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Jellyfish and Jellyfish-like Organisms

Technical Brief — *Debris*

A pink meanie jellyfish feeds on a moon jelly (left, Smithsonian 2013). Hundreds of jellyfish block the trash racks (top right) and cover the floor (lower right) at the Orot Rabin Power Station in Hadera, Israel (www.dailymail.co.uk).

Jellyfish as Debris

Jellyfish and jellyfish-like gelatinous organisms can pose a significant threat to power plant cooling water intake structures (CWIS). In sufficient quantities, jellyfish can block intake screening equipment (e.g., bar racks and traveling water screens) leading to reduced cooling water flow or, in extreme cases, structural failure of the screening equipment. Furthermore, the passage of jellyfish into the circulating water system can result in the condenser tube plugging. Cooling water blockage is a concern as it negatively affects facility reliability and results in a loss of revenue. This technical brief provides background on jellyfish and jellyfish-like organisms as debris agents at power plant CWIS. It includes information on the organisms' biology, jellyfish blooms, and control strategies. It also provides a list of external resources such as key literature, websites, and contact information for technical experts on jellyfish.

ISSUE

Jellyfish, comb jellies, and salps (Phylum Cnidaria, Ctenophora, and Chordata, respectively) are gelatinous animals which live on the seafloor, swim within the water column, or drift with ocean currents. It is speculated that rising seawater temperatures, overfishing of predators and the availability of more nutrients have aided in the population explosion of many species of jellyfish and other jellyfish–like organisms (Smithsonian 2013). Whether the causes are natural or anthropogenic, these aggregations, more commonly known as jellyfish "blooms", "swarms", or "outbreaks", have begun disrupting fisheries, marine recreational activities, and are an increasing issue at power plant CWIS. Jellyfish populations can explode quickly and blooms can appear to come out of nowhere due to the organisms' ability to grow fast, reproduce quickly, and survive in environments most marine organisms find uninhabitable (NSF 2013).

However, recent research presented at the 2016 5th International Jellyfish Bloom Symposium (Barcelona) indicated that the perceived rise in jellyfish quantities and expanding geographic reach may not exist. Although jellyfish biology is well understood, the Symposium illustrated that knowledge of jellyfish blooms is just beginning.

BIOLOGY

While jellyfish, comb jellies, and salps share a similar morphology, they are biologically very different. Salps, which are planktonic tunicates, are more closely related to vertebrates (Madin 2010). Jellyfish and comb jellies are comprised of two major cell layers: the external epidermis and internal gastrodermis. Between each cell layer, the mesoglea makes up a kind of internal skeleton containing some structural proteins, muscle cells, and nerve cells. Jellyfish and comb jellies have no stomachs, intestines, or lungs. Instead, the gastrodermis lines an all-purpose gut and opening through which food enters, waste is eliminated, and reproductive cells are released (Smithosonian 2013).

Salps have gelatinous and transparent bodies that can be shaped like cylinders, spindles, or prisms. Salps move via jet propulsion by ingesting water at one end, passing it through its contracting hollow body, and ejecting it through a siphon on the opposite end. In the process, planktonic food items are filtered out using an internal mucous net (Sutherland and Madin 2010; Greenberg et al. 2010).

Globally there are approximately 4,000 species of jellyfish and up to 150 species of comb jellies. Not all species swim and float through the water, but those that do can drift with currents for thousands of miles. Jellyfish are carnivorous and eat plankton, crustaceans, and small fish. There are also a number of marine animals known to eat jellies including some fish species

