Vol. 3 Issue-11, July 2023 (e-ISSN: 2582-8223)

JUST AGRICULTURE
multidisciplinary e-Newsletter

Climate: Weather Elements of Concern in Aquaculture

Sagar Vitthal Shinde[1], Shamika Sawant[2], Sagar Sitaram Rathod[3], Prakash Patekar[4], Samad Sheikh[5], Ravikumar Chovatia[6], Kapil Sukhdhane[7]

[1]Ph.D. student, Division of Aquaculture, ICAR-CIFE, Panch Marg, Off Yari Road, Versova, Andheri (W), Mumbai, 400061
[2]Ph.D. student, Department of Aquatic Environment Management, ICAR-CIFE, Panch Marg, Off Yari Road, Versova, Andheri (W), Mumbai, 400061
[3]MFSc, Division of Fisheries Economics, Extension, and Statistics, ICAR-CIFE, Panch Marg, Off Yari Road, Versova, Andheri (W), Mumbai, 400061
[4]Ph.D. student, Department of fish nutrition, ICAR-CIFE, Panch Marg, Off Yari Road, Versova, Andheri (W), Mumbai, 400061
[5]Ph.D. student, Department of Aquatic animal health Management, ICAR-CIFE, Panch Marg, Off Yari Road, Versova, Andheri (W), Mumbai, 400061
[6]Ph.D. student, Department of Aquatic animal health Management, Kerala University of Fisheries and Ocean Studies, Panangad Road, Madavana, Junction, Kochi, Kerala 682506
[7]Scientist, Division of Aquaculture, ICAR-CIFE, Panch Marg, Off Yari Road, Versova, Andheri (W), Mumbai, 400061

ARTICLE ID: 15

Introduction

The practice of aquaculture is a way to achieve sustainability in the production of aquatic products. With the continued unsustainable harvests from capture fisheries, the sector is seen as the only solution to meeting the rising demand for aquatic products globally (FAO, 2020). According to FAO (2020), aquaculture's contribution to global fish production has continued to rise, reaching 82.1 million tons (46%) out of the estimated 179 million tons of global production. Furthermore, the share of aquaculture production out of the global fish production is expected to grow from the current 46 to 53% in 2030 (FAO, 2020).

However, the most urgent concern is whether the sector is growing sustainably and fast enough to meet the future projected demand exacerbated by a rapidly growing human population and a changing climate. Climate change is now considered a risk to global food production and a major threat to the quality and quantity of production (Myers et al., 2017). Food security, particularly access to dietary protein, is increasingly being threatened by the predicted effects of climate change (Kandu, 2017).

Climate change refers to variations that occur in the statistical distribution of weather over extended periods, typically ranging from decades to millions of years (IPCC, 2014).

These variations may occur in the average weather or simply in the distribution of weather events around an average, and may be limited to a particular region, or occurring across the whole globe (Yazdi and Shakouri, 2010). Humans have been recognized as the major contributor to climate change through the use of fossil fuels (coal, oil, and gas) for energy supplies as well as deforestation and forest degradation that emit greenhouse gases (GHGs) into the atmosphere. The increased accumulation of GHGs including Carbon dioxide (CO2), methane (CH4), nitrous oxides (N2O), and fluorinated gases in the atmosphere over the years has been linked to these human activities.

The Effects of Climate Change on Aquaculture and Implications on Sustainability

Climate change effects on aquaculture production are expected to be both direct and indirect (De Silva and Soto, 2009). The direct effects include influencing the physical and physiology of finfish and shellfish stocks in production systems, while indirect effects may occur through altering the primary and secondary productivity, and structure of the ecosystems, input supplies or by affecting product prices, fishmeal, and fish oil costs, and other goods and services needed by fishers and aquaculture producers (Adhikari et al., 2018).

Numerous reports have emerged showing that climate change effects on aquaculture may vary depending on geographical areas, economy, climatic zones, production systems, and cultured species (Cheung et al., 2013; Sae-Lim et al., 2017; Adhikari et al., 2018; Barange et al., 2018; IPCC, 2018; Zolnikov, 2019).

Rising Temperature

Temperature plays a critical role in the growth and development of aquatic animals (Ngoan, 2018). Fish, being poikilothermic, may particularly be sensitive to temperature variations resulting from climate change (Sae-Lim et al., 2017; Adhikari et al., 2018).

