CHAPTER 28

Diagnosis, Prognosis, and Management of Jellyfish Swarms

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Jellyfish includes creatures that are mostly constituted by water and have a gelatinous consistency. In this chapter, after providing a biological description of these organisms, the scales of variability associated to their life cycle and framing their dynamics in the context of the climate change, I review the diverse initiatives and management of coastal jellyfish swarms. Jellyfish swarms have relevant social and economic implications; however, systematic and periodic data of jellyfish occurrences along beaches is sparse. This data would help us to understand the inter-annual variability of the episodes of high jellyfish abundances and its potential relation to variable environmental conditions. Joint strategies with tools available to scientist, administration, policymakers, and stakeholders can optimize the cost of gathering these in situ data and maximize the benefit obtained from its scientific analysis. Three case studies of jellyfish blooms are presented, from which we can infer the importance of co-creation with stakeholders emerges as a key issue to allow for a solid understanding of the episodes and the implementation of appropriate knowledge-based future mitigation actions.

Jellyfish: Biological Description and Scales of Variability Associated to Their Life Cycle

Jellyfish, as a general term, includes creatures that are mostly constituted by water and have a gelatinous consistency. As gelatinous zooplankton they include a broad taxonomy, including numerous groups such as Ctenophores, Cnidarians, salps, larvaceans, molluscs, and worms. This chapter focuses on two phyla, namely Ctenophora and Cnidaria, which are the most relevant due to their great impact on the ecosystem and economy.

Biological description of jellyfish

Among the gelatinous zooplankton, there is a distinct group of carnivores in the pelagic environment, the Ctenophores (commonly known as comb jellies). Recently, a new hypothesis of animal evolution emerged indicating that all animal phyla originated from this group (Dunn et al., 2015; Jager and Manuel, 2016; Presnell et al., 2016; Shen et al., 2017), having regenerative capacities as adults (Martindale, 2016). They have been found to be important predators in the surface waters of the open sea in the North Atlantic and Indian Ocean (Harbison et al., 1978), in the

Prieto, L., 2018: Diagnosis, prognosis, and management of jellyfish swarms. In "*New Frontiers in Operational Oceanography*", E. Chassignet, A. Pascual, J. Tintoré, and J. Verron, Eds., GODAE OceanView, 737-758, doi:10.17125/gov2018.ch28.

Arctic Ocean (Purcell et al., 2010), in coastal areas of North and South America, Mediterranean, Black, Azov, Caspian, and Marmara seas (reviewed in Shiganova et al., 2001; Purcell et al., 2001, 2007) and recently in the North and Baltic seas (Hamer et al., 2011; Javidpour et al., 2009).

The other important group of gelatinous zooplankton is the phylum Cnidaria, which has an immense diversity and consist of five classes: Staurozoa, Hydrozoa, Anthozoa, Cubozoa, and Scyphozoa (Daly et al., 2007). Hydrozoa includes the family Physaliidae or the Portuguese Man-O-War (*Physalia physalis*), well-known due to its impact on human activities on the shore. Anthozoa includes all the corals species. Cubozoa has includes the deadliest species of jellyfish, which cause the Irukandji syndrome in tropical waters, while Scyphozoa includes species that the general public consider "true jellyfish" (Purcell and Arai, 2001).

A common feature of the phylum Cnidaria is the presence of stinging organelles, named cnidocysts or nematocysts, which are triggered by mechanical or chemical stimuli and are predominantly used for prey and defense (Beckman and Özbek, 2012). These cnidocysts are formed by a cnidoblast in which nematocyst are rolled in and prepared to be discharged in a harpoon-like fashion at high velocity (2 m/s) in order to inject the venom inside the target (Holstein and Tardent, 1984). The phylum Cnidaria englobes thousands of species that are present in all oceans, from the tropics to the polar areas, from the surface to the bottom. There are also a few freshwater species. Jellyfish belong to the mid-trophic level within the food web and are predatory zooplankton (Lehodey et al., 2010).

In general, the family Physaliidae are pleustonic, live in the surface of the water, and are open ocean organisms. They are common in tropical and subtropical regions in the oceans, ranging from 55ºN to 40ºS. The Portuguese Man-of-War is a colony of organisms constituted by groups of distinct forms and functional individuals: a polyp named pneumatophore is the sailing bag-form that provides the rest of the colony of the floating device; under the pneumatophore there are three different types of polypoids (gastrozooids for feeding, dactylozooids for defence and gonozooids for reproduction) and three types of medusoids (gonophores, siphosomal nectophores and vestigial siphosomal nectophores). Reproduction is sexual and gametes are spawned in the water, being the fertilization external. Portuguese Man-of-War possesses a singularly potent toxin (Burnett, 2000; Edwards and Hessinger, 2000), being physalitoxin the major protein of the venom, an hemolysin (Tamkun and Hessinger, 1981), which is contained in the nematocysts. The nematocyst venom of *P. physalis* can be lethal to animals and humans (Edwards and Hessinger, 2000), and the envenomation syndromes in humans are extensive (Burnett, 2000).

Regarding Scyphozoa, their size can vary widely from 12 mm to 2 m. They do not have specialized organs for respiration or excretion and generally, during their life cycle, alternate between pelagic and benthic phases. A typical life cycle of a scyphozoan is as follows: They are pelagic and reproduce sexually forming a ciliate planktonic larva named planulae. These larvae search for a surface to attach to and transform into polyps, starting the benthic phase of their life cycle. If the environmental conditions are favorable, polyps can reproduce asexually by different modes: budding, partial fission, and pedal cysts. Nevertheless, under adverse environmental conditions, some species can form podocyst (resting stages). The transition of jellyfish from the benthic to pelagic stages occurs during strobilation. Through this process, individual polyps metamorphose to form the juvenile pelagic stage (free-swimming ephyra) that mature into adult medusae. Depending on the species, strobilation is triggered by warming or cooling of the water (Sugiura, 1965; Calder, 1973; Hofmann et al., 1978; Prieto et al., 2010).

Scales of variability associated to the life cycle of jellyfish

Due to their complex and diverse life cycle, the scales of variability at which jellyfish are exposed to differ: from the ones affecting the benthic ecosystem to the ones acting on the pelagic system, both at coastal and open ocean scales. All those spatial scales also are subject to different temporal scales of variability: climate, seasonal, and meteorological. The variability of the ocean, both temporal and spatial, is described in the first chapter of this book.

The benthic ecosystem has some peculiarities from the point of view of a jellyfish population. For the polyps it has a "biological-spatial-limited" constraint associated to competition and predation. Also, if the environmental conditions (temperature, salinity, food availability) are not favorable, they cannot move to better settlement surfaces. Thus, survival during this life stage is closely linked to the local environment. Therefore, relative short periods of time with very cold temperatures (Prieto et al., 2010), drops in salinity associated to rivers outflows, or long periods of food scarcity (Prieto et al., 2010) would result in a population decrement.

During the pelagic vital phases, jellyfish are exposed both to open ocean and coastal scales of variability. Some species are rarely seen in open waters during their pelagic phase (e.g., *Cotylorhiza tuberculata*). Other species are common in the open ocean (e.g. *Physalia physalis* and *Pelagia noctiluca*) and are only observed in coastal areas when the currents and the meteorological conditions transport them to the shores (Licandro et al., 2010; Prieto et al., 2015).

