Chapter 5
Assessment of Environmental and Ecological Impacts

The installation of Kuroshio power plant entails the sudden appearance of hundreds of 50 m-wide power generating turbines anchored to relay platforms covering an area measured in square kilometers which, in turn, are anchored to the seabed by hundreds of cables, each several hundred meters in length. These installations are sure to have considerable anticipated and unanticipated impacts on local hydrological, ecological, and environmental conditions. On the other hand, natural disasters and climate changes may cause operational difficulties or damage the ability of the power plant to provide a steady source of power. These two types of impact, the impacts from and on the power plant, can be broken down into four categories (1) the impact of power plant operation on the Kuroshio motion, (2) the environmental impact due to power plant construction and operation, (3) the ecological impact due to power plant construction and operation, and (4) the impact of natural disasters and climate changes on power plant operation. All these issues must be carefully evaluated before construction is commenced, and will be discussed in details in this chapter.

5.1 Impacts of Power Plant Operation on the Kuroshio Motion

The turbines are deployed in the Kuroshio to convert current's linear momentum into angular momentum to drive the generators. This power conversion could slow down the current's motion; it then could have an impact on the circulation of the North Pacific Gyre, thereby affecting the ocean's ability to regulate the Earth's climate and potentially causing irreparable environmental and ecological damages. This issue needs to be carefully and thoroughly investigated to ensure that no such damage could have ever occurred. We begin this exploration with using control volume analysis to investigate the basic conditions required to maintain the Kuroshio's linear momentum. The simulation results derived from Chao's

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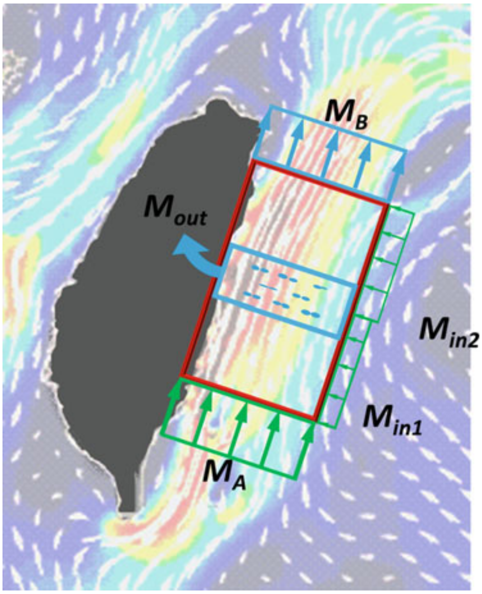

Fig. 5.1 Schematic of the control volume of the flow momentum conservation of the Kuroshio along the east coast of Taiwan

(Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008) global ocean computations are used to explain the turbines' impact on the Kuroshio's flow so that principles for turbine distribution in the Kuroshio can be proposed.

5.1.1 Conditions for Maintaining Kuroshio's Momentum

Figure 5.1 illustrates a control volume for the Kuroshio momentum. The control volume is set in the sea off Taiwan's east coast, with Taiwan on the left and no flow crossing this border. Assuming that a momentum M_A is for the northward flow entering the control volume from below, a momentum M_B is for the northward flow leaving the control volume at above and the momentum loss due to the turbines is M_{out}. The momentum loss should be amended by the flow coming from the Pacific Ocean on the right. Given this inflow momentum from Pacific at upstream of the turbine to be M_{in1} and at downstream to be M_{in2}, the balanced relationship of these five momentums can be expressed as:

$$M_A + M_{in1} + M_{in2} = M_B + M_{out} \tag{5.1}$$

To ensure that the linear momentum of the Kuroshio is preserved after passing through the control volume, one shall have $M_A = M_B$, and this can be done only with the condition $M_{out} = M_{in1} + M_{in2}$ holds. The two Pacific inflows to the control volume are generated due to the geostrophic balance relation of the Kuroshio.

As explained in Chap. 1, the Kuroshio is primarily driven by the shear stress from atmospheric circulation. As passing along the east coast of Taiwan, the Kuroshio is pushed to the right due to Coriolis force generated by Earth spinning. As a result, taking the mainland Taiwan as a wall to restrict the Kuroshio to move to the left, the sea level on the right hand side of the Kuroshio increases, which in turn generates a hydrostatic pressure pushing the Pacific water to enter the Kuroshio. This balance among the Kuroshio's linear momentum, the Coriolis force, and the hydrostatic pressure ensures the steady motion of the Kuroshio at east Taiwan. On the other hand, nevertheless, disturbing one of these three balanced forces would cause changes in the other two. For example, the appearance of the turbine cluster in the Kuroshio consumes the linear momentum of the Kuroshio, which in turn drives the inflows from Pacific into Kuroshio by hydrostatic pressure to form the momentum of the two inflow momentums $M_{\mathrm{in}1}$ and $M_{\mathrm{in}2}$ such that the balance of $M_{\mathrm{out}} = M_{\mathrm{in}1} + M_{\mathrm{in}2}$ may hold still. Please note that, without the presence of mainland Taiwan on the left of the Kuroshio, the inflow moments will not sustain and the Kuroshio momentum may dissipate through turbine's interaction.

To check the momentum balance of Fig. 5.1, Chao (Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008) uses the surface data of sea level, temperature, and salinity of the water surrounding the Kuroshio of November 4, 2008 and employ the global ocean simulation code to compute the ocean motion at east Taiwan. Results shown in Fig. 5.2 indicated that the surface level gradually increases towards the east to its highest point at 125°E, 22.5°N, as shown in Fig. 5.2a, and the velocity vector diagram (Fig. 5.2b) shows that the highest elevation locates exactly at the center of the large eddy in the Pacific. The rotation of this eddy is obviously driven by the Kuroshio, and the Coriolis effect generated by the Kuroshio's flow elevates the sea level around the eddy, and this difference in sea level between the eddy and the Kuroshio generates the hydrostatic pressure to balance the Coriolis force generated by Earth spinning (Fig. 5.2c).

From the above discussion, we can derive the following conclusions: To ensure the appearance of turbines does not impact the Kuroshio's flow conditions, the location and the number density of the turbine installation must be carefully designed to ensure that there are sufficient seawater inflow into the Kuroshio from the Pacific Ocean to compensate for the current momentum lost to the turbines. Once this principle of maintaining the Kuroshio's momentum is securely established, we can consider using a staggered matrix formation to install turbine cluster so that the number of turbine can be maximized and the performance of downstream turbines is not compromised by wakes generated by upstream turbines [1, 2].

Although the conditions for maintaining the Kuroshio flow are simply straight forward, in practice such ideal conditions must be carefully benchmarked on the basis of field test data. But, however, the in situ test is expensive and dangerous, we therefore suggest that, prior to the actual installation of turbines at sea, Chao's global ocean computation code (Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland,

