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Invasive Aquatic Species and Ships Across the Sea – The IMO Response, Reflections and Directions

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In the last ten years or so, scientists, governments, the community and industry have come to increasingly recognise the harm that invasive species can cause to marine and aquatic environments. Today, invasive species are considered to be one of the major threats to marine biodiversity, as well as posing significant economic and public health problems.

Every major international conference on the environment in the last decade, including the United Nations Conference on Sustainable Development in 1992, the Conferences of Parties to the Convention on Biological Diversity, the World Summit on Sustainable Development in 2002 and the 5th World Congress on Protected Areas in 2003, have highlighted the issue of invasive species, and called upon governments and industry to act.

While shipping is by no means the only route through which harmful species may invade new areas, ballast water and hull fouling are both contributors to this global problem, and both the International Maritime Organization – IMO, and the shipping industry have taken concerted action to find ways to address the issue.

IMO has been working to address the ballast water vector for more than 10 years, developing two sets of guidelines and executing a major effort to assist developing countries through the Global Ballast Water Management Programme –GloBallast. In February this year, IMO's efforts were rewarded with adoption of the new International Convention on the Control and Management of Ships' Ballast Water and Sediments by a Diplomatic Conference convened by IMO at its Headquarters in London.

This act, providing a uniform and effective international instrument to regulate ballast transfers, is perhaps one of the most significant global environmental achievements in the early part of this Century. When one considers the enormous scientific and technological challenges, and the highly complex and multi-disciplinary nature of the problem - encompassing biology, chemistry, engineering, law, economics and ecology, not to mention ship design, construction and operation - achieving consensus on the convention must be seen as a major credit to the efforts of delegates from IMO member States and the staff of the IMO Secretariat.

The importance of international standards and a uniform global approach cannot be over-emphasised when dealing with a trans-boundary industry like shipping. The new ballast water management Convention will certainly have impacts on the industry; however these will be far less disruptive than the alternative, potentially disparate regional and unilateral responses, which would undoubtedly proliferate in the absence of the Convention.

The new Convention provides flexible options and builds on the complimentary roles of coastal, port and flag States in protecting the marine environment. It retains the current management measure of ballast water exchange at sea, for the foreseeable future, while providing for continuous improvement by setting standards to stimulate the development of alternative, more effective management measures over time.

Much work remains to be done however, to ensure that the ballast water management Convention enters-into-force as soon as possible, and that parties to the Convention implement it effectively through appropriate national legislation. There is also much work still to be done to develop technical guidelines under the Convention, including among others, guidelines for approval of ballast water management systems and prototype treatment technologies.

In developing regimes to regulate shipping, we must bear in mind the vital role this industry plays in our lives and the economy. Shipping is truly global and multi-national, carrying more than 90% of world trade. As such it underpins

Bioinvasions in North America's Great Lakes and the Shipping Vector

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The Laurentian Great Lakes have 176 established nonindigenous species (NIS) of which over 40% have been attributed to the ship vector. The invasion rate in these waters has increased to nearly six times the previous rate since the opening of the St. Lawrence Seaway in 1959. Interestingly, the invasion rate of ship-vectored faunal species has increased despite implementation of voluntary guidelines (1989) and mandatory legislation (1993) requiring open-ocean ballast water exchange. Such an increase in the face of current ballast water exchange policies may be related to the fact that 90% of transoceanic vessels entering the Great Lakes-St. Lawrence Seaway during the 1990s reported no ballast on board (NOBOB) and were therefore exempt from the legislation. NOBOB ships unload cargo at their first port of call, take on Great Lakes water (mainly from Lakes Ontario and Erie), which mixes with residual water and sediments present in the tanks of these vessels, and release this mixed ballast water prior to leaving the Great Lakes. Of all the Great Lakes, Lake Superior receives the most ballast water discharges from both ballasted and NOBOB ships but has sustained surprisingly few invasions since 1959, possibly owing to its relatively inhospitable physical environment. Recent studies have revealed that NOBOB vessels may carry viable resting eggs, and these vessels may pose an invasion risk to Great Lakes waters.

NOTES

Vectors for Introduction of Alien Macroalgae in Europe: Hull Fouling

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Shipping is recognized to have played an important role as a vector of transfer for marine species by the way of hull fouling throughout the past centuries. Nowadays, transport occurs principally through ballast water tanks. However, boat fouling could actually be underestimated as very few studies have been undertaken recently.

The present study has been carried out in the harbour of Sète (south coast of France) during 2003. A total of 23 ships with IMO registration have been surveyed for macroalgal fouling. Origins of the ships were Mediterranean Sea, Western Pacific, Indian Ocean, Atlantic coasts of Europe, Africa and South America. Lengths varied from 54 to 225 m. The last dry docking has been undertaken for all ships in the last 30 months. Except in one particular case, hulls were covered with tributyltin (TBT) based paintings.

More than 20 species of macroalgae have been found, mainly cosmopolitan species. When painted with non-toxic "antifouling", a high macroalgal diversity has been observed, with species having a smaller range of native distribution.

The potential adverse effect of the future ban of TBT and consequences on macroalgal introductions will be discussed.

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Quantifying the Efficacy of Mid-ocean Ballast Water Exchange: An Experimental Approach

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It is widely recognized that invasions by nonindigenous species represent one of the most significant threats to global biodiversity. Within aquatic environments, ships' ballast water serves as a primary vector for the transfer of species, and many documented invasions are now attributed to ballast-mediated introductions. Mid-ocean Ballast Water Exchange (BWE) has been advanced as one method to reduce the transfer and subsequent establishment of coastal organisms by ships. BWE involves the replacement of coastal ballast water with open ocean water. Through BWE, many coastal organisms are released into the open ocean, where conditions are usually not appropriate for their survival. Conversely, coastal environments do not favor most oceanic organisms that become entrained during BWE. This method is currently being promoted worldwide, and is immediately available on many ships to reduce the risk of invasions, but few data are available to evaluate its efficacy.

In this study, we quantitatively measured the efficacy of BWE in reducing concentrations of coastal macrozooplankton (biological tracers) and Rhodamine dye (physical tracer), using controlled experiments on eight replicate voyages. The experiments occurred aboard oil tankers, traveling along western North America to Alaska in 1998 and 1999, with voyage durations between 2 to 8 days. On each voyage, we sampled at least one 'experimental' tank, which was subjected to BWE by either of two methods: (i) 100 % Empty-Refill (ER) exchange, (ii) Flow-Through (FT) exchange, including 100% FT and 300% FT. We also sampled one 'control' tank, which was not subject to any form of BWE, on each voyage. Within each tank (experimental and control), replicate samples were collected at least before and after exchange.

To estimate the effect of BWE on the initial water mass, a known concentration of Rhodamine dye was placed into all tanks before the commencement of the voyage, and changes in concentration were estimated using whole water samples taken with a Niskin bottle from multiple depths. To estimate the effect of BWE on zooplankton, samples were collected using bottom to surface net (80 µm) tows within ballast tanks. Replicate net tows were taken at a minimum of two locations in each tank on multiple occasions during the voyage, allowing comparisons of temporal changes and spatial (within tanks) heterogeneity in zooplankton abundances.

Zooplankton analyses were restricted to organisms that occurred in the coastal zone, to remove possible confounding effects of entrainment during exchange in open ocean. Seventeen coastal zooplankton taxa were chosen as 'target taxa', allowing us to compare changes between treatments (control and experimental tanks) and to estimate the effect of BWE.

Survivorship of zooplankton within non-exchanged (control) tanks showed considerable temporal and spatial variability, and BWE resulted in significant reductions in zooplankton density. The 100% ER treatment consistently showed greater reductions in density than did 100% or 300% FT treatments. Relative to control tanks, BWE by the ER method resulted in reductions of zooplankton densities by an average of ~99%, compared to ~60% for 100% FT and 75% for 300% FT. Measurements of BWE efficacy using Rhodamine dye revealed similar results.

Our data suggest that BWE is highly effective at removing coastal zooplankton from ballast tanks. These results differ from some previous reports, which suggest that the efficacy of BWE can sometimes be relatively low. We suggest that this difference may result largely from methodology, whereby earlier studies did not control for initial starting concentrations (which can be highly variable) but instead compared densities on ships that undertook BWE to those that did not. In general, our data suggest that BWE is a useful management tool to reduce organism transfers and should result in reduced likelihood of invasions.

Ballast Water Management: Toward Understanding Treatment Efficacy

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Ships have been an important mechanism for the transfer and establishment of non-native species in coastal ecosystems throughout the world. In US waters, for example, ships have historically been responsible for most known invasions, and ship-mediated invasions have exhibited an exponential increase over the past two centuries. A similar pattern has emerged in many different global regions, increasing both scientific and public concerns. Over the past few years, a growing number of policies and management efforts have emerged to reduce the likelihood of transfers by ships' ballast water.