Some live on the surface of the water (e.g., *Physalia physalis*). If they have a symbiotic relationship with some species of algae in, then these Cnidaria species need light for the algae to perform the photosynthesis and they live in the first few meters of the water column (e.g, *Cotylorhiza tuberculata*). Therefore, all these species are more exposed to surface currents and winds. Other species perform vertical migrations (e.g., *Pelagia noctiluca*), being at the surface at night and at considerable depth by day (Franqueville, 1971; Larson et al., 1991; Mariottini et al., 2008) in response to zooplankton, on which they prey (Giorgi et al., 1991; Zavodnik, 1991; Malej et al., 1993).

Jellyfish Dynamics and Climate Change

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report confirms that warming of the climate system is unequivocal (IPCC, 2013). More than 60% of the net energy increase in the climate system is stored in the upper ocean (0–700 m) during the 40-year period from 1971 to 2010 (IPCC, 2013). But also the ocean is an important sink of atmospheric carbon dioxide (CO_2), as it has absorbed close to 30% of the CO_2 emitted since the industrial revolution (Khatiwala et al., 2013; Le Quéré et al., 2015). This sink of CO_2, even though it has been shown beneficial at a global scale by mitigating the greenhouse effect, has been demonstrated to carry out deleterious effects on the oceanic environment. This is due to the fact that it provokes a gradual decrease in the seawater pH, a phenomenon known as oceanic acidification (Caldeira and Wickett, 2003).

Independently of future predictions scenarios, there are several general hypotheses of the marine ecosystem change associated with global warming. First, the increase in temperature in the surface ocean provokes an increase in stratification and therefore a decrease in winter mixing with the concomitant decrease in nutrient supply to the surface waters. This change in the nutrient concentration results in a decrease in phytoplankton biomass and, at the same time, a shift in the dominant phytoplankton group, from large diatoms to small cocolithophorids (Watanabe et al., 2003). Because of these differences in the phytoplankton, a decrease in the zooplankton biomass and a shift in the dominant zooplankton group occurs, being that jellyfish are the dominant group.

There are more changes in the ecosystem associated with global warming that affect jellyfish population dynamics, such as changes in fish resources (due to their predator-prey interaction), the increase in temperature, and ocean acidification. At the community level, it has been suggested that within the same trophic level, the most tolerant species to the increment of the level of dissolved CO_2 could replace more vulnerable species (Kroeker et al., 2013). This change in community structure towards the dominance of few generalist species would benefit non-calcifying and opportunistic species (e.g., jellyfish and anemonies; Winans and Purcell, 2010).

Purcell et al. (2007) performed a revision of the response to global warming for eight long-term datasets of gelatinous organisms at a global scale, confirming that in five of those time series an increase in frequency has been registered. More recently, Condon et al. (2012) carried out a study to question how much of the perception of the increment on gelatinous organisms was real or just a vision of change from a human perspective. Nevertheless, in diverse sub-basins of the Mediterranean Sea a change in the frequency of the blooms of *Pelagia noctiluca* has been confirmed (Daly Yahia et al., 2010; Kogovsek et al., 2010). This species also proliferates in the North Atlantic (Licandro et al., 2010). Additionally, a greater abundance of *Cotylorhiza tuberculata* and *Rhizostoma pulmo* have been observed in the last 100 years in the Mediterranean Basin (Kogovsek et al., 2010). In the case of *C. tuberculate,* it has been verified that mild winters and an earlier onset of spring will cause a proliferation of *Cotylorhiza tuberculata* during the summer season (discussed later in the chapter).

Laboratory analyses have shown that the increment of water temperature provokes an increase in the asexual reproduction rates of the polyps in Scyphozoa (Widmer, 2005; Wilcox et al., 2007; Purcell et al., 2009). Regarding the capacity of these organisms to tolerate the increase in dissolved CO_2, it has been demonstrated that the associated decrease of seawater pH decreases the size of the statoliths since these are formed by calcic carbonate or calcic sulphate (Winans and Purcell, 2010). The statoliths are sensor organs for orientation and they are essential for survival in the jellyfish life stage (the pelagic one). The interactive effect of warming and acidification on the formation of the statoliths has been evaluated also in the cubozoan *Alatina nr mordens* (Klein et al., 2014). The authors concluded that the number of polyps decreased, suggesting that the asexual reproduction would be slower in an ocean more acid and warmer. Although the polyps could tolerate future conditions of climate change scenarios, it was less probable that they would proliferate in the long-term. Nevertheless, it was pointed out that if the acidification occurred gradually, *A. mordens* could expand to colder waters in short periods of time, as has been evidenced previously in this and other tropical species (Richardson et al., 2009). These results agree with observations that point out that also non-calcifying organisms are not immune to the ocean acidification, although the future evolution of their communities in an increasingly acid ocean is not yet known (Doney et al., 2009; Kroeker et al., 2013).

Initiatives and Management of Coastal Jellyfish Swarms

There are several environmental conditions that favor jellyfish blooms. First, jellyfish can survive environmental conditions that are deleterious to most other organism, such as contaminated water or water with very low oxygen concentrations also known as "dead zones" (Richardson et al., 2009). Second, overfishing eliminates their predators and at the same time their competitors on resources since fish and jellyfish both prey on zooplankton (Purcell et al., 2007).

Figure 28.1. Example of a jellyfish swarm of *Pelagia noctiluca* in the Mediterranean Sea.

When a jellyfish swarm occurs, it has different implications at the social, economic, and ecologic levels (Fig. 28.1). Compared to 100 years ago, the impact of this phenomenon on the recreational uses of the shore is higher due to the simple fact that now there are "more people in the water" (Brinkman and Burnell, 2009). Additionally, jellyfish swarms can interfere with aquaculture (Bosch-Belmar et al., 2017), fisheries activities (reviewed by Purcell et al., 2007), and clog the cooling systems of power plants (Angel et al., 2016).

At the community level, the proliferation of jellyfish has implications for the flux of carbon along the food web, as has been noted by Condon et al. (2011) in their hypothesis of the "jelly carbon shunt." According to the authors, when a jellyfish swarm occurs, less carbon reaches the economically important upper trophic levels such as fish, and more carbon is retained in jellyfish biomass.

An invasion of non-native jellyfish can occur through the ballast-water of commercial ships. This occurred in the late 1980s in the Black Sea where the ctenophore *Mnemiopsis leidy* was introduced (Kideys, 2002). The species provoked a decrease in non-gelatinous zooplankton biomass, which increased the biomass of phytoplankton causing an increase in turbidity. All these changes in the ecosystem were reflected in a marked decrease in the Turkish anchovy landings (Kideys, 2002).

There are several international jellyfish database initiatives, most based on citizen science (public participation in scientific research) activities, that appeared recently due to the socio-economic impact of jellyfish swarms and the public interest that emerged. One is "JellyWatch" (http://www.jellywatch.org/), which covers all oceans and seas. For the Mediterranean Basin there is a similar platform that originated in 2013 known as the "Jellyfish Spotting Campaign" of the European project PERSEUS (http://www.ciesm.org/marine/programs/jellywatch.htm). Another initiative at the Mediterranean scale within the framework of the Mediterranean Science Commission (CIESM) is the "CIESM JellyWatch Program". The philosophy of this initiative is different from the other two, in that the information is obtained from focal points of diverse operational areas (http://www.ciesm.org/marine/programs/jellywatch.htm).

