A review on technical constraints, opportunities and needs to ensure the development of the mariculture sector worldwide – tropical zone

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Jeffs, A.G. 2013. A review on the technical constraints, opportunities and needs to ensure the development of the mariculture sector worldwide – tropical zone. *In* A. Lovatelli, J. Aguilar-Manjarrez & D. Soto, eds. *Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges. FAO Technical Workshop, 22–25 March 2010, Orbetello, Italy*. FAO Fisheries and Aquaculture Proceedings No. 24. Rome, FAO. pp. 101–133.

ABSTRACT

This paper provides an overview of the technical constraints, opportunities and needs for enabling the development of open water mariculture in the tropical regions of the world. Global mariculture production has been growing rapidly in recent years. In many areas where this activity has expanded rapidly there is increasing pressure on the available coastal space for mariculture and conflict with other coastal resource users. This has resulted in initiatives to move mariculture further from the coast and most often also into deeper water. These open waters are generally more exposed to wind and waves, and therefore, require more advanced aquaculture technology and infrastructure in order to remain effective. Two approaches have emerged. Firstly, the evolution of existing commercial mariculture technologies mostly through more robust construction of coastal mariculture systems making them suitable for open waters. These mariculture systems are being increasingly commercialized, with the higher infrastructure and operating costs offset by greater scale of production and the increased use of remote control technologies. Secondly, the development of novel open water mariculture technologies, which mostly involve large-scale structures that can be submerged to avoid the wind and wave exposure encountered in offshore situations. While many of these novel mariculture systems are only in the design stages or are being operated on an experimental basis, an increasing number are coming into commercial-scale production. Most of this technological and commercial development is occurring in the cooler water regions of the world where the majority of large-scale commercial mariculture production currently occurs, especially for finfish. However, there is significant potential for the development of mariculture in the world's tropical zone, with many countries within this zone now actively encouraging mariculture development. There are some examples of companies taking advanced commercial mariculture technologies, including open water technologies, into the tropical zone. In general, the tropical region of the world's oceans provides some significant advantages for aquaculture. Most importantly, the waters are warm and usually with a limited seasonal fluctuation, which can deliver very fast growth rates in species suited to these conditions. Throughout much of the tropical zone, wind and wave conditions tend to be less, than in cooler waters, especially in an equatorial belt which is largely free from tropical cyclones. Tropical waters also tend to have lower nutrient levels and phytoplankton production, which probably makes many open water areas in the tropical zone unsuitable for macroalgal and filter feeding shellfish mariculture production. However, such conditions are very appropriate for finfish farming, which has been at the forefront of much of the open water aquaculture development internationally. Large-scale commercial mariculture of tropical finfish, even in coastal waters, is beginning to emerge with work on a variety of suitable species. Advanced knowledge and greater experience of suitable tropical finfish species, such as cobia (*Rachycentron canadum*), will provide a stronger basis for advancing open water mariculture in the tropical zone. Further advances could be achieved for developing nations in the tropical zone by encouraging the improvement of mariculture governance and planning, as well as assisting with technological and personnel capability in open water mariculture. It is recommended that these areas should be the focus of future international initiatives in collaboration with developing nations.

INTRODUCTION

Aquaculture has been the fastest growing animal food producing sector in the world for many years (FAO, 2009). In the early 1950s, the global aquaculture production amounted to less than 1 million tonnes per year and by 2006 this had grown to 51.7 million tonnes with a value of USD78.8 billion, an annual growth rate of nearly 7 percent.

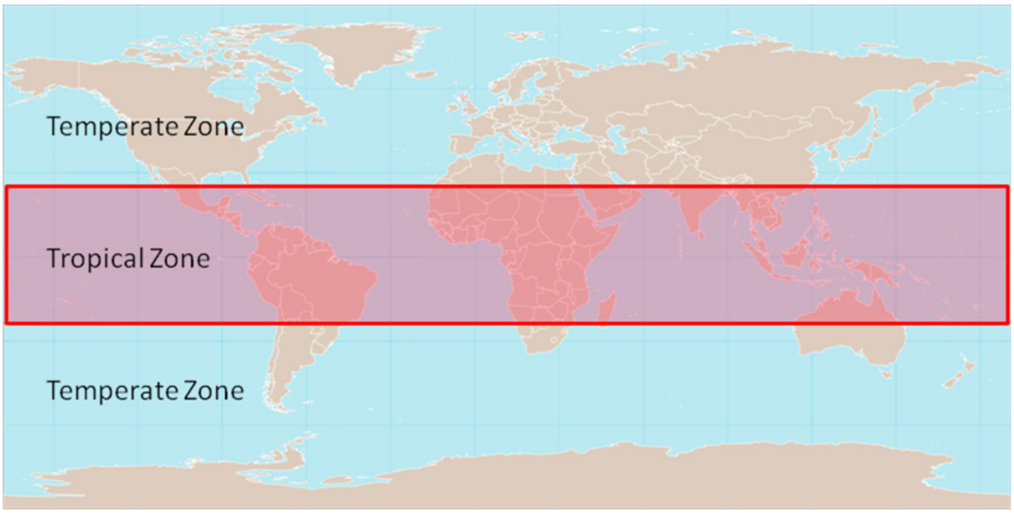
Mariculture makes up nearly half of global aquaculture production, estimated at 31 million tonnes in 2006 (including aquatic plants, but excluding brackish waters). However, since 2000, growth in the production volumes from global mariculture has been slower (5.4 percent average annual increase) than freshwater (6.5 percent) and brackish water (11.6 percent) aquaculture (FAO, 2009). However, the trend is reversed for the growth in the value of production; mariculture (8.3 percent average annual increase), freshwater (7.8 percent) and brackish water (5.9 percent) aquaculture, which reflects the higher value per unit weight of mariculture production. Partly, as a consequence of these trends, there is strong interest from developing countries in expanding mariculture.

A number of developing nations have approached the Food and Agriculture Organization of the United Nations (FAO) for assistance with mariculture development, especially relating to the development of off-the-coast and offshore mariculture. There is a wide range of issues associated with moving mariculture further from the coast, including technical feasibility, regulatory and environmental concerns, as well as potential conflict with other resource users.

In response to these requests, FAO has launched a project aimed at gathering global information on the potential for the development of off-the-coast and offshore mariculture by considering technical, biological, spatial, environmental, socio-economic, legal and policy issues. This paper represents part of the first phase of the project, reviewing technical issues relating to the sustainable development of off-the-coast and offshore mariculture in the tropical zone of the world.

The scope of this review is to examine the current mariculture technologies for the global tropical zone and to identify and discuss the current developments and emerging issues, especially in relation to the future opportunities for development of open water mariculture in developed and developing nations. The aim of the review is to help with

FIGURE 1
Tropical and temperate zones of the world for the purposes of this review paper



Source: Modified Wikimedia Commons image.

the development of recommendations and broad guidelines on technical issues that need to be investigated to ensure the expansion of mariculture in the future, and to identify priority actions that could be coordinated at the international level particularly by agencies, such as the FAO, to assist lesser developed nations.

This paper is one of the reviews that have been prepared and has been integrated to form a global synthesis of knowledge for open water mariculture that will help to underpin proposals for a global programme for the development of open water mariculture.

For the purposes of this review paper the following definitions apply:

Tropical zone – region of the Earth between the Tropic of Cancer and Capricorn, as opposed to the "temperate zone" in between these and the (Ant-) Arctic circles (Figure 1).

Off-the-coast – mariculture locations that are between 500 m to 3 km from the coastline, less than 50 m water depth, and have up to 3–4 m significant wave height.

Offshore – mariculture locations that are greater than 2 km from the coastline, but generally remaining on the continental shelf, but are greater than 50 m depth, and have greater than 5 m significant wave height.

Open water aquaculture – refers to both off-the-coast and offshore mariculture.

Significant wave height – the average wave height (trough to crest) of the largest third of waves encountered at a site.

Global trend toward off-the-coast and offshore mariculture

The global aquaculture industry is growing rapidly and evolving in response to key factors, such as changes in technology, markets, economics, species availability, feed sources, disease, public perceptions and environmental constraints. Many of these key factors are important considerations for the future development of offshore mariculture within the tropical zone.

Mariculture in most parts of the world, especially in developing countries, usually begins on a small scale in sheltered inshore waters using simple aquaculture technology, such as pens in shallow water, where the contained farm stock are easily accessible under a range of weather conditions and can be closely observed for security reasons (Ackefors, Huner and Konikoff, 1994; Beveridge, 2004). As mariculture activities have required more space to accommodate growth, or they have come into conflict with other coastal activities, they have increasingly moved further away from the coast into less sheltered waters. This has required improvements in mariculture technology to withstand the greater physical forces (winds, waves, currents) and the greater depth of water in which farms are located. In general, the greater the distance offshore that a mariculture activity is located, the more complex the aquaculture technology required, the greater the capital investment required for establishment, and the higher the ongoing operating costs. Despite these economic disincentives, in the past 25 years commercial-scale mariculture has increasingly been expanding further from the coast mostly using modifications of existing farm technology and husbandry that has firstly been developed in inshore waters (Beveridge, 2004). To a large extent it has been made economically viable by a concomitant increase in the scale and efficiency of mariculture, which has been sufficient to offset the greater capital and operating costs. As a result, off-the-coast mariculture is now commonplace in many developed countries and is increasingly being utilized in developing countries for the expansion for mariculture.

Moving mariculture even greater distances from the coast is more challenging, both technologically and economically. For more than 30 years there has been extensive research and development, as well as some commercialization of offshore mariculture. The offshore mariculture technology that is emerging is markedly different to that used for off-the-coast mariculture, which has evolved directly from inshore technology. While the utility of some offshore mariculture technology appears to have largely been proven, the commercial application of the technology has been slow and remains limited in extent, and is most often being applied at the margins of the "offshore", i.e. two kilometres from shore (O'Hanlon *et al.,* 2003). The reason for this probably relates to economics, especially the substantial establishment costs, risks from adverse natural events, and uncertain financial returns (Beveridge, 2004; Stickney, 2009). However, like the development of the preceding inshore and off-the-coast mariculture, once offshore technology has become standardized and common practice, its application will undoubtedly increase and the entry barriers, such as establishment costs, will decrease.

There are strong influences that are encouraging further movement of mariculture activities into open waters. In many countries with well-developed mariculture industries, there is frequently increasing concern about environmental carrying capacity and associated issues, such as disease and stock escapes (Tacon and Halwart, 2007). There is also growing conflict between mariculture and other users of coastal waters in situations where there has been rapid expansion of coastal aquaculture. In many parts of the world, a number of well-organized non-governmental organization (NGO) groups have also been effective in influencing public opinion against the proliferation of mariculture in coastal waters. As a result, it has become increasingly difficult in many nations to secure new growing space for mariculture in coastal waters. Moving mariculture into more open waters, further from the coast, is one means to avoid these issues.

Driving the need for increased mariculture production is the continuing growth in global market demand for seafood products, which is a result of an increasing global population and increasing per capita fish consumption despite the more or less static production from capture fisheries. Aquaculture production has been responding to this increasing global demand in a number of ways, not only by increasing production. Up until the last decade, much of the aquaculture production focus has been on higher value species such as shrimp, cod, salmon, bass and seabream, which have all had strong increases in production (FAO, 2009). This has been due to the commercial opportunities to increase returns through economies of scale in production and supply, and to build on the existing market recognition of these aquaculture products. Some lower value aquaculture products, such as mussels, have also continued to increase in production to meet demand. However, in the last decade some relatively low-value aquaculture species, such as catfish and tilapia, have shown dramatic increases in production and trading (FAO, 2009). Interestingly, these species are entering and finding rapid acceptance in new markets, where they were previously virtually unknown. This is because they are meeting consumer needs for moderately-priced white fleshed fish that is distributed through supermarkets and food service channels.