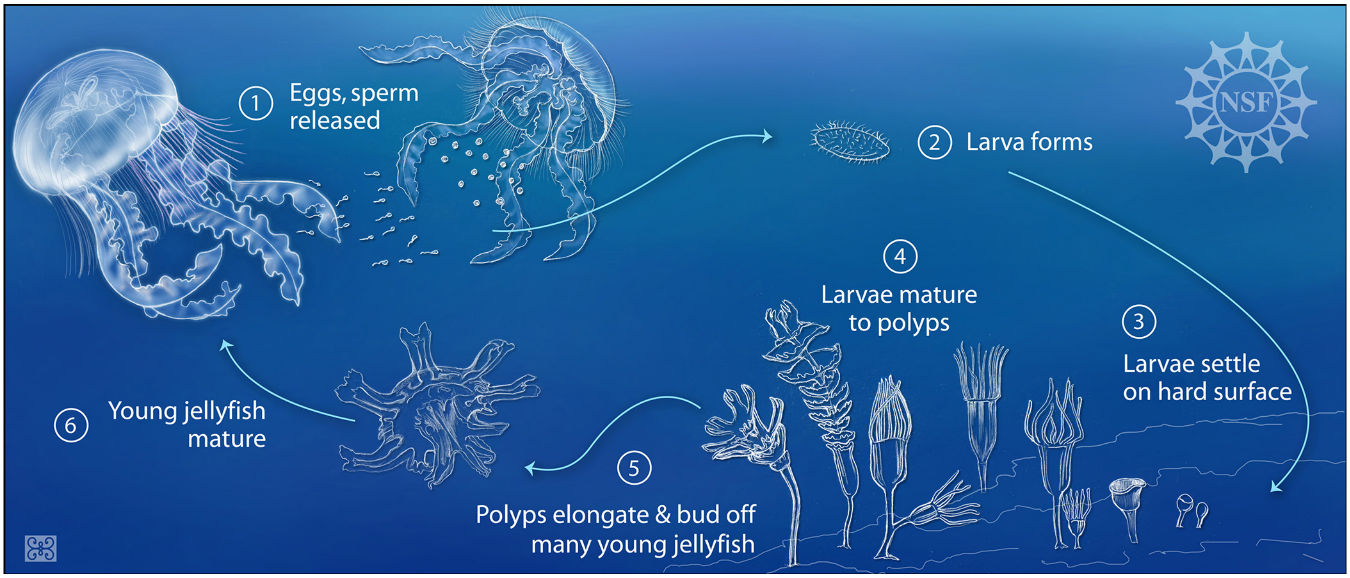

Figure 1 – Jellyfish reproductive cycle (Image from NSF website:http://www.nsf.gov/news/special_reports/jellyfish/jelly_life.pdf)

and even endangered leatherback turtles (Dermochelys coriacea) (Smithsonian 2013).

There are approximately 50 species of salps throughout the oceans. Some look like tubes or long snakes, while others look more like chandeliers hanging in the water. They can exist as single animals called solitaries or as chains called aggregates and populations can grow rapidly under the right conditions (Madin 2010).

Jellyfish, comb jellies, and salps have very different reproductive cycles. Comb jellies have the least complex reproduction, relying on self-fertilization, since most comb jellies are hermaphroditic (Smithsonian 2013). Salps represent the next level of reproductive complexity with solitary salps reproducing via asexual budding to produce the next generation. The offspring of asexual budding emerge as an aggregate from the parent. Aggregate salps can reproduce sexually, releasing solitaries into the water column (Rakow 2009).

Reproduction of "true" jellyfish is more complex than that of salps (Figure 1). Adult female and male jellyfish release eggs and sperm, which unite to produce a larva (planula) that attaches to a hard surface. Living stationary (sometimes for decades) in the polyp phase, it awaits favorable conditions, at which point it elongates and buds off, releasing many young jellyfish. Though little is known about the polyps' formation (since they are rarely found or studied in the wild), it is believed that fields of polyps release immature jellyfish simultaneously, creating tens of thousands at a time. These juvenile jellyfish rapidly mature into adults and repeat the cycle (NSF 2013). Most jellyfish species live less than a year and some of the smaller species may only live a few days (http://www.jellywatch.org/blooms/facts).

Adult jellyfish are very adaptive and can survive well in varying environments and new ecosystems. They have broad diets, reproduce quickly, can alter body size based on food availability, and can tolerate low-oxygen water (Smithsonian 2013).