With the predicted 1.5◦C rise in average global temperature this century, increased mortalities are likely to occur for most fish, especially cold-water species, such as the Atlantic halibut, Salmon and Cod, and intertidal shellfish due to thermal stress (Hamdan et al., 2012; Gubbins et al., 2013). Therefore, prolonged temperature stress may affect aquaculture productivity through various ways centered on lowered output. For example, chronic stress may affect the neuroendocrine and osmoregulatory systems, altering cardiorespiratory performance and aerobic scope as well as immune responses of several economically important species (Zhang et al., 2019).

Furthermore, metabolism and physiology, as well as feeding behavior and growth performance of most finfish and shellfish species are likely to be affected (Lemasson et al., 2018). Additionally, rising ocean temperatures and consequential ocean acidification slowly weaken the ocean carbon sink capacity, giving rise to alterations in the hydrology and hydrography of water systems, and the occurrence of red tides (Cochrane et al., 2009). These effects may lead to increased management costs and low productivity that threaten the economic and social sustainability of aquaculture production. Environmental sustainability may also be affected by thermal stratification in deep water bodies resulting from temperature variations which may affect the distribution and abundance of nutrients in the water, and in case of upwelling occurrence, aquaculture producers operating in open waters will suffer from severe economic losses (Seggel et al., 2016).

On the other hand, warmer periods (within species' tolerance conditions) may promote longer growing seasons, especially in temperate regions, and favor the production of warmer water species, such as the Giant tiger prawn, Tilapia, Oysters, and Mussels (Guyondet et al., 2018; Collins et al., 2020). Larger-scale investors that run hatcheries in sheltered locations may also benefit from market opportunities emerging due to the decline of preferred specimens in the wild as a result of degrading coral reefs (Bell et al., 2010).

Besides, warmer periods may provide opportunities to culture new species and facilitate further developments in genetic improvements of aquatic organisms (Gubbins et al., 2013; Bueno and Soto, 2017). These opportunities will favor social sustainability through increased production outputs and employment opportunities, and economic sustainability through increased profits and reduced management costs in these area.

Ocean Acidification

Ocean acidification occurs due to a decline in pH levels of ocean water for an extended period (usually over decades) resulting from atmospheric CO2 uptake (Richards et al., 2015; Bahri et al., 2018). The oceans are estimated to store about 50 times more CO2 than the atmosphere (Seggel et al., 2016). The projected increase in CO2 uptake by oceans at 1.5◦C or more global warming will have adverse effects on the growth, development, calcification, survival, and abundance of several aquatic species (IPCC, 2018).

Increased accumulation of CO2 in water could result in increased water acidity levels (pH decrease) (Rodrigues et al., 2015; Clements and Chopin, 2016) which threatens the environmental sustainability of aquaculture production systems through water quality deterioration leading to poor productivity. Moreover, the rise in ocean acidity reduces the availability of carbonate required for the construction of coral skeletons (Calcification) in shell-forming organisms, such as shrimps, mussels, oysters, or corals (Kibria et al., 2017), which potentially threatens marine aquaculture production (Rodrigues et al., 2015).

In seawater, rising acidity levels could significantly affect the physiology and metabolism of aquatic species by disrupting the intercellular transport mechanisms (Pörtner et al., 2004)

Diseases and Harmful Algal Blooms

Diseases in aquaculture, such as bacterial, parasitic, viral, and fungal diseases are likely to be affected by a changing temperature regime, but in a largely unpredictable manner (Collins et al., 2020). When cultured species are exposed to thermal stress conditions, they become more susceptible to diseases and that warmer conditions may result in the establishment of exotic diseases (Collins et al., 2020).