At the national level, there are several citizen science initiatives including: the app "MeteoMeduse" in Italy (https://www.focus.it/ambiente/natura/meteomeduse), "Seawatchers" in Spain (http://www.observadoresdelmar.es/projecte-3-que-pots-fer-tu.php), or "Spot the jellyfish" in Malta (http://oceania.research.um.edu.mt/jellyfish/ReportForm.html). Some campaigns are even focused solely in one species (e.g., the dangerous box-jellyfish) as seen in this one for Alatina alata (https://www.surveymonkey.com/r/XCFQTJ9).

The National Center for Ecological Analysis and Synthesis houses a compilation of scientific data regarding gelatinous zooplankton. The Jellyfish Database Initiative (JeDI; http://people.uncw.edu/condonr/JeDI/JeDI.html) is a scientifically-coordinated global jellyfish database spanning the past two centuries.

Regarding management, in areas where the jellyfish sting is potentially dangerous, there are some web pages that provide warnings or alerts, as is the case in Hawaii in the United States (http://beatofhawaii.com/hawaii-jellyfish-stings-2013-caution-dates-and-new-treatment/) or in Australia (http://www.outback-australia-travel-secrets.com/box-jellyfish.html#box-jellyfish-season). In other areas, where the jellyfish stings are not dangerous but still the use of the shore is intense and the general public needs to know where the jellyfish are located, there are web pages such as that in the France Mediterranean coast (http://meduse.acri.fr/carte/carte.php) or the Red Cross (http://jav.cruzroja.es/appjv/consPlayas/fichaPlaya.do) in the Spanish coasts.

Applied Cases and the Importance of Co-creation with Stakeholders

Jellyfish swarms have relevant social and economic implications; however, systematic and periodic data of jellyfish occurrences along beaches is sparse. The availability of this data would help us understand the inter-annual variability of the episodes of high jellyfish abundances and its potential relation to variable environmental conditions. Joint strategies with tools available to scientists, administration, policy makers, and stakeholders can optimize the cost of obtaining these in situ data and the benefits achieved from its scientific analysis. An international workshop dedicated to improving the monitoring and research of jellyfish was held in Cadiz (Spain) in 2015 (Prieto et al., 2016). It brought together scientists and stakeholders interested in research and management of jellyfish bloom phenomena. Workshop participants concluded that jellyfish should be monitored on a regular basis, taking advantage of both citizen science and a systematic, robust monitoring program, and that ultimately the monitoring of jellyfish should become mandatory. For both approaches, one has to:

- define the purpose of monitoring;
- establish a sampling scheme (where, when, and how often);
- standardize methodologies and set up monitoring protocols; and
- establish training programs.

Additionally, the various citizen science initiatives need to coordinate. Moreover, scientists could benefit from including data collected from fishermen or other sectors, such as offshore aquaculture operators, dive clubs, marine protected area supervisors, lifeguards, sailors, or enthusiast naturalists. Including these stakeholders in observation programs would increase the spatial coverage of observational data and generally increase the number of observations (both coastal and non-coastal observations).

The lack of standardized approaches and methodologies for jellyfish monitoring was also recognized as an important issue with regards to systematic monitoring programs by the United Nations Educational, Scientific and Cultural Organization (UNESCO; see https://en.unesco.org/themes/monitoring-ocean) and previous programs such as the Global Ocean Ecosystem Dynamics program or the U.S. Joint Global Ocean Flux Study (Knap et al., 1996). Although there is still a relative lack of methodological papers concerning jellyfish monitoring, the United Nations Environment Programme released such a report 25 years ago that can be built upon (UNEP, 1991). The creation of a jellyfish occurrence database in the Ocean Biogeographic Information System and the formulation of data-sharing policy were also mentioned as important (Prieto et al., 2016).

The Balearic observation system

A joint stakeholder-scientist pilot strategy was designed and tested in the Balearic Islands during Summer 2014, in the framework of the Balearic Islands Coastal Observing and Forecasting System (SOCIB) activities of the Strategic Issues and Applications Division (Tintoré et al., 2013). In a pioneering effort, several governmental services from the Balearic Islands worked together with scientists to upload jellyfish observations in real time, establishing a new database generated under scientific standards that will help us gain a solid understanding of the episodes and the implementation of appropriate knowledge-based future mitigation actions.

The system is still operative and now involves the regional fisheries, environmental and emergency administrations, charter associations, as well as Consejo Superior de Investigaciones Científicas (CSIC) institutes and SOCIB. For the first time, a systematic program of routine jellyfish observations was established with qualified and trained personnel, monitoring at high spatial and temporal resolution in three different types of coastal areas: marine reserves, coastal waters around one mile offshore, and beaches. The system includes a web platform and an associated database that compiles the daily sightings in five marine protected areas, with several observation sites, each manned by the General Directorate of Fisheries and Aquaculture personnel from 33 routes (with 66 sites) of the coastal area boat cleaning services from the General Directorate of Water Quality, and at 120 beaches where monitoring is carried out by lifeguards from the General Directorate of Emergencies (Fig. 28.2).

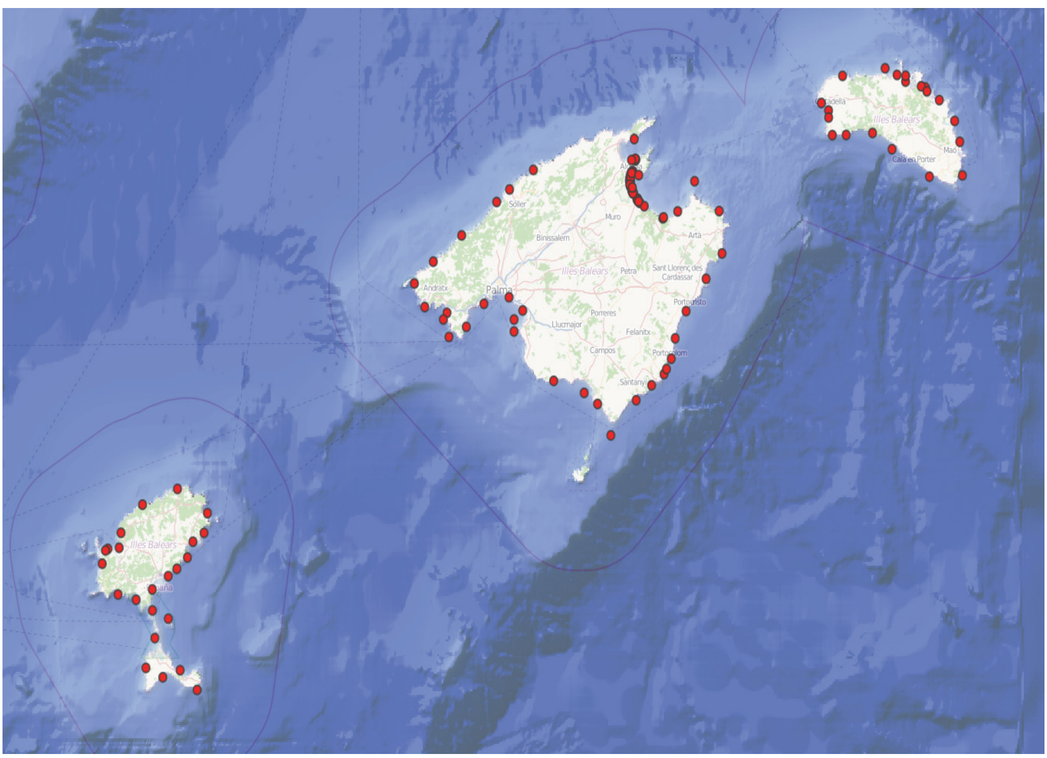

Figure 28.2. Observations points of the Balearic Jellyfish Observation System.