There remain many fundamental gaps in knowledge about the efficacy of management strategies to reduce new coastal invasions. These can be divided into three general categories. First, the relative importance of various transfer mechanisms (vectors) to observed invasions is still often not clear, due to the existence of multiple plausible vectors for invasion events. Second, efforts to measure effects of treatment options to reduce species transfers, especially across a wide spectrum of organism types, are still at an early stage. There is a great deal not yet known about treatment effects on both quantity and quality of organisms across the wide spectrum of taxa, life stages, and environmental conditions involved in transfers. Third, and perhaps most importantly, the quantitative relationship between the number of propagules (organisms) delivered and the likelihood of colonization, or the "dose-response" relationship, is poorly resolved.

In the first category, it is clear that the relative importance of vectors varies in space and time and that shipping continues to be an important vector. In North America, for example, most marine invasions are attributed to shipping as either a sole source or one of multiple possible sources. However, within the "shipping vector", it remains a challenge to clearly distinguish the relative importance of ballast water versus hull fouling, because many organisms have life stages that can occupy either ship habitat. In addition, unlike surveys of biota in ballast tanks, there are few contemporary analyses of hull fouling communities on modern ocean-going vessels.

As for the effect of treatments to reduce species transfers, a proximate measure of efficacy, much of the current efforts have focused on Ballast Water Exchange (BWE). BWE is intended to flush out ballast tanks at sea, reducing the concentration of coastal organisms that can become established at subsequent ports of call. Further, it is believed coastal organisms discharged at sea, or oceanic organisms discharged in nearshore (port) environments, pose little risk of establishment.

We have quantified the efficacy of BWE to reduce the transfer of organisms on > 24 different voyages, using controlled exchange experiments. The experiments were conducted on multiple vessel types, including U.S. Navy vessels, commercial oil tankers, container ships, and bulk carriers. On each voyage, we measured changes in rhodamine dye and zooplankton concentrations in identical fashion for paired exchanged (experimental) and unexchanged (control) tanks at multiple time points: Before BWE, after 100% BWE, and sometimes after 200% BWE..

Results across these studies show strong concordance, indicating BWE is highly effective at removing the original water mass (rhodamine dye) and waterborne organisms, excluding benthic or biofilm communities (which were not examined). This contrasts with a review of previous studies, for which efficacy measures show a wide range. We suggest that this difference results largely from methodology, whereby some earlier studies did not control for variation due to ship, ballast tank, or time (see also abstract by Verling).

We are aware of several other studies underway to examine the effects of BWE, as well as a variety of other treatment methods, on entrained organisms. We anticipate rapidly increasing knowledge about the capacity of various treatments (including BWE) to reduce organism transfers by ships' ballast water. Despite the current efforts to advance technologies for ballast water treatment, these efforts are still in the development and testing stage, and full-scale implementation is clearly many years away. For the near future, BWE should be encouraged to the full extent possible, as a treatment method that is readily available and that is able to significantly reduce transfers of coastal biota.

Finally, although progress is evident in measuring the efficacy of treatments to reduce organism transfers, insufficient attention is given to understanding dose-response relationships. The efficacy of treatments to reduce invasions, the ultimate measure of efficacy, is only coarsely understood. Several lines of evidence indicate reduction in organism transfers should reduce invasion success. Yet, the likelihood of invasion associated with various levels of transfer, and how this varies spatially and temporally (and taxonomically), is largely unexplored in marine ecosystems. It is this very relationship that is key to understanding invasion risk and developing science-based "standards" for ballast water treatment. Thus, a quantitative understanding of the dose-response relationship is a high priority for invasion biology and management.

NOTES

Modeling of Ballast Water Flow Dynamics to Understand Ballast Water Exchange

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A Ballast Water Modeling Program was initiated to address the problem of aquatic invasive species (AIS) entering United States waters from ballast water. The objective of the program is to develop an experimentally-validated computational fluid dynamics (CFD) model of flow in a bulk carrier ballast tank that can be used to study fluid flow dynamics during ballast water exchange. Development and validation of a computational flow and mixing model will provide interested parties (researchers, naval architects, ship owners, masters, port authorities, lawmakers) a tool to better understand the fluid dynamics occurring in ballast tanks, predict the efficacy of ballast exchange as an AIS management and treatment practice, assist with the design and implementation of treatment technologies, track and minimize the accumulation of sediments, and to identify deadspots (i.e., areas where water does not mix, exchange, or flush during ballast exchange) and other flow phenomena in these tanks.

Mid-ocean ballast water exchange (BWE) is presently the primary management practice with widespread acceptance for reducing or preventing the spread of nonindigenous aquatic species via ballast water. While ballast exchange by itself may not be a viable long-term solution, it likely will continue to be used for the foreseeable future and may ultimately be combined with some other technologies and management approaches. Therefore, it is essential to fully understand the ballast exchange process and what occurs inside a ballast tank during exchange. Attempts to determine the efficacy or effectiveness of BWE have produced inconsistent and generally unsatisfying results most likely due to the complex structure and inaccessible location of typical ballast tanks, such as double bottom tanks and lower wing or hopper side tanks. These difficulties have limited experimental design and resolution of sampling to determine the effectiveness of ballast water exchange. The development of a computer-based model of the flow dynamics in ballast tanks makes should provide several advantages over the experimental approaches to date.

This paper describes the use of a small-scale physical model to conduct experiments that are the first steps in a staged progression of research to provide data to validate the CFD models and their interrelation. The scope of the present study only included dilution and mixing experiments that yield the fluid fraction of the original fluid within the ballast tank during exchange. Fluid fraction of the original ballast tank fluid was measured using laser-induced fluorescence (LIF). The original fluid is "tagged" by premixing a small concentration of rhodamine into the tank fluid before the experiment. Selected two-dimensional planes inside the tank were illuminated by a laser light sheet from a pulsed Nd:YAG laser and recorded using a digital camera with a resolution of 2048 x 2048 pixels. Through calibration using normalization from a "reference" image, this technique not only yielded useful visualization of the mixing phenomena within the tank but provided an accurate quantitative measurement of the fluid fraction of the original fluid. Once normalized, the fluorescence recorded by each image pixel in the illuminated plane is directly proportional to the fluid fraction of the original fluid.

Transfer of Nonindigenous Species to the Laurentian Great Lakes in Residual Ballast Water from No-Ballast-On-Board (NOBOB) Vessels

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The majority (>90%) of vessels entering the Laurentian Great Lakes are laden with cargo and declare no-ballast-on-board (NOBOB) status. Current ballast exchange regulations do not apply to NOBOBs despite the presence of tonnes of residual salt-, brackish- or fresh-water, sediments, and the species contained in these ballast tanks. Residuals may eventually be released into the Great Lakes after ballast unloading events are conducted within the system, thus potentially transferring nonindigenous species (NIS). During 2001 and 2002, we sampled residual ballast water from 66 tanks on 30 ships at their first port-of-call in the Great Lakes, and recorded 7 rotifer and 37 microcrustacean species, predominantly cyclopoid and harpacticoid copepods, as well as 8 species of cladocerans. We detected three non-indigenous cyclopoid species (*Acanthocyclops venustus*, *Eucyclops serrulatus*, *Cyclops abyssorum*), and three nonindigenous cladoceran species (*Daphnia magna, D. cristata, D. atkinsoni*) currently not found in the Great Lakes. Total invertebrate abundance was not related to ballast water salinity, although total invertebrate species diversity was significantly higher in high salinity water.

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Modeling the Risk of Invasion by Diapausing Eggs in Residual Ballast Sediments

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Ballast water has been recognized as the primary vector for the introduction of aquatic nonindigenous species (NIS) to the Great Lakes. As a result, ballast water exchange regulations were enacted that effectively require inbound ships to exchange fresh or brackish ballast water with open-ocean saltwater if that water is to be discharged in the Great Lakes. However, the rate of discovery of new NIS in the Great Lakes is now three times that of pre-regulation. This may be a result of the increased importance of alternate vectors, such as residual ballast sediment. In this study, we model the risk associated with invertebrate diapausing eggs in residual ballast sediments as a possible vector of NIS to the Great Lakes. We used both biological (egg density, viability and species richness) and physical (sediment volume) parameters to estimate the number of viable propagules carried by the 'average' NOBOB vessel. An additional parameter, describing the potential for introduction based on *in situ* hatching experiments, was added to estimate invasion risk. Both hatch rate and species diversity was higher in laboratory trials than in the in-situ hatching trials, indicating that although NOBOB vessels can carry a large number of propagules (2.3×10^6 eggs per vessel), the introduction potential of NIS via diapausing eggs in residual sediments is low, as compared to the traditional ballast water vector. Both temperature and sediment depth were found to be important variables affecting introduction potential. Lastly, we attempted to predict the rare occurrence of 'high-risk' sediments by comparing our laboratory results with physical ship characteristics and ballast history information.