EXTENT AND OCCURRENCE OF BLOOMS

Speculation that jellyfish blooms have increased in recent decades is under debate. Some scientists and conservationists believe that humans have influenced the marine ecosystem to such an extent that systems are out of balance, resulting in massive increases in global jellyfish populations (Schrope 2012). Still, the analyses of most existing data sets demonstrate that jellyfish populations naturally fluctuate over the long-term (8 to 100 years) with variation in climate (Purcell et al. 2007; Purcell 2012). For example, the northern sea nettle (Chrysaora melanaster), common in the Bering Sea, showed a dramatic increase in population during the 1990's, peaking in summer of 2000, and then declined and stabilized at a moderate level after 2001, which coincided with warmer water temperatures (Brodeur et al. 2007).

One data set that is difficult to ignore is the growing number of reports of problems associated with jellyfish blooms (Figure 2). For example, in Japan over the last 10 years, a dramatic increase in moon jellyfish (Aurelia aurita) has been noted by fishermen. A majority (65%) of those fisherman surveyed believe jellyfish populations have increased during the last 20 years (Purcell et al. 2007). Han and Uye (2010) note that since the first jellyfish-caused (A. aurita) shutdown of a nuclear plant in 1996, the shutdowns have only become more frequent and the chronic blooms more commonplace. In 2006, the USS Ronald Reagan aircraft carrier was powered down while docked in Brisbane, Australia after thousands of jellyfish were sucked into the ship's water intake diminishing its ability to condense steam from the ship's turbines (Hilburn 2007). A swarm of Australian spotted jellyfish (Phyllorhiza punctata) forced the closure of six Spanish beaches in the summer of 2011 after 100 swimmers were treated for jellyfish stings (NewScore 2011) and more recently in Volusia County, Fl, more than 2,000 swimmers were stung during an extended jellyfish bloom (Daily Mail 2018). In 2011 alone, jellyfish

Figure 2 – Jellyfish blooms in the Gulf of Mexico (image from Monty Graham, Dauphin Island Sea Lab) and an Australian sign warning swimmers of jellyfish (inset image from Flickr user rezendi).

blooms shut down power plant facilities in Israel (Orot Rabin, a coal-fired plant), Scotland (Torness, a nuclear plant), Japan (Shimane, a nuclear plant), and the U.S. (St. Lucie, a nuclear plant in Florida) (Schrope 2012). In April 2012 a large swarm of salps caused a temporary shutdown of Pacific Gas and Electric Company's Diablo Canyon Nuclear Station. Diablo Canyon had also been previously shut down by jellyfish in 2008 (NRC 2008). In early September 2013, Sweden's largest nuclear power plant, Oskarshamn, on the Baltic coast was shut down (similar shutdowns occurred in 2005) by an influx of jellyfish of the genus Aurelia (Mengewein 2013). A giant jellyfish swarm event disrupted operations at the Israeli Ashkelon power plant in 2015 (Schuster 2015).

Scientists who believe blooms are on the rise have identified several possible causes including: climate change, eutrophication, overfishing, and ocean sprawl – excessive development of the coast and open marine areas (Purcell et al. 2007).

Climate Change

Changing environmental factors may directly affect the size, location, and timing of jellyfish populations. Increasing ocean temperatures caused by climate change may be helping jellyfish populations reproduce at a faster rate (Purcell 2005; Han and Uye 2010). For example, the mauve stinger (Pelagia nocephrae) was found to have faster growth at a water temperature of 19°C than at 13.5°C (Purcell et al. 2007). Changing climates have also reduced rainfall in the temperate zones. With reduced rain runoff from land, coastal salinity levels remain high and allow better survival closer to shore, increasing jellyfish-human interactions (Dabir and Kale 2012). Reports indicate that increasing carbon dioxide concentrations in the atmosphere have led to a decrease in ocean water pH. It is speculated that ocean acidification could have detrimental effects on calcifying organism that build skeletons or shells of calcium carbonate. This could, in turn, benefit jellyfish and other non-calcifying gelatinous organisms that are able to thrive in more acidic environments (Purcell et al. 2007).

Eutrophication

An ecosystem's response to the addition of artificial or natural nutrients is generally characterized by an increase in biomass at all trophic levels. In most cases, increased nutrient loads in a marine environment are a result of human development in coastal areas and can be associated with pollution, fertilizers, sewage, and aquaculture (Dabir and Kale 2012). More nutrients mean more food which results in greater reproductive output (Purcell et al. 2007). Eutrophication often results in lower dissolved oxygen levels as biomass increases, especially in bottom waters. Fish avoid or can die in environments with lower oxygen levels; however, many jellyfish species are tolerant of low oxygen and can take advantage of areas with reduced competition for resources (Purcell et al. 2007).