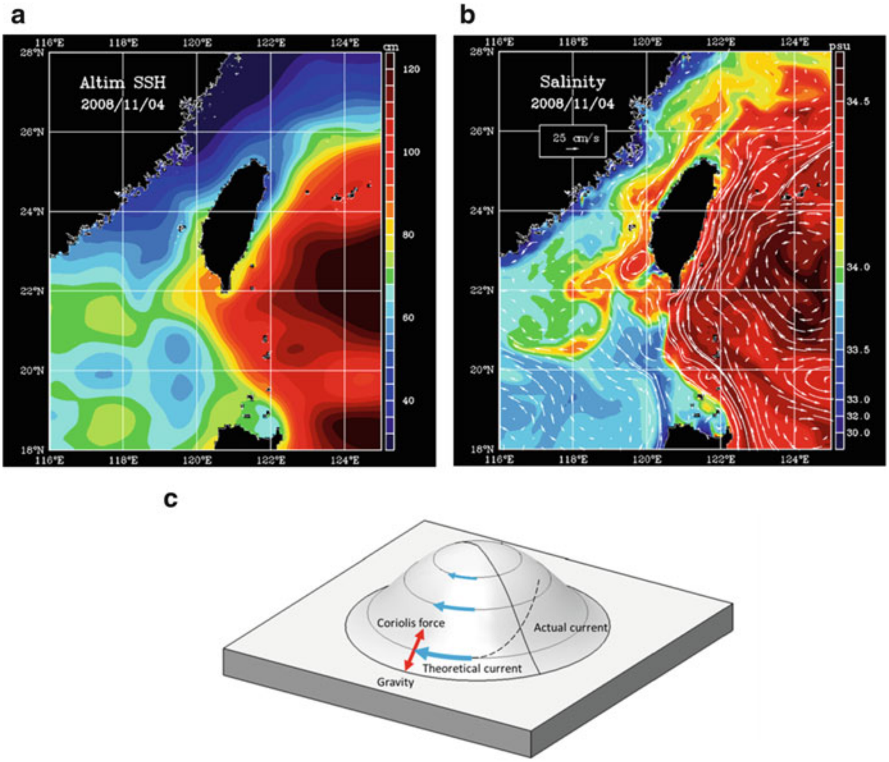

Fig. 5.2 Examples to explain the geostropic nature of the Kuroshio at east Taiwan. (**a**) Sea level distribution of the Kuroshio waters at east Taiwan. (**b**) Velocity vectors of the ocean flow and salinity distribution of the Kuroshio waters at east Taiwan (Courtesy of Professor Shenn-Yu Chao [Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008]). (**c**) Schematics of the balance sustained among the flow momentum, the Coriolis force, and the hydrostatic pressure due to sea level difference

2008) shall be used to implement computational experiments, such as the cases shown in Sects. 5.1–5.3 and the two representative experiments to be illustrated in the following two sections.

5.1.2 Case 1: The Impact of a Spanwise-Deployed Turbine Cluster

Chao (Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008) placed a 60 MW turbine cluster between Lu-Dao and Tai-Dong, which is simulated by a series of

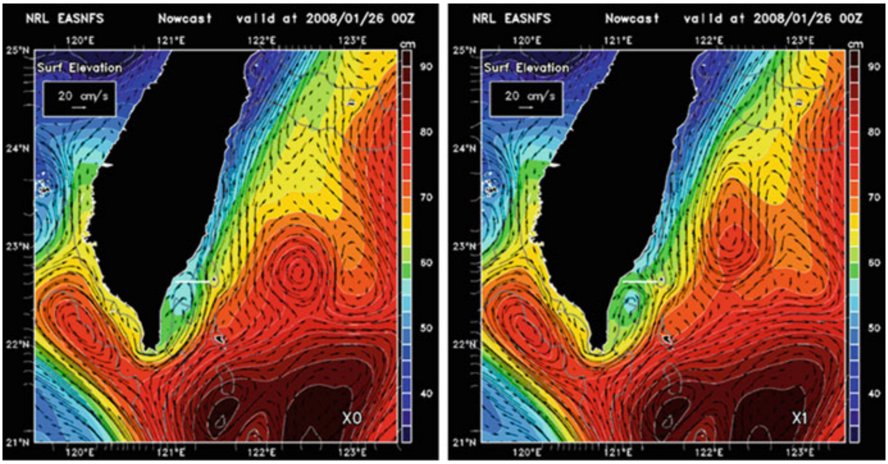

Fig. 5.3 Influence of the 60 MW turbine cluster deployed in the spanwise direction of the Kuroshio between Taiwan and Lu-Dao. The image on the *left* figure shows the flow velocity and sea level distribution without turbine, while the *right* figure shows those with turbines deployed along the white line. The *color* gradation indicates sea elevations, while the *arrows* indicate the flow velocity and direction (Courtesy of Professor Shenn-Yu Chao [Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008])

momentum sink uniformly distributed in the spanwise direction of the Kuroshio, as shown by the white line of Fig. 5.3. Note that, in Fig. 5.3, the results of the left figure are for the case without turbine cluster while those of the right figure are for the case incorporating the 60 MW turbine cluster. Computations were conducted over a 5-month period from January 1, 2008, with initial conditions taken from real-time forecasting data for the same period in the Western Pacific. Figure 5.3 shows the results averaged over 5 months, with colors representing sea elevation (cm) and the length of the black arrows indicating the speed of the current.

When performing the computations, Chao distributed the turbines along the white line at a depth of 50 m to feed off the Kuroshio's energy, evenly dispersing a loss of 60 MW of energy along the white line. The 60 MW power is accounted for by 300 turbines each generating 0.2 MW of electricity. The turbines have a cut-in speed of 0.5 m/s and a nominal flow speed of 1.2 m/s (i.e., the flow speed required to produce 0.2 MW of electricity per turbine). Note that, due to unsteadiness of the Kuroshio, power output cannot always be maintained at 60 MW.

The computational results show that, without the turbine cluster (left figure), a clockwise vortex forms at the eastern edge of the Kuroshio at 122.2°E, 22.8°N. Adding the 60 MW turbine cluster (right figure) causes this vortex to move northwest, compressing the current and increasing the Kuroshio's flow rate north of the white line. These results indicate that the Kuroshio and its adjacent waters are affected by the presence of turbines. However, carefully comparing these two flow velocity vectors reveals that the presence of turbines of this case does not reduce the Kuroshio momentum. Rather, the closing of the distance between the vortex on the right and Taiwan causes a compression of the Kuroshio, which in turn slightly accelerates the Kuroshio's flow speed. This result confirms the control volume scenario of the previous section that the waters of the Kuroshio are fed by two sources, one from the south and one from the east, and the added momentum from the Pacific will compensate for momentum lost to the turbines.

5.1.3 Case 2: The Impact of a Streamwise-Deployed Turbine Cluster

In this case, Chao (Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008) installed five turbine clusters along the Kuroshio Front, the band of greatest flow velocity. These installations each produced 100 MW, for a total installed capacity of 500 MW, and the location of each cluster is represented by an X in Fig. 5.4. Computations were run over 12 months beginning in January 2012, using data taken from the above-mentioned satellite of weather forecasting system. The figure on the left shows the results without the turbines, and shows a large eddy on the right with surface elevations more than 40 cm higher than that of the Kuroshio. The figure on the right shows the flow with five turbine clusters being placed, implying that the presence of 500 MW turbines has no apparent impact on either the eddy or the flow rate of the Kuroshio, thus fulfilling the key requirement of turbine installation mentioned above. In addition to the minimal impact on the Kuroshio flow, the placement of these turbine clusters relatively close to land means they can be anchored with shorter cables, thus simplifying construction and maintenance and lowering down the cost in general.

Figure 5.5 shows the changes over time for the energy absorbed by the five turbine clusters in Chao's example (Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008), with results showing that the average extracted energy is 414 MW, with an variation amplitude of 90.2 MW. Assuming turbine efficiency to be 33 %, the total average power generation reaches about 138 ± 30 MW. Figure 5.5 illustrates an interesting phenomenon: at the outset of winter (November), turbine energy absorption can reach about 500 MW, with absorption levels remaining above average between January and June. However, in summer and autumn, this energy changes several times, dropping to about 100 MW on several occasions. This phenomenon does not correspond to that illustrated in Chap. 1, where the Kuroshio's energy peaks in spring and summer before weakening in winter. Chao's proposed explanation hold that this change in power output is caused by the Kuroshio's Front sweeping past the turbine clusters, and not by the seasonal change of the Kuroshio