The vulnerability of finfish and shellfish to pathogens is a major determinant of diseases and is likely to be affected by both direct and indirect thermal stressors (Chiaramonte et al., 2016). Therefore, warm water disease outbreaks are predicted to occur more frequently in addition to the possibility of discovering new ones under a changing climate (Sae-Lim et al., 2017). Rising temperature is likely to accelerate the replication rate, virulence, life cycle longevity, and transmission of pathogens among several finfish and shellfish species (Marcogliese, 2008). Moreover, the increasing temperature pressures may promote the emergence of epizootic diseases in aquaculture and cause serious economic challenges

Algal blooms are a serious threat to the environmental sustainability of aquaculture production. For example, flagellates and dinoflagellates taxonomic groups, and other harmful species have been reported to contain potentially toxic or nuisance species that can be responsible for stress or kills in finfish and shellfish (Gubbins et al., 2013; Basti et al., 2019). Consequently, this could have negative implications on the social and economic aspects of aquaculture sustainability

Changes in Rainfall (Precipitation) Pattern

Changes in rainfall patterns will affect aquaculture production and sustainability in two directly opposite ways; increased rainfall (Flooding) and periods of low or no rainfall

(Drought). Increased levels of rainfall, particularly if it occurs as heavier events, will increase the production risks in lowland areas (Bell et al., 2010). These risks include losing fish from ponds during floods, invasion of ponds by unwanted species, and ponds damage resulting from infilling and washing away of walls (Rutkayova et al., 2017). The mixing of pond water and fish with those in the wild could negatively affect the environmental sustainability of aquaculture production mainly through the introduction of invasive fish species and water quality deterioration.

Heavier rainfall may increase the areas suitable for aquaculture ponds that rely on rainwater in low-lying tropical regions, thereby favouring the social and economic sustainability in such regions (Bell et al., 2013). Drought events may lead to water stress, such as shortages and quality deterioration that have negative effects on aquaculture production (Hambal et al., 1994).

The predicted water shortages driven by climate change will lead to increased conflicts for water among the different user groups, such as aquaculture, agriculture, domestic, and industries (Handisyde et al., 2006; Barange et al., 2018). This will affect all the dimensions of aquaculture sustainability.

Sea Level Rise

Sea level rise projections by IPCC (2018) indicate that the rise will be around 0.1 meters lower under 1.5◦C global warmings compared with 2◦C by 2100. The rise in sea level may destroy several coastal ecosystems, such as mangroves and salt marshes, which are considered crucial for maintaining wild fish stocks, as well as supplying seed for aquaculture production (Kibria et al., 2017). This will negatively affect aquaculture breeding programs and the economic sustainability of the sector. Higher sea level is predicted to affect aquaculture production facilities, such as ponds, cages, tanks, and pens particularly in lowland regions through the intrusion of saline water (Kibria et al., 2017).

Salinization of groundwater is regarded as harmful to aquaculture, freshwater fisheries, and agricultural production (Handisyde et al., 2006; Kibria et al., 2017). Therefore, salinization renders aquaculture environmentally unsuitable for production leading to higher production costs and lower economic gains.

Sea level rise is also likely to result in changes in species composition, organisms' abundance and distribution, ecosystem productivity, and phenological shifts that may threaten inland and marine aquaculture production (Doney et al., 2012). On the positive side, sea-level rise may increase the areas suitable for brackish water culture of high-value species, such as shrimp and mud crab.

Uncertainty of External Input Supplies

Agriculture and capture fisheries are the primary sources of external inputs for aquaculture production, suggesting a strong relationship among these systems. According to Cochrane et al. (2009), aquaculture is a complementary activity to capture fisheries, and though more similar to agriculture in its practice, it has important links with capture fisheries.

While agriculture is the main source of ingredients for energy requirements in aquatic animal feeds and likely to be the main supplier of protein sources in the future, capture fisheries are currently the principal supplier of protein sources as well as wild seed and broodstock for aquaculture (Hardy, 2010). Recently, due to the declining fish catches from capture fisheries, there has been an increasing channeling of cereal and soy production to aquaculture production for feed manufacturing (Ytrestoyl et al., 2015). However, due to its sensitivity to climate change effects, agricultural production is under threat and hence, the supply of these inputs to sustain aquaculture production continues to be threatened as well (Khatri-Chhetri et al., 2019).

The ineffective management of fisheries and rising fishmeal prices are already a significant threat to aquaculture production sustainability (Black and Hughes, 2017). Generally, the projected impact of climate change on agriculture and capture fisheries is expected to lower the availability and increase the cost of the inputs, such as fish seed and feed ingredients required for aquaculture production. Consequently, aquaculture production costs are expected to rise, making it more difficult, especially for small-scale producers to survive in the sector.