Consumers are also increasingly looking for reassurance on production characteristics for aquaculture products, especially food and environmental safety (FAO, 2009). Ultimately, this may benefit offshore mariculture production as it has the potential to be seen by consumers as more environmentally sound than coastal mariculture production methods. Consumers of aquaculture products are also increasingly demanding convenience, palatability and a diversity of product offerings largely due to urbanization, increasing affluence and the reduced time people have available for food preparation (FAO, 2009). As a consequence, there has been an increasing amount of value-adding in aquaculture products. Previously, aquaculture products, such as farm-raised salmon, were more usually sold fresh to attempt to attract premium prices, but they are now increasingly being processed into value-added products (Tveterås and Kvaløy, 2006). More than 90 percent of the international trade in fish and fisheries products is now in processed forms, while 10 percent is live, fresh or chilled. Exports of frozen fish have been increasing, from 31 percent of the total quantity of fish exports in 1996 to 39 percent in 2006.

There have also been enormous recent changes in seafood value chains, with the rise of supermarkets and chains of food service outlets as the increasingly dominant consumer outlets for seafood (FAO, 2009; Tveterås and Kvaløy, 2006). These have become major influences on aquaculture production as they are demanding reduced pricing, increased coordination of their suppliers, greater supply volumes, more product differentiation, and assurances of food and environmental safety (Tveterås and Kvaløy, 2006). These forces have driven rapid vertical and horizontal integration among many aquaculture producers. Furthermore, the desire to increase efficiency has seen moves to decrease the labour costs in aquaculture production, by replacing manual tasks with mechanization, or the increasing use of sources of low-cost labour, especially in developing countries, such as in parts of Asia (FAO, 2009; Tveterås and Kvaløy, 2006). For example, the People's Republic of China has recently emerged as the largest trader of seafood products in the world due to its extensive importing, processing, and re-export of seafood products from around the world. Developing countries now provide over half of the fishery products entering into international commercial trade (Möller, 2003). These countries have acquired the expertise and processing technology, as well as satisfying the stringent safety and quality requirements of demanding affluent markets, especially in Europe and the United States of America. They are well placed to connect with more local sources of aquaculture supply, if they can be developed, such as from mariculture in open waters.

There has also been a recent trend to move more aquaculture production to low-labour cost countries, which also often have fewer regulatory constraints on aquaculture development (FAO, 2009; OECD, 2010). Many of these developing countries, such as the Republic of the Philippines, the Kingdom of Thailand and the Socialist Republic of Viet Nam, are within the tropical zone. Much of this mariculture production has initially been undertaken by small-scale family farming units using simple technology and most often in shallow coastal waters, often known as artisanal aquaculture (OECD, 2010). This situation is changing rapidly with the introduction and growth of larger-scale commercial production by corporate entities that are introducing advanced aquaculture technology, often with foreign expertise and investment. In many developing nations this trend for attracting foreign aquaculture investment and expertise is being actively encouraged with significant financial incentives by governments. For mariculture in the tropical zone this is significant because there are relatively few existing species that have the capacity to be immediately transferred into large-scale open ocean aquaculture, building from an assured base of well-developed commercial production in inshore waters. The application and development of new aquaculture technology appears to have been holding back the rapid expansion in the tropical zone for emerging commercial finfish species, such as cobia, Asian seabass (barramundi; *Lates calcarifer*), and a range of tropical grouper and snapper species (FAO, 2009). However, there are signs that this is changing with some recent significant commercial mariculture developments in developing countries.

To become commercially established, the expansion of aquaculture output from these species needs to be able to rapidly capture a larger share of the global market (FAO, 2009). This can be achieved by substituting products already on the market, especially through price competitiveness. However, the ability to maintain substantially lower prices than competitors usually requires culture technology improvements, faster or more efficient growing species compared with those generally used in the industry, and larger scale production. Therefore, aquaculturalists have to overcome biological and technology hurdles to create new production cost advantages, such as from integrated hatcheries, on-growing facilities and economies of scale in input procurement and growout. For widespread commercial uptake of open water mariculture, the technology must provide sufficient financial advantages to make the product competitive in the marketplace, while also providing sufficient financial return to offset the additional capital cost and operating cost for this open water mariculture technology. This is a significant challenge for the wider introduction of offshore mariculture technology, when there appears to be capacity to further expand coastal and off-the-coast mariculture, especially in the tropical zone. This expansion has already begun to occur rapidly in recent years for finfish species in countries such as China, the Republic of Korea and the Philippines (Chen *et al.*, 2007; Chen *et al.*, 2008; De Silva and Phillips, 2007). Further mariculture development potential is readily available in other tropical regions of the world, especially Asia, but is constrained by a lack of political, financial and physical infrastructure, as well as a shortage of available aquaculture expertise and capital.

Concerns about climate change and global energy supplies may in the future have an impact on more energy-intensive forms of aquaculture production (FAO, 2009). It is likely that mariculture in open waters will prove to be more energy intensive due to the transit distances involved in servicing farms, however, improvements in automation may reduce energy-intensity of this form of production. Remote automation appears to be a current focus for development activities for offshore mariculture (Browdy and Hargreaves, 2009). Future increases in energy prices may also favour increasing aquaculture production in developing countries which have less substitution of labour with more energy-intensive mechanization. This is unlikely to be offset by the distance from market as transport costs are typically only a small component of the price of final consumer-ready aquaculture products (FAO, 2009).

Off-the-coast and offshore mariculture technology

There is a small amount of published information on offshore seaweed farming, but it is not an area that has attracted a great deal of research or commercial attention (Buck and Buchholz, 2004) at the global level.

Off-the-coast commercial shellfish mariculture has been occurring in a number of locations as an extension of existing shellfish farming in more sheltered waters (New Zealand Ministry of Fisheries, 2009). Typically, these activities are in large embayments where some degree of shelter is already provided rather than in more open waters. The same farming methods as are used in more sheltered waters are normally used (e.g. Japanese long-line system for mussels), but often with the use of heavier gear, including larger floats, anchors and mooring lines to cope with the additional stresses of greater wave and wind exposure (Fredheim and Lien, 2003; Jeffs *et al.*, 1999; Jenkins, 1985; Johns and Hickman, 1985; Lien and Fredheim, 2003). However, using this technology for shellfish mariculture in more open waters is problematic because of greatly increased strain loads on farm infrastructure, especially between floats on the backbone lines during large wave conditions (Merino, 1997). Increased vertical movement in the farming structure due to wave motion can also result in the detachment of farm stock such as for mussels which rely on byssus thread attachment to the farming structure. Offshore mariculture of shellfish has been undertaken on an experimental scale at a number of locations in temperate regions where large-scale commercial shellfish farming is more prevalent (Bonardelli and Levesque, 1997; Chambers *et al.*, 2003; Langan, 2000a; 2000b). These have concentrated on submerging traditional suspended longline and pearl net culture systems to depths of 20 m below the sea surface to avoid the difficulties of retaining surface floats in exposed open waters, but with stronger mooring systems. This approach has worked well and survived the effects of high winds (100 km h^{-1}) and seas generated by a hurricane, as well as wave heights in excess of 6 m (Langan, 2000a; Paul, 2000). However, some difficulties were encountered in maintaining the correct headline depth as the mussel stock grew and added increased weight to the submerged floats. As a result, some floats collapsed due to the increased water pressure from being pulled to greater water depths. (Chambers *et al.*, 2003). Besides the failure of floats, some problems have also been encountered in offshore shellfish farms with fouling and predation by sea stars (Chambers *et al.*, 2003; Hampson *et al.*, 1999).

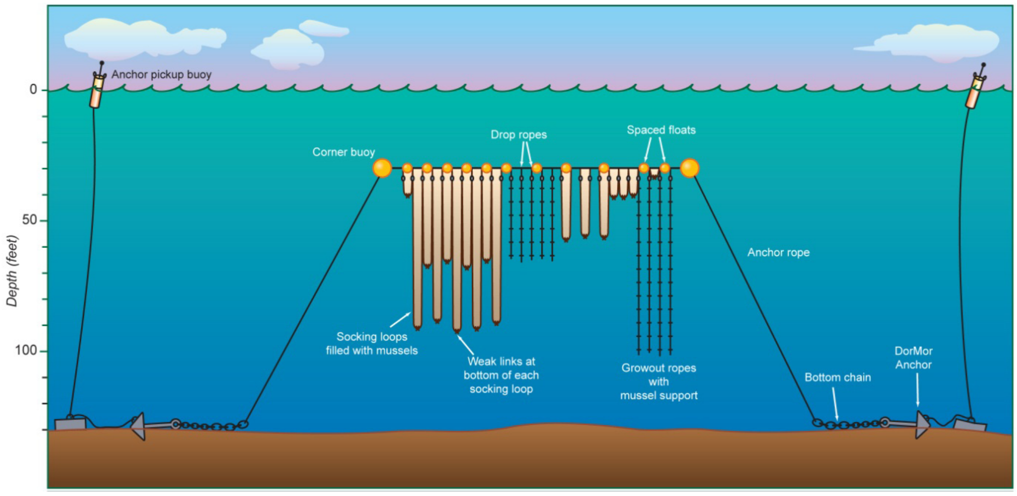
There are currently, several commercial producers using the offshore shellfish farming technology developed by the University of New Hampshire, on a relatively small-scale (R. Langan, personal communication, 2009) (Figure 2). One farm is operating around 1.2 km off the coast of California and has about 15 working longlines, each producing around 10 tonnes of blue mussels (*Mytilus galloprovincialis*) per line with a 6–8 month production cycle (www.sbmariculture.com). The company is also exploring the culture of Pacific oysters and rock scallops. Another commercial operation is off the coast of New Hampshire, and while there is a longline capacity to produce 90–100 tonnes annually, the operator has not come close to full utilization of the gear for a number of logistic reasons. Two further initial farms have recently been set up off the coast of Massachusetts, and if they show initial commercial success they will look at further expansion. There is reportedly another commercial-scale shellfish farm using the offshore farming technology in the Black Sea in the Republic of Turkey, but details of their location and production are sketchy.

Interestingly, these initial commercial efforts at commercializing offshore shellfish mariculture methods developed by the University of New Hampshire at a site 10 km (52 m depth) offshore have been located closer to the coast and in shallower water; New Hampshire commercial farm site (4.5 km and 35–40 m), California commercial site (1.2 km and 45 m), Martha's Vineyard, Massachusetts sites (3 km and 26 m) and (4 km and 32 m), Rhode Island sites (4 km and 25 m) and (6 km and 38 m) (R. Langan, personal communication, 2009). This trend is in line with economic modelling which predict that distance offshore is an important factor for determining the major operating costs of an offshore mariculture operation (Kite-Powell *et al.*, 2003b).