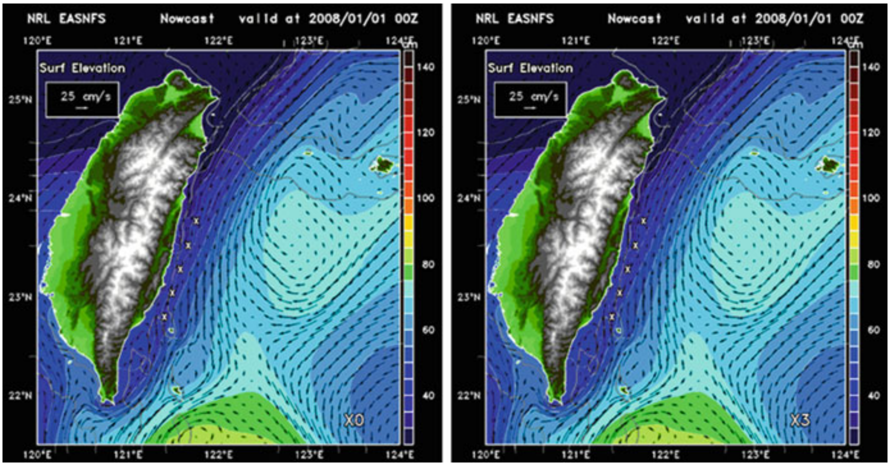

Fig. 5.4 Influence of the 500 MW turbine clusters deployed along the streamwise direction of the Kuroshio at east Taiwan. The *left* and *right* figures, respectively, show the flow field without and with turbine clusters. The turbines are separated into five clusters, each is of 100 MW and denoted by a *white X*. The *color* gradation indicates sea level, showing that the sea level of Pacific at east is in average 40 cm higher than that of the Kuroshio at west (Courtesy of Professor Shenn-Yu Chao [Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008])

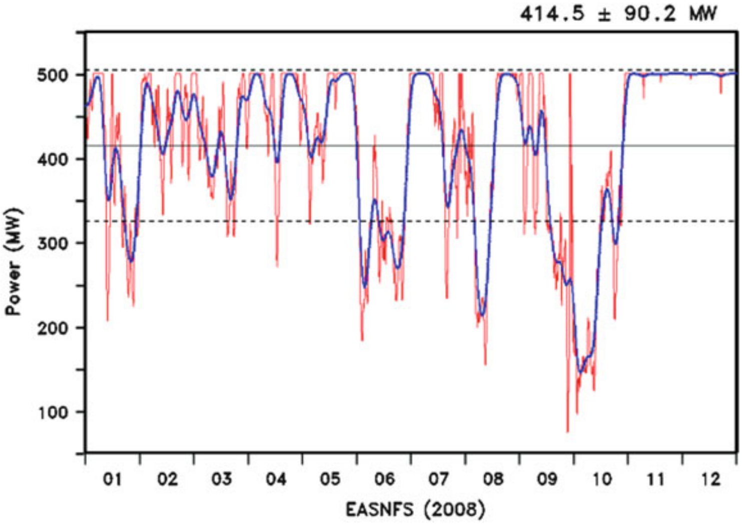

Fig. 5.5 The variation of the power output of the above-mentioned 500 MW turbine clusters in 2008. The *red line* shows instantaneous change, while the *blue line* shows a 5-day moving average (Courtesy of Professor Shenn-Yu Chao [Exploring Kuroshio's energetic cores with an ocean nowcast/forecast system. Private communication, University of Maryland, 2008])

itself. In other words, this distribution and placement of turbines are closely related to the stability of the Kuroshio's frontal moving lines. Therefore, to properly place the Kuroshio power plants, one must not only consider the quality of the Kuroshio's velocity but also its stability.

However, how much energy can be developed in the Kuroshio basin without impacting the normal circulation of the North Pacific or the local marine environment and ecology? Answering this question requires detailed computer simulations with long-term monitoring of the selected site to form an overall assessment. Generally speaking, the degree of impact generated by extracting energy from the Kuroshio is related to the following natural or human factors (1) the type of turbine used, (2) the density of turbine distribution, (3) characteristics of surrounding flow, seabed terrain, and geology, and (4) other factors such as measures for environmental protection, fishery rights, national defense, and international intervention. On the understanding that the Kuroshio's driving force will promptly compensate for the extracted force, the initial assessment should consider the development of 10 GW of installed capacity off Taiwan's east coast. Nevertheless, accurate investigation and simulation of the Kuroshio along with a careful selection of the development site should allow for the potential development of 30 GW of installed capacity [3]. Note that Taiwan's current total installed electrical generation capacity is 43 GW, implying that the development of the Kuroshio power plants can be of significant impact on Taiwan's energy policy.

Although the flow characteristics of the Kuroshio near Taiwan are known through many initial computations and test results, during the development of site selection and plant operations, on-site computations, measurements, and analysis shall be conducted on a continuous basis. This can be accomplished using global nautical analysis software with timely satellite data, thus providing a complete and timely analysis of overall flow changes in the Kuroshio. To meet the actual operating needs of the power plants, forecasting capabilities should be established to offer predictions at least 3 days in advance. Overall computations and regular measurements are a necessary part of selecting the development site, and are core technologies which must not be neglected after operations begin.

5.2 Environmental Impacts of Power Plant Construction

It was described in Sect. 2.3 the extensive range of large-scale equipment and rigs required for the construction of the Kuroshio power plant, along with the hundreds of anchors and cables required to fix the installations in place. In particular, the construction of the turbines and relay platforms is a long-term, large-scale, highly complex construction project. Once construction is complete, the operation of the power plants is subject to an even greater array of known and unknown influential factors. All of these may have a significant impact on environmental and ecological conditions in the Kuroshio waters.

The ecological investigation presented in Chap. 1 indicates that the Kuroshio water ecosystem includes a wide range of native and migratory species which breed in the area. The environmental impact of the installation of Kuroshio power plants can be classified as short-term, medium-term, and long-term effects, each with different impact levels and causes. This chapter discusses the impact of power plant construction and operation in terms of these three time frames, noting that there are three types of potential environmental impacts: (1) the construction of new harbor facilities may impact the coastal environment, (2) the power plant anchorages may impact the seabed environment, and (3) the floating power plants may impact the seaborne environment through various kind of pollution. In the following, detailed discussions on above factors are made, and results may serve as a point of reference for the enactment of relevant legislation and regulations for the power plant construction.

5.2.1 Impact on the Coastal

Constructing the Kuroshio power plant will require temporary and permanent harbor facilities for the assembly, storage, and loading of the turbine and relay platform components. Among eastern Taiwan's current harbors, only Hua-Lien Harbor and Su-Au Harbor are of a relatively large scale, but still offer insufficient space and inadequate facilities for the construction of the Kuroshio power plants. As will be noted in Chap. 6, the optimal installation site is in the seas between Tai-Dong and Lu-Dao, an area not served by any large-scale port, thus it's clear that new harbor facilities and piers may need to be built and land reclaimed.

Port facilities commonly use breakwaters or gravel embankments, which will change local geological and geomorphological conditions and cause siltation which, if not carefully planned, can render the facilities unusable for the long term. At the same time, the construction of large breakwaters on sandy shores can result in large-scale erosion, which will significantly increase the turbidity of local water and interfere with local sediment conditions, thus indirectly causing significant changes to the local topography. These changes can have a significant impact on nearby benthic organisms, coastal fish, and crustaceans, such as crabs living in sandy areas which will migrate or disappear given loss of their habitat. Breakwaters can also kill coral reef formations: dumping large blocks stirs up sediments, covering local habitats and increasing local turbidity, while considerable quantities of dust will be washed downstream from the construction area, thus increasing local turbidity conditions out at sea.

Both new harbor construction and pier expansion will require coastal engineering including various kinds of harbors, coastal highways, breakwaters, tidal barriers, and land reclamation which will have varying degrees of impact on coastal and marine ecosystems. Therefore, an in-depth investigation of coastal environment conditions is needed prior to any development. During construction, constant attention must be paid to minimize changes in local ecological conditions, and the area must be restored after construction is completed. An overall assessment must be made of all possible construction-related damage, and a plan must be prepared for post-construction restoration before construction commences.

