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Polar Epsilon MODIS and fused MODIS / RADARSAT MetOc products for national defence and domestic security

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Polar Epsilon MODIS and fused MODIS / RADARSAT MetOc products for national defence and domestic security

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Abstract

In preparation for Polar Epsilon's MODIS and RADARSAT satellite reception systems, this project investigates meteorology and oceanography (MetOc) products derived from MODIS data for defence, search and rescue and environmental security operations. It also investigates whether operational improvements can be gained through production of fused MODIS/RADARSAT products, but in both cases the emphasis is on detection of oceanographic parameters and features. This assessment is based on interaction with representatives of federal operational MetOc, search and rescue, ice and oil spill monitoring centres and synthesis of unclassified literature as a means to obtain (i) an up-to-date presentation of Canada's maritime rapid environmental assessment requirements and (ii) MODIS R&D recommendations for DRDC Ottawa. This information is used to develop a Canadian Forces strategy for MODIS product development, including identification of certain critical operational linkages. DRDC Ottawa's emerging RADARSAT fine-scale wind product is identified as a critical component of this strategy as is the need for a co-ordinated defence, search and rescue and environmental security operational MetOc data access and distribution system.

Résumé

La présente étude, entamée dans le cadre du projet Polar Epsilon en prévision de l'installation au Canada de systèmes de réception de signaux de satellite MODIS et RADARSAT, porte sur l'analyse de produits de météorologie et d'océanographie (MetOc) dérivés de données MODIS pour les opérations de défense, de recherche et de sauvetage et de protection de l'environnement. L'étude vise aussi à déterminer si la mise au point de produits fusionnant des données RADARSAT et MODIS permet d'obtenir des améliorations sur le plan opérationnel. Dans les deux cas, l'accent est mis sur la détection de caractéristiques et de paramètres océanographiques. La méthode appliquée est basée principalement sur l'interaction avec des représentants des centres opérationnels fédéraux suivants : centres MetOc, centres de recherche et de sauvetage, centres de surveillance des déversements de pétrole et centres de surveillance des glaces. Elle est aussi basée sur la synthèse de documentation non classifiée afin d'obtenir : i) une présentation à jour des exigences d'une évaluation rapide de l'environnement (REA) maritime au Canada; et ii) un profil de produits MetOc possibles. Ces renseignements sont ensuite utilisés afin d'élaborer une stratégie, destinée aux Forces canadiennes, pour la mise au point et le déploiement opérationnel de produits MODIS, et pour l'identification de certains liens opérationnels essentiels. Le produit RADARSAT à petite échelle sur les vents de RDDC Ottawa est identifié comme un élément essentiel de cette stratégie, tout comme le besoin d'un système opérationnel coordonné d'accès aux données MetOc et de distribution de celles-ci, pour les opérations de défense, de recherche et de sauvetage et de protection de l'environnement.

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Executive summary

Polar Epsilon MODIS and fused MODIS / RADARSAT MetOc products for national defence and domestic security

Vachon, P.W., Whitehouse, B.G., Renaud, W.M., De Abreu, R. and Billard, D.

DRDC Ottawa TM 2006-067; Defence R&D Canada – Ottawa; March 2006.

Introduction

The state of the ocean influences the performance of naval sensors, weapons, vessels and personnel and as result, military operations that monitor the behaviour of the ocean have advantage over those that do not. This also applies to domestic security-related operations including search and rescue, ice and oil spill monitoring, and detecting harmful biological substances. To further Canada's ability to monitor the state of the ocean for purposes pertaining to national defence and domestic security, the Canadian Space Agency initiated a Government Related Initiatives Project with DRDC Ottawa that focuses on marine applications of the MODIS and RADARSAT satellite sensors. This Technical Memorandum presents findings to date.

Results

The identified MODIS and fused MODIS/RADARSAT research and development strategy for DRDC Ottawa focuses on Canadian Forces operations (see table on next page) by expanding existing MetOc Halifax operational oceanic products into littoral waters. It includes usage of the MODIS ocean colour channels but largely involves the MODIS true colour, atmospheric and thermal IR channels. The strategy recognizes the finer spatial and temporal scales expected in littoral waters as well as littoral features not normally associated with existing oceanic products. Fusing MODIS and RADARSAT data may result in improved temporal and spatial resolution of littoral fronts, eddies, upwelling zones and freshwater plumes, but this has yet to be demonstrated. DRDC Ottawa's emerging RADARSAT fine-scale wind product is identified as a critical requirement for all maritime applications of RADARSAT.

There is an immediate need for a revised Canadian Forces strategy for MetOc applications of spaceborne multispectral sensors. The revised strategy would consider additional spaceborne sensors and recent developments within relevant American programs.

In addition to fulfilling requirements pertaining to military operations, the Polar Epsilon project will result in the Canadian Forces possessing MODIS data required by environmental security operations conducted by Environment Canada and Fisheries and Oceans Canada.

The key to successful fulfillment of these civilian and military requirements is access to the Earth-observation data in operational time frames and formats and fusion with other information. Unfortunately, Canada's operational oceanographic capabilities are emerging as a series of silos rather than as a cohesive federal infrastructure, thereby challenging successful implementation.

This is Canada's greatest impediment to expanding operational use of satellite sensors in the maritime environment. It is not a lack of detection capability or potential application.

Littoral Features Detected By MODIS in Canadian Waters	Also Detected By RADARSAT	Relevant Military Operations
Fog	No	surface navigation, search & rescue, surveillance with visible sensors
Aircraft contrails	No	beyond the scope of this report
Water temperature	No	all littoral naval operations
Turbidity / blooms	No	ASW, MCM, submarine and special operations
Fronts & eddies	Possibly	ASW, MCM, submarine operations, navigation
Freshwater plumes	Possibly	ASW, MCM, submarine operations
Upwelling zones	Possibly	ASW, MCM, submarine operations
Internal waves	Yes	ASW, MCM, submarine operations
Sea ice	Yes	ASW, navigation, search & rescue
Slicks (possibly)	Yes	surveillance

Littoral features detected by MODIS in Canadian temperate waters (ASW is antisubmarine warfare; MCM is mine counter measures).

Significance

This investigation identifies potential MODIS MetOc products, the Canadian Forces operations that will benefit from them and an inter-departmental approach to data access and distribution.

Future plans

These results are being considered by DRDC Ottawa, the Canadian Space Agency and maritime operations pertaining to National Defence, Environment Canada and the Canadian Coast Guard.

Sommaire

Polar Epsilon MODIS and fused MODIS / RADARSAT MetOc products for national defence and domestic security

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Introduction ou contexte

L'état de la mer influe sur le rendement des armes et des capteurs navals, des navires et du personnel à bord; par conséquent, les opérations militaires qui comportent un système de surveillance du comportement de la mer ont un avantage sur celles qui n'en ont pas. Il en va de même pour les activités civiles, y compris la recherche et le sauvetage et diverses activités de protection de l'environnement, p. ex. la surveillance des déversements de pétrole et la surveillance des glaces et la détection de substances biologiques nocives. Pour accroître la capacité du Canada à surveiller l'état de la mer dans l'intérêt de la défense nationale et de la sécurité civile, l'Agence spatiale canadienne a mis sur pied un projet PICG (Programme des initiatives connexes du gouvernement) de concert avec RDDC Ottawa. Ce projet porte principalement sur les applications maritimes des capteurs satelliportés MODIS et RADARSAT. Le présent document technique décrit les résultats obtenus à ce jour.

Résultats

La stratégie de recherche et de développement de RDDC Ottawa sur les données MODIS et sur la fusion de données MODIS/RADARSAT met l'accent sur les opérations des Forces canadiennes (voir le tableau qui suit) en étendant les capacités des produits océanographiques opérationnels de MetOc Halifax jusque dans les eaux littorales. La stratégie fait appel aux canaux MODIS infrarouges thermiques, atmosphériques et de vraie couleur. De plus, la stratégie permet de traiter les plus petites échelles spatiales et temporelles appropriées pour les eaux littorales, ainsi que les caractéristiques littorales qui ne sont pas normalement associées avec les produits océanographiques existants. Le fait de fusionner les données MODIS et RADARSAT pourrait améliorer la résolution temporelle et spatiale obtenue pour les fronts, les tourbillons, les zones de remontée des eaux et les panaches d'eau douce, en milieu littoral, mais il reste encore à le prouver. On considère que le nouveau produit RADARSAT à petite échelle sur les vents de RDDC Ottawa est un élément essentiel pour toutes les applications maritimes de RADARSAT.

Il existe, au sein des Forces canadiennes, un besoin immédiat d'une stratégie révisée relativement aux applications MetOc des capteurs multispectraux à bord d'engins spatiaux. La stratégie révisée tiendrait compte i) des capteurs exploités par des pays autres que les États-Unis, ii) du besoin de fusionner des données infrarouges thermiques et multispectrales dans des cadres temporels opérationnels, et iii) de l'évolution récente des programmes américains pertinents.

En plus de combler des besoins relatifs aux opérations militaires, le projet Polar Epsilon permettra aux Forces canadiennes d'obtenir les données MODIS requises par les opérations de protection de l'environnement effectuées par Environnement Canada et par Pêches et Océans Canada.

L'élément essentiel qui permettrait de combler ces besoins d'ordre civil et militaire est l'accès aux données d'observation de la Terre dans des formats et des cadres temporels opérationnels, et leur fusion avec d'autres données pertinentes. Malheureusement, les nouvelles capacités océanographiques opérationnelles du Canada sont caractérisées par une structure de hiérarchie verticale plutôt que par une structure fédérale cohérente, ce qui complique la mise en œuvre. Il s'agit là du principal obstacle qui nuit à l'extension de l'utilisation opérationnelle au Canada des capteurs satelliportés dans un environnement maritime. Le problème n'est donc pas lié à un manque de capacités de détection ou d'applications possibles.

Caractéristiques du littoral détectées par MODIS dans les eaux canadiennes	Aussi détectées par RADARSAT	Opérations militaires pertinentes
Brouillard	Non	Navigation de surface, recherche et sauvetage, surveillance par capteur (visible)
Traînées de condensation des avions	Non	s.o.
Température de l'eau	Non	Toutes les opérations navales dans le littoral
Turbidité / fleurs d'eau	Non	GASM, LCM, opérations sous-marines et opérations spéciales
Fronts et tourbillons	Probablement	GASM, LCM, opérations sous-marines, navigation
Panaches d'eau douce	Probablement	GASM, LCM, opérations sous-marines
Zones de remontée des eaux	Probablement	GASM, LCM, opérations sous-marines
Ondes internes	Oui	GASM, LCM, opérations sous-marines
Glace marine	Oui	navigation, recherche et sauvetage

Caractéristiques du littoral détectées par MODIS dans les eaux canadiennes tempérées (GASM signifie « guerre anti-sous-marine », LCM signifie « lutte contre les mines »).

Importance

La présente étude a permis d’identifier des produits MetOc MODIS potentiels, les opérations des Forces canadiennes qui pourraient en profiter, ainsi qu’une approche interministérielle pour l’accès aux données et leur distribution.

Perspectives

Les résultats obtenus sont actuellement examinés par RDDC Ottawa et par l’Agence spatiale canadienne. Ils sont également examinés en rapport avec des opérations maritimes effectuées par la Défense nationale, par Environnement Canada et par la Garde côtière canadienne.

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1. Introduction

The state of the ocean influences the performance of naval sensors, weapons, vessels and personnel and as result, defence and security operations that monitor the behaviour of the ocean have advantage over those that do not.

In the mid 1980s, the U.S. Navy shifted its meteorology and oceanography (MetOc) focus from open ocean to littoral waters. This initiated a renaissance in coastal monitoring and surveillance technologies and gave rise to the subject of rapid environmental assessment (REA). By definition, a REA provides deployed forces with environmental information in littoral waters in tactical time frames [1]. The word *rapid* refers to the time available to respond to a request for information.

Note the focus on littoral waters. In the civilian community this refers to the intertidal zone. In the military it is ill-defined but loosely corresponds to marine waters in which the seafloor influences the performance of acoustic sensors – in essence – continental shelf waters. Throughout this document we use the military definition.

Initially, NATO's REA program focussed on antisubmarine, mine and amphibious warfare, but it subsequently evolved to address the broader needs of expeditionary warfare and homeland security. Thus, in addition to international operations relating to Canada's participation in NATO and the United Nations, relevant domestic federal operations include maritime surveillance, search and rescue and disaster monitoring and response. The term *maritime surveillance* refers to ship detection and monitoring in support of fisheries, sovereignty, immigration and drug enforcement. Disaster response includes natural and human-induced disasters, such as storm surge, outbreaks of harmful algae and oil spills.

In addition to the Department of National Defence, these operations involve Environment Canada, Transport Canada and Fisheries and Oceans Canada, the latter of which includes the Canadian Coast Guard. The Royal Canadian Mounted Police are also involved, albeit indirectly.

Arguably, the environmental parameter that is most critical to these littoral operations is the surface wind vector, which refers to the speed and direction of the wind at or near the surface of the ocean. But depending upon the operation, one or more of the following oceanographic parameters and features may have priority: bathymetry, surface and subsurface temperature, salinity, density, currents, surface and internal waves, sea ice, bioluminescence, algal toxicity, turbidity, fronts, eddies, mammals, ambient noise and seafloor composition.

Numerous countries are able to forecast meteorological conditions in maritime environments, but only the United States, France and perhaps the United Kingdom have developed their MetOc skills to the point where they are starting to forecast the behaviour of the ocean itself, in addition to the atmosphere above it. No country, however, has mastered the subject of ocean forecasting.