Off-the-coast sea cage farming of a variety of finfish species has been occurring for many years based on designs that were the result of incremental development of floating sea cages traditionally used in coastal waters. Floating sea cage designs made of plastic (high density polyethylene) for culturing finfish were first made by Polarcirkel in the Kingdom of Norway in 1974 and this style of plastic cage is now widely used around the world for mariculture in both coastal waters and off-the-coast situations (www.akvasmart.com; www.aqualine.no) (Svensson, 1993). Floating sea cage systems made of flexible rubber have also been important in the development of off-the-coast

FIGURE 2

Submerged longline system for offshore mariculture of shellfish, such as mussels and scallops



Source: Hoagland, Kite-Powell and Jin, 2003 – Illustration by Jack Cook, Woods Hole Oceanographic Institution.

sea cage farming (Gunnarsson, 1993). The first rubber sea cage systems fitted with plastic collar rings (Bridgestone Hi-Seas fish cages; Gunnarsson, 1993) were first used in Japan in the early 1980s and then their use spread around the world. These floating plastic and rubber cage systems increased in size from earlier designs used in shallow water, increasing from 10 m to 20 m hexagonal cages and the depth of the nets that were held beneath them also increased from 10 m to 30 m depth. Subsequent research has found that larger sea cages tend to result in faster growth of fish (20–30 percent in some instances), better feed conversion, lower mortality and better quality fish (Chen *et al.*, 2008; Guldberg *et al.*, 1993). These are important findings for considering further increases in the size of culture systems. During the 1980s there was substantial development work undertaken on floating sea cage designs in response to increasing demand from the mariculture industry to be able to operate sea cages in more open waters (i.e. significant wave height to 4 m or surviving waves of 7 m once in 30 years) and the ability for sea cages to be towed from one location to another to allow culture areas to be fallowed (Svensson, 1993). The efforts resulted in more integrated floating sea cage farming systems, including base platforms for feeding and managing groups of sea cages and advanced mooring systems and floating structures that were capable of withstanding more extreme weather conditions. These more robust systems were also able to withstand the stress of being handled with large servicing vessels of 30–40 m in length, such as pulling alongside cages in high seas. Since this time, further remote operational technology has been developed for offshore sea cage farming situations, including for monitoring fish, managing feeding, as well as providing security from large marine predators and theft (Davis *et al.*, 1993; Dunn and Dalland, 1993; Jackman and Ace-Hopkins, 1993).

Typically, all of these sea cage designs utilized a floating frame that supports the net pen and usually have frames made of steel walkways connected by hinges, floating sections of rubber hose or sections of floating plastic pipe (Beveridge, 2004). The floating cage is held in position by one or more anchors and weights are used to hold down the net pen in the water column. These cages are sufficiently flexible to ride out the wave loadings in sheltered or semi-sheltered situations where smaller and shorter period waves are the norm (Beveridge, 2004). However, in fully exposed open water situations, the greater wave periods and wave heights place extreme forces that are generally beyond the operational limits of conventional floating sea cage designs and materials (Loverich and Croker, 1993). The wave motion causes flexing of the floating frame and deforms the net pen effectively reducing the area available for fish culture within the pen by up to 80 percent because the fish need to remain within a volume where the wave particles do not pass through the net pen mesh (Lien, 1993). As a result, a very wide range of designs and concepts have been promoted for offshore mariculture (Beveridge, 2004). A large number of these evolved from offshore oil and gas engineering designs, and some have promoted the use of modified petroleum infrastructure that is no longer in use (Hanson, 1974a; 1974b; Ribakoff, Rothwell and Hanson, 1974; Stickney, 1997). This included bottom-supported platforms, such as Texas towers, jack-up rigs, and monopods, as well as floating and semi-submersible platforms, including modified conventional ships and barges, as well as net pens supported between moored spar bouys.

FIGURE 3

Farmocean offshore system – semi-submerged offshore sea cage system for offshore mariculture of finfish

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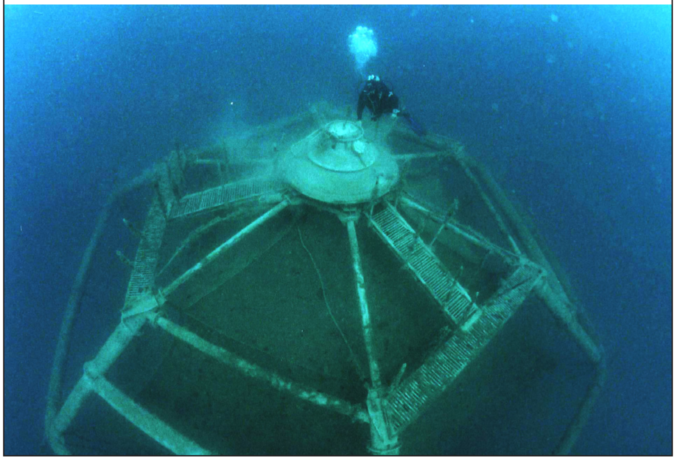
A frequent approach to overcoming the problem of wave stresses on offshore mariculture infrastructure is to enclose and submerge the infrastructure either permanently or during periods of adverse weather. This results in decreased stress on the infrastructure because water particle motion due to the waves in the sea decreases exponentially from the surface and is reduced to zero at a depth corresponding to half the wave length (Beveridge, 2004). Submerging sea cages also has potential advantages in avoiding conflict with some other water users, such as boat traffic. It can also help in avoiding surface jellyfish swarms and damage from collisions with floating debris (Beveridge, 2004; Ryan, Jackson and Maguire, 2007). Submerged cages tend to be more difficult to operate and cause problems for the culture of some species. For example, submerged cages are thought to cause problems for swim bladder physiology of some fish species, such as salmon which have an open duct between the oesophagus and the atmosphere and need access to the atmosphere in order to fill the swim bladder with air (Rubach and Svendsen, 1993).

Offshore sea cages of a wide variety of designs have been devised, built, tested and commercialized to some extent over the past 30 years or more (Beveridge, 2004). It would appear that some submerged and semi-submerged sea cage designs are beginning to emerge as the most likely types to be commercialized more widely.

Semi-submersible Farmocean sea cages (Figure 3) were designed in the Kingdom of Sweden and first used in 1986 and are now widely used, especially in Europe and the Mediterranean (Beveridge, 2004; Scott and Muir, 2000). They consist of a semi-submersible steel ring and cone pontoon, topped by a feed silo and computer control centre. Parts of the ring can be flooded to provide ballast and semi-submerge the structure. Beneath the metal cone a sea cage is suspended and held down by weights at its base and the internal volume of the sea cage can vary in size from 2 500 to 6 000 m^3. The conical pontoon is moored to the seafloor from the outer circular pontoon. These seacages are capable of containing up to 150 tonnes of fish and withstanding waves of over 5 m in height.

FIGURE 4

Sadco-Shelf sea cage – submerged offshore sea cage system for offshore mariculture of finfish



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Another offshore sea cage design that has been used in Europe and the Mediterranean is the Refa sea cage which is a semi-submersible tension leg design (Beveridge, 2004; James and Slaski, 2006; Scott and Muir, 2000). The sea cages are moored to the seafloor directly beneath the sea cage so that under extreme conditions they are designed to submerge of their own accord (www.refamed.com). A plastic frame is used to provide buoyancy at the surface and to form the circular shape of the enclosed net pen which ranges in size from 10 to 20 m in diameter and 800–12 000 m^3 in volume and is capable of holding up to 300 tonnes of fish at a high stocking density. Concerns have been raised regarding the mooring arrangements and deformation of the net pen when this design of sea cage is under load (Ágústsson, 2004).

Sadco-Shelf is a rigid hexagonal cage design constructed of tubular steel that is fully submersible (www.sadco-shelf.sp.ru) (Ágústsson, 2004; Beveridge, 2004) (Figure 4). In the submerged position the sea cage is reported to be able to withstand waves over 15 m in height and current speeds in excess of 1.5 m s^{-1}. The Sadco 2000 model has a sea cage that is 16 m in diameter and has a volume of 2 000 m^3 that is capable of producing 80 tonnes of finfish. The design includes a 2 000 litre submersible fish feed reservoir with automated feeding. Sadco sea cages have been deployed in the Caspian, Black and Mediterranean Seas.

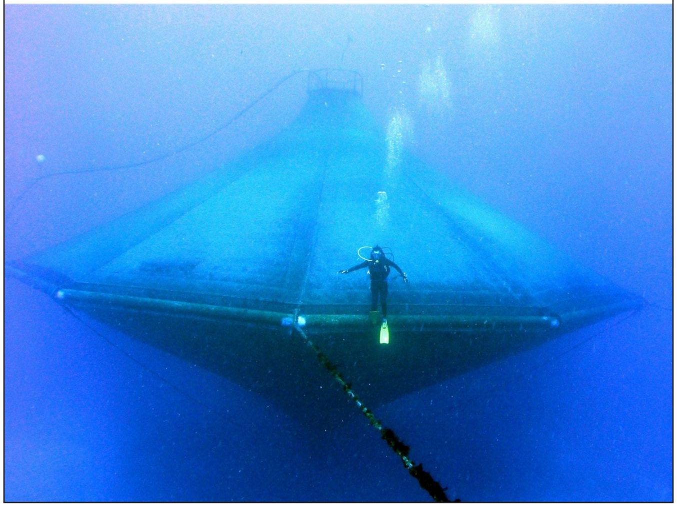
Other submersible rigid sea cage designs include the Trident and MII (Marine Industries and Investments) sea cages, however, there appears to be relatively little recent information on their use suggesting they have not found favour with researchers and potential commercial users (Ágústsson, 2004; James and Slaski, 2006; Scott and Muir, 2000). The Trident cage is reported to have withstood breaking waves of over 3.5 m in height and wind speeds of over 100 km h^{-1} while partially submerged.

The designs of submersible open ocean sea cages that have been most widely used, especially in the tropical zone, are Ocean Spar designs (www.oceanspar.com, www.snapperfarm.com) (Baldwin *et al.*, 2000; Halwart, Soto and Arthur, 2007; James and Slaski, 2006). Ocean Spar sea cages have been used in Hawaii (USA), Puerto Rico, Bahamas, Gulf of Mexico, Cyprus and New Hampshire (USA). These sea cages consist of a central hollow steel spar that is used to control buoyancy that is surrounded by a ring made of pipe steel of 20 m or more in diameter that is used as a frame for holding the net pen. The submersible sea cage can be brought to the surface through altering the buoyancy of the cage structure. The sea cage has a volume of 3 000 m^3 and there is the potential to build larger units. The cages have withstood extreme weather conditions, including hurricane winds of over 100 km h^{-1} for almost 24 hours in the Bahamas with no damage to the submerged cage or the contained fish (Benetti, 2004). The cage has also survived waves in excess of 5 m height on the eastern part of the United States of America and the design has been modelled to withstand waves up to 9 m (Ágústsson, 2004). The difficulties reported with operating this sea cage system relate to the initial high capital cost, the requirement for costly diver servicing of the cage, shark damage to netting and the need for a more efficient feeding system (Ágústsson, 2004; Halwart, Soto and Arthur, 2007; James and Slaski, 2006; Scott and Muir, 2000).

Several submersible sea cage designs have been developed in China and Taiwan Province of China, including the PDW and SLW designs in China (Chen *et al.*, 2007; Chen *et al.*, 2008; De Silva and Phillips, 2007; Guo and Tao, 2004; Xu, 2004). The PDW designs are especially designed for farming flatfish and have multiple layers to facilitate the bottom dwelling behaviour of the cultured flat fish. An experimental PDW sea cage survived typhoon winds over 90 km h^{-1} and waves of over 5 m in height.

FIGURE 5

Ocean Spar SeaStation 3000 sea cage submerged in the blue waters off Cape Eleuthera in the Bahamas



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Economics

The operation for many years of off-the-coast mariculture for fish and shellfish in many parts of the world would tend to confirm that this activity can be financially viable for some species in some locations using existing technology. However, globally, the commercialization of offshore mariculture technology is still emerging and the application of the technology on a commercial-scale is still relatively small, but increasing in recent years consistent with improving prospects for establishing consistent commercial viability (Halwart, Soto and Arthur, 2007; James and Slaski, 2006). The vast majority of this activity relates to finfish farming and much of it is being conducted in the tropical zone because of faster growth of fish due to higher water temperatures, as well as more favourable operating conditions, e.g. more flexible regulatory regimes, better water clarity, more consistent and favourable weather conditions.