In addition, the above-mentioned coastal construction may also cause coastal habitat loss or degradation, resulting in population depletion or even the destruction of certain species. For example, seawalls and breakwaters in Kin-Men, an island belonging to Taiwan located at south-eastern China, were built along the high tide line destroying the breeding grounds of local horseshoe crabs. In another example, the Peng-Hu branch of the National Ocean Species Repository was constructed on a natural intertidal reef, causing the destruction of fry, octopus, snail, shellfish populations along with local seaweeds.

There are two main causes of habitat destruction. The first is land reclamation or breakwater construction, covering natural coastlines in cement and damaging biological growth of coastal habitats (reefs, sandy shorelines, and wetland). Second, the construction of jetties interrupts the movement of sediment, causing silting upstream of the jetty and erosion downstream. This unbalanced sediment load changes the feeding conditions for benthic species, while also changing the composition of their habitats.

The above-mentioned disruptions of habitat quality or survival conditions are primarily caused by the construction of seawalls and tidal barriers, which block the hydrological cycle of coastal wetlands and reduce tidal water level fluctuations, while changing seawater in- and outflows and salinity levels, thus gradually compromising the functions of wetlands ecosystems. Construction can also result in the concentration of suspended solids, noise, and vibration, which can interfere with the respiration, feeding, and breeding behavior of marine organisms, especially fixed or poorly mobile organisms. This phenomenon is already visible in the waterfowl conservation area in I-Lan's Wu-Wei Harbor, in the reservoirs of Hsin-Chu's South Harbor, in Taipei's Guan-Du Nature Park, and in coastal wetlands all around Taiwan.

On the other hand, the Kuroshio power plants will produce electricity which is transmitted to the coast via transmission cables. Studies have shown that the magnetic field formed by the transmission cable may slightly alter the geomagnetic characteristics of the surrounding rock, which can impact the direction or delay the timing of the migration of fish. However, currently, there is no clear evidence to indicate that the submarine cable's magnetic field will have a significant impact on benthic or migratory fish [4, 5], but this may simply indicate insufficient research. Thus, it is important to continuously monitor relevant data upon project completion to provide a reference for future construction.

Finally, we must mention the potential impact on the many government-recognized culturally sensitive sites on Taiwan's east coast. Prehistoric cultures—including Nagahama Culture, Jomon Pottery Culture, Kirin Culture and Jingpu Culture—have been identified in five sites, with another 21 sites to be developed. At the same time, there are ten protected fisheries where all extraction of aquatic plants and animals is prohibited in a 500 m band extending out from the mean high tide line. These restrictions have not only contributed to the restoration of coral reefs but have also lured back large groups of migratory reef fish, and protected loggerhead turtles have been seen coming ashore. If the Kuroshio power plants are installed in this area, a strict environmental impact assessment would have be required to guarantee the design and construction are in line with the relevant laws and regulations to ensure the sustainable development and operation of the power plants.

Based on the above discussion, we propose the following conclusions: Poorly designed marine engineering will result in an increased adverse environmental impact while also increasing future maintenance and management costs, such as the dredging of silted harbors, and the storage and disposal of silt. At the same time, additional investments must be made to prevent the collapse of the foundations of coastal highways through the increased installation of breakwaters. New harbors and embankments will severely disrupt sediment flows, resulting in coastal erosion and soil loss. This significant ecological impact will significantly interfere with coastal flow conditions and sediment transport while decreasing sediment stability and water quality, reducing biodiversity and causing potentially irreversible soil loss in coastal areas [6].

5.2.2 Impact on the Seabed

The seabed refers to the areas of extremely steep slopes at the sea floor, most produced by multiple geological processes and reactions of the oceanic plates, including sedimentation and plate tectonics, and occasionally underwater volcanoes. On the east coast of Taiwan, the most famous such feature is a series of small undersea volcanic hills off of Gui-Shan Island, which are characterized by a unique ecology. In addition, some undersea areas feature seabed hot springs which form their own special ecosystems with sulfur as the main metabolic element. Bacteria thrive in these environments, along with tubeworms and crabs which feed on the bacteria. Benthic organisms (e.g., crustaceans, mollusks, benthic fish, and some sessile organisms such as ascidians and sponges) are found in tide pools, close to shore, and on the continental shelf and slope. Most fishery resources, including more valuable lobsters and groupers, are also concentrated along the coastal continental shelf. The continental shelf harbors a biological habitat vulnerable to the impact of fishing, including bottom trawling, which can permanently damage benthic habitats. Marine debris isn't necessarily destructive and may, in cases, provide an improved shelter in the form of artificial reefs.

Figure 2.4 shows the Kuroshio power plant's relay platform anchored to the seabed by hundreds of cables. Each anchor needs to be drilled, piled, and grouted, processes that may destroy seabed sediment and rock. However, Chap. 4 notes that the seabed anchor points are separated by a distance of approximately 70 m, resulting in a relatively low density of anchorage, thus ensuring the damage can be rapidly restored. Upon completion, hundreds of seabed anchors will be installed on the seabed, connected to a double-number of cables, and this large-scale introduction of foreign objects may produce a significant impact on local seabed ecology. In addition, the construction and operation of Kuroshio power plants may result in the loss of large-scale equipment and rigs on the seabed. Such objects are usually made mostly of steel and, if it cannot be recovered, would form an artificial reef with an impact on benthic habitats. In general, artificial reefs are made to simulate natural reefs, changing the surrounding seabed and currents, boosting marine biodiversity and biomass to restore or extend existing fishing grounds or seed new fishing grounds.

The waters off of western Taiwan feature many artificial reef installations including several decommissioned warships. Warship reef projects are governed according to certain criteria including full appearance, barrier-free, and zero pollution. Certain components are completely removed prior to sinking the ship, including on-deck towing winches, anchors, booms, lifeboats and their fixtures, and gun mounts. The interior is cleaned of rubbish, instrument panels, machine oil and grease, asbestos bulkheads, and other potential pollutants, and the hull is thoroughly cleaned to prevent contamination of the marine ecological environment. A year-long survey of the entire warship reef zone found over 7 phyla, 11 families, and 14 genus of organisms, including mollusca, arthropoda, echinodermata, annelid, protochordata, ectopora, and proifera. In addition, over 18 families and 28 genus of fish of different sizes were found, suggesting good potential for the development of sport fishing and diving.

The Kuroshio basin has depths reaching into thousands of meters and, unlike the above-mentioned warships, objects sinking from the Kuroshio power plants would not be dropped specifically for the purposes of creating artificial reefs. Thus, careful ongoing observation would be required to determine whether these objects do, in fact, create artificial reefs. However, the large-scale structures of the power plants, suspended at a depth of several tens of meters, may attract concentrations of plankton, thus creating a form of aquatic habitat, providing aquatic life with a place for breeding, feeding, migration, and predator evasion. In addition, given the distribution of thousands of anchors and cables across the seabed may result in the development of alternative habitats for deep sea dwellers.

5.2.3 Impact on the Water: Material Contamination

Most coastal engineering involves the use of concrete, with seawalls and breakwaters forming a smooth, nonporous structure which changes little over time, leaving snails, crabs, sea urchins, and other animals no place to hide from predators, thus reducing overall biodiversity. At the same time, concrete has a high endothermic coefficient, especially when applied in large-scale seawalls. In summer, this raises the temperature of adjacent waters, resulting in thermal pollution. Marine organisms have a low tolerance for sudden temperature increases, and such high temperatures can result in malformations or death.

However, on the other hand, the porous surface of concrete provides cover for crustaceans and polychaetes, making it suitable for artificial and algal reefs. The interior of lightweight, porous concrete features continuous pores and is highly permeable, making it useful for balancing local ecological environments, but its low strength and light weight requires careful engineering design. Interstitial biofouling between the matrices can provide fry or other marine animals with places to hide and rest, but the number of pores must be limited to inhibit the overproduction of algae-eating animals, such as sea urchins [7].