Changes in Sea Surface Salinity

Salinity is seen as a variable parameter reflecting the input of freshwater from precipitation, ice melting, river runoff, loss of water through evaporation, and the mixing and circulation of ocean surface water with underground water (Koblinsky et al., 2003; Cochrane et al., 2009). Variations in sea salinity may occur due to increased evaporation resulting from rising temperature and ocean circulation changes or induced directly by climate change

(Cooper, 1988; Robinson et al., 2005). These variations may affect oceanic circulation and stratification, and hence, the ocean's capacity to store heat, and carbon and nutrient circulation (Seggel et al., 2016)

Most aquatic organisms have specific salinity levels within which they can survive, any alterations may lead to mortalities and production losses (Jahan et al., 2019). In stripped catfish, salinity levels above optimal requirements have been reported to cause reduced survival, growth, and red blood cells, suggesting an effect on the fish's immune system (Jahan et al., 2019).

Severe Climatic Events

Severe climatic events, such as cyclones, waves, and storms are expected to influence aquaculture development especially marine ornamental products, and those in coastal areas (Toussaint et al., 2018). The occurrence of storm surges, waves, and coastalcoastal erosion are considered the most dangerous threats to aquaculture production and other related coastal activities (Hamdan et al., 2012)

Erosion are considered the most dangerous threats to aquaculture production and other related coastal activities (Hamdan et al., 2012). Severe storms will result in high losses to the farmers due to damage on farms resulting in higher costs of recovering the damaged activities (Canadian Institute for Climate Studies, 2000).

The increased storminess projected for certain seasons in certain regions may also increase the risk of aquatic organism escapes due to equipment failure and may require site relocation or changes in production practices which may seriously affect the social and economic sustainability of aquaculture in these areas (Gubbins et al., 2013). On the other hand, severe climatic events, such as storms will likely play a significant role in mixing water columns and nutrients that have previously been restricted to certain columns due to thermal stratification (Seggel et al., 2016) which could promote the environmental sustainability of aquaculture production

Cage culture are at higher risks as increased storminess may lead to aquatic organism escapes due to equipment failure , require site relocation or changes in production practices which affect the social and economic sustainability of aquaculture (Gubbins et al., 2013).It also lead to disruption of fishing and fish processing activities and damage to fishing vessels, gear, and coastal infrastructure including dwellings; impacts on the safety of fishers at sea and fish-workers on land; and jeopardizing the wellbeing of fishing households and their entire coastal communities.

Extreme cold

The occurrence of extreme cold may be due to quick and sudden drops in water temperatures associated with strong cold fronts and/or snow and ice run-off orprolonged periods of cold air temperatures which gradually drop water temperatures below a point that fish cannot withstand. It acts as aenvironmental stressors impactingthe survival and physiology of aquatic animals as fish can sustain slight fluctuations in water quality measures, but sharp variations adversely affect fish health.

Extreme cold can alter the function of gill membranes, resulting in salt dysregulation and ultimately dehydration. And while fish can often swim away from environmental stress, they can be vulnerable to sudden temperature drops, or end up trapped by currents or other ocean conditions. It leads to Lower growth, survival rate, and physiological impairment (Dülger et al., 2012, Islam et al., 2020, Yilmaz et al., 2020).Sudden drop in temperature also leads to cold-induced fasting, thermal stress and metabolic depression.

Hailstorms

Changing storminess affects marine life and habitats, with potential negative consequences for fish catch and the wellbeing of coastal communities. Occurrence of Hailstormsdrastically changes the water temperature and oxygen levels. The colder water temperatures mixing with warmer water which results the pond turning over and depleting oxygen, resulting in fish kill. Storms radically change fish populations via temporary or permanent displacement, and can interrupt fish larval dispersal and damage or destroy essential habitat that fish depend upon. Changing storminess also poses a direct risk to fisheries i.e, storms disrupt fishing effort and pose a physical threat to fishers, their vessels and gear, as well as to fishing communities and their infrastructure (Sainsbury et al., 2018).

Wider implications of the impacts of climate variation on fisheries

Many artisanal fishers are extremely poor. Even in cases where they earn more than other rural people, fishers are often socially and politically marginalized and can afford only limited access to health - care, education and other public services.

Social and political marginalization leaves many small-scale and migrant fishers with little capacity to adapt, and makes them highly vulnerable to climate impacts affecting the natural capital they heavily depend on for their livelihoods. Heightened migration to cope with and exploit climate-driven fluctuations in production may worsen a range of cultural, social and health problems.