The American and French lead in ocean forecasting can be traced to their capitalization of four areas of innovation that emerged throughout the 1990s: Earth-observing satellites, super computers, mathematical models of environmental processes and the Internet. Since the 1990s, web-based geospatial information technologies have been added to the equation. They enable operational application of distributed geo-referenced databases through popular web browsers.

In situ sensors are the most widely used and often most accurate type of environmental sensor, but Earth-observing satellite sensors provide the required synoptic view of both littoral and open ocean surface waters, on a global basis, and can be deployed covertly. These two types of sensors are interdependent. Satellite sensors, for example, require calibration and validation with *in situ* sensors to produce quantitative information.

Both the spatial and temporal variability of littoral environmental processes are such that most sampling techniques are prone to aliasing. Although probably never stated as such, the Department of National Defence Polar Epsilon project diminishes this fundamental issue by applying civilian satellite sensors to military operations [2]. By using Canada's RADARSAT synthetic aperture radar sensor and NASA's multispectral MODIS sensor to support maritime defence and civilian security operations, Polar Epsilon will provide synoptic views of littoral and oceanic waters, which will diminish temporal resolution issues.

A previous DRDC Ottawa study of MetOc aspects of project Polar Epsilon [2] concluded that certain maritime defence and security applications of MODIS have been overlooked and require definition, and that there is a need to further investigate whether inherent temporal and spectral limitations of RADARSAT and MODIS can be diminished by merging their products.

Certain potential MODIS products have been overlooked because it is not common to consider littoral applications of multispectral bands designed for land and atmospheric applications. Usually, such bands lack required sensitivity. The relevant MODIS bands, however, are four to five times more sensitive than those on Landsat ETM+ [3].

This document identifies MetOc parameters and features relevant to Canada's maritime defence, search and rescue and environmental security sectors. Specifically, it uses the civilian literature to identify littoral defence, search and rescue and security applications of MODIS and fused MODIS/RADARSAT products, and applies these findings to identify Polar Epsilon REA products for development and operational deployment. In so doing, it also identifies operational linkages that are viewed as being critical to successful deployment.

2. Required MetOc parameters and features

This section summarizes meteorology and oceanography (MetOc) parameters and features required by Canadian Forces operations, including search and rescue operations conducted jointly with the Canadian Coast Guard. It approaches the subject from two overlapping perspectives – established and emerging priorities. Established priorities include antisubmarine and mine warfare, search and rescue and submarine operations. Emerging operational priorities are expeditionary warfare and maritime surveillance. Environmental security is an emerging issue that could become a priority.

The ranking of these priorities is influenced by specific events and therefore is transient. The 2003 survey results presented in Figure 1, for example, are already out of date as at that time Canada had deployments in the Persian Gulf, which increased the priority of mine countermeasures (MCM). The heavy maritime surveillance emphasis in Figure 1 largely arose in the post 9/11 time frame. Present priorities reflect recent changes at the Chief of Defence Staff level and focus on domestic and expeditionary operations, the latter of which involves joint operations that encompass allied capabilities. As the priority of these operations is fluid, MetOc centres located in Halifax and Esquimalt require the means to address any of them on short order.

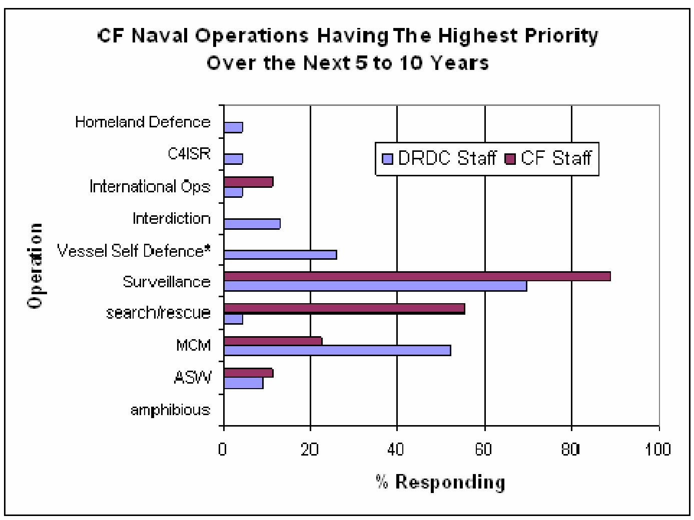

Figure 1: Operations having the highest priority over the next five to ten years, as perceived in 2003 by representatives of DRDC Atlantic and MetOc [4].

As a result of a strong Cold War era focus on antisubmarine warfare, almost all Canadian Forces MetOc personnel specialize in meteorology and acoustics, not in meteorology and oceanography. And although antisubmarine warfare does not have the operational priority it had during the Cold War, from a training perspective this focus has not changed. In 2003, for example, only three to five of the Canadian Forces' 17 oceanography / underwater acoustics officers had specialized in oceanography in their post-graduate work. The remainder had specialized in acoustics. And presently, within MetOc Halifax there are 21 military personnel - 16 meteorological technicians, three sonar operators and two naval officers – one an oceanographer and the other an acoustician, with the oceanographer serving as a deployable oceanographer. To put this scenario in perspective, in 2003, the U.S. Navy had 430 oceanographers in uniform [5].

2.1 Established priorities

2.1.1 Submarine operations, antisubmarine and mine warfare

When an oceanographer is required to be on a ship, the deployment is fulfilled by the above referenced shore-based MetOc oceanographer. Both MetOc Halifax and Esquimalt have a deployable oceanographer, who on average spends six out of eighteen months at sea. They assist antisubmarine warfare operations by providing acoustic range predictions, which includes determination of water density, particularly with respect to water temperature. Their work also involves delineation of bulk water masses, fronts and eddies.

This oceanographic expertise is in demand during deployments where there is a submarine threat, otherwise, ship operations use environmental assessment products pertaining to sea state (i.e. significant wave height), sea ice, wind and other meteorological information, most of which is produced by shore-based Environment Canada staff at MetOc Halifax.

Oceanographic products produced by MetOc Halifax may include climatology data obtained from: the Allied Environmental Support System; the U.S. Navy's Modular Ocean Data Assimilation System; AVHRR satellite sensors; shipboard bathythermographs; and *in situ* sensors. MetOc Halifax uses these data to produce its biweekly ocean feature analysis, which delineates thermal fronts, eddies and bulk water masses.

Canada's recent purchase of Victoria-class submarines will increase requirements for REA products and skills originally developed in support of antisubmarine warfare. The submarines are intended to be used for various operations such as surveillance and sovereignty patrols.

Submarine operations support staff foresee their REA requirements as falling into two categories: (i) information pertaining to ocean acoustics and (ii) all other environmental information [5]. The acoustics category is of highest priority and its MetOc requirements are similar to those for antisubmarine warfare. For both operations, however, requirements in littoral waters are only partially fulfilled through existing MetOc products which were largely designed for Cold War era antisubmarine warfare operations in blue (i.e. oceanic) waters.

Littoral operations require environmental products more frequently than biweekly and often at higher spatial resolutions. Furthermore, an oceanographic parameter required to determine acoustic range is water density, which in oceanic waters of interest to antisubmarine warfare is largely a matter of water temperature. In near-shore littoral waters, however, salinity can also have a profound effect on water density.

In addition, in littoral operations the seafloor influences the performance of acoustic sensors, whether they are being used in support of antisubmarine warfare or submarine operations. Bathymetry is an issue in littoral waters and the ambient noise issue differs significantly with factors such as the presence of mammals (e.g. whales), coastal shipping operations and relatively fine-scale near-shore wind processes influencing the surface noise parameter.

MetOc Halifax recognizes these littoral requirements and has either initiated or is otherwise participating in research and development projects designed to fulfill them. It is, for example, engaged in a cooperative project with DRDC Atlantic's antisubmarine warfare unit that aims to address issues pertaining to seafloor characteristics and the location of marine mammals. DRDC Atlantic has also stated that internal waves are of potential relevance to antisubmarine warfare.

Another profound oceanographic limitation within Canada is that although the country has world-class meteorological forecasting capabilities, it lacks an operational ocean forecasting (i.e. modelling) capability other than regional demonstration systems operated by research staff. Environment Canada, Fisheries and Oceans Canada and the Department of National Defence are working cooperatively with various universities to address this issue. Environment Canada and Fisheries and Oceans Canada have implemented parameter-specific coastal forecasting systems, including coastal tide, storm surge and wave forecasting models.

The two highest priority REA requirements within the second submarine category (i.e. "all other environmental information") are (i) surface and subsurface currents and (ii) turbidity. Both are required in near-real time, but for different reasons. Water currents are required by all sea-going vessels for navigation purposes. Turbidity pertains to vessel and mine detection and diver operations and therefore is also required for antisubmarine and amphibious warfare and MCM.

Operational water current and turbidity products are not provided by existing MetOc operations although relevant R&D initiatives are in progress. Again, the mismatch between existing capabilities and emerging requirements is rooted in environmental differences between Cold War era oceanic waters and the present-day focus on littoral waters. Turbidity, for example, is not a significant issue in oceanic waters.

Another secondary REA requirement is assessment of bioluminescence. Currently, no country has an operational bioluminescence product *per se*. It is required both for antisubmarine warfare and submarine operations to detect or avoid detection by airborne sensors.

Amphibious warfare can be a significant component of expeditionary warfare. As a result, submarine operations staff indicate that they foresee increasing interest in environmental assessment of the near-shore. Of foremost interest in this zone is water density, as it is critical to calculating buoyancy parameters. Amphibious operations also require knowledge of beach conditions, near-shore bathymetry, turbidity, sea state and currents. However, beach analyses (e.g. composition, bearing strength of material, delineation of vegetation, roads, etc) and bathymetric mapping are not the responsibility of MetOc operations.

Most of NATO's mine warfare specific REA products are similar to those identified above for antisubmarine warfare and submarine operations. They are outlined in NATO EXTAC 777 and their relevance to Canadian Forces operations are outlined in TACNOTE 1520.

2.1.2 Search and rescue

The Joint Rescue Coordination Centre (JRCC) Halifax is a joint Canadian Forces/Canadian Coast Guard facility. Its mandate is to conduct search and rescue operations off the east coast of Canada within the geographic area shown in Figure 2. Although the facility is commanded by the military and housed within Maritime Forces Atlantic Headquarters, its environmental trajectory analysis infrastructure is run by the Canadian Coast Guard, not MetOc Halifax.

JRCC Maritime REA requirements pertain to its mandate to locate ships, boats, life rafts and people. The information is required in surface waters only, to a depth of a few metres, and in most cases operations occur within littoral waters. Requirements, in order of priority, are (1) synoptic surface currents, (2) wind and (3) a tertiary group comprised of sea state (wave height), sea-surface temperature**,** fog (i.e. visibility) and sea ice.

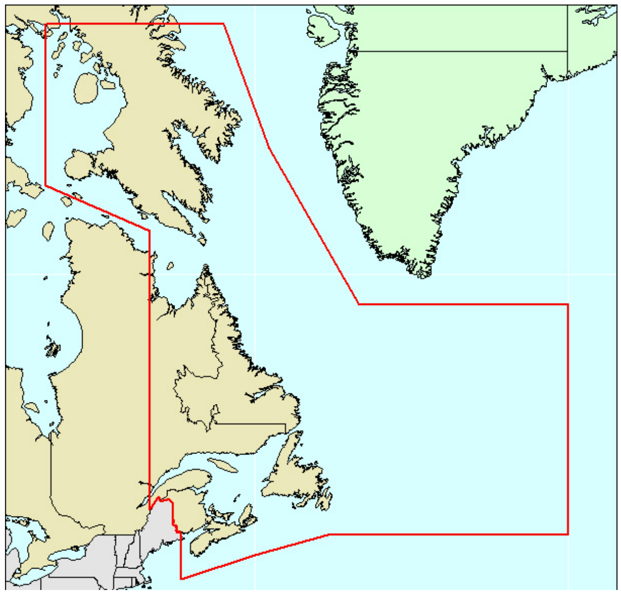

Figure 2: Geographic jurisdiction for JRCC – Maritimes Region

JRCC refers to synoptic surface current vectors as the *total water current*. They are required for trajectory analyses of submerged or low-wind profile targets. Canada does not have an operational synoptic surface current product and therefore JRCC relies on historical databases of surface current information, some going back to North Atlantic pilot charts, but may augment this information with near-real time surface drift data obtained by air deployable surface drifting buoys called self locating datum marker buoys and by oceanic mesoscale information provided through the French Mercator program. At times, the historical pilot charts can be widely inaccurate. In which case, surface current information obtained by the air deployed drifters can be crucial. The drifters, however, are recognized as being point source sensors. Therefore, JRCC has submitted proposals to the search and rescue New Initiatives Fund to acquire and install Codar SeaSonde® radars to obtain operational synoptic surface currents.

As JRCC does not have actual synoptic surface current data its search and rescue deployments are based largely on a trajectory model called CANSARP. It is constrained by surface wind fields provided by Environment Canada and NOAA, and by the aforementioned historical and buoy data. CANSARP was developed by Seaconsult Marine Research Ltd and is maintained through the Canadian Coast Guard College in Sydney, Nova Scotia. Surface wind vectors are required in their own right for analyses of leeway (i.e. direct influence of wind on exposed-target drift).