The construction of Kuroshio power plants is unlikely to use concrete outside of the caissons for the seabed anchoring system. However, power plant construction could still cause significant and complex damage to the seabed environment, and thus should not be included in the selection range. The Kuroshio power plant primarily consists of three elements: the turbines, the relay platform, and the cables. Aside from the metal turbine blades and structural supports, the rest of the structure is built from composite materials which have a very small chance of causing seaborne pollution. Similar to the turbines, the links connecting the relay platform components are made of metal or composite materials. Two possible contamination sources are the lubricant leaking from the bearings or universal joint, but the design should specify the long-term stability of the seals for these two components, which should prevent such leakage from occurring. In addition, given the potential for corrosion and biofouling, all coatings used must be environmental grade to avoid releasing toxins into the water. Finally, the cables will be made of a light, tough polyethylene material that does not pose potential contamination issues.

5.2.4 Impact on the Water: Chemical Contamination

Marine chemical pollution can result from heavy metals, oil, toxins, and environmental hormones from river runoff, boats, or underwater equipment and drilling platforms. Heavy metal pollution is mainly caused by the introduction of copper, silver, mercury, or other toxic elements into otherwise clean water. For example, the chain plating industry creates large volumes of wastewater contaminated with heavy metals, and silver contamination primarily comes from the production of $AgNO_3$ by the photographic negative industry (though modern digital cameras produce virtually no silver contamination). Mercury has many uses, but mercury contamination is less of a problem these days. Oil pollution is an almost daily occurrence in the oceans, with marine oil spills occurring from ship-board mixing plate and crane operations, or from damaged oil tankers.

Most sources of large-scale toxic contamination are related to stranded ships or human-applied pesticides. Taiwan has experienced ship-borne toxic leaks in the past, including leaks of toluene in 2005 and ethyl acetate in 2006. Pesticide contamination is not only toxic to fish but also results from the use of antifouling paint on ship hulls. In addition, environmental hormones refer to the release into the environment of molecules having a hormonal effect. Sources include pesticides, plasticizers, dioxins, and metals, and can damage the immune, nervous, and endocrine systems. In the past, antifouling paint included tributyltin (TBT), which included environmental hormones which can damage the internal navigation system of cetaceans, causing them to beach.

The most serious source of chemical contamination may be oil from the wrecks of large ships or tankers, leading to the large-scale and long-term destruction of the ocean and coastal environments. For example, in March 1989, the U.S. Exxon Valdez oil tanker ran aground off of Anchorage, Alaska [7], while in September 2002, the Prestige sunk off the coast of Spain [8], both causing extreme damage to the local environment which have yet to completely recover. Instances of large-scale pollution have also occurred in the waters around Taiwan. In February 1977, the Kuwaiti tanker Borag, carrying 32,000 metric tons of crude oil, ran aground off the northern coast of Taiwan, spilling at least 15,000 tons of crude and contaminating the entire north coast. Data from an ecological and environmental investigation provided by north Taiwan's nuclear power plant indicated that the spill cost local fisheries substantial losses of over USD32m [9]. In January 2001, a Greek-registered cargo vessel—the Argos—ran aground in southern Taiwan, spilling about 1,100 metric tons of fuel oil, contaminating an area measuring 20 ha and causing serious damage to the local marine ecology and biological resources [10]. In addition, the back-to-back wrecks of the Sam-Ho Brother and Dewi Bunyu in 2005 and 2006 spilled vast amounts of chemicals and fuel oil into the waters off Taiwan, causing irreparable harm [11].

The Kuroshio power plants may prove to be a source of pollution, most likely due to a leakage of the lubricant used in the universal joints. Lubricants do not easily dissolve in water, and may accumulate on the seabed where they can persist for up to 5 years, causing extensive damage to local ecosystems [12, 13]. To reduce the potential for environmental damage, the lubricants used must be durable but biodegradable, such as Fuch Titan GT1 biodegradable oil [12]. In addition, the rust-proofing or anti-biofouling coatings of the turbine bodies and relay platform floats may cause toxic discharge into the environment, but this can be avoided through redesign following stringent antipollution requirements. If occasional toxic discharges do occur, the amounts involved will be too small to cause damage. Finally, engineering processes must be designed to minimize or entirely avoid chemical pollution caused by dust or paint from the construction process.

In conclusion, the construction process must consider and prevent many types of chemical pollution on land and sea, including heavy metals and oils. Long-term monitoring will be required to guard against contamination from the anticorrosion coatings of vessels and the generators and from lubricant leaks. The following table lists the characteristics and durability of several anti-biofouling paints [14–17]. Regardless of whether these paints are cytotoxic or not, the selected materials must be free of organotins and be in wide use worldwide. The inherent difficulty of maintaining the turbines beneath the surface also puts a premium on the durability of these materials. If the generators can support it without losing too much efficiency, an electrical antifouling system would be ideal but cost considerations may result in a biological cytotoxic solution being more practical. Irgarol 1051 is

Table 5.1 Characteristics of various products for antifouling coatings [14–17]

Product ID/coating type	Effect	Target organism	Features	Durability
Irgarol 1051	Biological poison	Algae	Durable	1–3 years
Diuron	Biological poison	Algae	Durable	5 years
Chugoku Sea Grandprix 500	Biological poison	–	Extensively used in deep-sea vessels	3 years
Jotun Sea Quantum	Biological poison	–	Contains copper hydrolysis paint	5 years
Sigma Alphagen	Biological poison		Contains copper hydrolysis paint	5 years
Electrical Anti-fouling System	Current used to prevent biofouling	None	Used on large cargo vessels, minimal environmental impact	61 months[a]
Silicon fouling-release coating	Reduces biofouling	None	Easy to clean, rarely needs to be reapplied	At least 2 years[b]

[a] Actual vessel data

[b] Data taken from a hull rinsed after 2 years of use

currently one of the most widely used coatings, but its limited durability potentially makes it less suitable for use for the Kuroshio power plants. In addition, while a copper coating is durable, high concentrations of copper are harmful to biological organisms; thus, the use of any coating containing copper must ensure not to increase the background copper concentrations in the Kuroshio (Table 5.1).

5.2.5 *Impact on the Ocean: Noise Pollution*

“Noise” refers to sounds that are either unfamiliar or unpleasant to marine animals, or which exceed a certain frequency, causing changes in their behavior or physiological state. In the ocean, noise sources can be generated by wave and wind action, seismic activity, or human and animal activity. These noises are referred to as “background noise,” and are primarily caused by bubbles resulting from the action of wind on the water. In tropical waters, some background noise is caused by the activity of biological organisms, such as shrimp which use sound to stun their prey and warn off predators, or by the rapid movements of mammals while swimming or feeding. Generally speaking, the frequency of these sounds can exceed 100 kHz. An additional source of background ocean noise is sound waves used by cetaceans for communication, courtship, navigation, and to locate food and obstructions.

Over the past few centuries, increased human activity on the seas has also contributed to background noise. The main sources of anthropogenic noise in coastal areas include recreational activities, coastal construction, shipping, and industrial activity. Offshore man-made noise comes mostly from ship propulsion systems and turbines, along with sound generated from waves slapping against the hulls of fishing boats, cargo vessels, military ships, submarines, and research vessels. Regardless of source, anthropogenic noise has an impact on other organisms. For example, the activity of fishing boats and whale watch boats can drive dolphins and other cetaceans away from their habitats near ports or otherwise change their behavior to avoid the sound. In addition, some migratory fish have been found to change their movement and group behavior to avoid sources of industrial noise, including forming denser schools and reducing their foraging. Noise pollution poses a threat to various biological organisms, not only changing the ways in which they interact but also disrupting their ability to procreate. Because sound can travel ten times faster in water than in air, the effects of noise pollution at sea are vastly magnified.