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Viability of Invertebrate Diapausing Eggs Exposed to Saltwater: Implications for Great Lakes' Ship Ballast Management

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International shipping has been the dominant vector of nonindigenous species introductions to the Laurentian Great Lakes over the past century. Apparent ballast-mediated invasions have been recorded in recent years, despite the implementation of voluntary ballast water exchange regulations in 1989. Since unregulated "No-Ballast-On-Board" vessels currently dominate inbound traffic to the Great Lakes, it has been proposed that live or dormant organisms contained in residual ballast of these vessels may be partially responsible for recent invasions. Alternatively, euryhaline species may pose a significant invasion threat because they can potentially survive ballast exchange. In this study, we explored whether exposure to open-ocean water (32%) reduced the viability of invertebrate diapausing eggs in ballast sediments. Sediments collected from three transoceanic ships and from three freshwater habitats were exposed to open-ocean seawater. Egg viability, assessed as the abundance of taxa hatched between exposed and unexposed sediments, was not affected by saltwater exposure in any experiment. Species richness of hatched diapausing eggs was reduced by saltwater exposure in only one of seven trials. Our results indicate that oligostenohaline zooplankton potentially pose an invasion risk because their diapausing eggs are largely resistant to exposure to open-ocean saltwater.

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US Coast Guard Shipboard Technology Evaluation Program

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The Shipboard Technology Evaluation Program (STEP) is a voluntary program available to all vessels subject to the Coast Guard's Ballast Water Management (BWM) regulations, 33 CFR § 151 Subparts C and D. The STEP is intended to facilitate the development of effective BW treatment technologies, thus creating more options for vessel owners/operators seeking alternatives to ballast water exchange. An increasing number of alternative ballast water treatment (BWT) technologies capable of significantly reducing the probability of introducing foreign organisms via ballast water discharges are being developed and tested as small to mid-scale prototypes. However, complete evaluations and refinement of the capabilities of such systems require ship-scale installations that are tested for longer periods of time under a wide range of conditions. As on-board installation and testing costs are likely to be significant, vessel owners/operators are understandably reluctant to participate in onboard testing projects. To encourage ship owners/operators to participate in projects designed to test the effectiveness of prototype treatment systems under real world, operational conditions, the Coast Guard is implementing the STEP.

This program is intended to facilitate shipboard testing of prototype treatment systems aboard a limited number of vessels for research and development purposes. Vessels accepted into the STEP may be granted a conditional equivalency to future ballast water discharge standard regulations, for up to the life of the vessel or the system, while the prototype system operates satisfactorily. The length of the period of equivalency is dependent upon the date on which the vessel applies to the experimental program. However, in the event that subsequent information on the experimental system indicates the potential for an adverse affect to the environment, risk to the vessel or human health, acceptance in the STEP will be withdrawn. In addition, participation in the STEP may be discontinued if a system no longer performs satisfactorily. Lessons learned in this effort will help resolve the technical challenges associated with employing these BWT systems on operational vessels, and will also facilitate development of the formal procedures for general approval of BWT systems.

The Coast Guard will accept or reject applications to the STEP on the basis of reviews by Coast Guard staff and the recommendations of an independent review panel with expertise in experimental investigations of biota associated with ballast water, water treatment technology, naval architecture, and marine engineering. The purpose of the independent review is to ensure that vessels accepted into the STEP are conducting rigorous and scientifically supportable test programs. To make the reviews as uniform as possible, the process will adhere to an explicit protocol, including standard review questions addressing specific issues. These protocols are described in the application package available from the Coast Guard. Specific conditional requirements will be identified for each vessel accepted into the program, based on the details of the vessel's design, operation, and study plan. With the exception of the equivalencies provided by the STEP, discharged ballast water must meet all other federal, state, local, and tribal environmental regulations.

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The US Ballast Water Technology Demonstration Program: Progress Report

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The Ballast Water Technology Demonstration Program was authorized by the National Invasive Species Act of 1996 and has been administered by the US Fish and Wildlife Service and the National Oceanic and Atmospheric Administration, since it was first funded in 1998. In 2002, the US Maritime Administration became a third federal partner in the program. The objective of the Ballast Water Technology Demonstration Program is to demonstrate effective ballast water treatment technologies that are practicable for use on commercial ships in American waters. The Ballast Water Technology Demonstration Program has, thus far, been administered through a system of competitive grants. From 1998 to 2002 the FWS and NOAA spent $5.803 million to fund 30 ballast water technology demonstration projects. The ballast water technologies that have been studied and/or demonstrated as part of the Program include: oxidizing biocides (peracetic acid, ozone, chlorine); non-oxidizing biocides (juglone, menadione, gluteraldehyde); separation (filtration, hydrocyclone, centrifugation); energy (ultraviolet, acoustic, thermal); Depressurization; Deoxygenation; Exchange; Onshore Treatment; Redesign of Ships or Tanks. In addition, the Program has funded basic research into microorganisms transported in ballast water and potential invasive species transfer from No-Ballast-On-Board (NOBOB) ships.

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Evaluation of Filtration Components for Ballast Water Treatment

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Considerable efforts throughout academia and industry are currently focused on technologies to reduce or eliminate the translocation of organisms in ships ballast water. In support of these technologies, a pilot-scale facility to test candidate technologies has been constructed. The intention of the pilot scale facility is to supply a means to test shipboard equipment as close to full-scale as possible with increased control of the various parameters affecting performance, which are typically unknown or uncontrolled in the ship's environment. For example, input water properties are controlled by the surface waters which the ship typically operates in, whereas the waters utilized at the test facility may be supplemented to adjust organism densities, salinity and suspended solids. In the past year, this facility has been conducting experimentation to evaluate the test facility and also ballast water treatment equipment.

A variety of filtration technologies exist on the market today which may be viable candidates for the removal of biological organism from ships ballast water. In the present document, the results of testing at the pilot scale facility are reported. These systems included a disc, a screen and a media filtration system. Additionally, combinations of these units were evaluated. These filters were evaluated for the relative ability to reduce particulate concentrations and biological organisms of ambient water drawn from the Gulf of Mexico. Where appropriate or necessary, the test waters were supplemented with concentrations of Arizona Test Dust to alter the total suspended solids and overall turbidity. Particle counting was used on the input and output of each filtration systems to evaluate filter removability. Direct enumeration of organisms in the feed water and filtrate were utilized to evaluate effectiveness in the removal of organism. Discussion of the performance of each system and their combinations over the size ranges 10-30, 50-80 and 100-200 microns are reported.

NOTES

Evaluation of a New Method for Control of Aquatic Invasive Species: Effects of Carbon Dioxide and Stack Gas Supersaturation on LT_{50}

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Release of ballast water from ships is a major transport mechanism for nonindigenous aquatic organisms as recognized by the 1996 National Invasive Species Control Act. Approximately 40 000 major cargo ships operating worldwide pump ballast water on board to ensure stability and balance. Ship surveys have demonstrated that ballast water is in general a non-selective transfer mechanism — many taxa representing planktonic and nektonic organisms capable of passing through coarse ballast water intake screens are common. These include zebra mussels, Asian clams, bloom forming dinoflagellates, fish and crustaceans. Current control methods rely on ballast water exchange at sea but this is only partially effective and can result in excessive structural loading of the ship's hull. There is a pressing need for new economical and safe control strategies. Aquatic species, in general, are intolerant to increases in dissolved carbon dioxide concentrations given its effect on water, blood and hemolymph pH. These species are also sensitive to elevated total dissolved gas pressures. The gas bubble disease that develops following exposure can, as with carbon dioxide exposure, cause mortality. We are exploiting this sensitivity by developing a control method based on manipulation of dissolved gas concentrations — supersaturation of blood and tissues with gas followed by an induced (short-term) pressure release. Specific hypotheses being tested, are 1) supersaturation of water with carbon dioxide, power plant exhaust (CO_2, 14%; O_2, 4.5%; N_2, 81.2%; SO^2, 0.3%) or a combination of these gases will cause mortality of target species; and 2) control method efficiency is dependent on dissolved gas concentrations, treatment duration, target species and life stage.

Tests to date have been completed using replicate bench scale hyperbaric chambers that provide temperature and dissolved gas pressure control. Results indicate carbon dioxide and power plant exhaust are effective at controlling a wide range of target species, including mollusks, crustaceans and fish. Required exposure periods (LT_{50}) are relatively short and decrease with increasing gas supersaturation levels. Gas recovery and reuse methods developed have reduced gas requirements by up to 85% making the method attractive in ballast tank applications as well as water conduits susceptible to fouling with exotics such as the Zebra Mussel. Further refinement of the method is required prior to application by industry. Specific needs currently being addressed include 1) modeling the effect of ballast tank geometry on gas transfer and mixing 2) evaluating the potential for use of diesel engine exhaust gases; and 3) demonstrating method effectiveness in water conduit applications.