Although a host of new environmental information products have become available in recent years, they are not used operationally at JRCC as they cannot automatically incorporate these new products into CANSARP, which has become an operational bottleneck. CANSARP has not changed significantly since 2000 when the Coast Guard incorporated information from self locating datum marker buoys.

There are no specific problems with existing sources of wind information, but there is curiosity within JRCC with respect to a RADARSAT high-resolution wind product, assuming it is provided in operational formats and time frames and at no incremental cost to search and rescue operations. Similarly, there is interest in RADARSAT-derived ocean feature products such as current shear, fronts and eddies. This type of information could lead to incremental improvement in the Centre's ability to estimate target drift.

Sea-surface temperature is used to estimate survival time in frigid waters. JRCC obtains sea-surface temperature information every Tuesday and Friday from MetOc Halifax. This information is at times one to four days old, which limits its application to search and rescue in littoral waters. As a result, at times JRCC accesses operational sea-surface temperature information provided by American universities via the Internet, but it is not provided in near-real time.

Wave height is required for determination of sensor range (i.e. ability to search with human eye) and sea ice charts are required for navigation purposes. JRCC uses wave and ice products developed by Environment Canada, Fisheries and Oceans Canada and NOAA.

JRCC requires a fog product that delineates the location of fog banks. Presently, Canada has no such product that can be trusted enough to incorporate into operational planning strategies.

There is no operational value in plankton bloom (i.e. chlorophyll_a), bioluminescence, turbidity, internal wave, or seafloor environmental information products within JRCC as such information is not critical to search and rescue. Nor does JRCC envisage operational value in satellite-derived bathymetry products. The Centre operates largely within domestic waters where hydrographic charts provided by the Canadian Hydrographic Service meets their needs.

2.2 Emerging priorities

2.2.1 Maritime surveillance

Maritime surveillance is an existing priority [6] but has emerging issues from a MetOc perspective [2, 5]. The key environmental parameters when operating ship detection sensors are wind, waves and currents, with wind having the greatest influence on RADARSAT's ship detection capabilities. As summarized above, these parameters are also required for several other operations. But the RADARSAT ship detection technique has a twist with respect to wind data as they are required at much finer spatial resolution, in certain cases an order of magnitude finer than provided by standard public wind forecasts. In addition, the wind information must correspond in time with the satellite overpass, or close to it [2].

2.2.2 Expeditionary warfare

Canada's emerging interest in expeditionary warfare reflects priorities established by the Department of National Defence and NATO, as depicted in Table 1. This table is based on information provided by Dr. Peter Ranelli, NATO Undersea Research Centre, La Spezia, Italy.

Table 1: The evolution of tactical military oceanography within NATO. Based on information provided by P. Ranelli, NURC, Italy. Reproduced with permission.

TIME FRAME	1980s	1995	2005
Military Era	cold war	regional crisis	expeditionary warfare
Domain	deep water	unknown coastal waters	sea, air, land
METOC Focus	oceanographic & acoustic databases	modelling & GIS	modelling, covert sampling data management & fusion
Response Time	weeks to days	days	days to minutes

Expeditionary operations may involve any or all of the naval activities addressed in this report, thus encompassing all of the environmental parameters and features identified within. There are, however, important differences between operations conducted in domestic and foreign waters.

Military sensors deployed in low latitude tropical and subtropical environments may differ in performance and therefore utility when deployed in Canada's mid-to-high latitude temperate and Arctic waters. Multispectral sensors, for example, may provide insight into littoral bathymetry in relatively clear tropical and subtropical waters, but not in opaque temperate waters. And multispectral and thermal IR sensors are impaired or rendered useless by cloud cover, which is much more prevalent in temperate than tropical environments.

2.2.3 Environmental security

The phrase environmental security is not common. It refers to both naturally occurring and human-induced (i.e. anthropogenic) environmental events that can influence the safety or security of maritime communities, such as harmful algae blooms, oil spills, storm surge, etc.

Related operations are usually led by departments other than National Defence. However, upgrades underway within the Maritime Security Operations Centres, which are under the jurisdiction of the Department of National Defence, will result in a cooperative approach to environmental security within domestic waters. Specifically, the MODIS and RADARSAT satellite reception facilities being installed at Maritime Atlantic and Pacific Headquarters as components of the Polar Epsilon project will provide the Canadian Forces with sensors that can be applied to environmental security operations. MODIS, for example, can detect algae blooms, which may be harmful, and RADARSAT is already used operationally to detect oil slicks.

3. MODIS

The Polar Epsilon project will provide MetOc Halifax and Esquimalt with direct reception of environmental data from the MODIS sensor on NASA's Terra and Aqua satellites.

MODIS is a wide-swath multispectral sensor operating in the visible and infrared bands of the electromagnetic spectrum. Due to sensor design and calibration issues it exhibits striping over water. Although distracting, the striping does not overly depreciate qualitative use of the imagery. MODIS' swath width is 2330 km across track. It has 36 bands with spatial resolutions varying between 250 m and 1000 m at nadir: 250 m at nadir for bands 1–2, 500 m for bands 3–7 and 1000 m for bands 8–36. NASA's standard products from these bands are listed in Table 2.

MODIS/Terra was launched into a polar-orbiting, sun-synchronous orbit on 18 December 1999 with a five year design life and started collecting MODIS data on 24 February 2000. It crosses the equator descending at 10:30 am local time. The ocean colour channels (8-16) of MODIS/Terra are no longer being processed by NASA due to calibration issues, but the other bands remain functional. This means it is still possible to obtain products designed for atmosphere, land and cryosphere applications for MODIS/Terra but not ocean products.

Aqua was launched on 4 May 2002 and started collecting MODIS data on 24 June 2002. It crosses the equator ascending at 1:30 pm local and is fully functional. It provides ocean products at 1 km resolution every two days for a given location on Earth. In combination with MODIS/Terra, it provides land, atmosphere and cryosphere products at 250–1000 m resolution with a daily effective revisit time.

MODIS has 36 bands, but the 250–500 m bands 1–7 are of primary interest to this project, particularly the true colour product produced from bands 1, 3 and 4. Although these bands are four to five times more sensitive than those on Landsat's ETM+ sensor [3] they are optimized for the high reflectivities used in terrestrial and cloud applications, not the low reflectivities encountered in open ocean applications. As a result, in littoral waters they detect features present in sun glint and the atmosphere, but unlike Landsat-type sensors they also detect elevated reflectances resulting from suspended sediments, coloured dissolved organic matter and relatively high phytoplankton concentrations. In open ocean waters they mostly detect features present in sun glint and the atmosphere.

This focus on the higher resolution 250–500 m MODIS bands is based on results of a preliminary investigation which demonstrated that various coastal features of interest to littoral operations are observed within these bands [2]. In addition, at 1 km spatial resolution, the MODIS "ocean" products generated from bands 8–16 may have insufficient spatial resolution to resolve littoral features [7, 8].

The remainder of this section profiles MetOc parameters and features that are observed by MODIS and are required by Canadian Forces or Joint Rescue Coordination Centre (JRCC) operations. It is noted that primarily this involves MODIS bands 1, 3 and 4, but other MODIS bands are also critical to these applications. Ice applications of MODIS are covered collectively with RADARSAT ice applications in Section 4.5 and therefore are not considered further within this section.

Table 2: Standard MODIS/Aqua products. "MYD" is the NASA identification for Aqua, "MOD" is used for Terra (not shown). All ocean products are at 1 km resolution

SUBJECT	PRODUCT ID	PRODUCT
Calibration	MYD 01	Level-1A Radiance Counts
	MYD 02	Level-1B Calibrated Geolocated Radiances
	MYD 03	Geolocation Data Set
Atmosphere	MYD 04	Aerosol Product
	MYD 05	Water Vapour
	MYD 06	Cloud Product
	MYD 07	Atmospheric Profiles
	MYD 08	Gridded Atmospheric Product
	MYD 35	Cloud Mask
Land	MYD 09	Surface Reflectance
	MYD 11	Land Surface Temperature & Emissivity
	MYD 12	Land Cover/Change
	MYD 13	Gridded Vegetation Indices
	MYD 14	Thermal Anomalies, Fires & Biomass Burning
	MYD 15	Leaf Area Index & FPAR
	MYD 16	Evapotranspiration
	MYD 17	Net Photosynthesis and Primary Productivity
	MYD 43	Surface Reflectance
	MYD 44	Vegetation Cover Conversion
Cryosphere	MYD 10	Snow Cover
	MYD 29	Sea Ice Cover
Ocean	MYD 18	Normalized Water-leaving Radiance
	MYD 19	Pigment Concentration
	MYD 20	Chlorophyll Fluorescence
	MYD 21	Chlorophyll_a Pigment Concentration
	MYD 22	Photosynthetically Available Radiation (PAR)
	MYD 23	Suspended Solids Concentration
	MYD 24	Organic Matter Concentration
	MYD 25	Coccolith Concentration
	MYD 26	Ocean Water Attenuation Coefficient
	MYD 27	Ocean Primary Productivity
	MYD 28	Sea Surface Temperature
	MYD 31	Phycoerythrin Concentration
	MYD 36	Total Absorption Coefficient
	MYD 37	Ocean Aerosol Properties
	MYD 39	Clear Water Epsilon

3.1 Atmospheric features

Features outlined in this section are present in the atmosphere above littoral waters, not in the water column itself. Cloud monitoring is beyond the scope of this report, but the Joint Rescue Coordination Centre has a need for an operational fog product, and ship stack effluents relate to the *raison d'être* of the Polar Epsilon project – ship detection.

3.1.1 Fog

Poor visibility is a defence-and-security-wide issue. It affects vessel navigation, deployment of search and rescue assets and the federal government's ability to conduct visual surveillance operations. The issue is relevant to both domestic and foreign operations, particularly with respect to fog detection in littoral waters. The frequency of fog over the Grand Banks of Newfoundland, for example, is the highest recorded – world-wide – at approximately 30% for June–August and 10–15% for September–November [9].

Sea fog (i.e. fog over marine waters) forms as a result of humid air being brought to its dew point, often by contact with cold sea water, but it also forms in relatively warm sea conditions. It may persist for hours to days and often has diurnal and seasonal characteristics. Fog forecasting is still problematic and therefore meteorological agencies cannot forecast sea fog consistently [9, 10, 11].

This limitation increases the value of direct observation by wide-swath satellite sensors that detect fog at required resolutions. Ellrod [12] and Lee et al. [10] recognize the superiority of satellite sensors operating in visible bands for daytime fog detection, but due to their unavailability at night advocate application of the GOES nighttime fog product, which is based on the 3.9 um (GOES band 2) shortwave and 10.7 um (GOES band 4) longwave infrared channels. This technique is used by the U.S. National Weather Service and is founded on fog applications of the infrared channels on NOAA's polar-orbiting AVHRR sensors.

Figure 3 is a MODIS/Aqua image showing fog off the southwest tip of Nova Scotia in August 2005. Fog is also evident in the Terra image acquired on the same day (Figure 4) and changes in fog patterns between the two images, which were acquired hours apart, are evident. As of November 2005, NASA's visible Earth website includes 221 examples of fog observed by MODIS (http://visibleearth.nasa.gov and search under "fog and MODIS").

In addition to the daytime bands used to produce Figures 3 and 4, MODIS has short and long-wave infrared bands (20–23 and 31–32). MODIS' visible bands are of higher spatial resolution than GOES' (250 m versus 1,000 m) and its infrared bands are at 1 km resolution compared with GOES' 4 km (5–6 km at mid-latitudes). On the other hand, GOES is a geostationary satellite and therefore has outstanding temporal resolution (30 minutes or less) and field of view. In combination, the two MODIS sensors have an effective revisit time of approximately 24 hours.

Fog can be distinguished from higher cloud formations in satellite imagery. New methods are emerging for supervised MODIS cloud classifications [13] and unlike higher cloud formations, fog does not cast a shadow on the surface of the ocean when viewed by spaceborne multispectral sensors. NASA includes a cloud shadow indicator in its cloud mask product. Coastal fog also often exhibits a sharp boundary at the water–land interface. Lee et al. [10] capitalize on this observed boundary effect when applying their shortwave infrared detection techniques to fog. The shadowing and land boundary effects are evident in the Southwest Nova region of Figure 3.