Overfishing

Overfishing of both predators and forage fish opens up ecological space for jellyfish. Commercial fishing reduces the number of jellyfish predators like chum salmon (Onorhynchus keta), butterfish (Peprilus triacanthus), and spiny dogfish (Squalus acanthias) (Purcell et al. 2007). Overfishing can remove the natural check that maintains jellyfish populations. In addition, jellyfish are known to prey on eggs and larvae of those same fish, and their increasing numbers may make it difficult for depleted fisheries to rebound (Stone 2010). The fishing industry also reduces forage fish populations which compete with jellyfish for resources. Fewer competitors results in increased zooplankton for a growing jellyfish population to feed on (Purcell et al. 2007).

Ocean Sprawl

Humans have disturbed the marine environment in many ways either through alterations to the shoreline or through construction in coastal waters. Docks, marinas, breakwaters, oil platforms, and artificial reefs all provide surfaces for jellyfish polyps to anchor and accumulate in large numbers (Purcell et al. 2007). These structures are often in shoreline areas and have the potential to increase both the presence of polyps and the probability that jellyfish blooms will occur. Coastal power plants' thermal discharges could perpetuate the problem by creating areas of elevated water temperature which is beneficial to the reproduction and growth of many jellyfish (Purcell et al. 2007).

Laboratory studies and SCUBA surveys conducted by Duarte et al. (2013) have linked the increase in jellyfish blooms to the proliferation of artificial structures in coastal zones from ocean sprawl. SCUBA surveys were conducted over a wide geographical range (Japan, UK, Spain, and Solvenia). In addition, Duarte et al. (2013) report on recently conducted field and laboratory experiments designed to determine the extent of jellyfish planulae settlement on various artificial surfaces. The field experiments were conducted in the Chesapeake Bay with Chrysaora quinquecirrha and the lab experiments were conducted with Cotylorhiza tuberculata under conditions simulating the Spanish Mediterranean Sea. Duarte et al. (2013) found that there was a significant difference in settlement preference for C. tuberculata and C. quinquecirrha polyps across substrates types and that recruitment on artificial substrates was similar to or greater than recruitment on natural ones. Potentially suitable artificial structures for polyp settlement commonly associated with ocean sprawl includes pillars, platforms, walls, piers, floating docks, oil rigs, aquaculture structures, rip rap, bridges, buoys, moorings, ship hulls, and garbage (Duarte et al. 2013). Research by Tomaru et al. (2014) on the recruitment of moon jellies (A. aurita) reached a similar conclusion – that the prevalence of artificial (particularly plastic) substrates may provide increased recruitment area for jellyfish. Lo et al. (2008) also concluded that the presence of floating aquaculture rafts was among the principal factors contributing to large populations of A. aurita in Tapong Bay, Taiwan.

New Concepts

Some recent studies on the formation of blooms have looked at the issue from a broader perspective, analyzing how current research may be impacting our perception of these events (rather than using site- and species- specific studies to define a global problem). Sanz-Martin et al. (2016) compiled a dataset of over 100 recent papers which evaluated the extent and occurrence of jellyfish and assessed how they presented their arguments for or against the expansion of jellyfish blooms. They concluded that most of the papers presented the data in a way that unnecessarily facilitated the perception that these blooms were increasing. Another study (Dawson et al. 2014) found that in many different locations (Palau, Australia, England, Bering Sea), differences in population genetics and local environmental conditions were large factors in bloom events. There was also evidence of previous local environmental conditions having a larger impact on population levels than current conditions. The authors suggest that assessing singular species in singular locations is more effective than trying to develop geographically-broad analyses. However, synthesizing multiple geographically-focused analyses can help reveal larger-scale population phenomena.