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Rapid Deoxygenation of Ballast Water: Effectiveness and Applicability of a Bio-reactive Process

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Laboratory experiments in 200-liter tanks were conducted to determine the effectiveness of a bio-reactive process to induce rapid oxygen depletion in ballast tanks in order to reduce the risk of transferring invasive aquatic organisms. Results showed that dissolved oxygen levels dropped below 0.2 mg/L in 1 to 5 days after the beginning of the treatment. The rate of oxygen depletion in water was inversely related to temperature ranging between 4 and 25°C. The performance of the process is similar in both fresh and salt water and was unaltered by the level of mixing of the medium. Hypoxic conditions (<0.2 mg/L) were maintained up to 12 days after inoculation. During treatment, levels of nitrates dropped to zero, while levels of ammonia increased. Levels of dissolved organic carbon declined and particulate carbon and particulate nitrogen both increased over time. Production of hydrogen sulfide was noted but levels were low and tended to increase with experimental temperature. Toxicity testing using Microtox bioassay showed no evidence of environmental toxicity of the treated waters once discarded. The above results suggest that this technology seems environmentally-safe and that its application as a ballast water treatment method on board ships should be considered. A cost-benefit analysis of this method relative to other treatment methods is presented.

NOTES

Treatment of Ships' Ballast Water Using the Strong Dielectric Barrier Discharge

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Until now, no effective method is used in the treatment of ship's ballast water on board. A physics method is studied that the electrons are accelerated and then the gas molecules are aroused using a strong dielectric barrier discharge. With this method, the strong electric field ($E_d \geq 400Td$, $1Td=10^{-17}Vcm^2$) is formed with the thinner α-Al_2O_3 dielectric layer in the micro- gap at a high pressure ($P \geq 0.1Mpa$ or $n=2.6x10^{-19}/cm^3$). The electrons achieve the average energy of above 12eV. As a result, O_2 in air and H_2O in seawater are ionized and dissociated into a number of activated particles such as OH, O_2^+, $O(^1D)$, HO_2 radicals, and then dissolved into a part of seawater to form the dissolved hydroxyl radicals. The ratio concentration of OH is 23.4mg/L in 20t/h pilot-scale system and injected into the main pipeline of ballast water discharge. The experimental results are as following:

1) OH radicals are dominantly produced from the positive ions O_2^+ reacting with H_2O to form the water cluster ions.
2) The concentration of killing organisms in ship's ballast water is only 0.63m/L.
3) The duration to kill mono-cell algae, bacteria and protozoan are very fast only 2.67s.
4) The hydroxyl radicals have much stronger oxidized and decomposed actions to the photosynthesis pigments of phytoplankton. The contents of chl-a, chl-b, chl-c and carotenoid are decreased to 35%-64% within 8.0s further to the lowest limit of test after 5 minutes.
5) The lipid peroxide degree of cell is increased three times. The basic life substances, monose, amylose, protein, DNA and RNA of cell, are greatly destroyed. Also CAT, POD and SOD of antioxidant enzyme system are obviously destroyed. Biochemistry processes is the main reasons of organism cell death.
6) The quality of ballast water is greatly improved. With the duration of 2.67s, the decrease rates of COD, nitrite and ammonium salt are 100%, 98.3% and 99.5% respectively, and the turbidity is decreased to 50%. DO is increased 77% due to the decomposition of residual OH.
7) The equipment of hydroxyl solution has some advantages such as small volume, simple operation and low running cost, which is only 1/30 cost in comparison with the open-ocean- exchange of ship's ballast water.

In a word, the treatment of ships' ballast water using OH radicals is a kind of advanced oxidation method, which realizes Atom Economy, Zero Emission and Zero Pollution in the process of the production of OH radicals and the killing of organisms in ships' ballast water. Invasive marine species can be killed in ship in the process of the discharge or inputting ballast water.

NOTES

Development, Verification and Installation of Electro-ionization Technology for Ballast Water Treatment on a Cruise Ship

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Ballast water discharge, which is causing severe worldwide economic, ecological and health concerns, has been the focus of intensive research and development by Marine Environmental Partners, Inc. (MEP) and has led to the introduction of the MariSan™ ballast water treatment system. Incorporated into its multi-step sanitation process is electro-ionization. MEP tested its capabilities in a system built and operated in the laboratory at Nova Southeastern University Oceanographic Center (NSU) and onboard Carnival Cruise Lines' MS Elation.

The complete MariSan™ Ballast Water System includes:

1) Solids removal module,

2) Seawater electrolysis module,

3) Ambient air ionization (IONZTM) module, and

4) Static mixing module.

MEP subsequently sold and installed a full-scale system on Carnival's Elation, and built a 1/20th scale model research unit housed at NSU for parameter experimentation.

Onboard and lab tests thus far show 95% or greater elimination of biota and system modifications produce no chlorine or bromine residuals. Chlorine and bromine are not added; biota inactivation is accomplished through the introduction of traces of bromine/chlorine that have been produced from the sea water through electro-chemistry. Ionized gases that have been produced from ambient air enhance sanitation and aid in the neutralization of the bromine/chlorine produced in the process.

Comprehensive independent toxicological tests on the ballast water effluent were performed using water treated by electro-ionization. Acute exposure test results indicated no surrogate organism (Mysid shrimp) death. Chronic static exposure (seven days) test results indicated no impact to growth or their ability to reproduce. A critical element of the MariSan™ ballast water system is its lack of environmental impact upon discharge.

Additional testing for the State of California Lands Commission and the United States Coast Guard will be conducted on various other life forms including:

- *Haliotus rufescens* - red abalone (invert. mollusc)
- *Crassostrea gigas* - oyster (invert. bivalve mollusc)
- *Mytilus* spp. - mussel (invert. bivalve mollusc)
- *Macrocystis pyrifera* - giant sea kelp (alga)

Testing for miscellaneous compounds possibly formed during the process also were conducted. This included testing for carcinogens, THMs, etc. Formal testing for California Lands Commission commenced in February 2004 and the results of all of this testing formed the basis of this presentation.

MEP specifically designed the MariSan™ ballast water system to meet the International Maritime Organization's (IMO) mandate for a system:

- Safe to ship and crew
- Environmentally acceptable
- Practical
- Cost efficient
- Biologically effective

With MariSan™ technology the hazards associated with open sea exchange are eliminated; testing has shown the effluent to have no affect on the natural ecology; the system has a small footprint enabling adaptation to confined space configurations; it is fully automated; and it is cost efficient to operate and maintain.

NOTES

Engineered Biomimetic Surfaces To Reduce *Ulva* Zoospore Settlement

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There is a significant need for coatings and substrates with the ability to tailor settlement and adhesion of biological organisms and cells. The cascade of events involved in biological adhesion to a synthetic surface is complex. Surface chemistry, topography, and bulk properties of the substrate all affect the strength of biological adhesion. The ability to tailor a surface to control bioadhesion would have implications in applications as diverse as ultrafiltration, coatings, and biomaterials. Coatings are specifically needed for the prevention of marine biofouling on surfaces such as the hulls of ships and water treatment facilities. The formation of marine biofouling is an intricate hierarchical process, involving the sequential settlement, adhesion, and growth of progressively larger and more complex organisms.

The marine alga, *Ulva*, is the most common macroalga that fouls ships and submarines. Fouling occurs by the settlement of motile spores, which subsequently adhere by the secretion of a glycoprotein adhesive that anchors the spore to the surface. Previous studies have shown that the swimming spores are able to sense the energetically most favourable location to settle on a given substrate, via settlement cues including phototaxis, chemotaxis and thigmotaxis.

Our research group has engineered surface topographies that significantly reduce marine fouling by optimizing mechanical and energetic effects. It has long been known that surface roughness affects wettability. Wenzel and Cassie have previously described the geometric relationships between surface topographies and both advancing and receding contact angles of liquids on solid surfaces. Kendall has described the influence of the bulk modulus and surface energy of a solid surface on adhesion strength of elastomers. Our group has combined these two concepts into engineered surfaces that mimic biologic surfaces that exhibit antifouling properties in the marine environment.

We will report on the effect of micropatterned surfaces for control of biological settlement and adhesion with respect to zoospores of the macrofouling alga, *Ulva* as well as large macrofoulers such as bryozoans and barnacles. The topographical features studied included ridges, diameter pillars, and a biomimetic engineered surface topography that resembles shark skin. The dimensions range from a sub-micron nano features to large features on the order of millimeters. Surfaces with dimensions greater than ca. 2 micron topographies, e.g., 2 µm wide x 2 µm deep, enhance settlement of the zoospores. Our first successful biomimetic engineered surface embossed on a polydimethylsiloxane elastomer has reduced settlement of the zoospores by 86%. This is compared directly with a control surface of the PDMSe that is topographically smooth to the nanometer scale. We will report on the physical and mechanical properties of the elastomers and the bioassays used to characterize both biosettlement and biorelease. These results are the first definitive example that minimally fouling substrates can be produced using microtopographies. Future studies will examine the limits of the models to predict the anti-fouling and foul-release behavior of engineered surfaces.