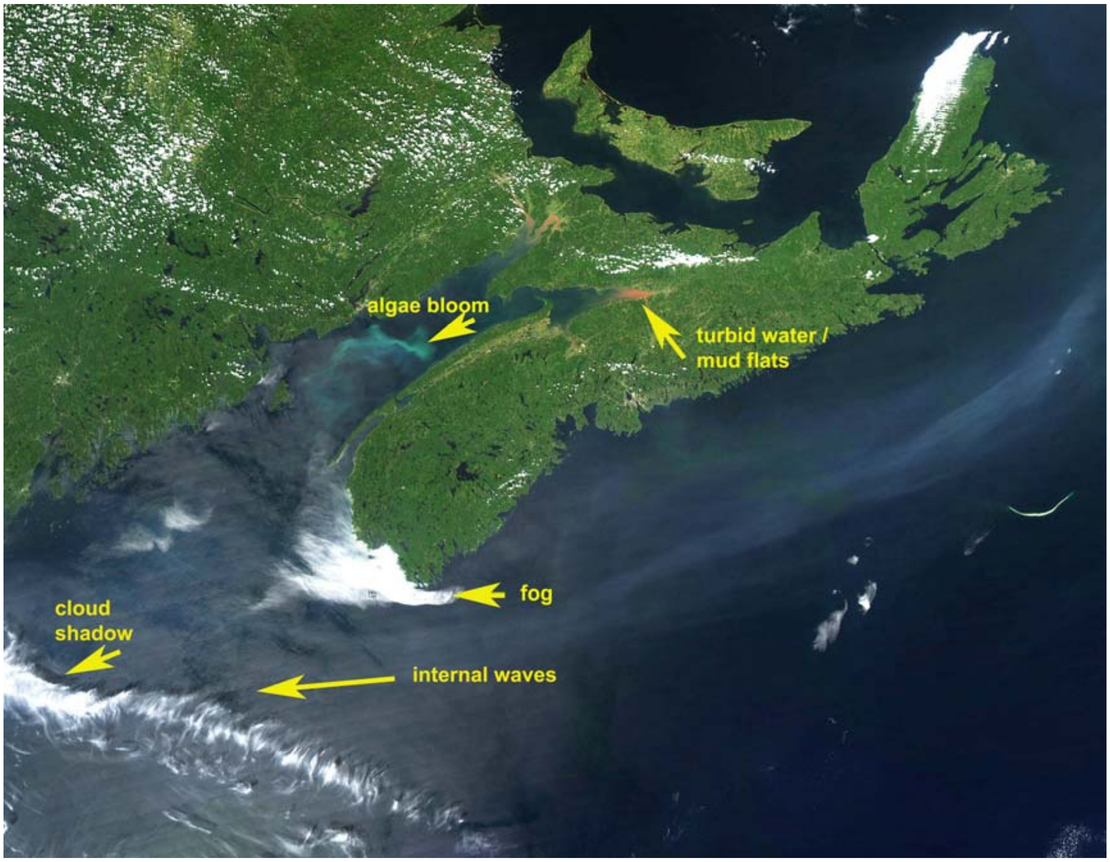

Figure 3: MODIS/Aqua true colour image for 8 August 2005. A large algae bloom is evident in the Bay of Fundy and internal waves are present in sun glint off Southwest Nova. Fog is seen off Yarmouth. Cloud shadows are evident from higher formation clouds. Turbidity features / exposed mud flats are evident in Minas Basin (reddish areas). Image courtesy of NASA.

3.1.2 Aircraft contrails and ship stack effluents

Jet aircraft contrails are a common site and can be seen in numerous MODIS images, however, MODIS has limited practical application to this subject [14], which is also beyond the scope of MetOc and JRCC operations.

A related but Polar-Epsilon-relevant subject is airborne effluents produced by ship engine exhaust stacks. These trails have been detected in daytime by comparing the 3.7 um channel with the 0.63 um and 11 um channels on NOAA's AVHRR sensor, which has a 1.1 km resolution, or by using composite channels of this sensor. These wavelengths are within MODIS Bands 20 (3.66–3.84 um), 1 (0.62–0.67 um) and 31 (10.78–11.28 um) respectively. Note that these bands include but also extend beyond the true colour bands. The ship tracks, however, are found infrequently in the images as they only occur under certain meteorological conditions [15, 16, 17].

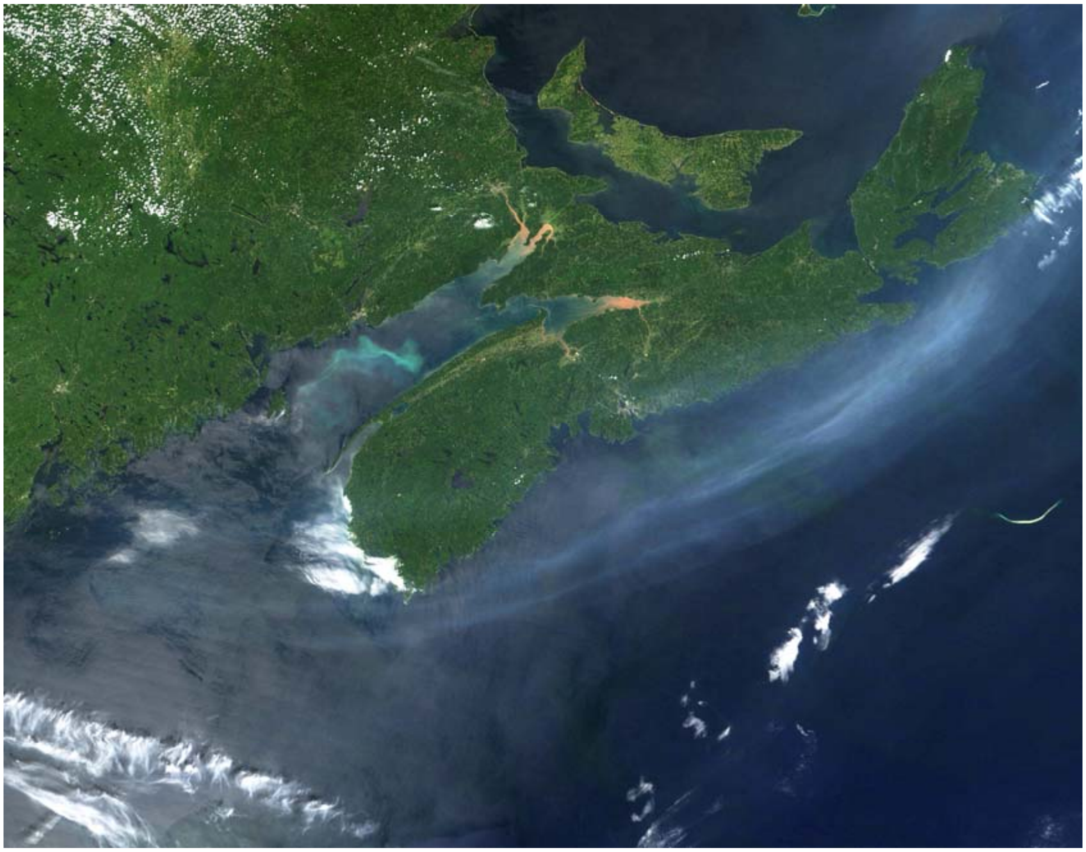

Figure 4: The MODIS/Terra image corresponding to Figure 3, but acquired three hours before. Note changes in transient features during this time, such as fog, clouds and the effect of tides on Minas Basin features. Image courtesy of NASA.

3.2 Ocean features

Marine features profiled in this section occur within the littoral water column in relatively high concentrations. The latter is a crucial condition because MODIS true colour products are designed for land and atmospheric applications and therefore have limited sensitivity for detecting features within the marine water column.

3.2.1 Bioluminescence

The only published example of bioluminescence detected from space used the visible / near infrared nighttime band of the Operational Line Scanner (OLS) sensor onboard the U.S. military's Defence Military Satellite Program [18]. The OLS was designed to monitor clouds and has been used to detect light from land sources, such as fires. This capability reflects the facts that the OLS has a sensitivity that is approximately four orders of magnitude higher than conventional spaceborne multispectral sensors and it is designed to be used at night. MODIS bands 1–19 are not included in MODIS night data. Thus, the night data use bands 20–36, which are designed for lower sensitivity atmospheric applications.

MetOc's MODIS data reception capability will allow the centre to produce various marine phytoplankton biomass and photosynthetic activity products, but these are not the same as bioluminescence. Only certain phytoplankton species are bioluminescent and present multispectral remote sensing techniques (e.g. MODIS) cannot differentiate species. It has been suggested that such discrimination requires spectral resolutions of 2 to 3 nm and therefore awaits development of suitable hyperspectral techniques [19].

Phytoplankton photosynthetic activity, which is estimated by MODIS by measuring chlorophyll fluorescence at 683 nm, and biomass products also do not include marine bacteria or zooplankton, certain species of which are bioluminescent under certain conditions.

Bioluminescent bacteria may luminesce without external stimulation, thus bioluminescence does not in itself indicate the presence of a vessel. In addition, the accuracy of biomass products derived from spaceborne data diminish in regions where the colour of the water is influenced significantly by something other than phytoplankton (e.g. most littoral waters).

3.2.2 Water masses, turbidity, fronts, eddies

Coloured dissolved organic matter (CDOM) exhibits quasi-conservative behaviour (i.e. over short time periods its concentration only changes as a result of mixing with other water masses); and as a result, it can be used to a limited extent to trace water masses of terrestrial origin in littoral waters [3, 19, 20]. It is cautioned that significant riverine input is required because CDOM is prone to photo-oxidation and therefore ceases to be conservative when exposed to sunlight for prolonged periods. The time frame in which this conservative behaviour is valid is on the order of days to weeks [see 19 and references therein]. The CDOM-salinity relationship also varies with location, thus site-specific ground truthing is required for quantitative analyses [3]. Johnson et al. [21], for example, used CDOM to trace a riverine plume to more than 100 km from its source.

CDOM has been detected with spaceborne multispectral sensors using bands in the 410–445 nm range (i.e. violet to blue), including NASA's MODIS 443 nm Normalized Water Leaving Radiance product [22]. Thus, to date it has not been determined using MODIS' true colour product, which is based on bands 1, 3 and 4, or band 3 (blue wavelengths 459–479 nm) alone, but with the sensor's ocean colour bands 8 and 9. This means that with MODIS, CDOM has been detected at a spatial resolution of 1 km but only with MODIS/Aqua as NASA is not processing these bands for MODIS/Terra. This results in a revisit time of approximately two days compared with the approximately daily revisit time for MODIS true colour products.

MODIS can detect littoral turbidity features at a spatial resolution of 250 m on a daily basis. Figure 5 is an example of this capability in Arctic waters. Kahru et al. [23] use a 250 m resolution MODIS turbidity product which is based on the difference between reflectance in MODIS bands 1 and 2 to investigate the amount of particulate material in the water column. Miller and McKee [8] use the same bands to investigate suspended particulate material except they simply process MODIS band 1, which at 620–670 nm is within the red band, and subsequently apply a cloud mask using band 2 data. Hu et al. [3] tried various atmospheric correction routines and concluded they yielded no significant difference due to sensor artifacts and calibration issues. Like Kahru et al. [23] and Miller and McKee [8] they found that ground truthing with *in situ* sensors provided significant correlations and concluded suitable ground truthing can result in synoptic maps of water quality. They raised the possibility of using these 250–500 m bands to sharpen 1 km ocean products produced by MODIS using techniques reported by Thomas et al. [24], but also cautioned that certain variations in open ocean chlorophyll as measured by MODIS may be due to sensor artifacts such as influences of polarization with viewing geometry. Light polarization increases with MODIS' viewing angle [3].

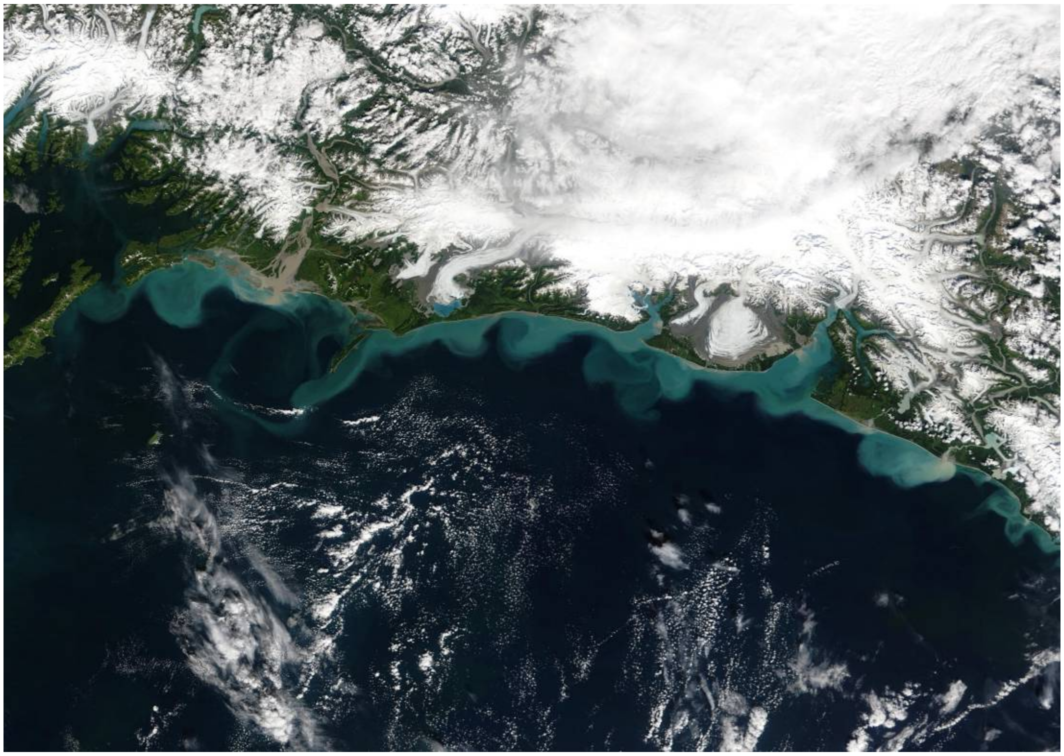

Figure 5: True colour 250 m resolution, MODIS/Terra image acquired 22 August 2003. Snowmelt and glacial runoff deposit sediments into the Copper River (left) which are subsequently dispersed into littoral waters of the Gulf of Alaska. Image courtesy of NASA.

In fact, nearshore turbidity plumes, fronts and eddies are routinely detected and delineated qualitatively by all polar-orbiting spaceborne multispectral sensors, even those designed primarily for land applications. This reflects the relatively high concentrations of such nearshore features. MODIS, however, is superior to its predecessors for this purpose due to its enhanced sensitivity [3, 25] and wide swath width.

