical and radar methods of measuring surface currents at high spatial resolution (nominally<100 m) from space can greatly advance our ability to monitor earth's oceans, coastal zones, lakes and rivers. In addition, satellite techniques for the detection and tracking of floating marine debris washed into the ocean following tsunamis and floods provides highly valuable synoptic overviews that cannot be obtained in any other way. This research has aimed to build on earlier pioneering work (e.g. *Matthews and Yoshikawa, 2012*) in the measurement of surface currents from space which led to the development of the Along-Track Stereo Sun Glitter (ATSSG) technique. The plan was to extend the new ATSSG approach both in terms of its oceanographic applications (new case studies) and in terms of its inter-comparison with radar-derived surface current data. In fact this research has successfully extended the technique of inter-satellite comparison through a study of surface currents and debris motions in the coastal zone adjacent to the Fukushima Daiichi nuclear power station, as observed within one week of the tsunami of 11 March 2011.

３．研究の方法

Good results from the mapping of surface currents and debris-motions in the post-tsunami Fukushima coastal zone have now been obtained using several multi-view satellite combinations, based on variants of the ATSSG "Along-Track Stereo Sun Glitter" concept first developed by *Matthews and Awaji (2010)*. In the initial application to JSPS for research support, I strongly advocated the use of this new technique and overall it has worked well. Inter-satellite comparisons, when correctly geo-registered, have yielded unique synoptic views of ocean currents and debris motions for large pieces of flotsam that originated from the general vicinity of the Fukushima Daiichi nuclear power station.

The following inter-satellite comparison pairs have provided the basic data input for this research. For the situation on 12 March 2011 (one day after the tsunami), I found that an inter-comparison based on RapidEye visible band data and RADARSAT Synthetic Aperture Radar data was the most useful, both in terms of the broad coverage that these sensors offered of the disaster zone and in terms of their high spatial resolution. Results in this case show the early distribution of the floating marine debris field and its response to an abrupt change in wind direction. For the 14 March 2011, a day of mostly clear weather, a number of possibilities became available. For the mapping of surface currents, a variant of the ATSSG technique was used with a combining high spatial resolution WorldView-1 and WorldView-2 visible band imagery. The motions and evolution of floating-debris clusters, on the other hand, were best revealed by comparing AVNIR-2 and ASTER visible band images (separated by 7.43 min) and, over a longer timeline, by comparing AVNIR-2 and WorldView-2 images (separated by 51.27 min). Furthermore, the acquisition of simultaneous AVNIR-2 and PALSAR-1 radar data by the ALOS satellite proved to be of immense value. A wealth of new results stemmed from the analysis of data acquired on 14 March 2011 (see below).

As most of the above satellite images were purchased using financial support from the present Kakenhi award, I would like to express my sincere thanks to JSPS for enabling me to perform this research.

４．研究成果

I wish to first emphasize the fact that that the ATSSG and other multi-satellite approaches adopted in this program have provided the only known means of mapping the surface-current field and of deriving debris drift speeds in the Fukushima coastal zone during the crucial period covering the first few days after the tsunami of March 2011.

Although one may expect that the disorder and confusion introduced by the tsunami should in principle offer little opportunity for the application of formal classroom oceanography, in fact my satellite-based research shows that, during the first few days after the disaster, chaos did not reign entirely. Rather, under the combined effects of waves, currents and largely steady southwesterly wind forcing in the days following 12 March 2011, the debris field reacted in a mostly predictable way. However, as this research is providing the first in-depth monitoring of an extensive distribution of floating material at unprecedented levels of resolution, it is to be expected that a number of new and interesting results have been uncovered. These new findings are described below.

Surface Current Mapping

Using a combination of WorldView-1 and Worldview-2 data from 14 March 2011 to provide a stereo Sun-glitter capacity, I was able to map surface currents within a section of the inner coastal zone stretching roughly from Ukedo port in the south to the Haramachi thermal power station in the north. These results reveal a complex pattern of surface currents which reverse from largely southward motions near the coast to generally northward (and faster) flows further offshore. There is also evidence of continuing tsunami-induced runoff of groundwater and river discharge within the mapped surface-current field. This latter observation may form the basis of an interpretation of later images (from 17 March 2011), which exhibit a number of puzzling “anomalies”. Furthermore, work is progressing in constructing a comparison between the satellite-based surface currents obtained in this study and those derived from high-resolution models of the Fukushima inner coastal zone by scientists at JAMSTEC *(Miyazawa et al., 2013; S. Varlamov, private communication)*. It is hoped that this comparative study will be published in due course.

Formation and Structure of the Fukushima Daiichi Debris Trail

The satellite images acquired in this study have enabled me to track the FDI floating debris field as it became rapidly sorted into an extensive corridor-like trail led by material with the highest “windage” factor (defined as the wind-forced drift speed as a percentage of wind speed). Modelling work based on the Large Eddy simulation (LES) approach performed by Y. Yoshikawa of Kyoto University has provided a useful means of interpreting these observed debris motions. During the initial post-deposition period, sorting based on windage value caused relatively rapid along-wind alignment (within 1 day) toward the southwest, with faster material leading. However, a veering of the wind direction toward the north east on the afternoon of 12 March 2011 caused an abrupt re-alignment of the debris-trail, as the faster material rapidly overtook the slower tail. Under continued south westerly winds, by 14 March 2011 the debris trail extended over 16 km in length and represented a jet-like surge in debris drift speed when viewed in cross section. As far as I am aware, such behavior has never previously been observed in this detail.