Social Impacts of Climate Change on Aquaculture

The social impacts of climate change on capture fisheries have received much attention, compared to those on aquaculture (Allison et al., 2005). This analysis concentrates on the vulnerable, poor fishing communities. In essence, the potential social impacts on fisheries are manifold, and primarily arise from:

- decreased revenues to fishers resulting from declines in catch and stock abundance (Luam Kong, 2002; Mahon, 2002);
- changes in migratory routes and biogeography of stocks affecting fishing effort, an example being increased travel time to fishing grounds (Dalton, 2001; Mahon, 2002);
- changes in harvest technologies and processing costs brought about by the need to capture new species (Broad et al., 1999); • damage to physical capital from severe weather events (Jallow et al., 1999);
- impacts on transportation and marketing chains/systems (Catto, 2004); and
- reduced human capital from severe weather events, increased incidence of red tides and associated shellfish poisoning (Patz, 2000)

Mitigation and Adaptation Options

Mitigation focuses on reducing or reversing the rate of climate change (Leal Filho, 2011; ACT, 2018). This involves mainly reducing GHGs emission with a special focus on CO2 emissions which accounts for more than 60% of human enhanced increases (IPCC, 2014; Environmental Protection Agency, 2016). Reductions in CO2 emissions may be achieved through a combination of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstock, product substitution, and carbon capture utilization and storage (IPCC, 2018).

Aquacultureproducers and other stakeholders may play a significant role in mitigating climate change effects by choosing production practices aimed at minimizing the emission of GHGs and use of environmentally friendly practices and technology, such as solar energy, proper feeding practices, and sustainable wastewater management to minimize air and water pollution (Barange et al., 2018)Effective mitigation requires collective action on a global scale since most GHGs accumulate over time and mix globally, resulting in a global effect (IPCC, 2014). It is suggested that mitigation be implemented hand in hand with adaption strategies for better and effective results (ACT, 2018; IPCC, 2019)

Adaptation focuses on building resilience to the consequences, and the capacity to utilize emerging opportunities sustainably and ethically (Bueno and Soto, 2017). It involves making considerations in advance, the expected changes, and taking those changes into account in short-term decision making and long-range planning (Yazdi and Shakouri, 2010).Long-term adaptation goals such as to increase the ability to adapt to the adverse impacts of climate change and foster climate resilience in a manner that does not threaten food production alongside the goal for mitigation is required.

Diversification of livelihoods may be one of the keys to successful adaptation - involves combining aquaculture production systems with other sectors, such as agricultural systems, either integrated or as separate systems or IMTA, shifting to aquaculture species, techniques, or areas that are less vulnerable or are more resilient to a changing environment .Another growing area that may be considered for adaptation is building adaptive capacity in aquaculture, especially for small scale producers through insurance schemes. Most climate change predictions indicate that small-scale producers will be the most affected due to poor adaptive capacity (IPCC, 2014; Barange et al., 2018). Hence, an insurance scheme could help them build resilience.

Conclusion

However, much of the currently available literature focuses more on the production system leaving out other stages, such as trade and marketing of aquatic products. The narrow focus of scientific studies limits our understanding of the extent to which the aquaculture sector will be affected and hence, adaptation options. Therefore, future studies and models should have a broader focus and encompass all stages of the aquaculture value chain.

References

ACT (2018). Mitigation, Adaptation, and Resilience: Climate Terminology Explained. Retrieved from: https://www.hidropolitikakademi.org/tr/news/ 22267/mitigation-adaptation-and-resilience-climate-terminology-explained

Adhikari, S., Keshav, C. A., Barlaya, G., Rathod, R., Mandal, R. N, Ikmail, S., et al. (2018). Adaptation and mitigation strategies of climate change impact in freshwater aquaculture in some states of India. J. Fish. 12, 016–021.