A standard multipsectral product produced at 1 km resolution by NASA, which is designed to indicate turbidity (i.e. suspended particulate material) within both the littoral and open ocean water column is the diffuse attenuation coefficient K490. It was developed using Seawifs water-leaving radiances at 490 and 555 nm [26] to be an indicator of the penetration of blue-green light into the water column. As the MODIS/Terra ocean colour channels are no longer processed by NASA, this product is only available for MODIS/Aqua.

Although several spaceborne multispectral sensors are designed for ocean waters, MODIS is unique in that it also has channels designed to concurrently determine sea-surface temperature, which can also be used to delineate fronts and eddies in all waters at 1 km resolution. Obviously, the sea-surface temperature product detects fronts and eddies that have a thermal signature whereas the above referenced products detect influences on water colour, such as organic matter. Not all fronts and eddies have both a thermal and biological signature.

3.2.3 Harmful algae blooms

MetOc Halifax's MODIS reception facility will allow the Canadian Forces to produce marine phytoplankton biomass and fluorescence products, but multispectral sensors cannot differentiate phytoplankton species and therefore are not capable of differentiating harmful from benign species. However, spaceborne multispectral sensors have been used to study blooms in conjunction with *in situ* sampling techniques that can identify the nature of the bloom (i.e. whether it is harmful). These spaceborne sensors also perform sentry duty by detecting previously undetected blooms, thereby directing the location for *in situ* sampling (i.e. adaptive sampling).

Such techniques are less accurate in littoral than open ocean waters due to the presence of colouring substances other than phytoplankton. However, improved results, in terms of differentiating phytoplankton from other littoral features, have been obtained by using MODIS fluorescence data derived from 1 km resolution bands 13–15 instead of the more common satellite-derived chlorophyll products [25, 27]. It is noted that the MODIS follow-on sensor (i.e. VIIRS on NPOESS) will not be able to measure fluorescence.

Standard ocean colour products produced at 1 km resolution are sufficient to detect and delineate phytoplankton blooms in oceanic waters, but may have inadequate spatial resolution for detecting harmful algae blooms in nearshore coastal waters.

As harmful blooms often occur in high concentrations in nearshore waters, often they can be detected qualitatively in MODIS true colour and turbidity products produced at a spatial resolution of 250 m [23].

Figures 3 and 4 are outstanding examples of a littoral algae bloom detected by MODIS true colour products. Although not verified, it is suspected that the bloom detected in these images is or became a harmful bloom because the coast of Maine was impacted by an extensive harmful algae bloom in the same month (U. Maine, personal communication) and toxic dinoflagellate blooms exhibiting the same pattern in the same area are well documented [28].

Studies of relationships between riverine CDOM (coloured dissolved organic matter) and littoral ecosystems are also advancing techniques designed to forecast harmful algae blooms [20]. Thus, it is feasible that the MODIS ocean features bands 8–9 could be investigated as an indicator for potential toxic blooms in littoral waters having significant fluvial input, such as the Bay of Fundy, in situations where a 1 km resolution product is adequate. Detecting CDOM with MODIS is discussed in Section 3.2.2.

3.2.4 Bathymetry and seafloor features

The bathymetry and seafloor features applications of MODIS are considered together as both require a clear and shallow water column that has low light absorption characteristics [29, 30]. Such conditions are prevalent in near-shore tropical and subtropical waters but not Canadian domestic waters, although they may exist in certain near-shore Arctic waters that are not ice covered.

These bathymetric and seafloor composition applications are limited to a maximum depth of approximately 20 m in clear waters and are based on observation of colour, particularly in the blue-green region (approximately 400–600 nm) as red light is strongly absorbed by water [30]. As described by Robinson [29, pg 232], "As the water becomes deeper …. the reflected light, originally white from the shallowest water, becomes progressively greener, then bluer – eventually reaching dark blue to black when the depth is sufficient that all wavelengths of light are absorbed before they can be reflected from the seabed."

The clear water column requirement is critical as there is no easy means to separate water column and bottom effects in the returning signal. Advanced techniques focus on application of hyperspectral sensors rather than multispectral sensors such as Seawifs and MODIS [31]. The multispectral Seawifs sensor, for example, is considered to lack the spectral resolution required to characterize bottom type [30].

In combination these findings suggest the bathymetry and seafloor composition applications of MODIS are limited to amphibious-type operations in tropical and subtropical environments and perhaps certain Arctic environments. Thus, they are relevant to NATO and humanitarian missions such as Canada's recent hurricane Katrina relief mission to the Southeast United States and anti-terrorism missions to the Middle East.

Seafloor composition is not relevant to search and rescue operations and Canadian search and rescue centres fulfill their bathymetric requirements with standard hydrographic charts. In addition, airborne LIDAR techniques are emerging as the preferred high-resolution remote sensing approach to bathymetric mapping of nearshore environments where covert sampling is not required and the water column is not turbid [32].

3.2.5 Natural and anthropogenic slicks

A search of NASA's Visible Earth image database for MODIS found no evidence of MODIS images depicting surface slicks, natural or manmade, and spaceborne multispectral sensors are not common in oil spill response operations [33].

There is one report of an oil spill being detected by MODIS [34]. In this particular case, slicks were detected using bands 1 through 4 at 250–500 m resolution. A dedicated atmospheric correction was required to facilitate differentiation of the slicks from background reflectances, and the authors noted *a priori* knowledge of local biogeochemical and oil spill conditions facilitated identification.

They also allude to the interesting point that MODIS could improve oil spill detection by spaceborne synthetic aperture radar by differentiating slicks of biological origin. This results from the fact that natural surface films are usually associated with phytoplankton blooms, although other natural sources may contribute [35]. There is precedence in terms of Seawifs being used to differentiate slicks of biological origin in synthetic aperture radar investigations of upwelling zones [36], which can be confused with zones of spilled oil.

MODIS' sea-surface temperature product may also identify areas of relatively cold water, which can also lead to false detection [35].

In short, MODIS does not need to detect the oil slick itself to improve detection by RADARSAT.

3.3 Features in sun glint

Features summarized in this section are detected in sun glint on the surface of the ocean. Sun glint is the component of the sun's ocean surface reflectance that is received by the sensor. It only occurs when there is suitable angle between the sun and sensor, which varies with season, latitude and satellite orbital parameters.

3.3.1 Internal waves

The only MetOc-relevant feature that fits into this category is internal waves, which are nonlinear waves generated within the interior of the ocean. As summarized by Apel [37] and Jackson [38], they are common in stratified waters influenced by strong currents and irregular topography, such as shelf breaks and offshore banks. The currents are usually tidal. However, any substantive disturbance penetrating the pycnocline can cause internal waves.

Jackson [38] concludes there are several hundred literature references to internal waves in the Southwest Nova – New England region, thus there is no doubt as to their existence in Canadian waters; indeed, they are ubiquitous in nature world-wide.

Internal waves exist on time scales on the order of days in oceanic waters and a day or so in littoral waters. Although their internal amplitudes are on the order of metres to tens of metres, surficial spatial scales are on the order of a kilometre to few tens of kilometres. They are known to travel up to hundreds of kilometres from their source at speeds between 0.5 and 1.0 ms^{-1}. Jackson [38] provides an overview of the various theoretical models used to characterize internal waves.

From a defence and security perspective, internal waves may influence (i) the performance of acoustic sensors and (ii) submarine operations [MetOc Halifax, personal communication].

MetOc Halifax has expressed interest in the subject but does not have an operational internal wave product and is uncertain as to how they would incorporate such a product into operations.

Internal waves are not relevant to search and rescue operations.

There are thousands of observations of internal waves in the sun glint of MODIS imagery [38] and NASA includes a sun glint indicator in its MODIS MYD/MOD 35 cloud mask product.

Figure 6 is an approximate representation of the effects of season and latitude on sun glint. It catalogues 3400 observations of internal waves in sun glint of MODIS imagery and is provided courtesy of Christopher Jackson of Global Oceans Associates, USA, who advises "There is also a longitudinal constraint in that the sunglint area does not cover the whole MODIS swath width." Figure 6 suggests that observing features in sun glint with MODIS is feasible in Canadian mid-latitude waters in late spring and in summer but not during the six month period of October to March, even though they do occur in winter [38]. In tropical waters, where Canadian Forces have conducted NATO and humanitarian operations, the technique is feasible year round.

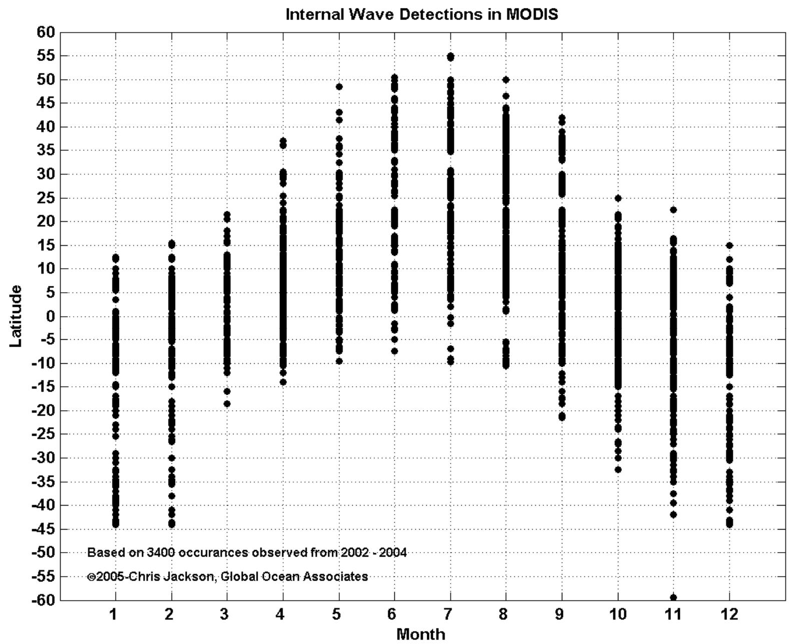

Figure 6: Internal waves identified in 3,400 MODIS images as a function of latitude and month. Courtesy of Christopher Jackson, Global Ocean Associates, USA.

With a spatial resolution of 250 m, MODIS true colour imagery will at times be at its spatial limit when attempting to detect certain aspects of internal waves [38], however, as this technique involves detection within sun glint by multispectral sensors, higher resolution commercial multispectral sensors operating at spatial resolutions of metres to tens of metres, such as IKONOS and SPOT, should also be able to detect such features in sun glint, albeit at very course temporal resolution and commercial prices. Apel et al. [39] were doing precisely this in the 1970s with Landsat-1. Even the human eye and photographs taken by astronauts onboard the international space station can see surface manifestations of internal waves in littoral waters.

It has been suggested that if the pycnocline (depth of maximum density gradient) is too deep, internal waves may not be seen in satellite imagery regardless of whether sun glint is present (Christopher Jackson, Global Ocean Associates, USA – personal communication).

4. RADARSAT

This project investigates the feasibility of enhancing the temporal resolution of MODIS products by also detecting the ocean feature with the RADARSAT synthetic aperture radar sensor. Thus, this section on RADARSAT is limited to features detected by both sensors.

RADARSAT-1 was launched in 1995. It has the potential of enhancing the MODIS program because its sensor is not restricted by clouds, the absence of light (i.e. nighttime) or the clarity of the water column, and does not require extensive atmospheric correction for quantitative analyses. For additional information on this satellite program visit http://www.space.gc.ca.

As the Polar Epsilon project will detect ships and oil slicks with RADARSAT at low to moderate wind speeds [2], environmental features that dominate the radar image at high wind speeds are beyond the scope of this report.

Relevant ocean features include internal waves, fronts, eddies, certain water mass boundaries, upwelling, slicks, bathymetry seafloor features and sea ice [38, 40, 41, 42]. With the exception of slicks, they are identified with synthetic aperture radar through detection of associated current shear, convergence or temperature gradient. Note that the technique does not sense the absolute current and that it is highly dependent on local wind conditions [43, 44]. The bathymetric and seafloor features components of the technique also require the presence of strong currents and shallow, well-mixed water columns. Thus, the feature can look different in images collected under different environmental conditions [43, 44]. The characteristics of the radar sensor itself, such as frequency, polarization and incidence angle, also influence detection. HH polarization (e.g. RADARSAT-1) provides stronger ocean feature signatures than VV. And as noted elsewhere [2], large quantities of imagery are required for operational application.

Collectively, these issues complicate advancement of the technique and therefore not surprisingly, with the exception of oil slicks, detection of the above listed ocean features by synthetic aperture radar does not enjoy wide, if indeed any, operational application presently.

4.1 Internal waves

Although internal waves are a subsurface phenomenon, internal wave detection by synthetic aperture radar is both well founded and documented [e.g. 37, 38, 45, 46]; to the extent that internal waves are considered by some [47] to be the most reliable empirical means by which to evaluate radar imaging models of ocean phenomena. Detection by this means is made possible by the fact that internal waves can influence the surface wave regime.

As discussed in Section 3.3.1, internal waves are also detected by MODIS in sun glint. But unlike MODIS, detection with RADARSAT is not limited by sun glint, season, latitude or longitude, and RADARSAT is capable of providing more than an order of magnitude improvement in spatial resolution.

Neither of these techniques, however, appear to be used operationally. This may reflect the belief that the outstanding issue in this field is not how the waves are generated or detected, but what is their significance in oceanography [48]?