One of the major delaying factors for progressing open ocean mariculture of finfish in tropical regions has been the absence of existing and well-established commercial mariculture of finfish species that would be suitable for offshore mariculture systems. Consequently, the development of offshore farming technology has had to contend with the development of mariculture techniques for largely unknown aquaculture species, simultaneously with developing new farming technology. This contrasts significantly with the development of off-the-coast mariculture mostly in temperate waters which has largely consisted of advancing mariculture infrastructure for existing aquaculture species for which the husbandry and commercial culture capabilities are well known from prior inshore mariculture experience. For temperate waters, where there is extensive commercial aquaculture of species, such as salmonids, there has been somewhat limited commercial appetite to move into offshore farming. This limited interest perhaps relates to the availability of existing coastal space for mariculture expansion and the opportunities for working to improve commercial returns from existing aquaculture operations through less risky and capital intensive developments, such as improving husbandry and feed formulation and delivery.

A number of published studies have been undertaken to investigate the economic viability of open ocean mariculture operations, for both shellfish and finfish, with conflicting results.

Economic modelling has suggested that open ocean mariculture of two species of shellfish, sea scallops (*Placopecten magellanicus*) and the blue mussel (*Mytilus edulis*), has the potential to be economically viable in temperate New England waters (Hoagland, Kite-Powell and Jin, 2003; Kite-Powell, Hoagland and Jin, 2003a; Kite-Powell *et al.*, 2003b). The study concluded that seabed seeding appeared to be the most promising approach for scallop culture as the costs of buying, maintaining, deploying and harvesting open water scallop growing structures was too expensive.

The modelling, that was based on growth data from experimentally grown mussels in offshore waters, predicted that commercial mussel culture using submerged longlines was potentially economically viable, provided a sufficiently high market price could be maintained. However, the risks of crop loss due to fouling and extreme weather posed a significant business risk. It was suggested that this risk might be overcome through the diversification of species (i.e. including sea bed enhancement of scallops) and this would also help to support the cost of the equipment required for servicing the offshore farm, such as vessels. The establishment of a farm required significant initial capital investment (>USD 1 million) with projections of positive cash flow first occurring three to seven years out depending on the landing prices for the cultured shellfish (Hoagland, Kite-Powell and Jin, 2003; Kite-Powell, Hoagland and Jin, 2003a).

Another study of the economic viability of longline farming of mussels in the offshore waters of Canada concluded that it was not economically viable, due in a large part to the slow growth of the shellfish in the cold waters (Bonardelli and Levesque, 1997). Economic analyses undertaken by privately owned mariculture companies in New Zealand has indicated that offshore mussel farming was likely to be marginal at best, despite New Zealand operating some of the most efficient large-scale mussel farming systems in the world and attracting a premium price in the market for the endemic mussel species (*Perna canaliculus*) (J. Wilson, personal communication, 2009). Regardless of the less than optimist economic projections, a number of commercial shellfish farms have emerged that are utilizing the offshore farming technology developed in New Hampshire (R. Langan, personal communication, 2009). However, despite extensive information searching, no examples of offshore shellfish mariculture could be found for the tropical zone.

A number of economic modelling studies have also been conducted for offshore finfish farming operations. An economic model was developed for a large-scale offshore sea cage finfish operation in the Gulf of Mexico (Posadas and Bridger, 2003). The model considered three potential finfish species for which growth and culture density data were available; cobia (*Rachycentron canadum*), red snapper (*Lutjanus campechanus*) and red drum (*Sciaenops ocellatus*). The modelling indicated that offshore mariculture of all three species were unlikely to be economically viable unless the scale of the farm was increased, landed prices were increased by at least USD1 kg^{-1} and stocking densities were very high. Cobia was the species that showed the greatest potential for reaching commercial viability.

An economic model was developed for a finfish mariculture operation in the open ocean off New England that was growing cod, salmon and flounder (Kite-Powell *et al.*, 2003b). The model suggested it would be economically viable and indicated the importance of parameters such as, the distance from shore to the farm site, feed cost and maximum stocking density, in determining commercial viability. The model also indicated that significant costs were associated with operating and maintaining the cage system, vessels, as well as staffing, emphasizing the importance of greater automation for operating open ocean farming systems.

An economic model was used to evaluate the potential for the production of gilthead seabream in floating off-the-coast cages in the Canary Islands and the Mediterranean, an activity that already occurs in the Mediterranean (Gasca-Leyva, León and Hernández, 2003a; 2003b; Gasca-Leyva *et al.*, 2002; 2003c). The modelling found that differences in the growth rates of fish due to differences in water temperature at different sites could be offset by harvesting at different sizes to meet differences in market preference. Variable costs, such as feed and labour, made up around 50 percent of total costs, whereas fixed costs were a smaller overall proportion of total costs (around 13 percent) making it more difficult to generate improved financial performance based on increasing the scale of production. Regardless, the most economic scale was predicted to be a large farm in the order of 48 000 m^3. Economic sensitivity analyses indicated financial returns were unexpectedly more sensitive to changes in the level of mortality and feed use than to all other variables, except for the commercial price for final product.

An economic model for mutton snapper production in an open ocean style sea cage system (Ocean Spar Technologies LLC – Ocean Spar SeaStation) in Puerto Rico concluded that the operation could be profitable provided the scale of production was increased significantly to reduce labour costs, and the cost of the farming technology was lower (Brown *et al.*, 2002).

An economic model for an open water Atlantic salmon farming operation producing 10 000 tonnes per annum indicated it would be economically viable (Ryan, 2004), although this conclusion has subsequently been questioned (James and Slaski, 2006).

Despite the uncertain economic predictions from modelling studies, a number of commercial or pilot scale open water finfish farming projects have progressed in the tropical zone during last decade, and new initiatives are developing. Experimental and commercial farms have been operated in Hawaii, Bahamas, Puerto Rico, Gulf of Mexico and further open water farms have been proposed or are under development in St Kitts, Panama and Belize (www.marinefarmsbelize.com) (O'Hanlon *et al.,* 2003).

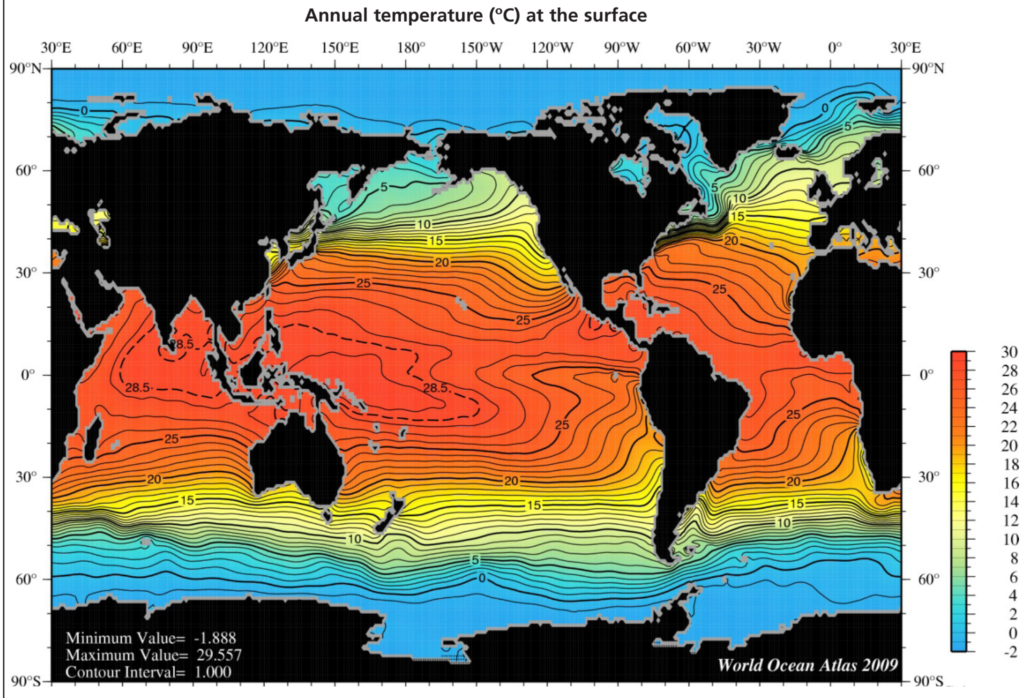
THE GROWING ENVIRONMENT

As might be expected, the world's oceans in the tropical zone generally have warmer surface waters than oceans in higher latitudes (Locarnini *et al.*, 2006) (Figure 6). Average annual sea surface temperatures within this tropical zone typically range between 24 and 31 °C.

Furthermore, the annual seasonal variation in sea surface temperature tends to be smaller for oceans within the tropical zone (typically a 1–2 °C range) than oceans in cooler regions of the world (typically a 5–10 °C range at latitude of 40°) (Levitus, 1987) (Figures 7 and 8). Nearer to the coast, larger annual variations in sea surface temperatures occur, typically 10–20 °C in sheltered waters. Diurnal variations in

FIGURE 6

Mean annual sea surface temperature (°C) of the world's oceans



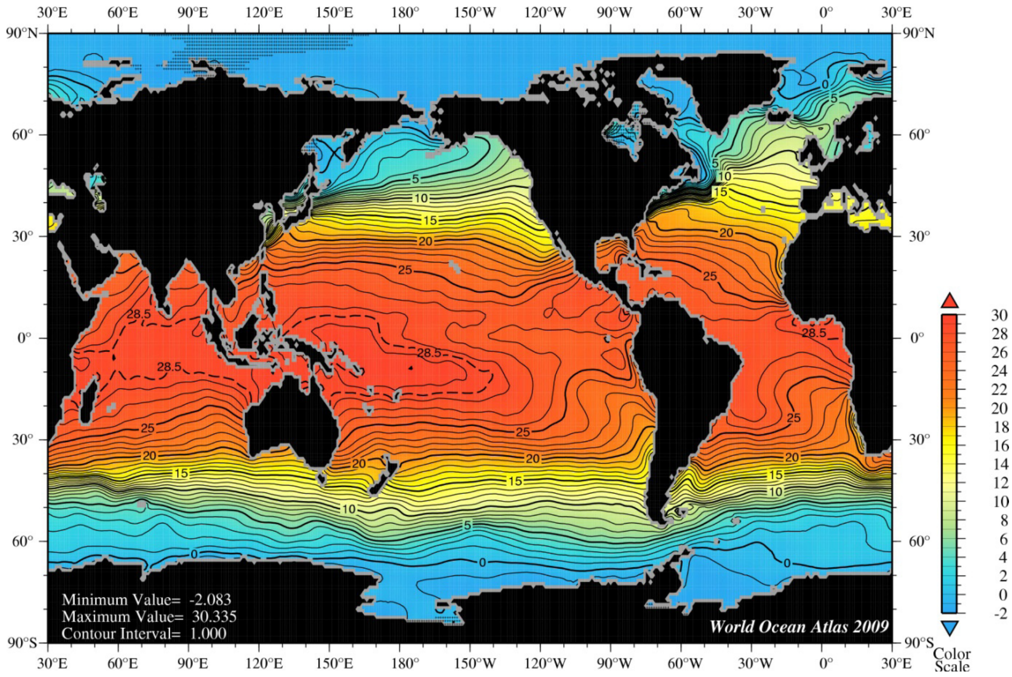
Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

water temperature also tend to be higher in sheltered and shallow coastal waters where a range of 2–3 °C is common and variations of 3–4 °C have been observed (Levitus, 1987). In comparison, offshore waters typically have a diurnal range of around 1 °C.