Many studies of ocean noise have pointed out that commercial shipping, seismic activity, sonar applications, marine engineering, dredging, and offshore drilling generate significant noise pollution which poses a threat to marine life [18–22]. These studies show a link between noise pollution and behavioral change in many marine animals, with many examples of animals abandoning their preferred habitats, and changing their feeding and diving habits. Other effects include changes to the form, volume, and rhythm of their own sounds, causing miscommunication and confusion which can result in mass beachings and collisions with ships. Many fish and marine mammals rely on sound for navigation, foraging, breeding, and communication. This reliance on sound is particularly acute among whales and dolphins: without external interference sound waves generated by whales can travel over 280 km, but external noise can reduce this range to below 90 km. Given background noise at 120 dB, the range is further reduced to less than 20 km, seriously affecting animal judgment and behavior [6]. Noise pollution at sea can also impact the fertility of marine animals and cause structural damage to fish to the point of rupturing fish maws. In marine mammals, it can cause deafness, loss of fertility, or even death.

In addition to marine animals, cephalopods and other marine animals are also vulnerable to the effects of noise pollution. Studies have found that sound can harm cephalopods in two ways: through the direct impact of sound waves and through partial damage to their internal balancing mechanisms. This can damage the animal's sense of direction which, in the case of giant squid, could lead it to be unable to distinguish up from down, leaving it vulnerable to extreme temperature change at varying depths which could prove fatal [19]. In recent years, noise pollution at sea has also resulted in numerous instances of dolphin strandings at different scales, including eastern Florida in 1998, and the Canary Islands in the late 1980s and again in September 2002 [18]. Noise problems are quite serious and should be carefully considered in the development of any marine facilities.

Construction of the Kuroshio power plant presents two key potential sources of noise: mechanical noise from the activities of ships and the construction platform and from seabed piling and anchor engineering. Both sources produce low-frequency, high-decibel noise which could have a considerable impact on local marine life habitats and must therefore be carefully evaluated. Power plant operation may also generate high-frequency, low-decibel noise from the interaction of the turbine rotor blades and the ocean current. However, as shown in Chap. 3, the turbines are designed to rotate slowly, at about 6 rpm. The potential separation of the flow field due to pressure change would limit the production of low-energy, high-frequency, low-decibel noise to the tips of the blades, and the acoustic distance this noise travels would be restricted to within 100 m of the turbine, and thus not affect the ocean environment.

5.3 Ecological Impacts of Power Plant Construction

Taiwan's Kuroshio features a rich ecosystem, and the impact that the introduction of a huge underwater installation such as the Kuroshio power plant will have on the fish and cetacean populations must be carefully evaluated. Especially, how cetaceans would respond to the installation of power plants in the Kuroshio shall be investigated carefully. Questions such as "Will they seek out new habitats, or will they gradually become accustomed to living among the installations? Could they possibly be killed by these artificial structures?" shall be answered before construction commences. Aside from cetaceans, other fish species may face similar problems. These are important conservation issues, and a comprehensive ecological impact assessment must be implemented by referring to all relevant domestic and international researches into marine conservation [23].

Animals potentially affected by the ecological impact of power plant construction in the Kuroshio water can be classified as phytoplankton, zooplankton, fish larvae and fish, and migratory fish and mammals. In addition to habitat destruction, the present assessment focuses on the potential effects on factors which can affect the growth of these populations. The impacts are categorized as occurring during construction and after construction, and are further classified as short term and long term. Details are shown in the following.

5.3.1 Impact on Phytoplankton

The key factor limiting the phytoplankton population of the Kuroshio is the supply of nutrient salts (to be discussed in conjunction with trace elements). The construction process may provide additional sources of nutrients. For example, the cement pumping and the large number of ships coming and going will agitate the water, thus resuspending inorganic particles, and localized human activity will introduce human waste and garbage. Iron and other elements from the ships and the generators may dissolve in the water, potentially spurring rapid phytoplankton growth [24]. On the other hand, low-level vibrations from construction will also increase water turbidity, increasing and agitating suspended particles, and thus decreasing light penetration to drive photosynthesis, which could reduce the total biological productivity of the entire upper water layer.

It's worth noting that phytoplankton biomass reaches its maximum density at depths between 30 and 100 m due to the abundant available light and relative scarcity of predators. Unfortunately, however, this depth range overlaps with the operational depth of the generators which will have an impact on multiple water layers. As such, the turbine clusters and relay platforms may have a "blackout" effect which may result in changes to the depth range for maximum chlorophyll concentrations. In addition, the rotation of the turbine blades may damage phytoplankton, and this rotation will cause vortices which may disrupt the normal exchange of water between upper and lower layers. Generator operation may also cause the temperature of the surrounding water to rise, which may alter local ecological structures. Metal used in power plant equipments may dissolve in water, thus increasing the nutrient concentrations of the surrounding water leading to an increase in algae growth and a corresponding increase in the growth of algae-eating animals. However, at the same time, this increased animal population will consume greater amounts of nutrients, thus reducing the overall nutrient supply and causing the algae to die off, reducing the supply of dissolved oxygen and thus impacting the growth of other organisms through a chain reaction. Finally, the phytoplankton in the area is already adapted to a low-nutrient environment. Introducing additional nutrients may spur phytoplankton growth, increase dissolved oxygen concentrations, and accelerate the settlement of carbon, but nocturnal phytoplankton respiration will release copious amounts of carbon dioxide which will likely contribute to global climate change.

As indicated by the above discussion, power plant construction is likely to increase the concentrations of seawater nutrients and suspended particles, which present both advantages and disadvantages for phytoplankton growth. Long-term operation of the generators and relay platform will interfere with water flow patterns that will have the greatest impact on chlorophyll in the water, and the dissolving of metals in the water will have a negative chain reaction impact on phytoplankton productivity. In addition, power plant construction and operation will have an impact on the type and volume of phytoplankton in the area, which will have a knock-on effect on local zooplankton. This is to be discussed in the following section.

In addition to the above-mentioned ecological impacts, the rapid growth of phytoplankton has the potential to impact the operating lifespan of the power plants. Equipments and mechanisms must be put in place for long-term observation of changing conditions, allowing for the implementation of controls and adaptations to avoid irreparable damage to the power plant facilities.

5.3.2 *Impact on Zooplankton*

The primary factor affecting zooplankton populations in the Kuroshio is the availability of food; thus, zooplankton populations are closely related to the distribution and productivity of phytoplankton. During the day, most zooplankton moves to deeper waters to avoid predators where they respond to lower temperatures by curtailing physical exertion. To ensure their safety and growth, they then move to the surface at night to feed and breed. Some zooplankton travel considerable distances during this vertical migration, following the greatest chlorophyll concentrations. With development and sexual maturity, they cease vertical migration and move to deeper water layers [25, 26]. While some carnivorous zooplankton exhibit no vertical migration (possibly related to their survival strategies) [27], overall the vertical migration ranges between 50 and 400 m below the surface.

The construction and operation of Kuroshio power plants may have a significant impact on the vertical migration of zooplankton. Construction will entail the frequent movement of many ships and operation of construction equipment which will cause vibrations, and power plant equipment will have an impact on the composition of adjacent water, both of which will affect the scope and timing of vertical migrations. In addition, the target depth of the power plant installation overlaps with the vertical migration range, and the rotation of the turbine blades may directly injure or kill zooplankton. In addition, the turbines may affect the lateral flow surrounding the zooplankton, thus causing them to be transported to another area which could affect the overall zooplankton ecology, or increase the competition for food thus changing the ecological structure. Once the power plants begin operations, this will become a daily occurrence, and will have a significant impact on zooplankton ecosystems near the power plants.

There are several ways to possibly remedy this situation. For example, power plant construction could be halted at night, thus reducing the amount of time zooplankton is exposed to disruption. An artificial chlorophyll water layer could also be implemented away from the Kuroshio water to create an environment for zooplankton vertical migration, thus maintaining the zooplankton ecological structure for the entire area. Additional research is required to establish the feasibility of other ecological preservation methods.