4.2 Natural and anthropogenic slicks

Detecting oil spills caused by the marine transportation and offshore oil and gas industries with spaceborne synthetic aperture radar is an accepted operational procedure [e.g. 35, 49, 50], especially when using radars operating at multiple frequencies [51]. Environment Canada, for example, in cooperation with Transport Canada and the Canadian Space Agency already has an operational oil spill monitoring program.

Natural slicks, as opposed to anthropogenic oil slicks, are also detected by RADARSAT and along with several other natural features, such as low wind speeds and upwelling, are a cause of false target detection in operational oil spill monitoring programs [2, 36].

Synthetic aperture radar has also been used in conjunction with CODAR SeaSonde® radars to detect and monitor terrestrial runoff of anthropogenic origin [52], which is the largest source of pollution in coastal waters [53]. The technique involves detection of associated surface slicks.

It has been stated that about 80% of the pollution that enters the ocean stems from land-based activities [54] and that in the USA, for example, only about 8% of the oil entering its coastal waters originates from marine vessels and platforms [55]. DiGiacomo et al. [52] also noted the potential connection between terrestrial runoff and harmful algae blooms, thereby suggesting that detecting terrestrial runoff by synthetic aperture radar could be used as a tracer for nutrient-laden inputs that are often associated with harmful algae blooms.

DRDC Ottawa's fine scale RADARSAT wind product will be able to decrease oil spill false alarm rates by identifying areas within the image where low wind speeds produce the same type of surface feature as the actual slick. Below 2–3 ms-1, the wind is not strong enough to generate Bragg-scale waves on the surrounding clean water. In this case, there is not adequate contrast between the clean and oil-covered water to permit detection by C-band radars such as RADARSAT [35]. The DRDC Ottawa wind product will also identify wind speeds above which synthetic aperture radar cannot detect the oil. This is generally within the range of 10–14 ms-1 [35], at which point the slick may disperse and mix within the water column.

DRDC Ottawa's RADARSAT wind product will also be able to identify areas within the RADARSAT image where natural slicks are dispersed by wind and therefore may not be present in the image (i.e. the Bragg waves are no longer damped by natural surfactants). DiGiacomo and Holt [56] state that this occurs at wind speeds greater than 7–8 ms^{-1}, whereas Holt [44] states 6–7 ms^{-1} and Alpers and Espedal [35] state above 7–10 ms^{-1}.

4.3 Water masses, fronts and eddies

Fronts and eddies are detected by synthetic aperture radar because such features are zones of current shear, convergence or sharp temperature gradients [44]. Water masses *per se* are not usually detected by this type of sensor, rather the boundaries of such features when they have the above stated characteristics. A possible exception to this is detection of subsurface water masses brought to the surface by coastal upwelling [36]. Of note is the fact that (i) local winds influence the effectiveness of the technique and (ii) coastal upwelling may be detected due to its associated cold water or biological activity.

There are numerous examples in the literature of the detection of fronts, eddies and upwelling zones by synthetic aperture radar, however, the technique does not appear to enjoy wide if any operational application. This likely reflects the pre-operational status of the technique [43] and the fact that other types of operational spaceborne sensors having greater temporal resolution and free access are also capable of detecting these features. Sea-surface temperature sensors such as AVHRR and multispectral sensors such as MODIS are used widely to detect thermal and biological fronts, eddies and associated water masses. A common example is delineation of the Gulf Stream, which is also detectable by synthetic aperture radar [e.g. 57, 58].

Thermal and multispectral sensors, however, are impeded or rendered useless by the presence of clouds, thereby again suggesting that the potential role of RADARSAT in this application is to complement the capabilities of other sensors. This idea is by no means new and again suggests that the primary impediments to utilization of this technique are operational issues, not a lack of detection technology [2].

4.4 Bathymetry and seafloor features

Civilian synthetic aperture radar satellite sensors have been detecting underwater marine features since the launch of SEASAT in 1978.

L-band sensors such as SEASAT are better than C-band sensors such as RADARSAT for this application, as they are less prone to wind effects [59], but during the latter-half of the 1990s, using the C-band synthetic aperture radars onboard ERS-1 and 2, a European company commercialized a technique that initially claimed to provide bathymetry in nearshore shallow waters experiencing strong tidal currents [60, 61].

There are two aspects to this subject – determining water depth and detecting bottom features. *A priori* knowledge of local wind, current and bathymetric conditions are required for quantitative analysis (i.e. determination of water depth). Earlier publications state vertical accuracies of 20–30 cm, however, the company’s web site now states that the technique assesses variation of the seabed – there is no mention of using it to determine water depth. This change from quantitative to qualitative application is also noted in a recent review of the subject [59].

Detecting bathymetric features with C-band synthetic aperture radar requires currents greater than approximately 0.5 ms^{-1}, a well-mixed water column, and wind speeds above 2–3 ms^{-1} but below 8–10 ms^{-1}. It is optimal between 3–6 ms^{-1} [59].

As is the case for detection of seafloor features with multispectral sensors, the technique is limited to shallow waters. Otherwise, the two approaches are fairly independent and therefore complementary. MODIS, for example, does not require the presence of strong currents to detect seafloor features but requires a clear water column. MODIS “sees” the actual feature whereas RADARSAT “sees” a surface manifestation of the feature. Sun glint impairs the MODIS application but is irrelevant to the RADARSAT application.

4.5 Sea ice

On an annual basis, Environment Canada's Canadian Ice Service uses 3,000–4,000 near-real time RADARSAT images to monitor and report on sea ice and iceberg conditions in Canadian coastal waters. RADARSAT and other C-band satellite synthetic aperture radars, like Envisat ASAR, have the ability to provide high resolution ice information regardless of cloud cover, day or night. RADARSAT consistently provides information on sea ice extent, amount (concentration) and type [62].

Satellite synthetic aperture radars have limitations for ice monitoring. Temporal limitations of the sensor/satellite prevents continual coverage of specific regions. As such, synthetic aperture radar data are not always available. Also, the complex and varying nature of the backscatter of the background ocean makes the separation of ice and open water occasionally difficult at C-band – often requiring expert analysis and ancillary datasets. If satellite synthetic aperture radar is unable to provide ice information, either due to lack of data or ambiguous information in the imagery, MODIS is used.

MODIS data are acquired by the Canadian Ice Service and utilized in a near-real time manner, primarily as a substitute and/or complement to satellite synthetic aperture radar data (i.e. RADARSAT and Envisat ASAR). Cloud-free MODIS images contain information useful for monitoring the location of the ice edge, as well as the location and amount of sea ice. Strong contrast between the visible reflectance of ice and water within MODIS's visible and near-infrared channels and the sensor's moderate resolution allow both the detection of sea ice and its concentration (or amount) relative to open water [62 and see Figure 7]. Strong thermal differences between ice and open water over much of the year also make MODIS thermal channels useful for detecting sea ice, albeit only at coarser resolutions than available via the AVHRR sensor.

The type (or by proxy, thickness) is more difficult to assess with MODIS since the ice surface is often covered by a bright snow which dominates the response at MODIS wavelengths. However, as seen in Figure 7, MODIS often provides enough detail to indicate the presence or absence of floe structure, which allows the presence of thinner ice regimes (up to 30 cm) to be assessed.

The decay (and by proxy strength) of sea ice has the potential to be monitored by MODIS and RADARSAT. Sea ice decay is characterized by changes at the ice surface and within the ice volume – there is a seasonal progression that can be monitored using MODIS and RADARSAT data [63, 64].

Automated extraction of sea ice information from MODIS is still hampered by inconsistent cloud detection and masking techniques.

Figure 7: MODIS true colour image of sea ice conditions in Northumberland Strait and off Nova Scotia collected 16 March 2003. Courtesy of MODIS Rapid Response Project, NASA.

5. Clouds in MODIS products

Clouds diminish or prevent oceanographic application of all spaceborne multispectral sensors. This has the effect of decreasing the frequency (i.e. temporal resolution) of usable imagery. Clouds do not, however, have the same effect on synthetic aperture radar sensors and this is the primary reason why this report investigates the idea of fusing RADARSAT and MODIS imagery.

This cloud effect is demonstrated in Figure 8 for the littoral waters of Nova Scotia for the period of 1 August 2005 through to 21 January 2006. The figure is based on a total of 324 MODIS Terra and Aqua true colour images obtained from NASA's Rapidfire Aeronet_Halifax data archive. The analysis is based on visual inspection of each image and therefore results are approximate.

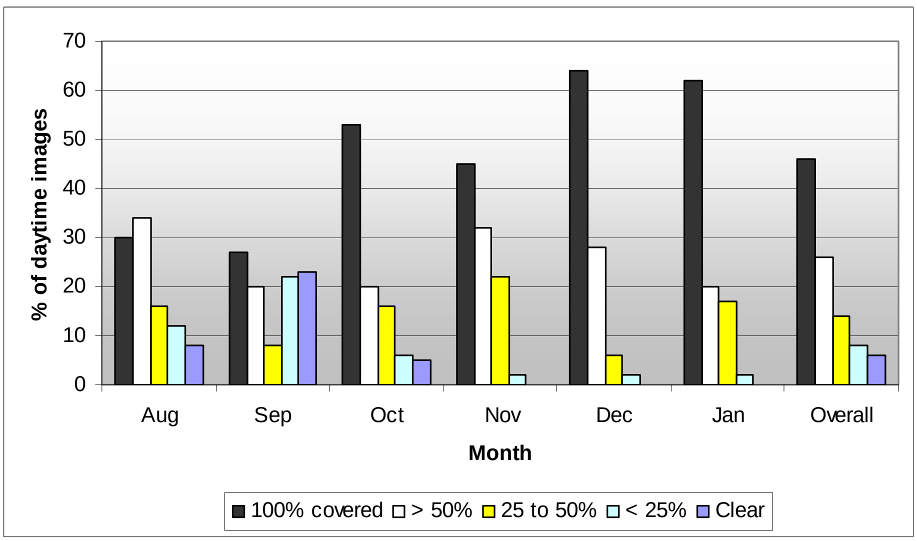

Figure 8. Percentage of Aeronet_Halifax MODIS images that contain clouds. The legend indicates the amount of image area covered by cloud. Clear means the image was virtually cloud free whereas 100 % means the image was either obliterated by cloud or unavailable.

Overall, 72% of the images were either completely or largely (i.e. greater than 50 percent) covered by cloud, however, the extent varied monthly. The best month was September, with 47% of the images falling within these two categories. The worst was December, when 92% of the images were either totally or largely covered by clouds, or missing. These observations provide insight into why cloud detection and masking is an essential component of marine monitoring with spaceborne electro-optical sensors.

The temporal resolution of the Terra images is shown in Figure 9. The Aqua images had a very similar distribution. This figure shows that a total of 10 virtually cloud free (i.e. "clear") images were obtained during this almost six month period and that in late fall and early winter it is common to have periods of three to five days when no images are usable for oceanographic purposes. In winter months it is possible to have periods of weeks when all of the images are either completely or largely covered by cloud, or not available. In total, less than 7% of the possible images were not available; most of these instances occurred in December and January.

These results are expected to vary with geographic location and from year to year within a given location, but the overall impact of cloud cover would be similar from year to year on a seasonal basis for a given location or climate.

As thermal IR and ocean colour channels are also inhibited by cloud cover, the effect of clouds on the temporal resolution of MODIS sea-surface temperature and ocean colour products is expected to be similar to that observed for MODIS true colour products.

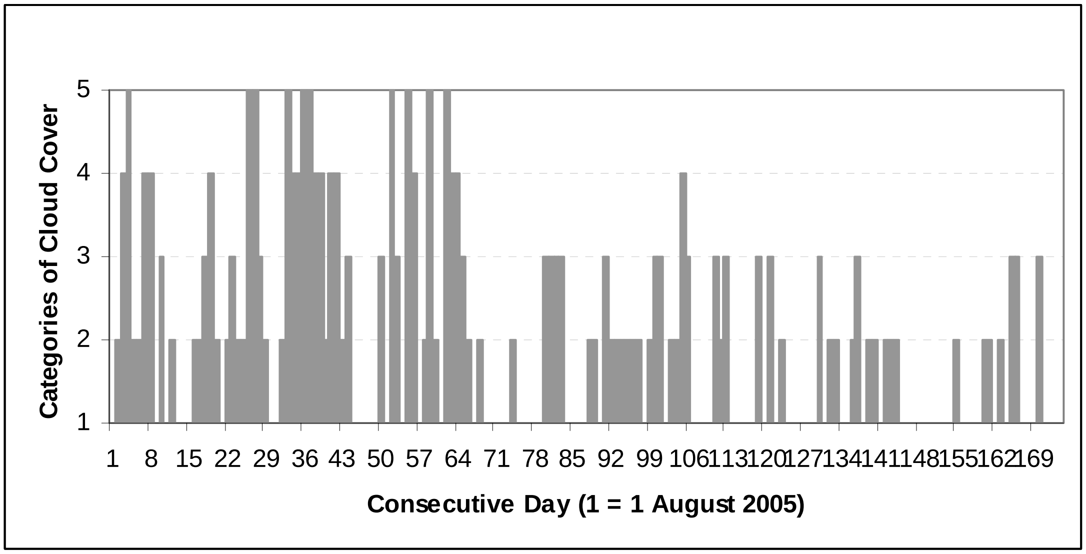

Figure 9. Temporal resolution of MODIS/Terra Aeronet_Halifax images described in Figure 8. Category 1 = 100 % cloud cover or no image; 2 = > 50 % cloud cover; 3 = 25 to 50 %; 4 = < 25 % and 5 = virtually clear image. The 174 consecutive day period runs from 1 August 2005 to 21 January 2006.