Other studies, however, have a more site-specific focus. For example, a study in Puget Sound (Greene et al. 2015) analyzed 40 years of trawl data which included forage fish and jellyfish catches. The authors analyzed how abundance varied according to sampling location (a corollary to anthropogenic impact) and climate patterns. Relative to jellyfish abundance, the authors concluded that "jellyfish-dominated catches increased 3- to 9-fold in Central and South Puget Sound, and abundance positively tracked human population density across all basins". Forage fish catches also tended to decrease in areas of high human population density. In certain areas of the sound, jellyfish abundance was correlated to both a decline in forage fish catch and an increase in human population density, suggesting that anthropogenic impacts (pollution, overfishing, etc.) can lead to an increase in jellyfish population potentially due decreased competition. Hamre (2015) also suggests that overfishing of competing forage fish may contribute to an increase in jellyfish blooms off the coast of Norway.

In addition to depletion of forage fish stocks, pollution has also been linked to increased prevalence of jellyfish. For example, Gusmão et al. (2014) assessed the distribution of jellyfish in the Atlantic Ocean off Brazil where large blooms of Aglaura hemistoma jellyfish have been attributed to the plumes of more polluted and eutrophic rivers.

These studies illustrate the importance of site-specific analyses in assessing the causes of jellyfish population expansion. Though global trends are not to be dismissed, developing effective control strategies is also something that is likely best served by a site- and species-specific approach (Gibbons et al 2016).

CONTROL

Methods and mechanisms for the control or eradication of jellyfish blooms are somewhat limited. This is in part due to the difficultly in studying jellyfish and the limited historical data on the causes of blooms. Currently there are a few documented control mechanisms under research and several initiatives being undertaken to identify and track jellyfish blooms worldwide.

Barriers and Diversion

Traditional debris screening and handling methods at intakes have proven to have limited success against jellyfish blooms, evidenced by the growing number of plant shut downs. In cases where carryover of jellyfish is an issue, operators are likely to consider switching from through-flow screens to other designs that minimize carryover (e.g., dual flow and Bilfinger Water Technologies - Passavant Geiger Multi-disc screens). In addition, some manufacturers (e.g., Bilfinger Water Technologies-Passavant Geiger) also offer automatically-raked bar screens that have been used to handle heavy jellyfish loads thereby reducing strain on the finer downstream traveling water screens.

A growing area of research has focused on developing physical barriers or diversion technologies to reduce jellyfish impacts on water intakes. For example, Lo (1991) conducted a laboratory study to evaluate the effectiveness of an air bubble barrier on neutrally-buoyant floats (jellyfish surrogate) under various water depths, unidirectional currents, air discharge rates, and wave conditions (Lo 1991). The results indicated that air bubbles alone were inadequate for preventing jellyfish ingress into intakes.

Later, Lo (1996) conducted additional laboratory studies to evaluate the use of a floating boom in concert with air bubbles to prevent the ingress of jellyfish under various current, wind, and wave conditions. Results indicated that the air bubble plume was able to lift the jellyfish to the water's surface and accumulate them behind the boom system where a suction pump could be used to move the jellyfish to safe discharge location away from the intake.

Detection and Removal

The growing issue and concern of jellyfish blooms disrupting power generation at power plants has fast-tracked research and development in many parts of the world. In Japan, the Higashi-Niigata Thermal Power Station has such an issue with jellyfish that engineers have developed an underwater image analysis system used to detect and remove jellyfish automatically (Matsuura et al. 2007). This system consists of an underwater camera mounted at the bottom of the CWIS, image analysis software to detect jellyfish, and a pump to remove detected jellyfish. In Malaysia, research has been conducted using an acoustic sensor to detect jellyfish (Samsuri et al. 2012). This preliminary study utilized jelly crystals as a surrogate and demonstrated success in detection with acoustics; however, further improvements are needed before full implementation on a larger scale is warranted. Brierley et al. (2004) also demonstrated the potential for using hydroacoustics to detect jellyfish and estimate abundance.