5.3.3 *Impact on Fish Larvae and Fish*

The migration and structure of larval fish is dependent on the ecology of the zooplankton on which they feed and any disruption of zooplankton populations by the power plants will be felt in the ecology and population structure of larval fish. Reef fish populations are dependent on the health of their habitats. Sediment disturbances caused by construction can cause massive damage to coral reefs, or anchors may be sunk in reef areas, making it difficult for fish to continue to inhabit the area, let alone continue to spawn normally, thus resulting in large-scale migration or destruction of fish populations. Once construction is complete, the power plant equipment will also create shade, thus reducing the light available to algae for photosynthesis, causing them to detach from coral reefs, killing the reefs, and disrupting fish habitats.

Habitat destruction and reduced food availability will also reduce the numbers and diversity of some large fish species. Although power plant equipment can form artificial reefs which can attract some types of fish to remain in the area, some species will be unable to transition from their natural habitats to artificial reefs. The eggs of some species, such as zooplankton, will be dispersed and may be damaged or destroyed by the action of the rotating turbine blades. Furthermore, the anticorrosion coating on power plant equipment may introduce a degree of biological toxins into the water, killing or driving off fish. Also, frequent ship traffic will frighten the fish, causing them to temporarily abandon their habitats.

On the other hand, the power plant's relay platform and many anchor cables may form a base for coral or ascidians to form another kind of "artificial reef." Given the large area of the power plant structure, this could provide a degree of shelter, allowing smaller animals to avoid predators and improving their chance of survival. However, there are different opinions on the ability of artificial reefs to attract fish, with some reports suggesting that artificial reefs are not actually related to the diversity or numbers of fish, nor do they clearly attract more types of fish or fish schools [28].

Once the power plants begin operation, the component with the greatest potential effect on fish species are the rotating blades of the turbines. As noted in Chap. 3, the design of the Kuroshio power plants intentionally calls for the blades to rotate at a rate of 6 rpm or less, in the hope of reducing the likelihood of the blades injuring smaller fish species and so that medium and large fish would instinctively avoid the blades or even become familiar with and synchronize their movements to the blade rotation, allowing them to coexist.

5.3.4 Impact on Migratory Fish and Mammals

Migratory fish and marine mammals largely travel in search of food, thus their numbers are restricted by food availability. As noted in the previous two sections, zooplankton and fish populations will both be impacted by power plant construction and operation; thus, we can expect that the numbers and distribution of migratory fish will also be affected. Previous surveys have shown that dolphins mostly live along the continental shelf at depths of 200 m and their distribution is closely related to the distribution of their preferred foods such as squid. Squid surface at night to forage, and dolphins follow them [29, 30]. Migratory fish such as swordfish and tuna forage in coastal areas on smaller migratory fish and reef fish. Prior research has shown that cargo ships and leisure boats have an impact on cetacean behavior. For example, female whales and dolphins try to avoid boats [31, 32].

In addition, cetaceans are usually driven off by offshore oil field construction and operations with their attendant ship traffic, drilling, and oil spills [33]. In addition, cetaceans are frequently injured by ship propellers.

Kuroshio power plant construction will assuredly entail noise and frequent ship traffic. If construction coincides with peak migration season (from early spring to the end of summer), migratory animals may avoid the area or detour around it. However, if construction occurs close to shore or in an important forage area, there is a high probability of injuries from turbine blades or accidental collisions with the platform, especially at night. Although some cetaceans rely on sonar rather than sight to forage, a lack of research into the impact of underwater equipment on cetaceans leaves us unable to conclude that cetaceans know to evade the turbines or whether the animals will suffer from being deprived of sustenance if the power plants are located near their important forage grounds.

The above-mentioned factors and degrees of severity are compiled in Table 5.2 below to provide a reference in assessing the impact and severity of Kuroshio power plant construction and operation on local ecosystems. Considering the cost of construction and environmental protection, we recommend selecting sites which avoid highly productive reefs or continental shelf areas to ensure local ecological conservation. Of course, no site selection will be completely harm-free but if, once built, the site attracts fish schools along with migratory fish and cetaceans, it could be beneficial to local ecologies and tourism. However, commercial fishing must be carefully managed and closing the power plant area to fishing would help ensure protect the generators and the local ecology.

In summary, the shipping activity and noise that Kuroshio construction would entail will cause migratory animals to avoid the area. Plant operation may generate noise levels which, combined with local ecological changes, may result in species leaving the area due to lack of food. Given that the width of the Kuroshio is at least 100 times greater than that of the power plant installation, the impact on fish migration will be limited but cannot be completely avoided. After all, the impact of the Kuroshio power plants on the Kuroshio ecosystem will be limited and localized. However, the ocean is constantly in motion, and chemical and noise contamination from the power plants will eventually have an effect on the local ecological balance.

5.4 Impacts of Natural Change on Power Plant Operation

Change due to natural cause will have far-reaching effects on the operation of Kuroshio power plants. The area off Taiwan's east coast is prone to typhoons and earthquakes, not only posing a significant threat to the security of the turbines and relay platform but also affecting power plant performance. In addition, climate change may exert long-term effects on the Kuroshio flow. This section explores these issues in depth.

Table 5.2 The level of impact of Kuroshio power plant on local ecosystems

	Habitat disturbance due to construction	Construction noise	Operational disturbance to habitat	Operational noise	Operational chemical contamination	Overall assessment
Phytoplankton	▲	▲▲	▲▲	▲▲	▲▲	▲▲
Zooplankton	▲	▲	▲▲	▲▲	▲	▲
Fish Larvae	▲	▲	▲▲	▲▲	▲▲	▲▲
Reef fish	▲▲▲	▲▲▲	▲▲	▲▲	▲▲	▲▲
Migratory fish	▲	▲▲	▲▲	▲▲▲	▲▲▲	▲▲
Cetaceans	▲	▲▲▲	▲▲	▲▲▲	▲▲▲	▲▲▲

Note: ▲, Light impact; ▲▲, Medium impact; ▲▲▲, Severe impact

Table 5.3 Typhoons attacked Taiwan over the past 30 years (1982–2012), including maximum wind speed and wave height [34]

Typhoon grade	Number of instances (1982–2012)	Maximum wind speed (m/s)	Wave height (m)	
			Generally	Maximum
Light	60	18.0–33.0	6–11.5	7.5–16
Medium	88	33.0–48.0	11.5–14 or above	Above16
Strong	44	51.0–70.0	Above 14	Above 16

5.4.1 *Impact of Typhoon*

Typhoons, also known as tropical low-pressure cyclones, occur in tropical and subtropical seas, and are a frequent cause of serious disasters in coastal countries and regions. Taiwan is situated in the Northwest Pacific and, on average, is hit by four to five typhoons per year, typically in a period lasting from late April to December, but with most storms concentrated in July through September. Over the past 30 years, Taiwan has experienced 192 typhoons. An average year will see about 80 tropical cyclones globally, of which more than one quarter occur in the Northwest Pacific region, making it the world's most active area for tropical cyclones (see Table 5.3).

Typhoons have a significant impact on the physical and chemical characteristics of the waters of the Kuroshio. The storms disturb the Kuroshio's path and reduce its flow rate, while strengthening upwelling and lowering the surface temperature. The impact of typhoons on the upper water layers are quite dramatic in the Kuroshio. Tsai and Chern [35, 36] found that when the movements of typhoon and the Kuroshio interact to produce a resonance, the energy of the wind can drive the seawater into a vertical mixing which reduces overall water temperatures. Without resonance, wind shear can result in lower water layers to rise through Ekman Pumping, thus cooling the upper layers. To provide a specific illustration of the types of disturbances and cooling phenomena typhoons cause in the Kuroshio, we present research findings for Typhoon Morakot.