The highly transient nature of certain cloud formations can be exploited in time series of images to decrease the effect of clouds on oceanographic applications. This is demonstrated in Figure 10, which includes the Aeronet_Halifax Terra and Aqua images for 30 October 2005. They were collected 1.5 hrs apart, during which time cloud formations moved in a manner that permits greater viewing of water areas through compositing of the two successive images. This technique works best for images having partial cloud cover as it requires sections of clear water to be present in both images. Presumably, this approach could be exploited to even greater benefit by also including images collected over the same waters on the same day by other similar multispectral sensors. However, as the scope of this investigation is limited to MODIS, these other sensors are not included in this analysis.

Figure 10 also suggests that insight into the dynamics of littoral features can be gained through the viewing of images collected hours apart. For example, turbidity and bathymetric features of the Minas Basin area are seen to vary between the images shown in Figure 10. Littoral MetOc dynamics are also observed by comparing Figures 3 and 4, which were collected three hours apart. This technique has been used widely with other types of imagery, such as ocean feature analysis with AVHRR. In fact, when the objective is to monitor oceanographic features common to various spaceborne sensors, such as certain types of littoral fronts, images from the various sensors may be used collectively to conduct the required analyses.

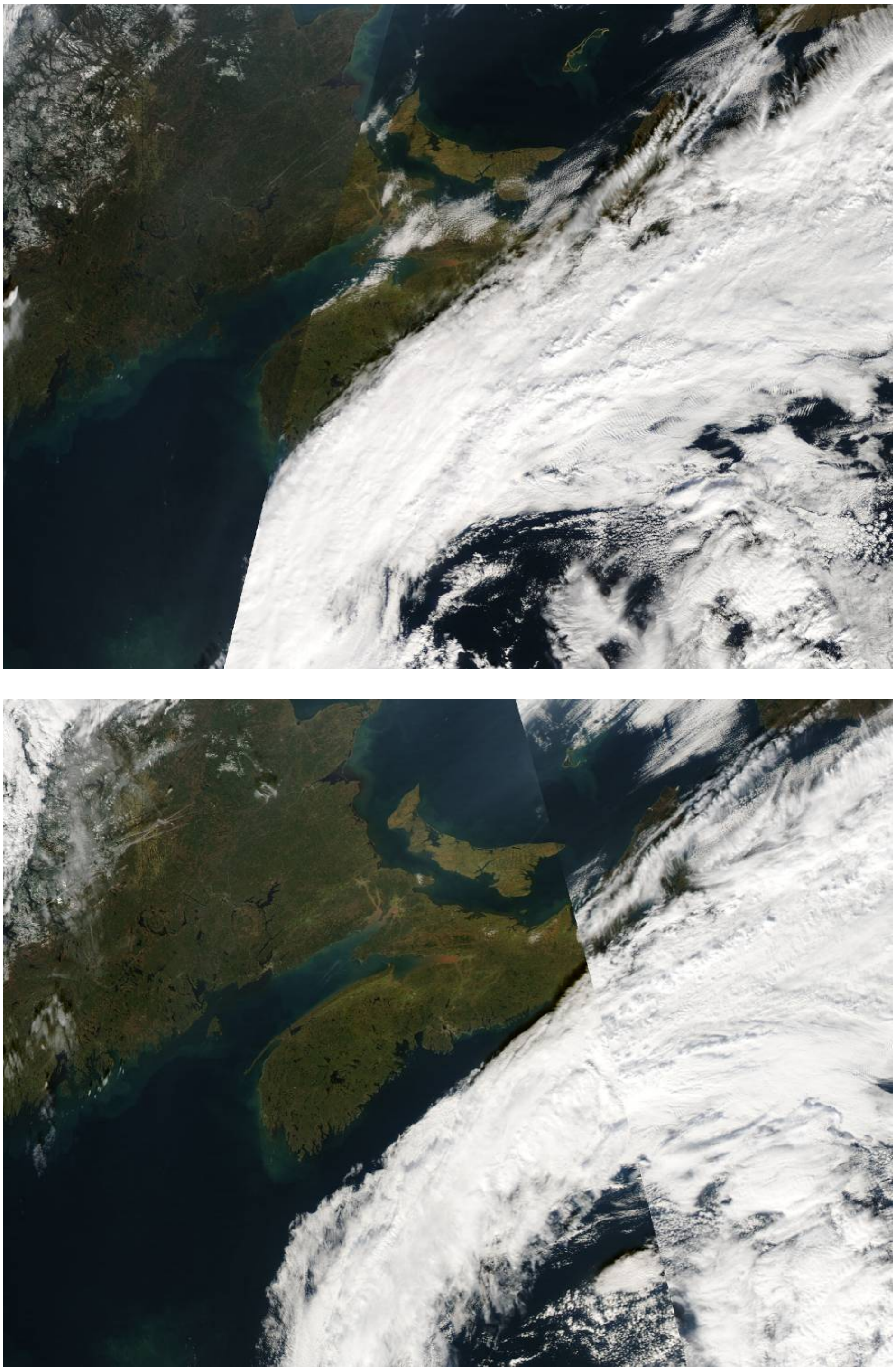

Figure 10. MODIS Terra (top) and Aqua (bottom) Aeronet_Halifax images for 30 October 2005. The Bay of Fundy / SW Nova Scotia passes were collected at 1610 and 1750 UTC respectively.

6. MODIS R&D Recommendations for DRDC Ottawa

This section identifies a MODIS and fused MODIS/RADARSAT research and development strategy for DRDC Ottawa which aims to advance Canadian Forces REA capabilities.

As reported previously [2] and depicted in Figure 11 [65], variations in wind conditions influence all maritime MetOc applications of synthetic aperture radar. Thus, DRDC Ottawa's emerging fine-scale RADARSAT wind product will be of operational benefit to all maritime users of RADARSAT – both civilian and military. It needs to be provided concurrently with the actual operational RADARSAT products.

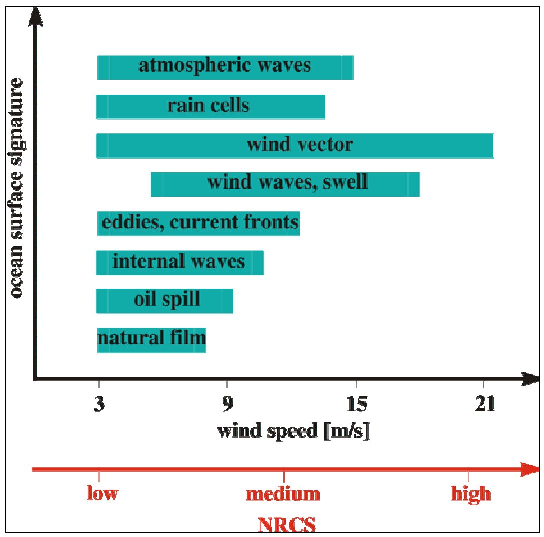

Figure 11. Approximate relationships between wind speed, normalized radar cross section (NRCS) and MetOc features observed by synthetic aperture radar. Reproduced with permission from Horstmann et al. [65].

The operational value of this RADARSAT wind product for ship and oil detection is not provision of wind vectors *per se*. It is identification of environmental conditions that limit or otherwise confuse successful application of this sensor. Thus, the final product provided to the user may not be a display of winds but a display of regions within the image that are or are not suitable for a particular interpretation. In the case of oil detection, for example, the product may be a display of regions within the image where the wind is too low or high for oil detection, where the wind disperses naturally occurring slicks, etc.

Neither the findings of this report nor actual war-time operations [66] support a DRDC Ottawa MODIS product strategy that focuses entirely or largely on MODIS' ocean colour channels. The sensor's true colour, atmospheric and thermal IR channels have potential for broad application to military operations. This differs from strategies that may be used by components of the civilian security sector (see Section 7.2.2), the academic oceanographic community and ecosystem-oriented departments such as Fisheries and Oceans Canada [67, 68], the latter two of which require quantitative analyses of biological processes, such as primary productivity. The recommended DRDC Ottawa strategy may evolve with emerging high-resolution ocean colour products [69], however, MODIS product requirements for the defence sector will remain more feature than process oriented and more immediate in terms of temporal requirements. Also, military operations may be unable to conduct *in situ* sampling and thereby have limited ability to quantify detected parameters.

Table 3 lists nine littoral features and one parameter (i.e. temperature) that can be detected with MODIS in Canadian (i.e. domestic) waters. Turbidity, fronts, eddies, freshwater plumes and upwelling zones are identified through their corresponding thermal or water colour signatures, the latter of which may be influenced by plant pigments, re-suspended sediments, suspended fluvial muds, humic substances, anthropogenic pollutants or any combination thereof. Although aircraft contrails are included in the table, they are beyond the scope of this report.

Littoral Features Detected By MODIS in Canadian Waters	Also Detected By RADARSAT	Relevant Military Operations
Fog	No	surface navigation, search & rescue, surveillance with visible sensors
Aircraft contrails	No	beyond the scope of this report
Water temperature	No	all littoral naval operations
Turbidity / blooms	No	ASW, MCM, submarine and special operations
Fronts & eddies	Possibly	ASW, MCM, submarine operations, navigation
Freshwater plumes	Possibly	ASW, MCM, submarine operations
Upwelling zones	Possibly	ASW, MCM, submarine operations
Internal waves	Yes	ASW, MCM, submarine operations
Sea ice	Yes	ASW, navigation, search & rescue
Slicks (possibly)	Yes	surveillance

Table 3. Littoral features detected by MODIS in Canadian temperate waters.

Sea ice nowcasting and forecasting is a civilian mandate fulfilled by Environment Canada and therefore is addressed in Section 7, as is fog and oil spill monitoring and detecting algae blooms. MODIS detects algae blooms and therefore may provide insight into the presence of naturally occurring surface slicks. Developing this aspect could lead to a decrease in the false alarm rate when using RADARSAT for oil spill monitoring.

Internal waves influence the performance of acoustic sensors and underwater vessels and therefore fall within military mandates. However, DRDC Ottawa was unable to identify a R&D role in this area and therefore this report provides no R&D recommendation for this application.

With the possible exception of fog and aircraft contrails, none of the applications listed in Table 3 are detectable in cloud covered waters. In general, cloud detection and masking routines will be required for MODIS' marine applications, which are also influenced by atmospheric aerosols.

RADARSAT penetrates cloud cover, thus will alleviate this problem when using MODIS for operations pertaining to internal waves, sea ice or oil slicks. RADARSAT may also do this for fronts, eddies, freshwater plumes and upwelling zones, however, these particular applications of RADARSAT have yet to be proven for operational purposes. It is also noted that RADARSAT operates at night whereas the true and ocean colour channels of MODIS, which depend on visible light, do not. This could be a factor, for example, when deploying MODIS for Arctic operations.

As auxillary information is required for both qualitative and quantitative interpretation, stand-alone MODIS images will have minimal operational value. Thus, the ability to fuse data products in operational time frames and formats is critical. Cloud masking and atmospheric correction of MODIS imagery are examples of this need.

The preferred RADARSAT satellite geometry for detecting ships is not optimal for detecting ocean features. Thus, RADARSAT imagery collected by Environment Canada in support of civilian operational mandates such as ice, oil spill and fog monitoring (see Section 7) will have greater MetOc application than imagery collected in support of ship detection operations.

Of equal significance are REA requirements that cannot be fulfilled with MODIS and therefore are not included in Table 3. Although MODIS may provide bathymetry and seafloor feature information for operational purposes in relatively clear tropical waters, it does not do so in Canadian temperate waters and therefore these features are not included in Table 3. Parameters pertaining to bioluminescence, turbulence and noise of biological origin cannot be derived from MODIS data in any marine waters and therefore are also excluded from the table. Biological aspects of MODIS are discussed further in Section 7.2.2.

Human resources within MetOc Halifax are heavily skewed towards meteorology and acoustics, and MetOc's operational products focus on open ocean waters, with the result that operational requirements pertaining to these subjects are largely fulfilled whereas those pertaining to operational oceanography in littoral waters remain largely unfulfilled.

D MetOc's operational oceanographic strength is water temperature and ocean feature analysis in open ocean waters. The recommended strategy is to expand this existing strength to littoral waters and to found emerging products on open-source, web-enabled, GIS technologies. This is recognized within MetOc, thus is not a new approach but an endorsement of the existing one.

The existing open ocean product delineates bulk water masses, fronts and eddies and provides a three-dimensional profile of water temperature. MODIS is capable of detecting fronts and eddies in all marine waters and of providing synoptic sea-surface temperature information. RADARSAT may augment detection of fronts and eddies and thereby alleviate limitations caused by cloud cover and darkness. It would also identify these features at a much higher spatial resolution.

In littoral waters additional oceanographic features become relevant to military operations, but not all of them can be detected with spaceborne sensors. As shown in Table 3, turbidity features, upwelling zones and freshwater plumes are relevant to littoral military operations and can be detected with MODIS. RADARSAT may augment detection of upwelling zones and freshwater plumes but is unlikely to provide any additional insight into turbidity *per se*.

There are several means to produce a MODIS turbidity product, but from a spatial and temporal resolution perspective the preferred uses the sensor's true colour channels to produce a product at 250 m spatial resolution on a daily basis at mid-latitudes. This has four times the spatial resolution and twice the temporal resolution of existing MODIS ocean colour products. Obviously, the true colour product does not have the best sensitivity, but for military operations in turbid littoral waters this may not be as critical an issue as spatial and temporal resolution.