FIGURE 7

Mean sea surface temperature (°C) of the world's oceans during winter (January–March)

Winter (Jan.–Mar.) temperature (°C) at the surface

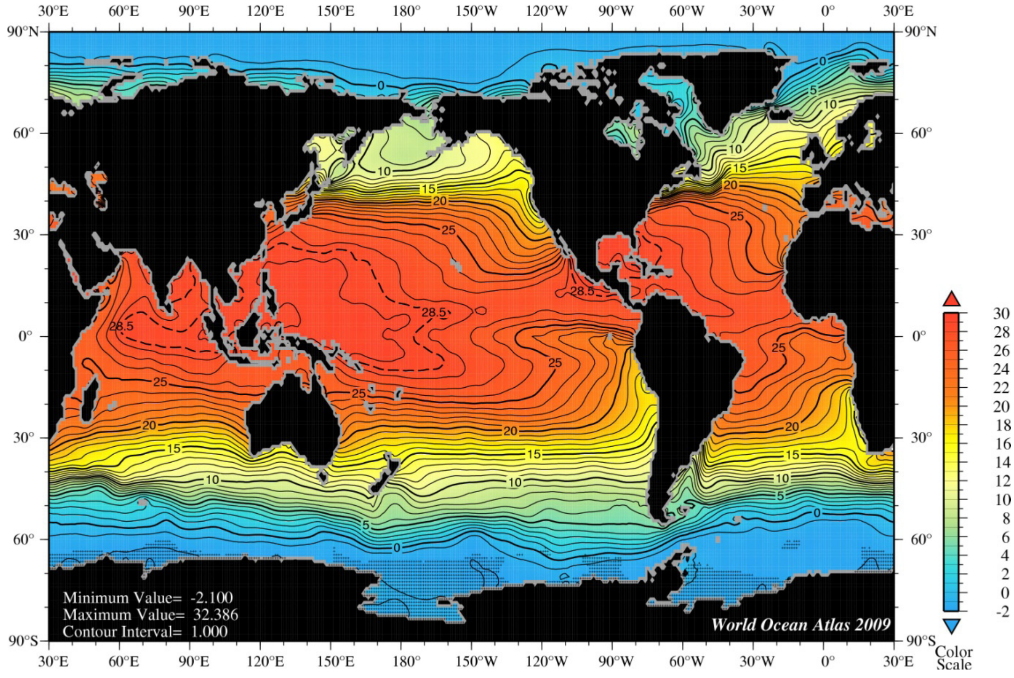


Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

FIGURE 8

Mean sea surface temperature (°C) of the world's oceans during summer (July–September)

Summer (Jul.–Sep.) temperature (°C) at the surface



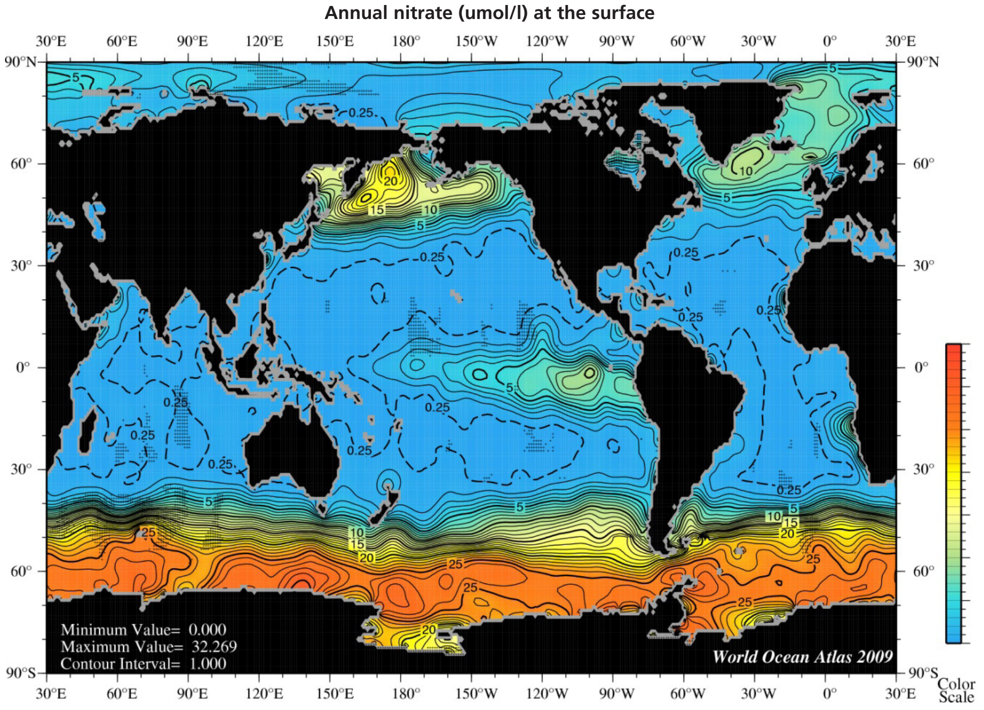
Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

The maintenance of a stable temperature regime at a mariculture location can assist in improving production, especially if the ambient temperature remains close to the optimum for the cultured species. Short-term fluctuations in temperature can stress some aquaculture species, especially finfish, which in turn can result in reduced culture performance (Wheaton, 1993). Consequently, offshore waters in the tropical zone have the advantage of providing stable water temperatures for mariculture, especially for species with matching temperature optima. Furthermore, mariculture species are poikilotherms with metabolic processes frequently limited by temperature. For this reason, many tropical mariculture species are capable of higher growth rates than their temperate water counterparts although their rates of natural mortality tend to be higher (Charnov and Gillooly, 2004; Griffiths and Harrod, 2007; Jensen, 2001; Pauly, 1980). Although it is not altogether clear whether the higher rates of natural mortality are related entirely to differences in predatory effects, or that endogenous physiological effects of temperature may also play a role.

The world's oceans in the tropical zone are characterized by generally lower primary productivity due to the nutrients required for plant growth being limited in surface waters, especially nitrate and phosphate (Garcia *et al.*, 2006b) (Figures 9, 10, 11 and 12). Low concentrations of silicate also greatly limits the production of diatoms in tropical zone waters, with dinoflagellate photosynthesis more important for primary production in the tropical zone (Figure 11). Primary production tends to be higher in the nearshore coastal zone where nutrients are brought into the surface waters from the land and the interaction of nutrient rich seawater with the seabed or land typography. Nearshore coastal waters also tend to have higher levels of detrital material and dissolved organic matter, both of which contribute to the nutrition of filter feeding shellfish, together with microalgal primary producers (Dame, 1996). Having evolved in shallow coastal waters, bivalves are most abundant and diverse in coastal waters where there is sufficient suspended material to support their lifestyle. Therefore, the mariculture of filter feeding shellfish, such as mussels and oysters, in

FIGURE 9

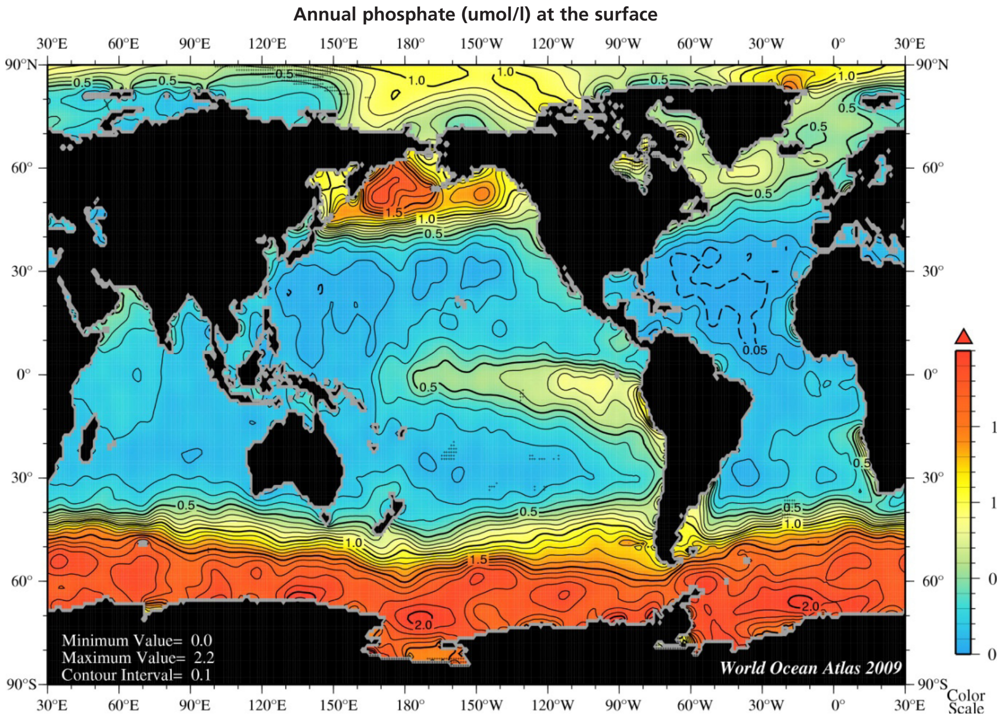
Mean nitrate concentration of surface waters of the world's oceans



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

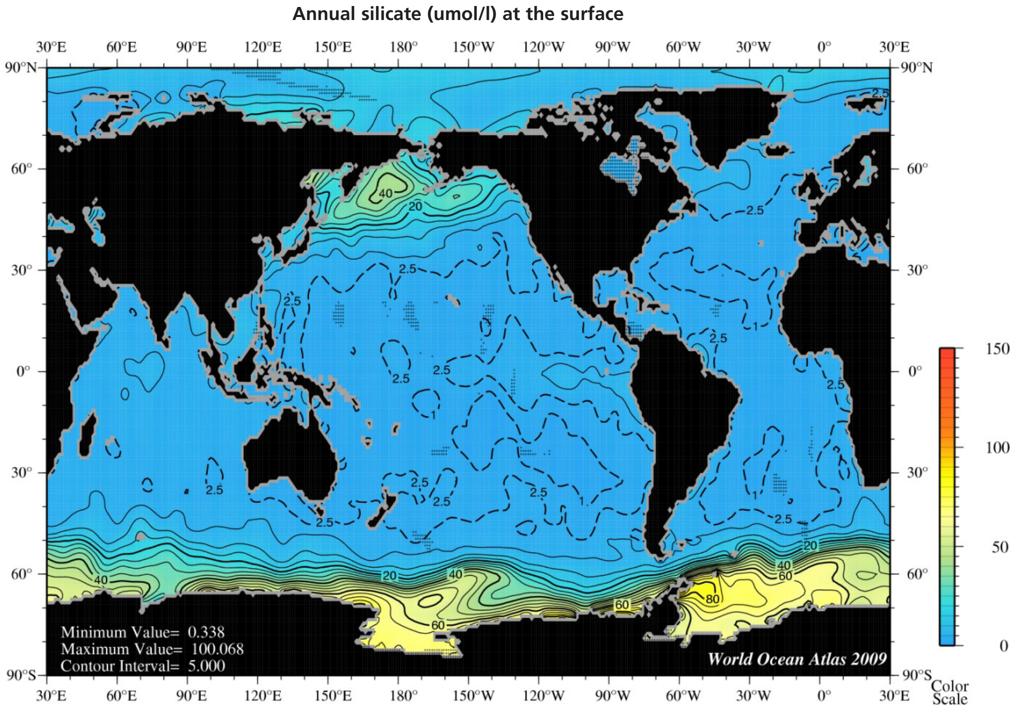
offshore tropical waters with low food availability is unlikely to be viable. Likewise, the culture of macroalgae in offshore tropical waters with low nutrient availability is also unlikely to be viable.