NOTES

Acute Toxicity of SeaKleen (Menadione) to Zooplankton Diapausing Eggs

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Of the vectors for nonindigenous species introduction into the US Great Lakes, transoceanic vessels are especially well known and problematic. Efforts to reduce the risk of nonindigenous species introduction from these ships have concentrated on preventing the release of ballast water collected at foreign freshwater ports. But ballast tanks devoid of water remain a threat due to the presence of residual sediment, which is known to harbor the resting stages (diapausing eggs or cysts) of invertebrates. Treatment of ballast residuals with biocides has been proposed as a possible control method, but the response of target organisms in the resting stage to biocides is not well understood. If biocides are to be used as a control method, vulnerability of resting egg stages to biocides must be assessed directly. We will report on the acute toxicity of SeaKleen, a commercial product consisting of Menadione, on rotifer, copepod, cladoceran, and brine shrimp resting eggs obtained from commercial sources, laboratory cultures, and lake sediments. New methods for the use of resting eggs in bioassays will be described. Additionally, the establishment of Artemia resting eggs as a standard test organism for toxicity studies examining aquatic invertebrate resting life stages will be advocated.

NOTES

Development of Full-Scale Ballast Water Treatment Systems for the Control of Aquatic Nuisance Species

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The paper will describe the Baltimore Harbor Ballast Water Treatment Program (the largest program of its kind in the US), which examines a variety of technologies designed to eliminate nuisance species from ships' ballast. The current program involves the testing of full-scale systems both in Baltimore Harbor and aboard commercial vessels. We will discuss the development of UV, biocide and physical filtration/separation systems during laboratory/mesocosms studies in our laboratory over a period of more than ten years and will report on their efficacy under shipboard conditions. We will also describe progress in deployment and testing of full-scale commercial trials of some of these systems developed as a result of this program. Finally, a soon to be conducted test aboard an operating cruise ship, fitted with a BWT system employing solids filtration and UV light irradiation will be discussed.

NOTES

Design Optimization and Test of an Onboard Treatment of Ballast Water (TREBAWA) – Combination of Hydrocyclone and UV

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The harmful environmental effects on the ocean environment as a result of translocation of foreign or unwanted aquatic bodies via ballast water are well documented. The TREBAWA group is a European consortium that addresses this issue by focusing on the development of a new technically and economically competitive ballast water treatment system to be employed onboard ship. The proposed system consists of a primary (hydrocyclone) pre-treatment phase together with a secondary integrated UV system to prevent microorganisms' transport by disinfection of the ballast water.

The paper will present research methodology applied in the project, the results of system design optimisation with computational fluid dynamics (CFD) simulation, system set up and operation, results of field tests, conclusions and recommendation to further work.

NOTES

Shipboard Demonstration of Chlorine Dioxide as an Effective Ballast Water Treatment on the M/V Atlantic Compass

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Chlorine dioxide has been used safely and economically for over 50 years in industrial and municipal applications to control microorganism. Chlorine dioxide is unique in effectiveness against all organisms. It does not form unwanted chlorinated by-products even in heavily contaminated water and after treatment it is environmentally acceptable. Chlorine dioxide can also be generated on site safely and economically.

Chlorine dioxide has been used successfully in brine applications from deep oil well applications to a disinfectant in contact lens solutions. However, the effectiveness of chlorine dioxide as an effective treatment for the control of invasive species was not determined until breakthrough research was conducted at the University of Rhode Island Graduate School of Oceanography in 2001.

Through the work conducted at the University of Rhode Island, it was found that a low dosage (5.0 mg/l) of chlorine dioxide is sufficient to kill 99% of zooplankton, phytoplankton, bacteria and viruses in seawater. The chlorine dioxide residual was depleted in less than 24 hours after treatment and there was no re-growth of any organisms. Chlorine dioxide can be safely manufactured on board ship and the treatment dosage will not affect the ship's base metals or coatings. The ability to neutralize invasive species at a low dosage and then be environmentally acceptable makes chlorine dioxide an excellent candidate for treating ballast water.

Ecochlor Inc. has installed its patented Ecopod™ System on board the M/V Atlantic Compass owned and operated by Atlantic Container Lines. The Atlantic Compass is a Swedish flagged, RORO / Containership that was built in 1984. The vessel has a length of 292 meters (958 feet), a breath of 32.26 meters and at max draft, a tonnage of 51,648 DWT. The Compass has two ballast water pumps that are each rated at 900 m^3 per hour.

The Ecopod™ System is a self contained system that was installed during normal ship operations as the vessel traveled from Antwerp, Belgium to Gothenburg, Sweden in May of 2004. Additional electrical installation for the system was done as the ship sailed from Liverpool, England to Newark, New Jersey. The Ecopod™ System installed on this vessel is designed to treat in excess of 2,500 m^3 per hour.

Chlorine dioxide has been produced by the Ecopod™ System during the initial stages of the demonstration. Ballast water was treated in Newark, New Jersey, Baltimore, Maryland and Portsmouth, Virginia. Chlorine dioxide demand testing was performed as well as residual decay in the treated ballast water. Chlorine dioxide residuals were verified to be less than detectable levels prior to discharge.

This paper will discuss the preliminary results of the collaborative study between Atlantic Container Lines and Ecochlor, Inc. and the future plans for independent verification of this technology.

NOTES

An Economical Ballast Water System – Combined Effects of Hypoxia (De-oxygenation), Hypercapnia and a Low pH by Inert Gas Infusion

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This paper describes the ship-board design of a ballast water treatment (BWT) system, which infuses inert gas into the ballast water. The tests and analyses show that the system effectiveness meets or exceeds the standards for ballast water treatment, as stated in the pending legislation in the United States or in the proposed rules of the International Maritime Organization (IMO). The infusion of the inert gas, has been laboratory tested at the Scripps Institution of Oceanography and results of the tests are presented.

Treatment methods and options to "kill" Aquatic Nuisance Species (ANS) introduced by ballast water, in the most cost effective and pragmatic approach, are discussed in this paper. The ballast water treatment method focuses on bubbling inert gas via a row of pipes located at the bottom of the ballast tanks. The infusion of the inert gas, a tri-mixture of about 2% oxygen, 12% to 14% carbon dioxide, and the rest nitrogen achieves de-oxygenation (resulting in hypoxia), elevated level of CO_2 (resulting in hypercapnia) and acidic pH. The very promising combined effects of hypoxia, hypercapnia and acidic pH on marine organism are discussed in this paper.

Research methods are described here-in. Several different marine invertebrates, plankton and a representative bacterium, *Vibrio cholerae*, were incubated in experiments to determine their survival. The parallel incubations were gassed with nitrogen (anaerobic control) or "Trimix" (2% oxygen, 12% carbon dioxide, balance nitrogen). Aerobic controls, which were gassed with air, were done in parallel for each incubation. The test results show that the treatment objectives are met. All organisms tested died within few hours after incubation by the "tri-mixed" inert gas. The survival rate appears to be significantly shorter than in anaerobic incubation. All invertebrates showed no mortality in aerobic incubations. *V. cholerae* was non viable (>99%) after an incubation period of 24 hours. Special consideration is given to the development of methods to determine unequivocally the time of death of plankton, microorganisms, and macroalgae.

Shipboard Installation: Analyses and a shipboard design of the treatment system are presented in this paper. Installing a cost effective, practical and viable ballast water treatment system on-board a ship is challenging because of the huge amounts of ballast that must be treated. There are at least half a dozen systems, which may be effective in "killing" ANS, but are impractical on board a ship, costly to operate, dangerous or grossly inadequate to treat large amount of ballast water in a given time frame. The ballast water system described and analyzed in this paper is based on a 300 000 dwt tanker, which carries about 128,000 tons of ballast. A cost estimate for the installation of the system on a 70 000 dwt tanker is also performed.

Shipboard System Description: Each ballast tank has rows of pipes at the tank floor with downward pointing nozzles. The pressurized inert gas is jetted downward out of the piping. The bubbles rise through the ballast water to the space above the surface, which has been (optional) previously underpressurized to – 2 psi. Details of the design study are presented as well as the economic analysis. Based on the 300 000 dwt tanker design, which carries 128,000 tons of ballast, the system described can effectively treat that ballast in approximately 48 hours. The pacing events in the establishing of the lethality in ballast water are the times required to elevate the concentrations of CO_2 and its ionic forms and the decrease of the oxygen level.

Economic Analysis: The economic analysis shows, for a 300 000 ton tanker utilizing its own inert gas generator, that installation cost of the ballast water system described here-in is approximately $2.7 million and the operating cost of treating per ton of ballast water is 3.8 cents. Similarly, for a 70 000 ton tanker the installation cost is approximately $1.5 million and the operating cost is 3.5 cents per ton.