All observations are performed following established protocols to obtain a systematic, periodic, routine monitoring, collecting information on the location and time each species observed. The application allows the filtering per species, location, or period. The web platform provides "heat maps" of jellyfish observation abundance (Fig. 28.3) and enables users to download the entire dataset. Currently, access is restricted to participating institutions.

Since 2014, more than 92,200 observations have been registered on the website. These include observations of the absence of jellyfish, and from the total number of observations only in 6,039 cases were jellyfish observed. Over the years, the most abundant species was *Pelagia noctiluca* (4097), followed by *Cotylorhiza tuberculata* (827), *Rhizostoma pulmo* (545) and *Velella velella* (240). The remaining jellyfish species were one order of magnitude lower, such as *Physalia physalis* (10) and *Aurelia aurita* (9). The most active users of the system are the beach emergency staff (with more than 70,200 observations), followed by employees of the boat cleaning services (20,700+ observations) and from the marine protected areas (1,250+ observations). In the future, the database will be expanded to incorporate information from meteorology and oceanography, in order to advance our understanding of the links among the jellyfish swarms in the shore and the different scales of variability at which they are affected.

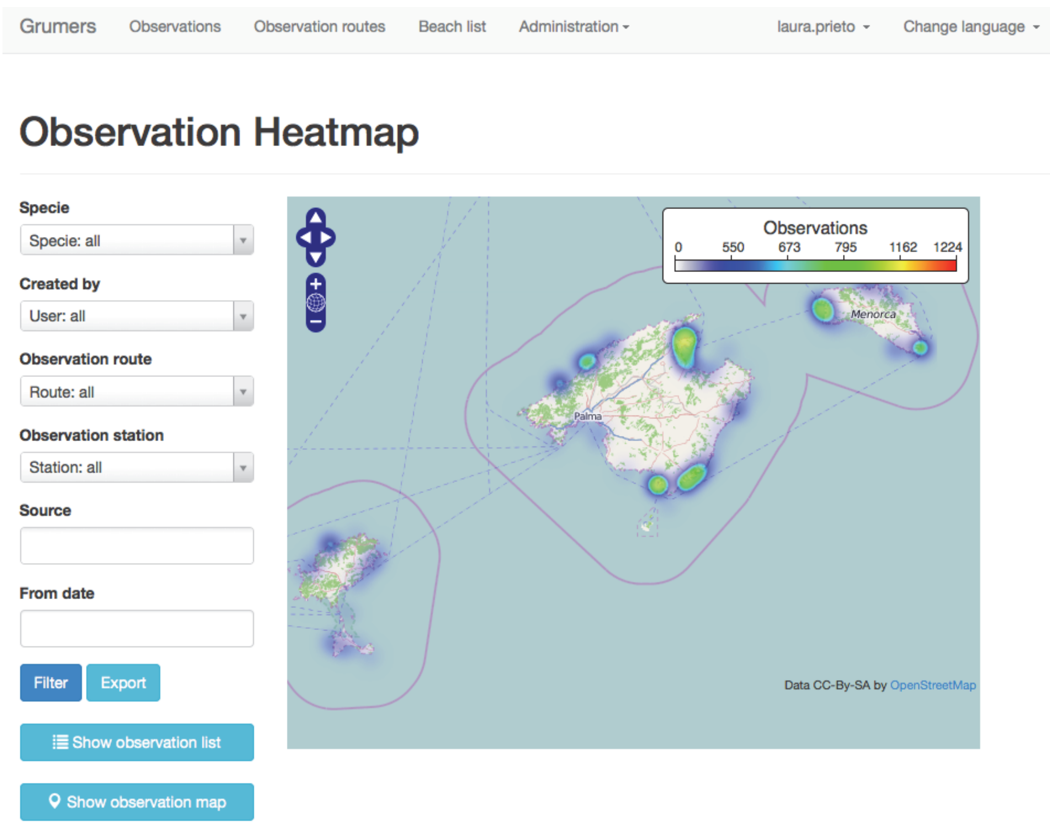

Figure 28.3. Example of an observation heat map from the GRUMERS web-platform for jellyfish observations.

Figure 28.4. Two stranded colonies of *Physalia physalis* on the Camposoto beach (Gulf of Cadiz).

The effectiveness of this new jellyfish observation system is clearly based on the quantity and quality of the data obtained being up to date. Using jellyfish database, it is possible to create a tool of operational oceanography in order to predict the occurrence of jellyfish swarms in the four Balearic Islands. To achieve this goal, the diverse coastal orientation, different currents, and variability of coastal winds on each of the four islands will be taken into account.

Physalia bloom of 2010

The year 2010 registered an unusually high record of Portuguese Man-of-War (*Physalia physalis*) sightings (Fig. 28.4) along the Mediterranean Sea and eastern North Atlantic. It was a remarkable year in terms of the frequency of occurrences, but also in terms of the total number of colonies that arrived (more than 100,000), as compared to 2009 and 2012 when there were less than 60 colonies (Fig. 28.5).

P. physalis sightings were compiled for eight years from different sources: media, national and regional agencies, and personal communications. A unique event between February-April 2010 was carefully monitored by the Technicians of the Consejeria de Medio Ambiente from the Regional Government of Andalucia, which monitored the entire coast and counted and measured all stranded colonies. Additionally, *P. physalis* sightings were analyzed from the database of the Jellywatch Program (Prieto et al., 2015).

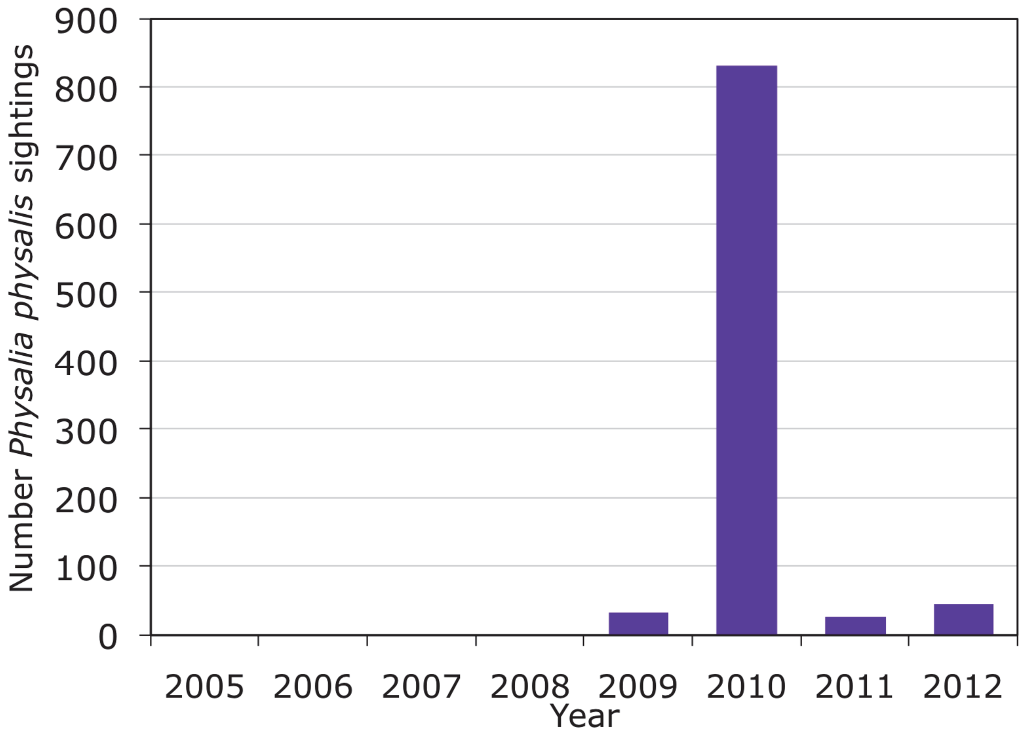

Figure 28.5. Total number of *Physalia physalis* sightings on the Mediterranean Sea and the Spanish and Portuguese Atlantic coasts during eight consecutive years (2005-2012).