MODIS data and derived products can be obtained from (i) NASA's Rapidfire site (http://rapidfire.sci.gsfc.nasa.gov/subsets/), which includes degraded JPEG true colour images within a few hours of satellite overpass and the original HDF files sometime thereafter, and (ii) the University of Wisconsin's satellite data site (http://eosdb.ssec.wisc.edu/modisdirect/), which provides the required GeoTIFF files as well as the underlying HDF files. The GeoTIFF files can be co-referenced with RADARSAT imagery using DRDC's IAPro software. It appears that at times the Wisconsin site only processes the Terra passes, which decreases the utility of this source and may require accessing NASA's data archive to obtain Aqua HDF files. These issues will be irrelevant for domestic waters once Polar Epsilon installs Canadian reception facilities.

A littoral ocean feature MetOc product will also need to address finer spatial and temporal scales than are usually encountered in open ocean waters. The existing MetOc product is produced twice per week at scales of tens of kilometres or greater. Ideally, in littoral waters it should be produced daily and at times it will need to resolve spatial features as fine as a few hundred metres.

Both MODIS and RADARSAT will help to address these resolution issues, although cloud cover will diminish the temporal resolution of oceanographic products produced from multispectral and thermal IR data. MetOc Halifax will be able to receive MODIS data on a daily basis, but cloud cover will decrease the temporal resolution of MODIS 250 m products to three to five days in all but the most favourable months and MODIS 1 km ocean colour and sea-surface temperature products to about once a week. This can be improved by fusing successive MODIS imagery, or imagery produced by other spaceborne sensors. This is a critical requirement for developing operational littoral ocean feature products, however, the existing Canadian Forces multispectral MetOc strategy does not include this approach. The potential operational benefit of including data produced by other spaceborne sensors requires investigation. Recent logistical issues also point to a need to revise the Canadian Forces existing multispectral strategy for MetOc operations. Polar Epsilon's MODIS reception facility will not be operational until 2008, the ocean colour channels on MODIS/Terra are no longer being processed, MODIS/Aqua's five year design life will be reached in 2007 and MODIS' follow-on system (NPOESS) is behind schedule.

Although MODIS/Aqua generates sea-surface temperature data, AVHRR will continue to be the primary source of synoptic sea-surface temperature information. In littoral waters, composite AVHRR sea-surface temperature imagery is required operationally on a daily basis by several sectors, not only to determine water temperature but also to detect ocean features that have thermal signatures, such as certain fronts, eddies, freshwater plumes and upwelling zones.

7. Recognizing related civilian security operations

This section recognizes the fact that Earth-observation infrastructure established through the Polar Epsilon project will result in the Canadian Forces possessing MODIS data required by environmental security operations that are within the mandates of other federal departments.

To achieve state-of-the-art in maritime rapid environmental assessment, certain federal departments will need to expand their cooperation with each other as a means to formulate a federal approach to accessing Earth-observation data in operational time frames and formats. Collectively, the relevant operations, namely those pertaining to Canadian Forces MetOc, the Canadian Ice Service, the Joint Rescue Coordination Centre, and harmful algae monitoring, form a cluster of maritime operations that will benefit from close cooperation.

Successful implementation of satellite products identified in this report requires data access in operational time frames, standardized file and product formats and fusion with other data. Unfortunately, Canada’s operational oceanographic capabilities in littoral waters are emerging as a series of silos rather than as a cohesive federal infrastructure, thereby challenging successful implementation. This situation reflects a potpourri of public mandates for littoral waters, but it also reflects the lack of a cohesive federal data access and distribution infrastructure. This is Canada’s greatest impediment to expanding operational use of Earth-observation sensors in the maritime environment. It is not a lack of detection capability or application.

From an Earth-observation perspective, the required operational MetOc data infrastructure should be designed to scale effectively in the face of the considerable increase in the use and volume of satellite data expected after 2012 (i.e. in the era of NPOESS).

The required system would be similar in function to NASA’s online near-real time MODIS Rapidfire system (http://rapidfire.sci.gsfc.nasa.gov/subsets/) except that it would focus on Canada, would have secure (i.e. limited) access, would use Open Geospatial Consortium standards and would not be limited to MODIS. Also, the system would support autonomous extractions of specific datasets in support of high volume data users. Given the critical nature of its dependencies, the system would require operational redundancy and monitoring.

The system’s utility to civilian federal user agencies will hinge not only on its ability to acquire and process data, but also on its ability to rapidly transfer the data to other operational centres. Cost and capacity of telecommunications from this system should be a significant factor in the design of any centralized acquisition system.

7.1 Environment Canada

7.1.1 Ice and oil spill monitoring

Deriving operational marine ice products with the aid of MODIS and RADARSAT imagery is an established application delivered by Environment Canada’s Canadian Ice Service.

Similarly, the Canadian Ice Service has Canada's operational mandate for oil spill monitoring. MODIS and DRDC Ottawa's fine-scale RADARSAT wind product may be applicable to operational oil slick detection. They should improve detection through reduction in false targets arising from areas of cold water, low or high wind speeds. It has also been suggested that MODIS could be applied to oil spill operations by identifying slicks of natural origin, thereby decreasing the false target rate, but this requires investigation.

Environment Canada receives and processes RADARSAT data for oil detection purposes within 1–1.5 hr of satellite overpass. MODIS products would need to be produced with the same latency, or better, in order to benefit this application.

7.1.2 Atmospheric visibility

In September 2005, the federal government's search and rescue new initiatives fund (NIF) approved a $1,275,000 research and development project led by Environment Canada for the purpose of developing an operational fog product for search and rescue. It is scheduled to be delivered in 2008. The proposal focuses on the use of NOAA GOES infrared channels, however, Environment Canada has since expressed interest in using MODIS true colour imagery. To date, fog has not been identified in RADARSAT imagery. The Canadian Ice Service is responsible for coordinating Environment Canada's future requirements for RADARSAT and MODIS imagery.

It is noted that although aircraft contrail analyses using MODIS true colour products is beyond the scope of this report, the U.S. Navy has produced impressive atmospheric demonstration products for this application over actual theatres of operation [66].

7.2 Fisheries and Oceans Canada

7.2.1 Search and rescue (Canadian Coast Guard)

The data access infrastructure, daily sea-surface temperature and visibility products discussed above will be of direct benefit to search and rescue operations.

Unfortunately, no existing Earth-observation satellite provides synoptic surface current vectors, which are the foremost REA requirement for search and rescue. And although Canada is experimenting with various surface current models for littoral waters, globally, such models are in a research and development phase and Canada does not have the *in situ* current measuring program required to validate such models on an operational basis.

Although RADARSAT can provide surface wind information, which is the second-highest priority REA requirement for search and rescue, it is uncertain whether incorporating RADARSAT winds directly into the CANSARP trajectory model will significantly improve search and rescue operations.

It is inconceivable that, upon initiation of a search and rescue operation, the Joint Rescue Coordination Centre would order RADARSAT imagery to obtain incremental improvement in MetOc information of secondary priority, assuming the satellite was in a position to immediately image the area of interest, which in itself is unlikely.

As stated throughout this and other [2] reports, perceived MetOc applications of RADARSAT will depend on imagery collected for other higher-priority applications. For example, if studies being conducted by Environment Canada conclude that RADARSAT-derived wind information significantly improves Canada's meteorological forecasting products, and Environment Canada revises its products accordingly, the Joint Rescue Coordination Centre would likely use this revised product. Presumably, this would not require any modifications to CANSARP, which already incorporates Environment Canada's products.

From a MetOc perspective, the CANSARP trajectory analysis program used by the Joint Rescue Coordination Centre has become an operational bottleneck. This report did not investigate federal trajectory models employed for ice forecasting or oil spill response, but observes that the three federal maritime operational MetOc-related centres identified in this report could develop a cooperative state-of-the-art operational trajectory analyses model for littoral waters. This aspect, however, is beyond the scope of DRDC Ottawa's existing activities.

7.2.2 Harmful algae blooms

Data provided by multispectral and synthetic aperture radar sensors cannot determine whether a bloom is toxic, whether it be natural or man made. Multispectral sensors do, however, detect algae blooms in general and thereby serve as littoral sentries. In combination with *in situ* sampling and trajectory analyses they can play a critical role in a synoptic defence and security strategy for detecting and tracking coloured toxic substances in littoral waters.

This application of MODIS is an extension of the ocean feature analyses application outlined in Section 6, but the mandate for toxic substance monitoring lies within Fisheries and Oceans Canada and in certain areas Environment Canada and the Canadian Food Inspection Agency. Another difference is that a harmful algae bloom product is likely to focus primarily on MODIS' ocean colour channels rather than its true colour or thermal infrared channels.

8. Summary

In support of Polar Epsilon, this project investigates meteorology and oceanography (MetOc) products derived from MODIS data for defence, search and rescue and environmental security operations. It also investigates whether operational improvements can be gained through production of fused MODIS/RADARSAT products, but in both cases the emphasis is on detection of oceanographic parameters and features.

DRDC Ottawa's emerging RADARSAT fine-scale wind product is identified as a critical component of an operational spaceborne multispectral product strategy, as is the need for a co-ordinated federal MODIS data access and distribution system.

Although the project identifies nine littoral features and one parameter that can be detected with MODIS in Canadian (i.e. domestic) waters, neither the findings of this report nor actual war-time operations support a DRDC Ottawa MODIS product strategy that focuses entirely or largely on MODIS' ocean colour channels. The sensor's true colour, atmospheric and thermal IR channels also have potential for broad application to military operations. This differs from strategies that may be used by components of the civilian security sector, the academic oceanographic community and ecosystem-oriented departments such as Fisheries and Oceans Canada.

RADARSAT penetrates clouds, thus will diminish the cloud-cover limitation when using MODIS for operations pertaining to internal waves, sea ice and oil slicks. RADARSAT may also do this for fronts, eddies, freshwater plumes and upwelling zones detected by MODIS, however, these applications of RADARSAT have yet to be proven for operational purposes. It is also noted that RADARSAT operates at night whereas the true and ocean colour channels of MODIS do not. This could be a factor when deploying MODIS in the Arctic.

D MetOc's operational oceanographic strength is water temperature and ocean feature analysis in open ocean waters. The recommended R&D strategy is to expand this existing strength to littoral waters and to found emerging products on open-source, web-enabled, GIS technologies. This is recognized within MetOc, thus is not a new approach but an endorsement of the existing one.

There are several means to produce a MODIS turbidity product, but from a spatial and temporal resolution perspective the preferred may use the sensor's true colour channels to produce a product at 250 m spatial resolution on a daily basis at mid-latitudes. This has four times the spatial resolution and twice the temporal resolution of existing MODIS ocean colour products. Obviously, the true colour product does not have the best sensitivity, but for military operations in turbid littoral waters this may not be as critical an issue as spatial and temporal resolution.

Both MODIS and RADARSAT will help to address resolution issues, although cloud cover will substantially diminish the temporal resolution of oceanographic products produced from multispectral and thermal IR data. This limitation can be diminished by fusing successive MODIS imagery, or imagery produced by other spaceborne multispectral and thermal sensors, however, the existing Canadian Forces multispectral MetOc strategy does not include this approach. Recent logistical issues also point to a need to revise the Canadian Forces existing multispectral strategy for MetOc operations.

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List of symbols/abbreviations/acronyms/initialisms

AERONET	Aerosol Robotic Network
ASAR	Advanced Synthetic Aperture Radar
ASW	Anti Submarine Warfare
AVHRR	Advanced Very High Resolution Radiometer
CANSARP	Canadian Search and Rescue Planning
CDOM	Coloured Dissolved Organic Matter
DRDC	Defence Research and Development Canada
ETM	Enhanced Thematic Mapper
GeoTIFF	Geographic Tagged Image File Format
GIS	Geographic Information System
GOES	Geostationary Operational Environmental Satellites
HDF	Hierarchical Data Format
HH	Horizontal Horizontal
ISTOP	Integrated Satellite Tracking of Polluters
JRCC	Joint Rescue Coordination Centre
MCM	Mine Counter Measures
MetOc	Meteorology and Oceanography
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NATO U	North Atlantic Treaty Organization Unclassified
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
OCM	Ocean Colour Monitor
OLS	Operational Line Scanner
R&D	Research & Development
RADARSAT	Radar Satellite
REA	Rapid Environmental Assessment
TM	Technical Memorandum (not TM as in “Thematic Mapper” on old Landsats)
VIIRS	Visible/Infrared Imager/Radiometer Suite
VV	Vertical Vertical

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In preparation for Polar Epsilon's MODIS and RADARSAT satellite reception systems, this project investigates meteorology and oceanography (MetOc) products derived from MODIS data for defence, search and rescue and environmental security operations. It also investigates whether operational improvements can be gained through production of fused MODIS/RADARSAT products, but in both cases the emphasis is on detection of oceanographic parameters and features. This assessment is based on interaction with representatives of federal operational MetOc, search and rescue, ice and oil spill monitoring centres and synthesis of unclassified literature as a means to obtain (i) an up-to-date presentation of Canada's maritime rapid environmental assessment requirements and (ii) MODIS R&D recommendations for DRDC Ottawa. This information is used to develop a Canadian Forces strategy for MODIS product development, including identification of certain critical operational linkages. DRDC Ottawa's emerging RADARSAT fine-scale wind product is identified as a critical component of this strategy as is the need for a co-ordinated defence, search and rescue and environmental security operational MetOc data access and distribution system.

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MODIS, RADARSAT, METOC, REA, rapid environmental assessment, defence, security

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