FIGURE 10
Mean phosphate concentration of surface waters of the world's oceans



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

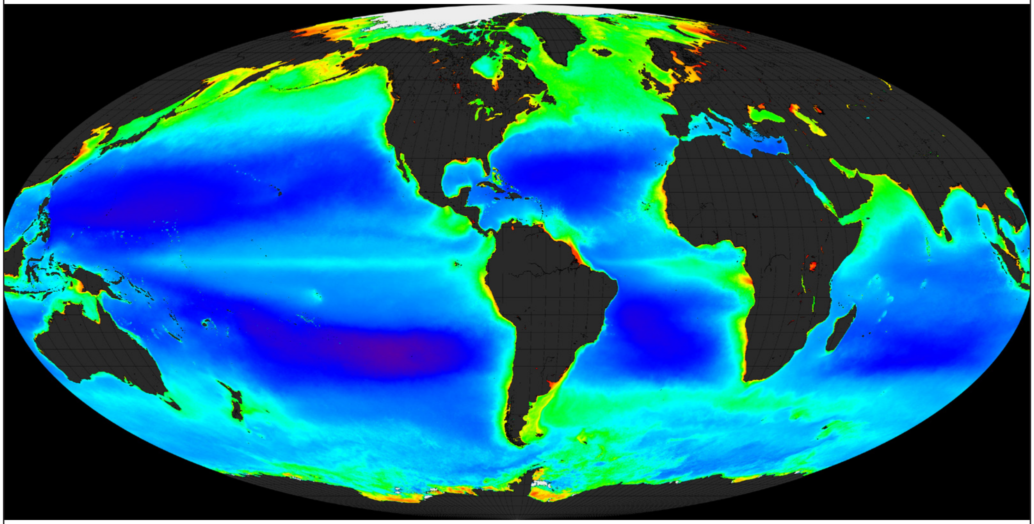
FIGURE 11
Mean silicate concentration of surface waters of the world's oceans



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

FIGURE 12

Mean chlorophyll-α concentration of surface waters of the world's oceans for the period of 1997 to 2009



Source: SeaWiFs satellite data from: http://earthobservatory.nasa.gov

Higher nutrient levels, in particular in coastal waters, are also frequently associated with some nuisance species for mariculture activities, such as harmful algal blooms and jellyfish swarms. These nuisance events are thought to be less frequent in offshore and tropical waters with generally lower nutrients levels.

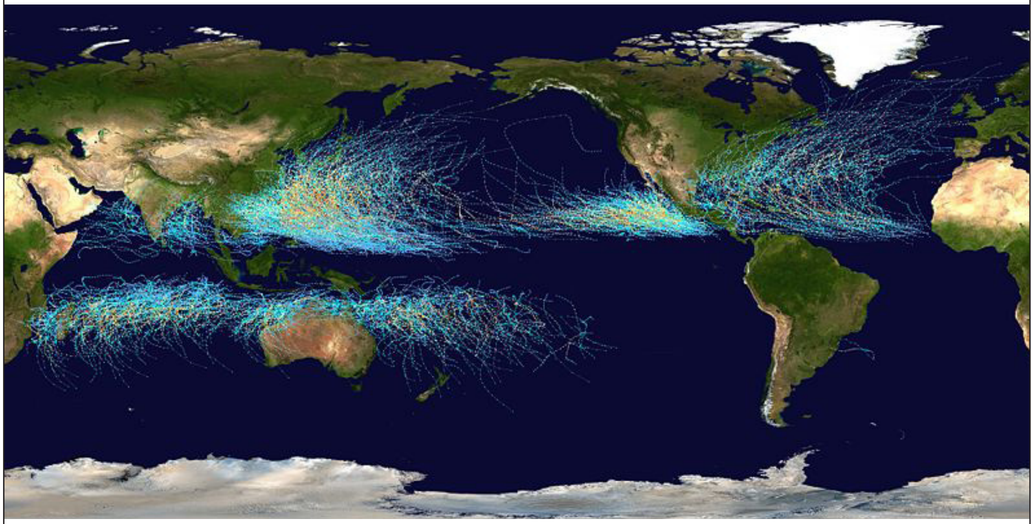
Nutrient turnover in tropical waters is significantly higher than in cooler waters at higher latitudes because of warmer water temperatures and high ambient light intensity enabling phytoplankton photosynthesis (Furnasa *et al.*, 2005). This may have important implications in terms of reducing the environmental effects of nutrient discharges from mariculture activities through their more rapid dispersal into the food chain. However, there are concerns that offshore aquaculture may result in environmental impacts through greater spread of nutrients into benthic communities that are less able to cope with high nutrient loads (O'Neill, 2007).

Coastal waters are also affected by discharges of pollutants from the land. For example, sewage discharges and water run-off from land used for farming of grazing animals releases faecal pollutants into seawater which can contaminate filter feeding shellfish in mariculture operations. This pollution risk is much reduced and resulting product quality can be improved as a result of mariculture activities being moved further from the coast (Brenner *et al.*, 2009; Stickney, 1997).

High sea surface temperatures that are 28 °C and over and are located in areas greater than 4° of latitude from the equator are the source of tropical cyclones, typhoons or hurricanes (Anthes, 1982; Chan and Shi, 1996; Nalivkin, 1983; Stow, 2004). Global climate warming is creating the sea temperature conditions conducive to the formation of tropical cyclones (Figure 13) and consequently, they appear to becoming more frequent and intense (Emanuel, 2005). These violent weather events take some time to build energy and are not officially classified as a typhoon until they generate a wind speed of more than 64 knots, although tropical storms of less than typhoon strength can form and travel in a similar fashion, and still be capable of causing considerable damage to infrastructure through flooding and high winds. Typhoons are characterized by a circling air mass and often have a diameter of influence of 500 km, with larger typhoons more than double this. Due to the rotation of the earth, tropical cyclones originating north of the equator always move in a curve to the north-west, into higher latitudes. South of the equator, typhoons always move in a curve to the west-south-west, into

FIGURE 13

Tracks of all tropical cyclones which formed worldwide from 1985 to 2005. The points show the locations of the storms at six-hourly intervals. The stronger the red hue in the tracks, the greater the wind strength for the cyclone



Source: http://en.wikipedia.org

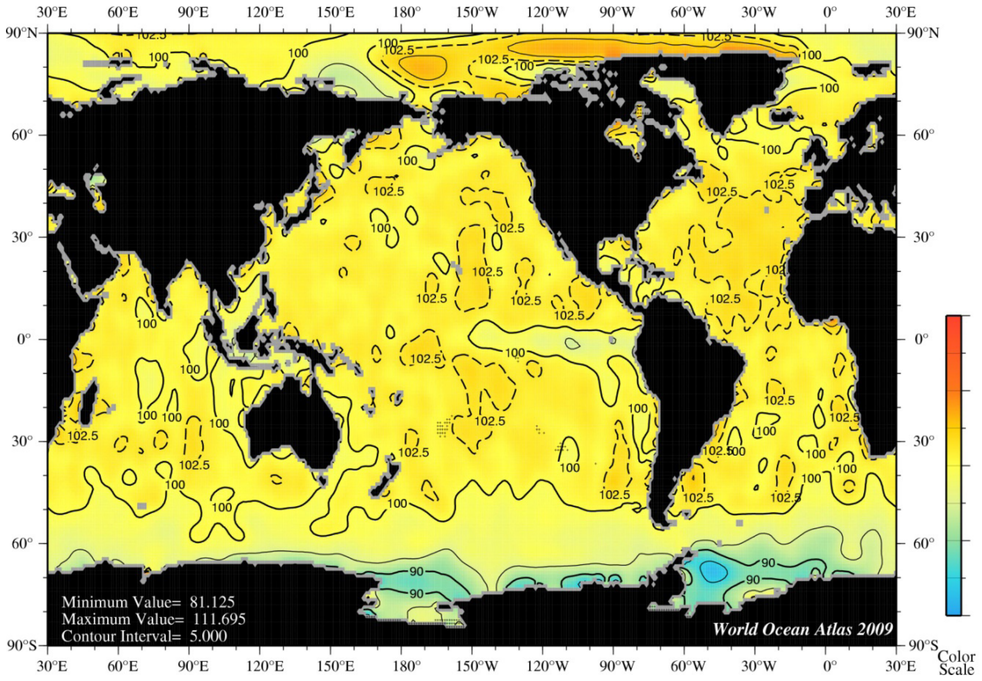
higher latitudes. Tropical cyclones represent a significant risk to mariculture operations due to the extreme winds which can create large wave conditions and for periods of up to a week or more. Such conditions are extremely challenging for retaining moored mariculture infrastructure while maintaining ongoing animal husbandry in off-the-coast and offshore locations.

In shallow coastal waters tidal movement is a dominant force for creating water currents that are vital for water exchange in mariculture. Local winds can also be important in creating movement in surface waters, but frequently coastal mariculture operations are sited in sheltered locations to avoid exposure to extreme wind and wave conditions. In the open ocean, tidal currents are relatively weak but can be important in some locations in creating mixing of deep ocean waters through the generation of internal waves (Egbert and Ray, 2000; Ross, 1995). This can lead to higher nutrient waters being brought toward the surface where they increase primary productivity. In the open ocean, local wind conditions and ocean currents are more important in generating movement of surface waters and the extent of this is variable depending on the location. Ocean currents are generated by a range of influences including water temperature, wind patterns, salinity and Earth's rotation which result in mass directed movement of ocean water. The strength of an ocean current at any location is also influenced by the interaction of the current with topographical features and other water masses. For example, ocean currents flowing between islands typically increase in speed. For off-the-coast and offshore mariculture the selection of sites with a suitable current regime is critically important to ensure sufficient water exchange, while avoiding excessive strain on moorings due to extreme current events. The presence of a continuous current of sufficient strength is particularly important for the culture of pelagic finfish at high densities in tropical waters due to their high oxygen demand and the reduced oxygen dissolution in warm seawater. Typically water currents in excess of 0.1–0.3 m s^{-1} are required in such circumstances.

While oxygen concentration in surface waters of the world's oceans are mostly in the vicinity of 100 percent, the higher sea water temperatures found in the tropical zone limits the dissolution of oxygen and carbon dioxide (Garcia *et al.*, 2006a) (Figures 14 and 15). Consequently, surface waters in the tropical zone contain significantly less dissolved oxygen than in temperate regions of the world and have a lower capacity to absorb waste carbon dioxide from aquatic animal metabolism. This is an important consideration for the offshore mariculture of pelagic finfish at high densities in tropical waters due to their high oxygen demand.