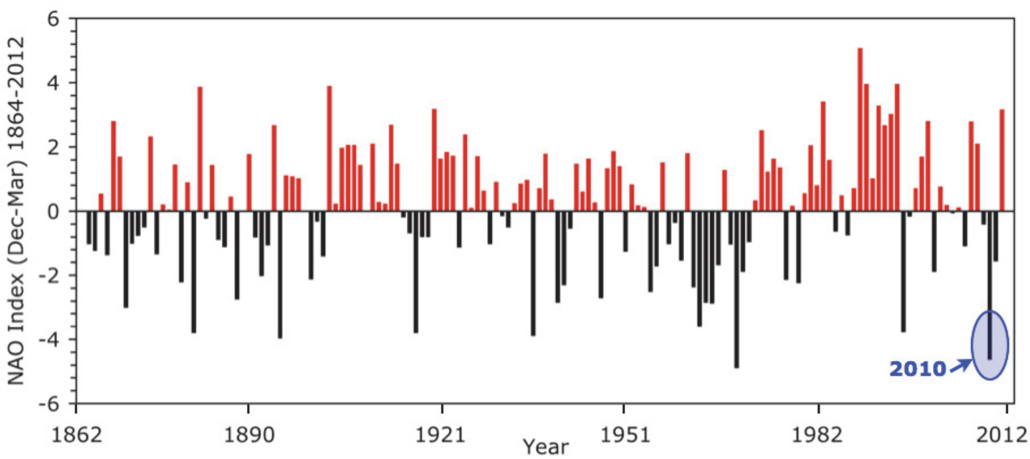

Figure 28.6. Winter index of North Atlantic Oscillation (NAO) based on the difference of the normalized sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland, since 1864. The station index value for year N refers to an average of December for year N-1 and January, February, and March for year N. The sea level pressure anomalies at each station were normalized by the division of each seasonal mean pressure by the long-term mean (1864–1983) standard deviation. Normalization is used to avoid the series being dominated by the greater variability of the northern station.

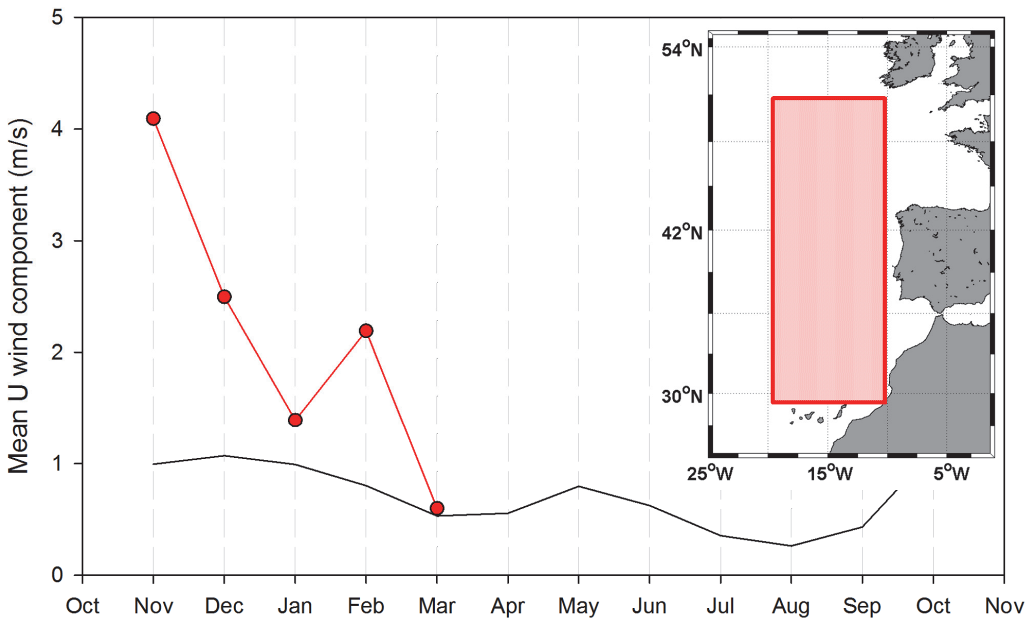

Figure 28.7. Winds components in the eastern North Atlantic from 50°N to 28°N and from -20°W to -10°W (red square in the map). The black line is the monthly climatology from 1979 to 2012 of the wind (U component). The red line shows the data from the 2009–2010 winter when westerlies (positive values) were much stronger in the entire basin compared to the climatology. The data are ERA-Interim analysis daily products (http://www.ecmwf.int/research/era/do/get/era-interim).

A reasonable explanation for the massive occurrence of the Portuguese Man-of-War within the Mediterranean Basin in summer 2010 is that specific climatic and oceanographic conditions during the previous winter in the North Atlantic favored the transport of these colonies into the Mediterranean Sea. The 2009–2010 winter had one of the most negative North Atlantic Oscillation (NAO) indices (− 4.64) measured during the nearly 150-year record (Fig. 28.6; Hurrel, 2012).

This climatic condition caused a stormy mid-latitude Atlantic, with increased storm activity and rainfall in southern Europe, the western Mediterranean, and North Africa. Thus, the climatic/oceanographic conditions have been analyzed for that particularly year, which turned out to be one year of stronger westerlies winds in the Northeast Atlantic basin compared to the time series from 1979 (Fig. 28.7).

A virtual experiment of the drifting of the individuals was performed using a hydrodynamical model. This consisted of using a Regional Ocean Modeling System (ROMS)-based numerical simulation forced with realistic winds (Advanced Scatterometer, ASCAT) and heat fluxes from ERA-Iterim, together with individual based model simulations (Prieto et al., 2015). The oceanic population of *Physalia physalis* started to appear stranded on the beach on February 22, 2010, and observations on the coast occurred from west to east advancing towards the Mediterranean, passing the Strait of Gibraltar and to the far east of the Alboran Sea (Fig. 28.8). The beaching timing observed was highly correlated to the simulations ($r=0.81$, $p<0.001$, $n= 18$). The results showed small differences in the overall estimated arrival of *Physalia* between the model experiment and the real observations.

Such high abundances of *P. physalis* were not observed during subsequent years (Fig. 28.5). According to the literature and observations, this species has been observed in the Mediterranean with Malta being the easternmost site (Deidun, 2010). Therefore, it is widely accepted that the presence of *P. physalis* along Mediterranean beaches is not likely to become a continuous problem (Prieto et al., 2015).