Ahmed, N. (2013). Linking prawn and shrimp farming towards a green economy in Bangladesh: confronting climate change. Ocean Coast. Manage. 75, 33–42. doi: 10.1016/j.ocecoaman.2013. 01.002

Ahmed, N., Thompson, S., and Glaser, M. (2019). Global aquaculture productivity, environmental sustainability, and climate change adaptability. Environ. Manage. 63:159. doi: 10.1007/s00267-018- 1117-3

Barange, M. (2019). Avoiding misinterpretation of climate change projections of fish catches, food for thought. ICES J. Mar. Sci. 76, 1390–1392. doi: 10.1093/icesjms/fsz061

Basti, L., Nagai, K., Segawa, S., Tanaka, Y., Toshiyuki Suzuki, T., and Nagai, S. (2019). Harmful algal blooms and shellfish aquaculture in changing environment. Bull. Jpn. Fish. Res. Educ. Agen. No. 49, 73–79.

Beach, R. H., and Viator, C. L. (2008). The economics of aquaculture insurance: an overview of the U.S. pilot insurance program for cultivated clams. Aquac. Econ. Manage. 12, 25–38. doi: 10.1080/13657300801959613

Belfer, E., Ford, J. D., and Maillet, M. (2017). Representation of Indigenous peoples in climate change reporting. Clim. Change 145:57. doi: 10.1007/s10584-017-2076-z

Bradley, M., Putten, I., and Sheaves, M. (2015). The pace and progress of adaptation: marine climate change preparedness in Australia's coastal communities. Mar. Policy 53, 13–20. doi: 10.1016/j.marpol.2014.11.004

Brander, K. M. (2007). Global fish production and climate change. Proc. Natl. Acad. Sci. U.S.A. 104, 19709–19714. doi: 10.1073/pnas.0702059104

Chan, F. T., Stanislawczyk, K., Sneekes, A. C., Dvoretsky, A., Gollasch, S., Minchin, D., et al. (2019). Climate change opens new frontiers for marine species in the Arctic: current trends and future invasion risks. Glob. Change Biol. 25, 25–38. doi: 10.1111/gcb.14469

Clements, J. S., and Chopin, T. (2016). Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. Rev. Aquac. 9, 326–341. doi: 10.1111/raq.12140

De Silva, S. S., and Soto, D. (2009). “Climate change and aquaculture: potential impacts, adaptation and mitigation,” in Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530, eds K. Cochrane, C. De Young, D. Soto, and T. Bahri (Rome: FAO), 151–212

Edwards, M., Johns D. G., Leterme S. C., Svendsen E., and Richardson A. J. (2006). Regional climate change and harmful algal blooms in the NE Atlantic. Limnol. Oceanogr. 51, 820–829. doi: 10.4319/lo.2006.51.2.0820

FAO (2018). The State of World Fisheries and Aquaculture 2018: Contributing to Food Security and Nutrition for All. Rome: FAO.

FAO (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in Action. Rome: FAO.

Handisyde, N., Telfer, T. C., and Ross, L. G. (2017). Vulnerability of aquaculturerelated livelihoods to changing climate at the global scale. Fish Fish. 18, 466–488. doi: 10.1111/faf.12186

Hardy, H. (2010). Utilization of plant proteins in fish diets: effects of global demand and supplies of fish meal. Aquac. Res. 41, 770–776. doi: 10.1111/j.1365-2109.2009.02349.x

Harvey, B., Soto, D., Carolsfeld, J., Beveridge, M., and Bartley, D. M. (Eds.). (2017). Planning for Aquaculture Diversification: The Importance of Climate Change and Other Drivers. FAO Technical Workshop, 23–25 June 2016. FAO Fisheries and Aquaculture Proceedings No. 47. Rome: FAO, 166 pp.

IPCC (2013). Summary for Policymakers, The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge; New York, NY: Cambridge University Press.

IPCC (2014). Climate change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report on the Intergovernmental Panel on Climate Change. Core writing team, R. K. Pachauri and L.A. Meyer. Geneva: Intergovernmental Panel on Climate Change, 151 pp.

IPCC (2018). Global Warming of 1.5◦C. An IPCC Special Report on the Impacts of Global Warming of 1.5◦C Above Pre-industrial Levels and Related Global Greenhouse

Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield.

IPCC (2019). Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, Summary for Policymakers Approved Draft. Geneva: IPCC

Seggel, A., De Young, C., and Soto, D. (2016). Climate Change Implications for Fisheries and Aquaculture: Summary of the Findings of the Intergovernmental Panel on Climate Change Fifth Assessment Report. FAO Fisheries and Aquaculture Circular No. 1122. Rome: FAO.