Discovery of the “Wind Restructuring” Phenomenon in the Open Ocean

Most significant, however, is the identification of an effect that up to now has only been observed in laboratory studies (such as those of *Mitsuyasu and Honda, 1986)*. The phenomenon initially involves a localized increase in near-surface wind speed along the low-surface-roughness corridors that run parallel to the debris trails. The latter were clearly identified in PALSAR Synthetic Aperture Radar data acquired on 14 March 2011 and simultaneous with AVNIR-2 visible band data. Based on estimates of local friction velocity derived from the satellite data, L. Ostrovsky of NOAA (USA) solved the Reynolds equations relevant this problem and thus derived an estimate for the near-surface wind increase of around 1 m s^{-1}. My data indicate that this enhanced wind then forces more rapid debris drift motions and thereby enhances debris-raft evolution and decay. As a result, the smooth increase in debris drift speed normally observed along the debris trail is disturbed by a region of faster debris drift-speeds, with the “overspeed” in this case reaching roughly 5 cm s^{-1}. An understanding of the wind restructuring mechanism and its consequences is required in order to fully understand the complex morphology of the “boomerang-shaped” debris rafts described in the following section. Furthermore, wind restructuring has wider implications for sea surface energetics, since slicks associated with Langmuir Circulation are largely ubiquitous throughout the global ocean.

Evolution and Decay of Debris Rafts

The data acquired in this study reveal a tendency for the tsunami-induced flotsam to gather into structured “rafts” of generally 1-10 km in extent, which were often fashioned into curved “boomerang-shaped” features. I define how these, in turn, were subject to active evolution driven by the local environmental conditions. Further modelling work based on a laboratory scale Large Eddy simulation (LES) performed by S. Komori of Kyoto University has provided useful insights into a “lateral instability” that causes decay through a quasi-periodic release of material from the outer edges of these rafts. As shedding continues through lateral instability, the combined effects of surfactant release, wake turbulence and debris-induced sheltering (from the ambient wave field) create a calm zone within the wake region upwind of the raft. Wind restructuring (described in the previous section) takes place in response this well-defined reduction in local surface roughness, enhancing the near-surface wind speed in the central region of the raft and causing it to buckle into a boomerang shape with the apex leading. Refraction then redirects waves of metric wavelengths (< 10 m) toward the center, leading to the transport of mobile material from the leading edge of the raft toward the apex of the boomerang. The convergence of refracted waves from the two sides produces a forward wave pressure and with material now focused at the apex of the boomerang-shaped raft the stronger wind forcing and forward wave pressure cause it to break away from the parent raft. Thus two distinct modes – the “lateral” and “apex” instabilities are chiefly responsible for the ongoing evolution of the debris rafts.

Summary

This successful project has produced a wealth of information on conditions in the Fukushima coastal zone in the crucial period directly after the tsunami. The multi-satellite approach used here has provided the only means available of mapping the behavior of the post-tsunami surface currents that had such an important influence on the dispersal of oil, contaminants and surface-floating debris. Furthermore, the project has revealed the internal dynamical structure established within extended trails of buoyant debris and has produced the significant discovery of “wind restructuring” taking place in the open ocean. Through this new understanding of the behavior of the near-surface wind field, it has been possible to interpret many aspects of the evolution and decay of the numerous floating debris rafts that were distributed throughout the coastal zone of NE Japan in the wake of the tsunami. Clearly, it is vital that every lesson should be learned in relation to the discharge of potentially contaminated material from coastal nuclear-power facilities. This work therefore continues and further discoveries are anticipated.

A paper describing some of the new results derived from this research program is presently under review for publication in Nature Geoscience (*Matthews et al., 2016*).

References

Matthews, J.P., and Awaji, T., Synoptic mapping of internal-wave motions and surface currents near the Lombok Strait using the Along-Track Stereo Sun Glitter technique, Remote Sensing of Environment 114, 1765–1776, 2010.

Matthews and Yoshikawa, Synergistic surface current mapping by spaceborne stereo imaging and coastal HF radar, Geophysical Research Letters, 39, L17606, doi:10.1029/2012GL052546, 2012.

Matthews, J.P., Ostrovsky, L., Yoshikawa, Y., and Komori, S., Tracking the early post-tsunami evolution of the Fukushima Daiichi Marine Debris Plume, *under review for Nature Geoscience, 2016.*

Mitsuyasu, H., and Honda, T., The effects of surfactant on certain air-sea interaction phenomena. In Wave Dynamics and Radio Probing of the Ocean Surface edited by O.

M. Phillips and K. Hasselmann, 95-115 (Plenum Press, New York) 1986.

Miyazawa, Y., Masumoto, Y., Varlamov, S. M., Miyama, T., Takigawa, M., Honda, M. and Saino, T. Inverse estimation of source parameters of oceanic radioactivity dispersion models associated with the Fukushima accident. Biogeosciences. 10, 2349-2363, 2013.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計 0 件）

〔学会発表〕（計 1 件）
John Matthews, “ Satellite monitoring of early post-tsunami marine debris evolution ”, International Workshop on Marine Debris, October 25, 2013, Okinawa Institute of Science and Technology Graduate University, Kunigami, Okinawa

〔図書〕（計 0 件）

〔産業財産権〕
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〔その他〕
ホームページ等
なし

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