FIGURE 14
Mean annual percent oxygen saturation of surface waters of the world's oceans

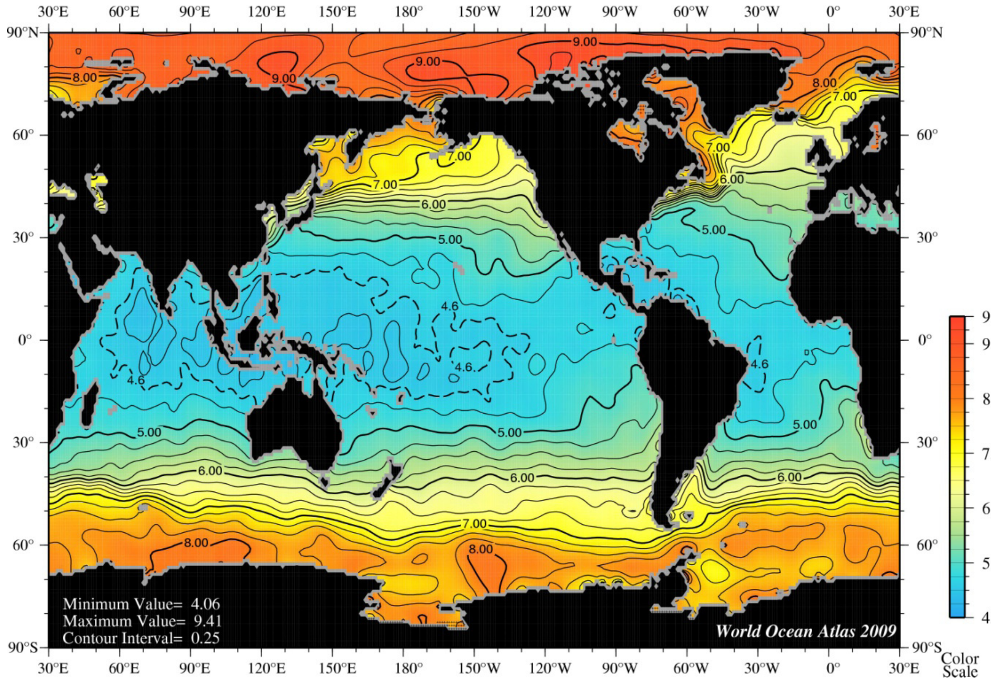
Annual percent oxygen saturation at the surface



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

FIGURE 15
Mean annual oxygen concentration of surface waters of the world's oceans

Annual oxygen (ml/l) at the surface



Source: World Ocean Atlas 2009 – National Oceanographic Data Center, www.nodc.noaa.gov

In general, there is less wind over the oceans of the tropical zone (Figure 16). Areas of stronger average winds are the "roaring forties" in the temperate zone of the Southern Hemisphere, the extra-tropical cyclonic activity over the Northern Atlantic and the Northern Pacific, and the Somali Jet in the Arabian Sea (Petersen *et al.*, 1997). In general, coastal waters benefit from land masses providing shelter from large-scale wind flows, but this sheltering effect is reduced with distance offshore from the coast.

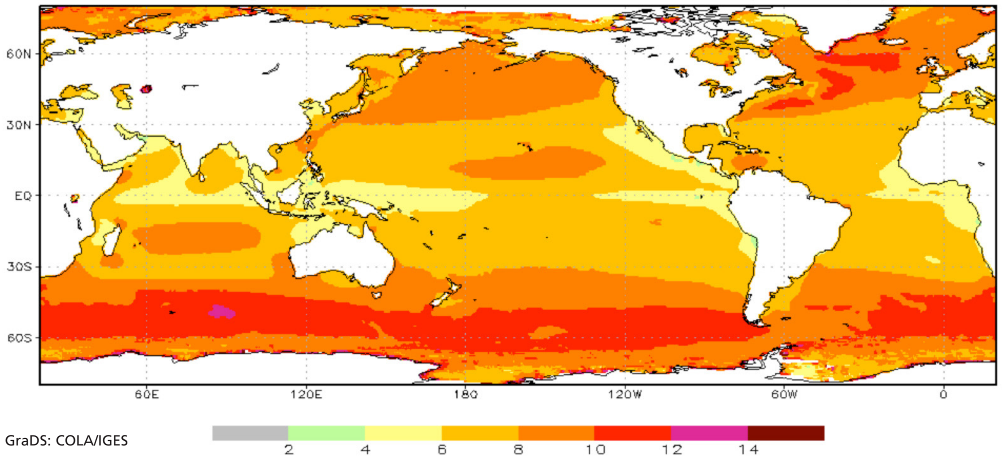
Average sea surface salinity reaches its maximum values (>35 ‰) in the subtropics at about 25° North and 25° South of the equator (Figure 17), especially in areas associated with the trade winds where evaporation due to wind and warm water temperatures exceeds replacement with precipitation (Antonov *et al.*, 2006). Coastal waters tend to have lower salinity due to accumulated freshwater runoff from the land mass into adjacent coastal waters. Waters with higher salinity also have a reduced ability to retain dissolved gases, which is important for respiratory gas exchange for cultured fishes (Stirling, 1985). Although many fish and shellfish species are euryhaline (i.e. capable of surviving in a wide range of salinities) their growth is influenced by salinity because between 10 and 50 percent of their total energy budget is used in osmoregulation (Boeuf and Payan, 2001; Gosling, 2003; Saxby, 2002). Furthermore, for fish there is evidence that food intake and stimulation of food conversion are both mediated by environmental salinity, sometimes in combination with temperature (Boeuf and Payan, 2001). The reasons for this are not entirely clear, but many hormones are known to be active in both osmoregulation and growth regulation, e.g. in the control of food intake. In general, it appears that marine fish tend to have higher growth rates in moderate salinity water <30 ‰. Therefore, mariculture in high salinity water, as is more frequently encountered in offshore situations, has the potential to result in reduced growth rates for some species.

The transparency of upper ocean waters in general is higher in open oceans, especially in the tropical zone (Pickard and Emery, 1990). Water transparency generally decreases in mid and higher latitudes, as in the vicinity of most coastlines. Lower water transparency is related to the increased presence of phytoplankton and other suspended and dissolved material in coastal and temperate waters. Overall, light tends to influence fish growth through stimulating food intake and better food conversion efficiency (Boeuf and Le Bail, 1999). Reduced water transparency has the potential to reduce the efficiency of visual feeding on pellets by cultured finfish, but the extent of this effect is likely to be influenced by the different behaviour and visual abilities of

FIGURE 16

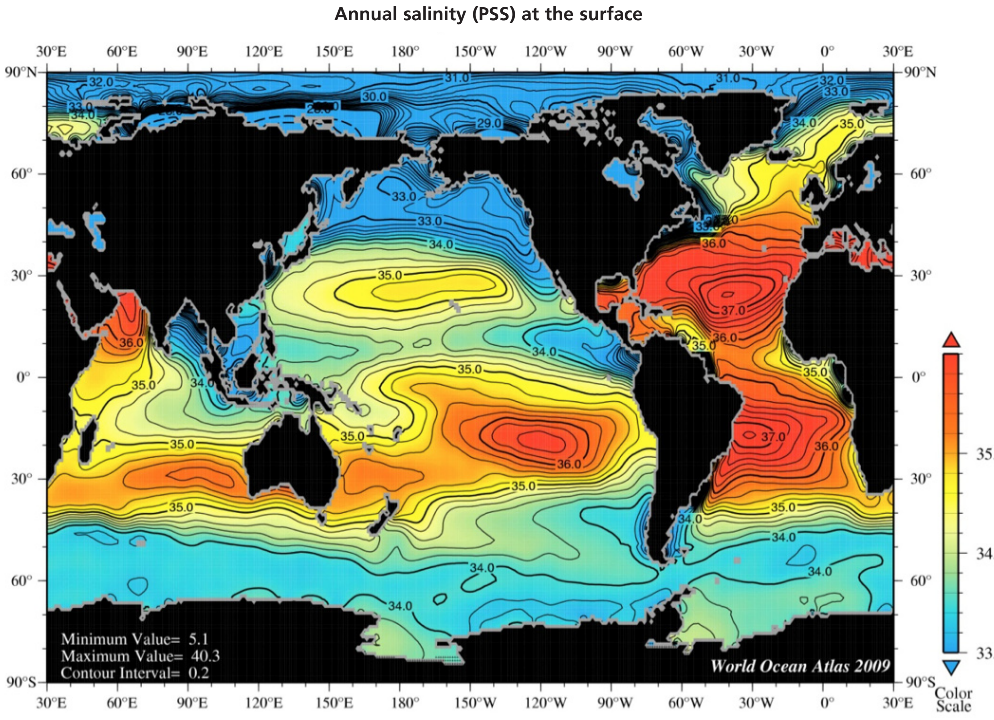
Average annual mean wind speed at 10 m elevation for the world's oceans

Climatological annual mean 10–m wind speed (m/s)



Source: Huai-Min Zhang, NOAA National Climatic Data Center, www.ncdc.noaa.gov/oa/rsad/seawinds.html

FIGURE 17
Mean annual salinity of surface waters of the world's oceans



Source: NOAA National Climatic Data Center, www.nodc.noaa.gov

different fish species (Ang and Petrell, 1998). High water transparency can also create husbandry issues for fish species that avoid high light situations (Fernöa *et al*., 1995). Indeed, light that is too intense may be stressful or even lethal for some fish species (Boeuf and Le Bail, 1999). Also, ultraviolet wavelengths from sunlight can penetrate high clarity seawater for a few centimetres especially when the sun's radiation is perpendicular to the Earth's surface, such as in the tropical zone (Beveridge, 2004). This situation creates a risk of ultraviolet burning of the skin of fish species that swim at the surface, a behaviour that sometimes is the result of low oxygen availability in the water (Halver, 1987).

Coastal mariculture in tropical zones in some locations has encountered problems with large fish predators, such as salt water crocodiles and sharks (Murray-Jones, 2004). Moving farms further offshore may reduce interference from large carnivorous reptiles which generally do not venture long distances from the coastline (Elsey, 2005). However, sharks do appear to be attracted to fish farming operations even where they are located some distance offshore (Godvin, 2005; Murray-Jones, 2004). Seabirds can also be a nuisance in preying upon fishes in sea cages and are found in coastal and offshore waters, especially in areas of high natural productivity (Beveridge, 2004).

The mariculture of organisms in open waters may avoid some problems with diseases and parasites. This is likely to be the case in offshore locations that are not frequented by wild populations of the cultured species that could act as a vector for the introduction or transfer of disease and parasites (Buck *et al.*, 2005; Hampson *et al.*, 1999; Naylor and Burke, 2005; Pennell and Barton, 1996). This situation is likely to apply equally to tropical and temperate ocean zones.

Marine mammals, sea turtles and whale sharks have been known to become entangled in mariculture infrastructure (Du Fresne, 2008; Lloyd, 2003; Paul, 2000). Members of these animal groups migrate widely in the oceans, and are frequently found in offshore waters, and some members tend only to be found in offshore waters, e.g. whale sharks and leatherback turtles. Both whale sharks and sea turtles are more commonly found in oceans of the tropical zone (Chen and Phipps, 2002; Spotila, 2004). However, species of marine mammals, both cetaceans and seals, are distributed throughout the world's oceans with some species migrating between temperate and tropical zones. There have been efforts to design remote warning and security systems for aquaculture sites to deal with both nuisance marine mammal predators and for early response for cetacean entanglement (Jackman and Ace-Hopkins, 1993; Paul, 2000).

Conflict of mariculture with other water users tends to decrease with distance from the coast, as does wilful interference, such as theft of aquaculture stock, due to the increased difficulty of access (McCarthy, 2002). In open waters the major users that mariculture comes into conflict with are shipping, naval activities, fishing and offshore petroleum activities.

SUITABLE SPECIES FOR OFF-THE-COAST AND OFFSHORE MARICULTURE

A very wide range of aquaculture species are used throughout the tropical zone, largely because of artisanal mariculture making wide use of local species, often by gathering wild juveniles for on-growing. A smaller number of species or clones of species have been distributed more widely for mariculture in the tropical zone, such as some seaweed species, e.g. *Eucheuma* spp. and *Kappaphycus* spp. (Luxton, 1999). With the profit margins involved in cultivating the currently available commercial seaweeds in the tropical zone it is unlikely that they would able to be commercialized in an off-the-coast or offshore situation. This negative outlook is regardless of the biological feasibility of culturing these species in open waters because of nutrient limitation (Firdausy and Tisdell, 1991; 1993).