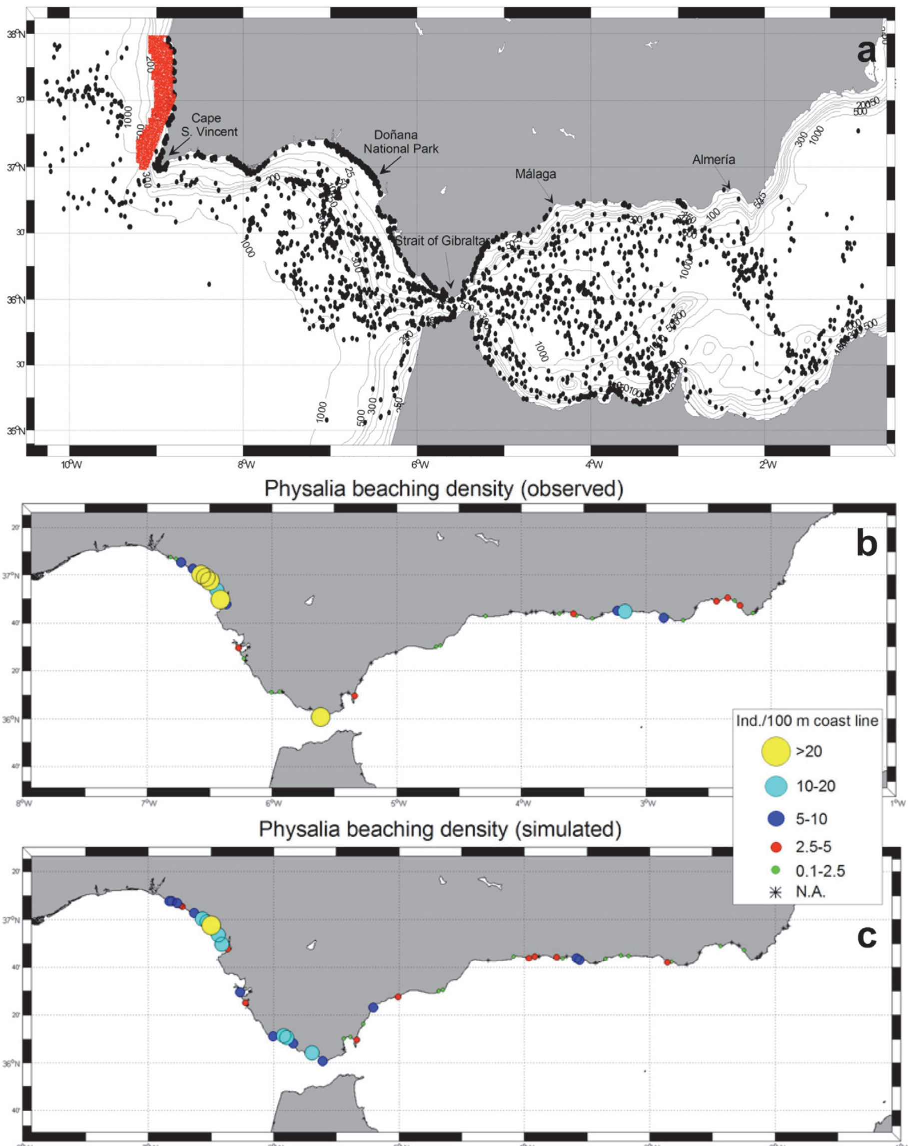

Figure 28.8. Simulation of Portuguese Man-of-War jellyfish drifting and real beachings during January–March 2010. (a) The virtual position of *P. physalis* on 26 January 2010 (beginning of the simulation) indicated by red dots and on 30 March 2010 (end of the simulation) in black dots. Cumulative density, colonies per 100 m of coastline and observed (b) and simulated (c) *P. physalis* arrivals to the Atlantic and Mediterranean coasts of the South Iberian Peninsula. The arrivals of *P. physalis* occurred from west to east both in the observations and in the simulation from 22 February to 30 March (from Prieto et al., 2015).

This applied case study was the scientific community's response to a policymaker's petition to better understand 2010's extraordinary event. Based in the knowledge obtained from this study, the next step will be to integrate the findings into a future operational oceanography tool. This will make it possible to forecast the potential occurrence of *P. physalis* in the Mediterranean Sea each year by evaluating the winter situation at the other side of the Strait of Gibraltar based on climatological, meteorological, and *P. physalis* population abundance data.

Decades of social impact of jellyfish blooms in a coastal lagoon

Cotylorhiza tuberculata, an exotic Scyphozoan in the Mar Menor, was selected as a case study for parameterization of an invasive jellyfish species. Mar Menor is the largest coastal lagoon exposed to intensive tourism in the western Mediterranean with a surface area of about 135 km^2 and a mean depth of about 3.5 m. *C. tuberculata* was not found in the lagoon prior to the lagoon's connection with the Mediterranean, when it was made deeper and wider in the 1970s to facilitate navigation. Since the early 1990s, high abundances of *C. tuberculata* during the summer have become an increasing problem for the recreational use of the lagoon. Local authorities have implemented programs for the removal of adult jellyfish by means of fishing vessels and they have installed nets to protect bathing areas from medusae. These programs have removed more than 5,000 tons of *C. tuberculata* during the most abundant summers (Fig. 28.9; ECOS, 2004).

Planulae appear in late summer and early autumn when adult females reach maturity. Consequently, their survival is linked to lagoon conditions in that season, when the physical environment can change abruptly in association with the passage of low pressure weather systems across eastern Spain.

Figure 28.9. Removal of *C. tuberculata* from Mar Menor using fishing nets (from La Opinión de Murcia, June 15, 2016).

Once polyps fix to the substrate during late summer and early autumn, they must survive until the following spring when strobilation occurs. Although medusae are more visible, polyps are the main stage of *C. tuberculata* in the lagoon in terms of residence time. Pelagic stages of *C. tuberculata* happen from June to September, whereas the benthic phase lasts for the rest of the year. Polyps must survive winter conditions, when light and food are lower than in spring and summer. In addition, although polyp sensitivity to salinity is very low, temperatures can drop dramatically in a shallow lagoon such as Mar Menor. One example of this control of polyp survival by temperature occurred in 2005 when, aside from being one of the warmest months of June in 20 years (mean water temperatures of 23 ºC), no outbreak of *C. tuberculata* was detected within the lagoon. To clarify this exception, it is necessary to consider the effect of temperature not only on strobilation but also on polyp survival. Fig. 28.10a shows the air temperature at the meteorological station of San Javier airport (in Mar Menor) for the winters between 1986 and 2005. During the winter of 2005 (from Dec 2004 to Feb 2005) a strong cold event with temperatures close to freezing during several days was apparent. As can be observed such a severe and persistent cold event was not present in other years (Fig. 28.10a). In addition, this event was accompanied by strong winds (Fig. 28.10b), which increased heat loss from the shallow lagoon in a period of very cold air temperature.

Although there are no in situ data for the winter of 2005, the water temperature during that time is likely to have dropped below 10 ºC, which poses severe stress on polyps as shown from laboratory experiments (Fig. 28.11). This may have caused the reduction of *C. tuberculata*'s polyp population in the lagoon. Thus, the high mortality of polyps at low winter temperatures seems to be a critical factor that controls polyp population in Mar Menor.