Tracking and Early Warning Networks

Marine biologist and jellyfish activists are turning to the web and social media to help develop a better understanding of how changes in the world's oceans are affecting jellyfish blooms. Jellywatch.org (Jellywatch) was created by the Monterey Bay Aquarium Research Institute in 2010 and is an active international collaborative project in which citizen activists can identify and record sightings of blooms (http://jellywatch.org/). Collaborative data collection sites like Jellywatch are being used to create scientifically-coordinated global jellyfish and environmental databases, such as the Jellyfish Database Initiative (JEDI) currently under construction by Jellywatch. The JEDI project will include data acquisition and statistical analysis, global maps of regional jellyfish blooms, information on jellyfish roles within the ecosystem, and discussions on the socio-economic ramifications of jellyfish blooms (Condon et al. 2013). The National Oceanic and Atmospheric Administration (NOAA) is taking this type of jellyfish bloom data a step further and creating tools for forecasting the presence of sea nettles (Chrysaora quinquecirrha) within the Chesapeake Bay. This NOAA project utilizes the established relationship between salinity and temperature conditions and the presence of sea nettles within Chesapeake Bay. NOAA updates a map (hourly) illustrating probable distribution patterns of sea nettles to help minimize jellyfish encounters (https://www.opc.ncep.noaa.gov/Loops/SeaNettles/prob/SeaNettles.shtml).
Japan has also implemented a forecasting project called STOPJELLY to better predict and control outbreaks of jellyfish that impact commercial fisheries (http://tnfri.fra.affrc.go.jp/kaiyo/POMALweb/e-stopjelly.html).

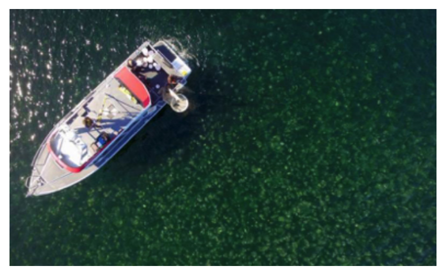

Figure 3 – Aerial image of a jellyfish aggregation captured by a University of British Columbia UAV (Schaub et al 2018).

More recently, forecasting efforts have tried to make use of rapidly-advancing drone and satellite technologies. Researchers at the University of British Columbia are using drones to monitor the behavior and size of large aggregations of moon jellyfish (Vancouver Courier 2018; Schaub et al. 2018). By comparing drone imagery (Figure 3) to net sampling, Schaub et al. (2018) were able to develop accurate biomass estimates of jellyfish aggregations. EDF Energy is co-funding a study with the Natural Environment Research Council Innovative Monitoring Approaches program that is evaluating the utility of satellite imagery for identifying and predicting the movement of

jellyfish and floating mats of seaweed. The work is being conducted through the Plymouth Marine Laboratory in the UK. The objective is to develop an early warning system to prevent power plant shutdowns. More information is available here:
http://www.pml.ac.uk/News_and_media/News/Predicting_blooms_and_blockages.

Eradication

Hyun Myung, a professor of robotics at the Korean Advanced Institute of Science and Technology (KAIST) and his group have developed a robot to combat jellyfish blooms (Figure 4). The Jellyfish Elimination Robotic Swarm (JEROS) is an autonomous vehicle equipped with navigation system, detection camera, and a grid for jellyfish removal (Kim et al. 2013). The JEROS camera system captures images which the on-board computer then processes to identify jellyfish. Once a group of jellyfish have been located, multiple JEROS are able to team up in formation to slice up approximately 900 kilograms (~2000 lbs) per hour of jellyfish through a grid system installed below each unit (Ackerman 2013). A prototype system has been tested in the field to demonstrate feasibility and more tests are planned to gather additional data (Kim et al. 2013). Though initial results appear promising, the prototype JEROS system may be limited in its effectiveness depending on the deployment location and the species being targeted. However, when some forms are cut into pieces, the pieces can regenerate into new individuals. For example, the sea walnut (Mnemiopsis), a type of comb jelly, is one of the more prolific breeders and even cut up bits will regenerate and resume normal life as whole adults in two to three days (Flannery 2013).