Effective Strategies that Work to Prevent the Spread of Aquatic Invasive Species by Recreational Boaters

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Effective public education is the key to prevent and slow the accidental spread of aquatic invasive species (AIS). While many human-mediated pathways exist for overland dispersal of AIS, recreational boaters are recognized as a primary pathway. Results of a Sea Grant-sponsored mail survey administered in Minnesota, Ohio, Vermont, Kansas, and California shows that AIS education can significantly change boater behavior to reduce their risk for spreading AIS. Minnesota and Vermont have invested more in AIS public education programming and used a greater variety of effective methods than the other states surveyed. Minnesota and Vermont boaters were most aware of AIS issues and reported taking action (90% and 82%, respectively) at water accesses to prevent their spread. Ohio boater awareness was also relatively high, however, less than half (45%) took actions to prevent AIS spread. Although AIS boater awareness was generally lower than other states surveyed, California and Kansas boaters regularly took appropriate actions at water accesses (40% and 30%, respectively) to prevent the spread of AIS. Another sign that AIS education works is that the percentage of Minnesota boaters who took action has increased by over 20%, compared to a similar Sea Grant survey in 1994 (when 70% took action).

Results indicate that boaters are willing to take action if they know what to do. Most often, boaters' motivations for taking action were to keep AIS "out of my lake" or because "it is my personal responsibility." Effective public education taps these motivations, stresses why preventing the spread of AIS is important, and delivers concise, consistent messages. Miscommunication like, "it's only a matter of time" or "it only takes one mistake to cause an infestation," confuses the message, undermines successes in behavioral change, and fuels public apathy.

Making AIS a priority through a comprehensive program of public education, monitoring, watercraft inspection, and enforcement is effective. (In particular, enforcement of state laws prohibiting transport of any aquatic plants, injurious species, and contaminated boats and water has successfully interrupted the pathways for AIS spread.) Using education as the 'carrot' and enforcement as the 'stick' is an approach that works.

Funding for this project was provided by a grant from the US National Oceanic and Atmospheric Administration to the National Sea Grant College Program through an appropriation by Congress based on the National Invasive Species Act of 1996.

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The GEF/UNDP/IMO Global Ballast Water Management Programme: Reflections, Achievements, Progress and Plans

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The Global Ballast Water Management Programme (GloBallast) is an international technical cooperation programme executed by the International Maritime Organization (IMO), with funding provided by the Global Environment Facility (GEF), through the United Nations Development Programme (UNDP), and with support from individual countries and the shipping industry. GloBallast activities commenced in March 2000 and are scheduled to run until September 2004.

The programme's Development Objectives are to assist developing countries to:

- reduce the transfer of harmful aquatic organisms and pathogens in ships' ballast water,
- implement existing IMO ballast water management Guidelines, and
- prepare for the implementation of a new international ballast water Convention.

The programme is working to achieve these objectives through six initial Demonstration Sites, located in the six main developing regions of the world, followed by regional replication and cooperation. At the global level the Programme has established information clearing-house mechanisms, including internet-based networks, directories and databases, has catalysed a more globally coordinated and cooperative research and development effort, is developing modular training packages and is implementing highly successful communication and awareness activities. Activities being carried out at the Demonstration Sites include:

- Establishment of national and regional institutional structures.
- Communication and awareness activities.
- Hazard analysis and risk assessments (developing standard methodologies).
- Invasive aquatic species surveys and monitoring and ballast water sampling (developing standard methodologies).
- Support for R&D of treatment technologies.
- Assistance with national ballast water policies, strategies, legislation and regulations.
- Training and technical assistance with implementation of the ballast water guidelines, compliance monitoring and enforcement.
- Assistance with developing self-financing and resourcing mechanisms.
- Regional replication of the successes at the initial Demonstration Sites and development of cooperative, multi-lateral regional action plans.

The GloBallast Programme is making a major contribution to addressing one of the greatest threats to the world's oceans, adopting a multi-disciplinary, inter-sectoral approach, embracing partnerships between governments and industry and for the benefit of both developed and developing countries. This paper will review progress to date, lessons learned and plans for the future.

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US Coast Guard Ballast Water Management Program: Battling Aquatic Invasions Through Regulations

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The Coast Guard is the US Federal agency authorized by Congress to develop a national regulatory program to prevent the introduction and spread of nonindigenous aquatic organisms into US waters via the operations of vessels. By direction of two Federal laws, the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990 and the National Invasive Species Act (NISA) of 1996, the Coast Guard has promulgated regulations and established ballast water management programs for the US.

Following the invasion of the Great Lakes by zebra mussels, the Coast Guard developed regulations in 1993, for vessels entering the Great Lakes with mandatory ballast water management practices, and extended these requirements to the Hudson River in 1994. Subsequent high profile invasions, particularly along the Pacific coast, prompted Congress to amend NANPCA with NISA in 1996. Under NISA, national voluntary guidelines on ballast water management (BWM) practices were developed for most vessels entering all other regions of the US after operating outside of the EEZ. One mandatory requirement common to all vessels regardless of entering the Great Lakes are any US port is the submission of a report detailing their BWM practices.

The Coast Guard submitted a report to Congress in June 2002, assessing compliance with the national guidelines and establishing the rate of compliance during the first two years of the voluntary program. The report concluded that compliance was so low that the data could not be used to extrapolate conclusions about industry activities as a whole. Therefore, the Coast Guard is promulgating regulations to address these issues.

The Coast Guard proposed a rulemaking in 2003, to establish penalty provisions for vessels bound to US ports that fail to submit a ballast water reporting form and for vessels bound for the Great Lakes or portions of the Hudson River who violate the mandatory BWM requirements. This regulation was promulgated in 2004. The Coast Guard also proposed another rulemaking in 2003, converting the national voluntary guidelines into a mandatory national BWM program. NISA requires that this mandatory regime be based on the previously established voluntary guidelines and that exemptions for safety concerns be included. This regulation was established in 2004. With the establishment of these two regulations, we have put together an enforcement and compliance program to ensure that vessels comply with these and future regulations.

Since early 2001, the Coast Guard has been working on a regulatory standard for the discharge of ballast water. We have begun the process with an analysis of the environmental impacts of several alternative ballast water discharge standards as required by the National Environmental Policy Act.

These regulations address very complex issues, so to assist the Coast Guard in their development, we are working in conjunction with several other Federal agencies to assist us with the analysis of environmental and economic effects of the regulations themselves as well as to address any endangered species issues that may arise from the development of these regulations.

It is clear that the continued introduction of nonindigenous aquatic organisms by ships poses a serious threat to the environment, economies and health of all nations. We have made great strides with our regulatory efforts this past year and are optimistic that they and future regulations will bear success.

Identifying Regions at Risk Using Time-series Analysis and Life-cycle Models

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Simple time-series models of the water temperature in locations across Australia (based largely on National Tidal Facility SeaFrame Data) have been developed as part of the on-going improvement of the Australian Ballast Water Decision Support System. The forecast time series is used to simulate the daily temperature stress on an organism introduced into each of these locations. When coupled with species-specific life-cycle models incorporating temperature tolerance information, these models allow a biologically "realistic" estimate of the probability that the species is able to complete its lifecycle (i.e., survive) in the new location. An invading organism must negotiate a number of abiotic (e.g., temperature, salinity, habitat) and biotic (e.g., predation, competition, disease) barriers in order to complete its life-cycle in a new environment. The probability that its temperature and/or salinity tolerances will not be exceeded is only one of a number of factors that reduce its chances in the new environment, and hence these models represent the maximum probability that the organism will complete its life cycle in the new locality. Nonetheless this approach provides demonstrable risk reductions over previous simpler approaches to this problem, and form an important new component of the ballast-water risk assessment recently implemented for domestic (i.e., regional) vessel traffic in Australian coastal waters. The models are able to account for and delineate variability and model uncertainty. Furthermore, regression analysis of the probability of survival and latitude highlights a number of interesting regional relationships and allows the probability of survival to be assessed for physically similar locations without specific data.

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Risk-based Decision-making and Optimization in Ballast Water Policy Development

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Invasive species continue to threaten coastal and inland waterways in many global regions, motivating policy action at the international, national, and local level. Ballast water introductions are a major focus of these policy efforts. Many different policies have been proposed with the current policies relying on ballast water exchange as the status quo action for ballast water treatment. At the international level, the recently adopted IMO Ballast Water Convention, when in force, will, in large part, require the attainment of ballast water concentration-based discharge performance standards between 2009 and 2021. The current research will direct significant attention toward examining which trade routes and vessel types present the greatest risk of introducing non-indigenous species; which suite of technologies will need to be employed on a particular vessel type that follows a specific route to reduce the concentration of organisms prior to discharge to a level that is below the specified discharge standard; the least cost solution for that vessel to come into compliance with the standard; and the cost-effectiveness of meeting the present standard and/or alternative standard(s).

The use of linear (and nonlinear) programming to explore tradeoffs between cost and benefits of new technology and to derive optima has a long history of use in energy-related sectors. More recently, Winebrake, Corbett and their collaborators have used it to derive optimal air pollution reductions from Passenger Ferries. We propose the use of a mixed integer, nonlinear programming model to evaluate the potential for technology-policy alternatives to mitigate introductions of organisms. In particular, the model will permit explicit evaluation of potential reductions, costs, and cost-effectiveness of different combinations of technologies and policy approaches to identify a set of candidate technology policies that may achieve environmental policy goals at least cost. Policies that could be evaluated include: no regulation, ballast water exchange, IMO convention concentration limits, more stringent concentration limits, quantity limits, and market-based mechanisms.