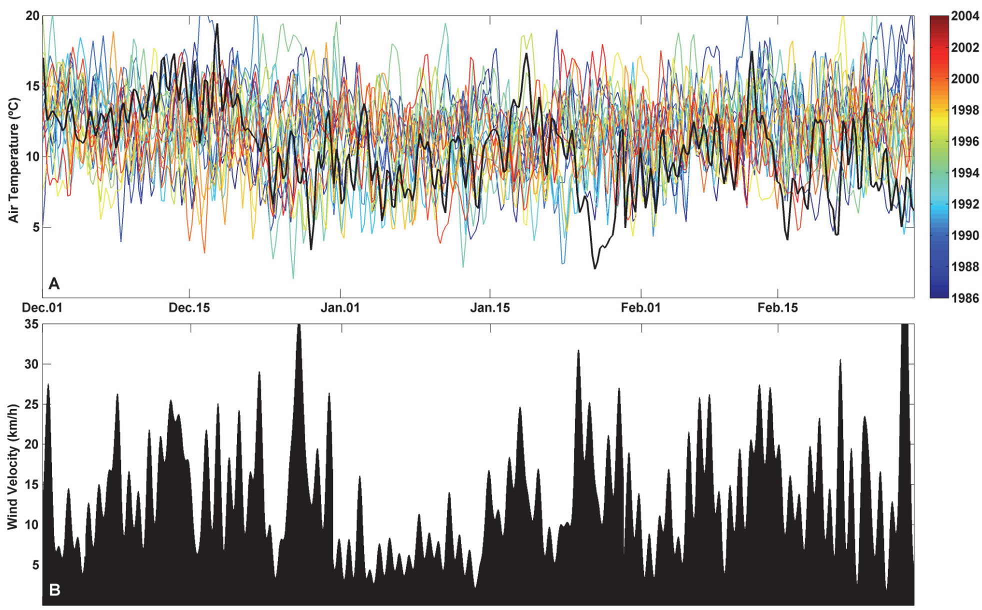

Figure 28.10. Temperature and wind in situ during winter. a) winter air temperature (from December to February, in ºC) at the meteorological station in the airport of San Javier (Mar Menor) during 20 years (each line, one winter). Thick black line is the winter from December 2004 to February 2005. b) wind velocity (km/h) at the airport of San Javier (Mar Menor) during winter of 2004-2005 (from December 2004 to February 2005).

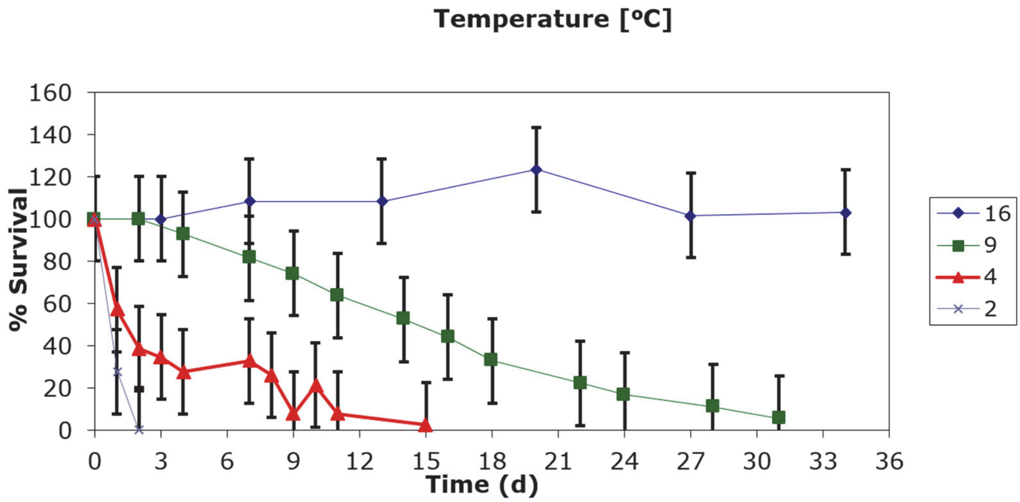

Figure 28.11. Polyp survival at low temperatures. Blue rhomboid, green square, red triangle and purple circle stand for 16, 9, 4 and 2 ºC respectively. Error bars are the standard deviation of the three replicates'. Survival is greater than 100% at 16ºC because of budding (asexual reproduction).

An increase in temperature results in higher strobilation rates compared to stable temperatures. Laboratory experiments confirmed that the scale of variability of the environment temperature to trigger the strobilation process needs to be seasonal (Prieto et al., 2010). No strobilation occurred in any of the treatments checked at synoptic scales (i.e., meteorological events with a time scale between days to weeks such as a storm or a drop of temperatures associated to a low pressure situation).

Early life stages of *Cotylorhiza tuberculata* are not sensitive to salinity variations or the availability of light or nutrients. However, temperature critically controls polyp survival and strobilation. Low temperatures imply reduced polyp survival during the winter. Abrupt water warming during spring triggers strobilation and, therefore, the start of the medusa phase of the life cycle (Fig. 28.12).

In coherence with laboratory results, these thermal controls determine the inter-annual presence/absence of outbreaks of this jellyfish in the Mar Menor lagoon (Prieto et al., 2010). Therefore, *C. tuberculata* populations fluctuate under the simple rule of "the warmer the better", with collapses after polyp mortality in severe winters and peaks in years with mild winters and long summers. A Bayesian model was developed to implement this simple rule in a tool with the potential to forecast the probability of medusa outbursts to help the management of the lagoon by the different stakeholders (Fig. 28.13; Ruiz et al., 2012).

This is a clear example of how solid scientific data can be incorporated into a social management tool to help marine policymakers. This tool is easy to implement, as demonstrated in the case of *C. tuberculata* populations in Mar Menor, as it only needs the air temperature from the nearby airport. The shallowest areas of the lagoon infer a tight connection between meteorology and oceanography in this case study. However, it can be adapted for analyzing the outburst risk of other jellyfish species thriving in other coastal confined areas. This can also help to explain past and future fluctuations of abundance in a thermally-changing ocean.

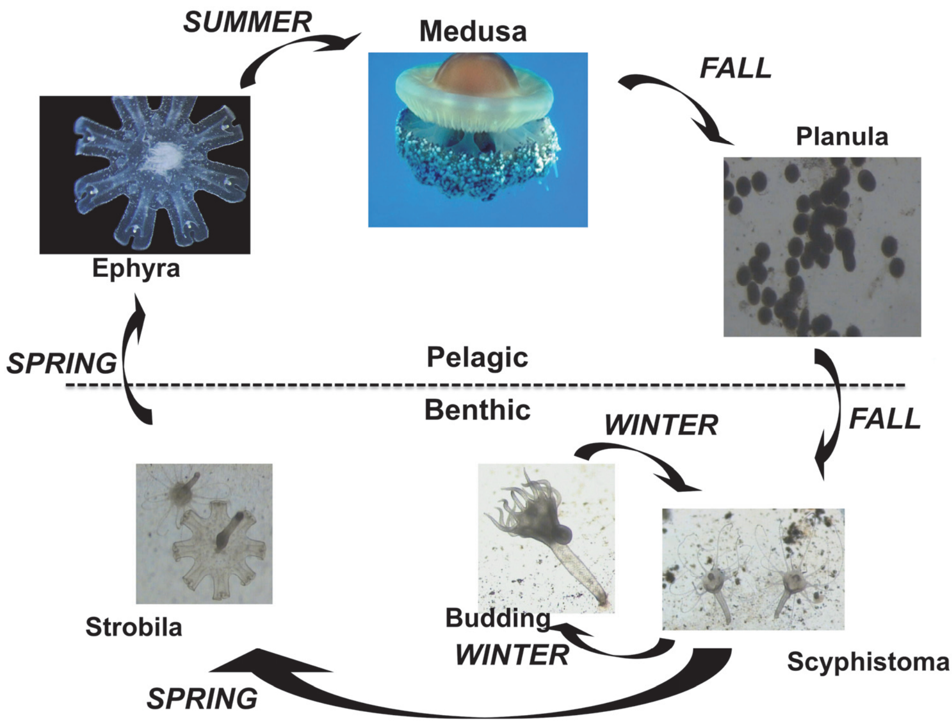

Figure 28.12. Illustrating thermal control and seasonal occurrence of *C. tuberculata* in Mar Menor.