Many species of filter feeding shellfish are cultured in the tropical zone, including species of oysters, mussels, clams and scallops. The production of many of these species in nutrient rich coastal waters has been increasing in many parts of the world, such as scallop production in China. Opportunities for production in off-the-coast or in offshore situations are likely to be limited in the tropical zone to areas with naturally high phytoplankton production due to localized nutrient rich current upwelling. Aquaculture in such a situation would require some significant market or production advantages, such as being certified free of pollutants, in order to offset the increased production costs over and above the same species being produced in more accessible coastal waters using existing technology.

The same situation would apply to the range of herbivorous molluscs (e.g. abalones, conch and sea snails, such as top shells), detrital feeding marine organisms (e.g. sea cucumbers, polychaete and sipunculid worms) and carnivorous invertebrates (e.g. whelks, crabs, lobsters and shrimp) that are cultured in the marine waters of the tropical zone mostly on a relatively small scale. For many of these species, the techniques for mariculture in marine sea cages is still in the development stage and are unlikely to be progressed to open water mariculture systems, until more fundamental husbandry and production issues have been resolved.

Finfish have been the major focus of most commercial interest in the development of open water mariculture technology in the tropical zone probably because the cage culture technology is already most advanced for finfish and they are capable of being farmed at high biomass on a large-scale, making the economics potentially more attractive. A number of species have been examined for their suitability for mariculture in offshore systems in tropical waters, and all of them are relatively new aquaculture species and are all fast growing carnivorous species. A wide range of characters make a good finfish sea cage aquaculture species, including fast growth, gregariousness and placid nature, disease and parasite resistance, high meat yield, high food conversion, easy larval production and good market characteristics of the finished product (i.e. high price, large and stable end market) (Engelsen *et al.*, 2004).

Cobia (*Rachycentron canadum*) is a species that is now attracting a great deal of commercial and research attention, especially for offshore mariculture application. The species exhibits extraordinary growth (4–6 kg in a year), with relatively high food conversion (FCR = 1.8) with likely future improvement, and few apparent diseases (Benetti, Clark and Feeley, 1999; Liao, 2003; O'Hanlon *et al.,* 2003). The species has been grown in offshore style sea cages with some initial success in Puerto Rico and in Taiwan Province of China (De Silva and Phillips, 2007). The species is found throughout much of the tropical zone of the world and has potential for development in open water mariculture in many parts of the world.

The mutton snapper (*Lutjanus analis*) was selected as one species that could be suitable for offshore style sea cages, including for pilot commercial scale operations in Puerto Rico, Bahamas and for the Gulf of Mexico (Benetti *et al.*, 2006; Benetti, Clark and Feeley, 1999; Benetti *et al.*, 2002; O'Hanlon *et al.,* 2003; Rotman *et al.*, 2003). This species tends to have slower growth than some other species, such as cobia.

A number of other finfish species indigenous to the Gulf of Mexico have also been identified as candidate species for open water mariculture which are characterized by good grow-out and market potential characteristics, including red drum (*Sciaenops ocellatus*) and red snapper (*Lutjanus campechanus*) (Bridger, 2004; Bridger *et al.*, 2003).

Amberjack species (*Seriola* spp.) are fast growing pelagic fish that are often identified as species with strong potential for open water mariculture. The greater amberjack (*Seriola dumerili*) has been identified as a candidate species for the Gulf of Mexico, and a Hawaiian amberjack species (*Seriola rivoliana*) is produced in offshore sea cage technology in Hawaiian waters (Benetti, Clark and Feeley, 1999; Corbin, 2006; Rotman *et al.*, 2003).

Another species with potential in Hawaii is known locally as "moi" or Pacific threadfin (*Polydactylus sexfilis*) and has been produced in a commercial-sized submersible sea cage in open coastal waters 1.6 km from shore (Brown *et al.*, 2002; Corbin, 2006).

There has been increasing production of a wide range of grouper species in Asia in recent years largely driven by their excellent eating qualities and good market prices, especially in live seafood markets in parts of Asia (De Silva and Phillips, 2007). Most production is currently in small family operated sea cages in shallow coastal waters and estuarine areas, although some of these species have excellent potential for large-scale commercial sea cage production.

Asian seabass or barramundi (*Lates calcarifer*) is another species for which production has been increasing in Asia over the past ten years and is becoming the focus of commercial scale sea cage farming in parts of Asia (De Silva and Phillips, 2007). The species also appears to have good prospects for sea cage mariculture in open waters.

FUTURE DEVELOPMENT OF OFF-THE-COAST AND OFFSHORE MARICULTURE

Technology for off-the-coast mariculture is well developed and is established in production systems in many parts of the developed world, especially for finfish production and less so for filter feeding shellfish production. In most instances, the development and application of this technology is the result of extending existing coastal mariculture activities further from the coast due to constraints on mariculture space in nearshore coastal waters. However, off-the-coast technology and capabilities do not appear to be present at any significant level in developing nations. This may be because many of these nations have not encountered or placed effective constraints on coastal space for mariculture. It may also be because a great deal of aquaculture in developing nations is extensive, low technology and run by small enterprises (usually families), rather than larger and more intensive corporate enterprises using more advanced technologies.

This situation appears to be changing, with increasing involvement of foreign-owned aquaculture corporate entities that are involved in establishing new operations in developing nations, and in so doing, delivering capital, technology and expertize, especially for finfish production. The motivation for investment by these companies is low labour costs and access to coastal growing waters, both of which are typically much less available in the developed countries in which these companies are usually based. Many of these developing countries, particularly in Asia, have previously demonstrated remarkable abilities to rapidly absorb, adopt and replicate new seafood technologies (e.g. development of shrimp aquaculture and seafood processing). Further rapid expansion of mariculture production in coastal waters in developing countries is likely to lead to pressures to move mariculture further from the coast to avoid competing coastal uses, especially coastal pollution which is an increasingly common feature of many developing countries in the tropical zone. These pressures will undoubtedly lead to the importation and local development of off-the-coast mariculture production, by building off the confidence of a well-established inshore mariculture industry.

Technology for offshore mariculture is not as well developed for commercial application as off-the-coast mariculture technology because it involves more than adaptation of existing aquaculture infrastructure. Offshore mariculture technology is mostly being driven by research and commercial interests in developed countries, but with many of them operating in the tropical zone, such as Hawaii (USA), Bahamas, Gulf of Mexico and Puerto Rico. Consequently, it is likely that future development and commercialization of this offshore technology will be in the tropical zone, but driven by commercial and research interests from developed nations, and within developing countries. However, this commercial development may take some time given that there is significant capacity for development of coastal mariculture in many developing nations in the tropical zone. Therefore, it is likely to be less costly to use existing and well-proven production technology closer to the coast, than utilize more costly offshore mariculture technology. In time this situation will change as increasing pressures on coastal resources encourage the use of waters further from the coast for mariculture expansion.

Recent interest in the development of energy production from the ocean (wind, wave and currents) may create synergistic opportunities for open water mariculture by establishing mooring and servicing infrastructure for energy production. However, similar opportunities for synergies with mariculture have previously been expressed in relation to offshore oil and gas infrastructure, but have not eventuated on any scale.

There are likely to be regional differences in the development of off-the-coast and offshore mariculture, with Asia continuing its rapid expansion of mariculture activities whilst other regions, such as Africa and Latin America and the Caribbean may move at a slower pace despite dramatic increases in seafood demand expected in parts of these regions (Brugère and Ridler, 2004; Jamu and Ayinla, 2003).

A large number of studies and projects have investigated and responded to the needs of developing countries for advancing mariculture, often providing substantial direct assistance with finances and capability. This sector is also well served by agencies such as WorldFish Center (WFC), Network of Aquaculture Centres in Asia-Pacific (NACA), Southeast Asian Fisheries Development Center (SEAFDEC), Sarnissa, the World Bank, Asian Development Bank, the Food and Agriculture Organization of the United Nations, in addition to the foreign assistance agencies operated by many developed countries. It is widely accepted that aquaculture development has the potential to provide a wide range of social and economic benefits to developing countries including, domestic food security, vital micronutrients (omega-3 oil) to domestic populations, foreign currency, relieving pressure on wild fisheries, as well as providing employment and economic development in rural communities.

There are a wide range of areas that have been identified as having the potential to provide improved aquaculture, especially in developing nations in the tropical zone.

Technical assistance is commonly identified as an important priority for assisting developing nations (Ackefors, Huner and Konikoff, 1994; Corbin and Young, 1997; Hanson, 1974a; 1974b; Lovatelli *et al*., 2008; Nash and Fairgrieve, 2007; The World Bank, 1991a; 1991b; 1991c; 1991d). Typically, this includes providing technical assistance in almost every area of aquaculture activity including, research, aquaculture technology in all production areas, training and experience for personnel, market knowledge, value adding, as well as the development of regional and international technical networks.

Improving the governance of aquaculture is also an area that is commonly identified as a priority for international assistance for developing nations including, better knowledge and systems for the management of aquaculture environmental impacts and diseases, aquaculture licencing, policy and implementation, as well as national and regional planning and promotion of aquaculture (Ahmed, Dey and Garcia, 2007; Lovatelli *et al.*, 2008; Nash, 1995; Nash and Fairgrieve, 2007; OECD, 2010). For example, the development and implementation of national aquaculture plans has recently been recommended as a priority for mariculture producing countries (OECD, 2010).

Among these previously identified priorities, assistance with the development of offshore mariculture is rarely, if ever, mentioned. This is probably because these nations are dealing with pressing issues associated with promoting and managing the development of existing inshore mariculture activities, so that open water mariculture is not seen as an immediate priority.

The growth and the orderly management of nearshore mariculture activities will ultimately lead to off-the-coast and offshore mariculture development as it has in developed nations. There are also some indications that off-the-coast mariculture developments may arrive sooner in some developing countries via foreign aquaculture companies attracted by substantial areas of new farming space and low labour costs, but wanting to avoid the growing inshore pollution and poor mariculture management regimes (e.g. disease control) which is commonplace in many developing nations in the tropical zone (Alongi *et al.*, 2003; Beveridge, 2004; Stickney, 1997). However, one of the main constraints for attracting domestic and foreign sources of capital investment and capability in aquaculture development continues to be the policy environment and political stability in developing countries in the tropical zone (Brugère and Ridler, 2004). Creating conditions that are conducive to investment by commercial aquaculture interests is thought to be a vital precursor for successful growth in aquaculture sectors in developing countries (Hishamunda, 2007; Jamu and Ayinla, 2003).

In contrast to developing countries, offshore mariculture is more prominent among the priority areas often identified for aquaculture development in developed countries. For example, in the United States of America the advancement of offshore mariculture technology through the improved automation and monitoring of offshore farming, an ability to supply and transport large batches of fish fingerlings to stock offshore farms have been identified as research priorities by aquaculture industry leaders (Browdy and Hargreaves, 2009). Similar sets of priorities that indicate the greater focus on advancing offshore mariculture are commonplace among other developed nations (Ágústsson, 2004; James and Slaski, 2006; NAC, 2007; Ryan, 2004; Ryan, Jackson and Maguire, 2007).

There are also international initiatives to promote open ocean mariculture including international conferences every two years, with the next planned for Izmir, Turkey, in October 2012 (www.offshoremariculture.com). The International Council for Offshore Aquaculture Development (ICOAD) was formed out of a similar conference "Farming the Deep Blue Conference" held in Ireland in 2004. The ICOAD has the aim of proposing "suitable technologies and methodologies for successful aquaculture operations in the offshore zone." The ICOAD was subsequently associated with a European Union-funded project to advance offshore mariculture technology which included some co-ordination work among European groups interested in advancing offshore mariculture (Ryan, 2004; Ryan, Jackson and Maguire, 2007). Encouraging more international collaboration and international sharing of technological developments is likely to assist in progressing open ocean mariculture, including for developing countries.

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