At present, we have begun to evaluate cost minimization and the risk of introduction based on several factors, including vessel type, voyage duration, port type/ecosystem (salinity, temperature), treatment-method effectiveness, treatment costs (capital and O&M), tank size, and volume of ballast water discharged. The presentation will include a formal presentation of the nonlinear programming model.

NOTES

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Integrating Science in Ballast Water Management

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Development of the Australian Port Monitoring Framework

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Australia has performed a series of baseline surveys in recent years to assess the spread and impact of introduced marine pests on Australian ports. While these surveys provided critical information used in the development of the policy response, the cost of these surveys meant that it was not possible to repeat them with the frequency required for ongoing management.

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US Coast Guard Ballast Water Management Program: Battling Aquatic Invasions Through Regulations

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The Coast Guard is the US Federal agency authorized by Congress to develop a national regulatory program to prevent the introduction and spread of nonindigenous aquatic organisms into US waters via the operations of vessels. By direction of two Federal laws, the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990 and the National Invasive Species Act (NISA) of 1996, the Coast Guard has promulgated regulations and established ballast water management programs for the US.

Following the invasion of the Great Lakes by zebra mussels, the Coast Guard developed regulations in 1993, for vessels entering the Great Lakes with mandatory ballast water management practices, and extended these requirements to the Hudson River in 1994. Subsequent high profile invasions, particularly along the Pacific coast, prompted Congress to amend NANPCA with NISA in 1996. Under NISA, national voluntary guidelines on ballast water management (BWM) practices were developed for most vessels entering all other regions of the US after operating outside of the EEZ. One mandatory requirement common to all vessels regardless of entering the Great Lakes are any US port is the submission of a report detailing their BWM practices.

The Coast Guard submitted a report to Congress in June 2002, assessing compliance with the national guidelines and establishing the rate of compliance during the first two years of the voluntary program. The report concluded that compliance was so low that the data could not be used to extrapolate conclusions about industry activities as a whole. Therefore, the Coast Guard is promulgating regulations to address these issues.

The Coast Guard proposed a rulemaking in 2003, to establish penalty provisions for vessels bound to US ports that fail to submit a ballast water reporting form and for vessels bound for the Great Lakes or portions of the Hudson River who violate the mandatory BWM requirements. This regulation was promulgated in 2004. The Coast Guard also proposed another rulemaking in 2003, converting the national voluntary guidelines into a mandatory national BWM program. NISA requires that this mandatory regime be based on the previously established voluntary guidelines and that exemptions for safety concerns be included. This regulation was established in 2004. With the establishment of these two regulations, we have put together an enforcement and compliance program to ensure that vessels comply with these and future regulations.

Since early 2001, the Coast Guard has been working on a regulatory standard for the discharge of ballast water. We have begun the process with an analysis of the environmental impacts of several alternative ballast water discharge standards as required by the National Environmental Policy Act.

These regulations address very complex issues, so to assist the Coast Guard in their development, we are working in conjunction with several other Federal agencies to assist us with the analysis of environmental and economic effects of the regulations themselves as well as to address any endangered species issues that may arise from the development of these regulations.

It is clear that the continued introduction of nonindigenous aquatic organisms by ships poses a serious threat to the environment, economies and health of all nations. We have made great strides with our regulatory efforts this past year and are optimistic that they and future regulations will bear success.

Identifying Regions at Risk Using Time-series Analysis and Life-cycle Models

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Simple time-series models of the water temperature in locations across Australia (based largely on National Tidal Facility SeaFrame Data) have been developed as part of the on-going improvement of the Australian Ballast Water Decision Support System. The forecast time series is used to simulate the daily temperature stress on an organism introduced into each of these locations. When coupled with species-specific life-cycle models incorporating temperature tolerance information, these models allow a biologically "realistic" estimate of the probability that the species is able to complete its lifecycle (i.e., survive) in the new location. An invading organism must negotiate a number of abiotic (e.g., temperature, salinity, habitat) and biotic (e.g., predation, competition, disease) barriers in order to complete its life-cycle in a new environment. The probability that its temperature and/or salinity tolerances will not be exceeded is only one of a number of factors that reduce its chances in the new environment, and hence these models represent the maximum probability that the organism will complete its life cycle in the new locality. Nonetheless this approach provides demonstrable risk reductions over previous simpler approaches to this problem, and form an important new component of the ballast-water risk assessment recently implemented for domestic (i.e., regional) vessel traffic in Australian coastal waters. The models are able to account for and delineate variability and model uncertainty. Furthermore, regression analysis of the probability of survival and latitude highlights a number of interesting regional relationships and allows the probability of survival to be assessed for physically similar locations without specific data.

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Risk-based Decision-making and Optimization in Ballast Water Policy Development

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Invasive species continue to threaten coastal and inland waterways in many global regions, motivating policy action at the international, national, and local level. Ballast water introductions are a major focus of these policy efforts. Many different policies have been proposed with the current policies relying on ballast water exchange as the status quo action for ballast water treatment. At the international level, the recently adopted IMO Ballast Water Convention, when in force, will, in large part, require the attainment of ballast water concentration-based discharge performance standards between 2009 and 2021. The current research will direct significant attention toward examining which trade routes and vessel types present the greatest risk of introducing non-indigenous species; which suite of technologies will need to be employed on a particular vessel type that follows a specific route to reduce the concentration of organisms prior to discharge to a level that is below the specified discharge standard; the least cost solution for that vessel to come into compliance with the standard; and the cost-effectiveness of meeting the present standard and/or alternative standard(s).

The use of linear (and nonlinear) programming to explore tradeoffs between cost and benefits of new technology and to derive optima has a long history of use in energy-related sectors. More recently, Winebrake, Corbett and their collaborators have used it to derive optimal air pollution reductions from Passenger Ferries. We propose the use of a mixed integer, nonlinear programming model to evaluate the potential for technology-policy alternatives to mitigate introductions of organisms. In particular, the model will permit explicit evaluation of potential reductions, costs, and cost-effectiveness of different combinations of technologies and policy approaches to identify a set of candidate technology policies that may achieve environmental policy goals at least cost. Policies that could be evaluated include: no regulation, ballast water exchange, IMO convention concentration limits, more stringent concentration limits, quantity limits, and market-based mechanisms.

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US Coast Guard Ballast Water Management Program: Prevention of Ship-mediated Invasions

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The US Coast Guard is the United States agency designated by Congress to develop a national regulatory program to reduce, and eventually prevent, introductions of nonindigenous aquatic organisms into US waters via the operations of vessels. At the direction of Congress, the Coast Guard has established mandatory ballast water management regimes for the Great Lakes and other regions of the US. The National Ballast Information Clearinghouse (NBIC), also established by congressional direction, collects the ballast water management (BWM) reports for vessels entering ports and places outside of the Great Lakes ecosystem and analyzes ballast data and patterns. Efforts are underway to maximize vessels' use of electronic means of submitting BWM reports. The database of information gleaned from the reports is available to the public at the NBIC web site, along with reports of analyses on the patterns of vessel entries and ballast water management practices. On the basis of the first biennial report of the NBIC, the Secretary of Transportation determined that compliance with the voluntary guidelines was insufficient, and directed that the program be made mandatory. The Coast Guard has subsequently initiated a series of regulations that implement penalty provisions for non-reporting and expands the reporting requirement to all ships operating in US waters, and converts the voluntary guidelines into a mandatory program. We have begun the process to establish ballast water discharge standards with an analysis of the environmental impacts of several alternative ballast water discharge standards as required by US law.

To support the development and implementation of this regulatory program, the Coast Guard has initiated a suite of Research and Development (R&D) projects. These projects include efforts to develop protocols for evaluating the effectiveness of treatment technologies, analytical methods for verifying BWE, and management practices that could be used to address the problem of NOBOB vessels, which cannot conduct BWE due to safety constraints. The Coast Guard and the Environmental Protection Agency (EPA) have established a formal engineering test program for ballast water treatment technologies within the EPA's Environmental Technology Verification (ETV) program. The ETV program is intended to accelerate the development and commercialization of ballast water treatment technologies through third party verification and reporting of performance. In support of development of our compliance and enforcement program, the Coast Guard R&D Center is coordinating the development of an improved method for verifying that ballast water in a vessel was in fact taken on in mid-ocean. The Coast Guard is also collaborating with academic and government researchers, and the shipping industry on studies that characterize the temporal and spatial patterns of NOBOB vessels, the amount and distribution of water and sediment carried in their ballast tanks, and the composition of the biological communities they carry. In addition, the Coast Guard has established a program to provide an incentive for ship owners to participate in the shipboard evaluation of prototype treatment systems. Under this Shipboard Technology Evaluation Program, ships operating an accepted experimental system would be considered to conditionally meet regulatory requirements for ballast water management for a specific period of time.