Summary and conclusions of applications of operational oceanography on jellyfish swarms: Present and future

Due to their diversity and the complexity of their life cycle, jellyfish can be used as a proxy to applied operational oceanography as applications of predictions systems. In the three case studies presented in this chapter, operational oceanography was applied in different ways. The first case study, the Balearic Jellyfish Observing System, is an example of taking a first step towards pre-operational oceanography applied directly to jellyfish swarm coastal management. The second applied case study, the Portuguese Man-O-War in the Mediterranean Basin, shows how operational oceanography has been already applied to effectively diagnose the past, and efforts are underway that will help operational oceanography be able to predict future events. In the last case study, management of jellyfish swarms in a marine lagoon, the tool obtained is already available for policymakers and stakeholders. Of course, we are now facing a moment where the oceanography technology for observation is advancing rapidly, together with models and data assimilation. We should include jellyfish research and monitoring as one of the targets to link operational oceanography to both coastal and open ocean environments.

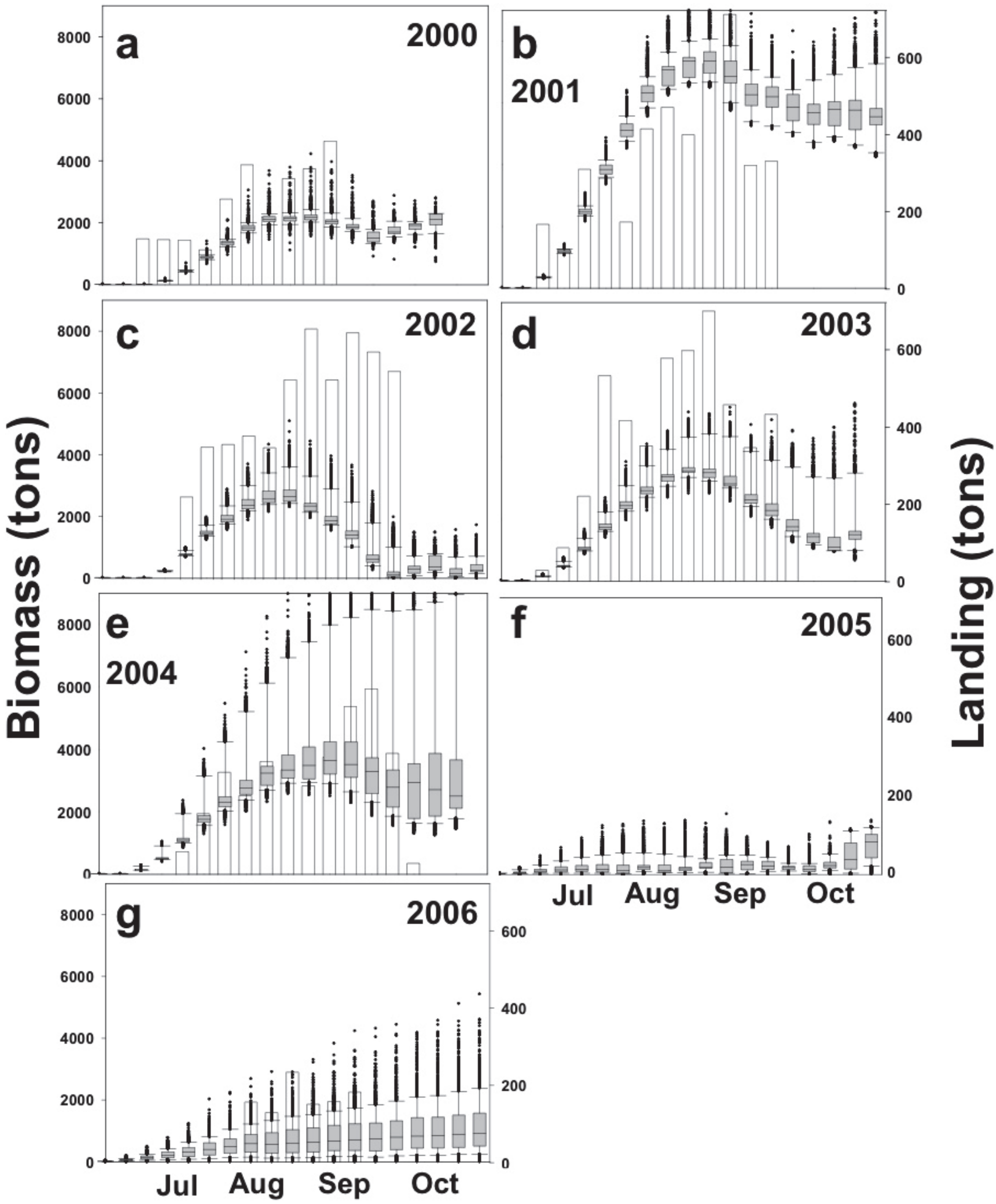

Figure 28.13. Medusa biomass and landings. Box plots for the posteriors of medusa biomass of the weekly-resolved model during years 2000 to 2006. Box limits and whiskers indicate respectively the 25–75 and the 10–90 percentile limits, dots are outliers. Vertical bars (right axis) are the weekly landing data from Consejería de Agricultura y Pesca (Región de Murcia; from Ruiz et al., 2012).

Acknowledgments

Thanks to Dr. Javier Ruiz and Dr. Ananda Pascual for encouraging me to write this chapter, to the research group of Ecosystem Oceanography (ICMAN-CSIC) for their assistance, to Dr. Joaquín Tintore, and to Antonio M. Grau for his support of starting the endeavor of the jellyfish observation system in the Balearic Sea (reflected in case study 1). Thanks to the Consejeria de Medio Ambiente of Junta de Andalucia (for *P. physalis* stranding data for case study 2). Also acknowledged is the Consejeria de Agricultura y Pesca of Region de Murcia for the jellyfish fishing data and the Agencia Estatal del Meteorologia of Ministerio de Medio Ambiente for wind data (both for case study 3). This work was support financially by the following projects: "Respuesta de medusas mediterráneas al efecto interactivo de motores climáticos de impacto: supervivencia en un mediterráneo más cálido y ácido" Med2CA (CTM2016-75487-R), "Forzamientos fisicos en la proliferacion costera de organismos gelatinosos (201730I072) and "Deteccion de medusas en el mar Balear y su relacion con las conduciones ambientales: hacia el desarrollo de un sistema de prediccion pre-operacional" (Govern de les Illes Balears, SOCIB and CSIC).

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