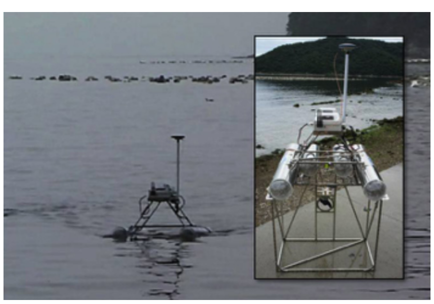

Figure 4 – Jellyfish Elimination Robotic Swarm or JEROS was constructed by a group at the Korean Advanced Institute of Science and Technology (Ackerman 2013)

Other Considerations

Recently, some have suggested jellyfish culls (creating jellyfish fisheries) to keep populations under control. Markets for jellyfish fisheries include as food, absorbent materials, and medicine. Many recent news articles have promoted dehydrated jellyfish as snack chips (https://www.npr.org/sections/thesalt/2017/08/09/542088042/when-oceans-give-you-jellyfish-blooms-turn-them-into-tasty-chips). In fact, jellyfish have been part of Asian diets for thousands of years. In addition, the collagen component of jellyfish has been promoted as an anti-arthritis agent. A combination of the potential positive uses for jellyfish and their nuisance status in many marine industries makes the development of a jellyfish fishery a very attractive control alternative. However, Gibbons et al. (2016) suggest that exploiting jellyfish abundance is not as simple a solution as it seems. They present a few specific cases (e.g., the Inland Sea of Japan and the East China Sea) where controlling the surge in jellyfish numbers is undoubtedly exacerbated by anthropogenic impacts such as overfishing, pollution, ongoing coastal development, and effects of ocean warming. In recognition of jellyfishes' ecological roles, Gibbons et al. (2016) caution against the overexploitation of jellyfish due to the potential for creating unintended ecosystem impacts. Instead, the authors suggest reducing anthropogenic impacts may be the best starting point while we continue to more thoroughly develop the basic research on jellyfish that can be used to support broad control/management decisions such as creating a fishery.

2016 Jellyfish Bloom Symposium

At the Jellyfish Bloom Symposium in Barcelona in May 2016, much of the research presented focused on the changing view of the world's jellyfish populations. Numerous papers and a plenary session focused on answering the question, is there evidence that jellyfish blooms are increasing? The key finding of this research was that there is no evidence or long-range patterns that suggest that blooms are increasing. However, there are limited long-term data sets to be analyzed and there seems to be some linkage with increased sea surface temperature and El Nino. The take home message was that much more research and development is needed. As the previously discussed research by Sanz-Martin et al. (2016) suggests, the increasing blooms may be communication-related (internet development, media miss-representation). No presentations were given on the subject of predicting jellyfish blooms. Evidently, the predictive science has not yet been developed. However, some research has been completed on bloom drift prediction. Researchers are using oil spill drift models to simulate the potential movement of blooms using current, wind, and wave patterns (Cucco et al. 2016).

One paper was presented relative to jellyfish blooms impacting the operation of electric generating facilities. The Korea Marine Environment Management Corporation presented their precautionary management of jellyfish blooms through polyp mapping work. The driver for this work is to reduce the annual damage caused to power plants, which is estimated to be approximately $260 million. Aurelia blooms every year along the coast of Korea and high-speed intake screens do not work at keeping jellyfish out of the downstream plant equipment. The current Korean policy is to map high probability polyp locations based on (1) artificial structures, (2) weak surface currents, and (3) eutrophic conditions. Divers then use high pressure water jets in early spring (before the release of the motile stage) to remove/kill polyps. Two test site removal areas have shown a reduction in blooms by 93%. Future plans include the reduction of artificial structures to restore natural shorelines (Hwang 2016).

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Websites

Fifth International Jellyfish Bloom Symposium
http://www.jellyfishbloom2019.co.za/

Sixth International Jellyfish Bloom Symposium (2019 Save the Date)
http://www.jellyfishbloom2019.co.za/

Jellywatch
http://jellywatch.org/

National Center for Ecological Analysis and Synthesis: Jellyfish Group
http://www.nceas.ucsb.edu/projects/12479

National Oceanic and Atmospheric Administration (NOAA) Chesapeake Bay Office: Forecasting Sea Nettles
https://www.opc.ncep.noaa.gov/Loops/SeaNettles/prob/SeaNettles.shtml

Population Outbreak of Marine Life STOPJELLY Project
http://tnfri.fra.affrc.go.jp/kaiyo/POMALweb/e-stopjelly.html

Experts

Below is a list of experts in the area of jellyfish biology and bloom research.

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