The Coast Guard leads US participation in negotiations at the International Maritime Organization for the Convention for the Management of Ships' Ballast Water and Sediments. The IMO Diplomatic Conference that took place earlier this year brought forth this international agreement and work continues on the development of guidelines that will support this Convention.

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Design and Testing of Incubator-Emergence Traps (IETraps) for Use in Hatching Studies in Ballast Tanks

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Sediments that accumulate in ballast tanks of transoceanic vessels have been shown to contain varying concentrations of resting stages (eggs, cysts, spores) of invertebrates and phytoplankton. Hatching of resting stages collected from ballast tanks under well-controlled optimized laboratory conditions revealed the potential risk for new invasions via these dormant stages. However, it is much more difficult to assess the extent to which such hatching occurs within ballast tanks under regular operating conditions. To solve these problems, a simple and low-cost incubator-emergence trap (IETrap) was designed for *in situ* hatching experiments conducted in ballast tanks on operating commercial vessels. The trap is constructed of standard PVC plumbing components and allows ballast water to enter, while excluding organisms in the incoming water and retaining organisms that hatch within the trap. However, whether the conditions inside the trap match those in the surrounding ballast water, especially the oxygen concentration, is of concern. The presence of sediment inside the traps and restricted exchange of ballast water inside and outside of the trap could lead to hypoxia or even anoxia within the traps, thus confounding *in situ* hatching trials. To evaluate this, two experimental designs were used. In one, live animals were added to a separate trap incorporated into each of four *in situ* hatching experiments conducted on commercial ships, and their condition was evaluated at the end of each experiment. For the second test, the sensor end of an In-Situ Corp. MP Troll 9000 probe was sealed in a trap to continuously record temperature, conductivity and dissolved oxygen within the trap. A second MP Troll 9000 was mounted immediately adjacent to the instrumented trap to measure ambient conditions outside the trap. The instrumented trap package was moored in a ballast tank that was then filled with Great Lakes water for an *in situ* hatching experiment conducted over an 11-day period during October 2003. This experiment was supplemented with additional laboratory tests. The combined field and laboratory experimental results will be presented.

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Analysis of Shipping Traffic Into US Waters by Vessel Service

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This poster presents an analysis of traffic patterns into US waters from ships traveling outside the US EEZ. Patterns are shown for numerous ship types and demonstrate the potential challenge we have in mitigating the spread on invasive species through ships' ballast water. As the poster shows, most ships transiting US waters do not have the opportunity to conduct ballast water exchange, which is the only economically feasible method of preventing ballast water discharges that are favorable to species proliferation. The poster also estimates the annual cost of a new US regulation requiring ballast water exchange for ships operating outside the US EEZ.

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Ballast Water Exchange in Regional Seas

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In February 2004 the International Maritime Organisation adopted a Ballast Water Convention. The convention includes ballast water treatment standards that aim to reduce the risk of introducing non-native species via ballast water. These standards will provide a benchmark for the development of ballast water treatment methods, which has been hampered in recent years by the lack of a treatment standard to aim for. Therefore, there is a current scarcity of technologies that are able to prove they can achieve the standard. Owing to the lack of treatment standards and the associated effect on technology development, many countries, including the United Kingdom, have had to rely on ballast water exchange as the only readily available method to reduce the risk of introducing non-native species.

Ballast water exchange was originally developed for vessels on trans-oceanic voyages as a means of reducing the risk of introducing non-native species via ballast water. The method involves vessels exchanging ballast water taken on in ports for water loaded in deep oceans. The assumption behind this method is that coastal species will be unable to survive in oceanic waters and any oceanic species loaded into the tanks will be unable to survive in the coastal waters of the vessel's next port of call. The method also relies on the fact that plankton are less abundant in open oceanic waters and carrying out the exchange therefore reduces the abundance and diversity of the plankton present in the tanks. Ballast water exchange remains the only readily available technique for managing ballast water, and although the majority of European shipping is regional and vessels are therefore not passing through deep waters, this method may be utilised in these areas owing to a current lack of alternative technology. If in-transit exchange of ballast water in regional seas is to be undertaken then it is important that the effects of such an exchange are better understood. A previous study carried out by Fisheries Research Services Marine Laboratory, Aberdeen seemed to indicate that, in some cases, there might be an increase in diatoms and dinoflagellates after exchange in regional seas. A three year follow on project at the Fisheries Research Services Marine Laboratory carried out a detailed assessment of the efficiency of in-transit exchange in the North Sea and Irish Sea on planktonic organisms in ships' ballast tanks.

The preliminary results would seem to indicate that ballast water exchange in regional seas might not be as effective as mid-ocean exchange. For example:

- When the original port water is of low salinity the salinity of the water in the ballast tanks after exchange does not increase to the same extent as when the original water was of a higher salinity. This could indicate that the original port water might not always be completely removed during the exchange process. Any low salinity water remaining in the tank would then have a dilution effect on the water loaded into the ballast tanks.
- For zooplankton, ballast water exchange generally resulted in a decrease in abundance but an increase in the number of taxa and diversity. Further analysis of the changes in the taxa present before and after exchange is being carried out.
- For phytoplankton, the initial results are more variable. The number of taxa increased on some occasions after exchange and decreased on others. There was generally a decrease in abundance after exchange. Further analysis is underway to determine the differences between the species present in the samples before and after exchange.

Overall, the initial results would seem to indicate that ballast water exchange carried out in shallow waters close to the coast may not be as efficient as exchange carried out mid-ocean. Further analysis of these data is underway and multivariate statistical methods will be used to determine the efficiency of exchange at reducing the abundance and diversity of plankton.

Pulsed Low Power Laser Irradiation as a Ballast Water Treatment Technique: A Laboratory Study

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Ships with ballast water on board act as a vector of aquatic species invasion. Even though the ballast water exchange regulations that were implemented in 1993 target at reducing the problem of nonindigenous species introduction, efforts continue to find a more effective treatment technique. Elevation of the ballast water temperature to above 30°C, irradiation of water using UV light and treatment of ballast water with biocides are some of the techniques that are being tried.

In this report we present data on the laboratory studies of the impact of low power pulsed laser irradiation from a Nd:YAG laser on three marine phytoplankton species. The phytoplankton species used were *Skeletonema costatum*, *Chaetoceros gracilis* (centrale diatoms) and *Heterocapsa circularisquama* (dinoflagellate). Individual cultures of these species were exposed to laser irradiation in a flow-through irradiation assembly (a glass tube of 50cm long and 2.5cm diameter and irradiated from the top (beam diameter 2.1cm) with two flow speeds 9 lit/h and 4.6 lit/hr (retention time 42 and 85sec, respectively). The results showed that the laser irradiation of fluence 0.1J/cm^2 resulted in a significant mortality of diatoms and dinoflagellate. The mortality for 4.6 lit/h flow was >90% in *S. costatum* and *H. circularisquama* and >70% in *C. gracilis*. The survived cells showed a sluggish post-irradiation growth (observed for 10d in an illuminated incubator at 21°C) compared to the non-irradiated control. The cells upon irradiation were found broken. This result shows that laser irradiation has the potential as a ballast water treatment technique to reduce the problem of species invasion via ballast water.

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Ships' Sea-Chests — A Dispersal Mechanism for Nonindigenous Species

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The transport of larvae in ballast water has been proposed as a dispersal mechanism for non-indigenous species. However, the larvae of many species are short lived and would not survive the long voyages involved in international shipping. They will metamorphose in the ballast tank, but the juveniles are unlikely to obtain sufficient dissolved oxygen and nutrition to survive. Since larval dispersal is unrealistic for these organisms, mature adults must have established the populations in the new environments. But how can the adult organisms be transported long distances?

The ascidian *Styela clava* is a good model for the study of long distance dispersion of organisms with short larval life-stages. It is oviparous; the eggs hatch after 12 to 15 hours and the larvae are active for approximately 12 hours. The larvae settle on a hard substratum and develop into sessile adults. *S. clava* is native to the northwest Pacific; it was first recorded in British waters in 1954, and has since spread along the west coast of Europe. The natural dispersal methods suggested for its spread involve drifting of larvae and adults attached to flotsam; the man-aided methods involve transport of juveniles and adults, either attached to oyster shells or to ships' hulls. However, the observed distribution of *S. clava* is extremely patchy. This heterogeneous distribution cannot be explained by natural dispersal or the presence of oyster fisheries. The adults are rheophobic, so hull attachment is an unlikely mechanism for dispersal, but they could be transported attached to the inside of ships' sea-chests. These seawater intake chambers provide a relatively sheltered environment in which the organisms can grow to maturity then spawn in any harbour with suitable water quality.

The paper reports the results of several examinations of ships' sea-chests and demonstrates that this is a suitable dispersal mechanism for a variety of marine organisms.

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