On August 2, 2009, the 11th tropical cyclone of the year (later named Morakot) formed about 1,000 km off the east coast of the Philippines. At 23:50 of August 7, the eye of the typhoon landed near Taiwan's Hua-Lien County, crossed northern Taiwan, and moved into the sea at west Taiwan from Taoyuan County at 14:00 of August 8. At the time of landing, the storm's central pressure measured 970 hPa, with winds near the center gusting to 33 m/s, making it a grade 12 storm. By 05:30 of August 10, Taiwan canceled the typhoon alert but maintained a storm warning. Over the course of less than a day, it brought heavy wind and rains that caused Taiwan's greatest natural disaster in 50 years and killed over 600 people. Figure 5.6 shows the path and the cloud image of Typhoon Morakot.

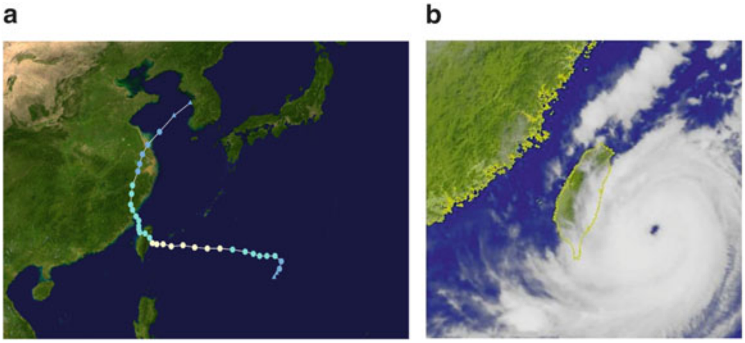

Fig. 5.6 The path and image of Typhoon Morako. (**a**) Typhoon's path. http://www.upload.wikimedia.org/wikipedia/commons/f/fd/Morakat_2009_track.png. (**b**) Typhoon satellite image. http://www.rdc28.cwb.gov.tw/data.php?num = 2009080804&year = 2009&c_name= =MORAKOT

As Morakot swept over Taiwan, sensors positioned by Tang et al. [37] between Taiwan and Lu-Dao found that a downwelling caused by the storm coincided with the ceasing of the current's northward flow of the current at depths between 50 and 150 m. However, at depths between 150 and 350 m, the northward current was found to be normal, while the east–west flow field turned west. This chaos persisted for over a day and a half. On August 9, after the typhoon had passed, the Kuroshio resumed its northeast flow at depths between 50 and 150 m. The cause of this disruption is still uncertain. In addition to the storm-caused downwelling, at the time the Kuroshio may also have been shifted west by the typhoon's landfall, causing the current's axis to bump up against Taiwan's landmass and sinking. In addition, it's possible that, at the coast, the typhoon triggered an edge wave to spread outward which impacted the Kuroshio. In addition to causing changes to the flow field, the typhoon also had an impact on the temperature field. As the typhoon made landfall, the waters at a depth of 270 m off the coast of Hua-Lien increased by 1 °C, likely as a result of the downwelling caused by the typhoon. However, this rise in temperature was followed by a gradual fall of 2.98 °C by August 9. This temperature drop may be related to a cold wake generated by the storm.

This cooling phenomenon was studied in depth by Dr. Ke Tungshan (2012) at Naval Research Lab of Miami. Using the East Asian Seas Nowcast/Forecast System developed by the U.S. Naval Research Laboratory, Dr. Ke simulated the flow conditions of the surrounding waters before and after Morakot hit Taiwan. Results indicate that, before the typhoon (Fig. 5.7a), a cold current flowed north between Taiwan's east coast and the Kuroshio's main axis, connecting to a cold eddy in the waters to the northeast. The approaching typhoon (Fig. 5.7b) brought large amounts of warm water from the western Pacific, temporarily blocking the northward flow of cold water and creating an anticlockwise cold eddy near Lu-Dao, which may be related to the above-mentioned westward flow. After the typhoon passed (Fig. 5.7c), the cold eddy began to drift north along the previously

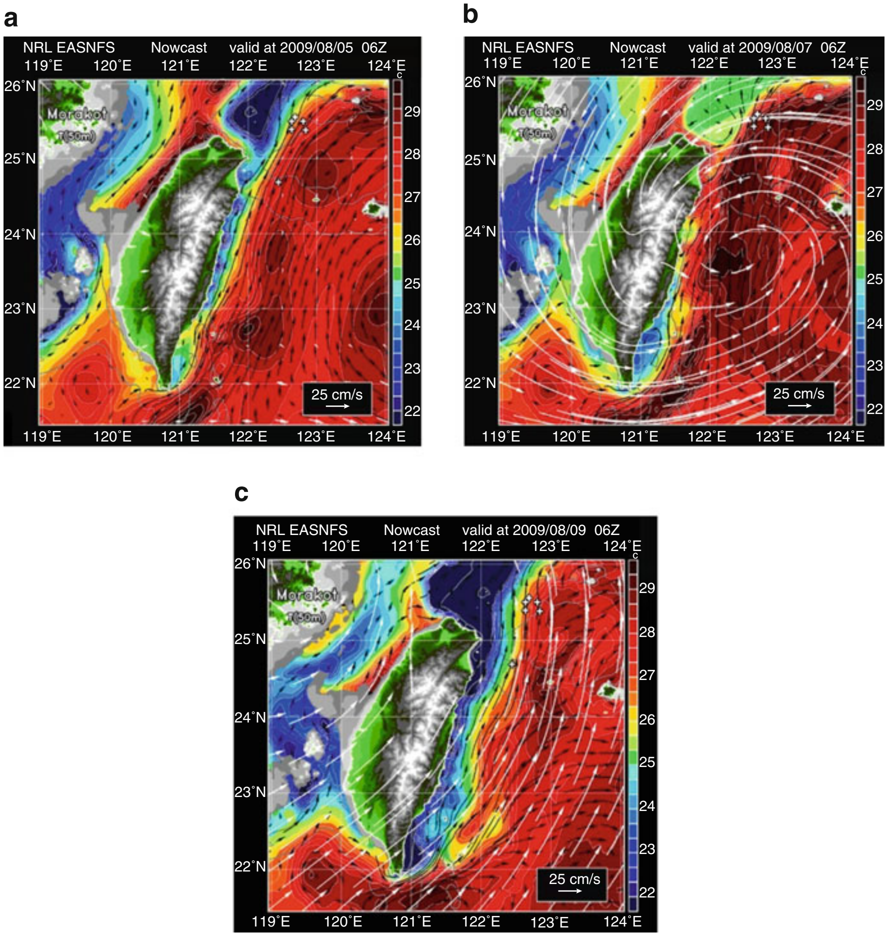

Fig. 5.7 Simulation results of the oceanic flow around Taiwan due to Typhoon Morakot's impact. The velocity of ocean flow is denoted by the black vectors, the velocity of typhoon is denoted by *white* vectors, and the *color* degradation denotes the sea level distribution. These computational results are obtained by running the global ocean model based on the East Asian Seas Nowcast/ Forecast System developed by the U.S. Naval Research Laboratory. (**a**) Before the attack of typhoon; (**b**) as the typhoon attacks Taiwan from the east; (**c**) after the attack of typhoon (*Source*: Tang et al. [37], courtesy of Dr. Ko Dong-Shan, NRL 2012)

established path, and was then incorporated into the cold eddy to the northeast. Finally, the cold current between Taiwan's east coast and the Kuroshio was restored. These simulation results are consistent with the analysis provided by Tsai and Chern [35, 36] in which typhoons coincide with a rise of cold water from the lower layers of the Kuroshio, followed by turbulent vertical mixing. Tsai and Chern noted that the degree of cooling is influenced by both the shape of the coastline and the topography of the local seabed, which also drive changes in the water temperature distribution.

Aside from reducing the performance of the Kuroshio power plants, the typhoon could also generate gigantic waves which could threaten the safety of the power plants. In ocean, most waves are wind-driven, beginning with tiny wind-blown ripples which gradually accumulate energy to become irregular oscillations. As they leave the wind zone, these oscillations gradually become more regular, forming wave with longer wavelengths before transforming into broken waves in the coastal shallows. Physical property analysis shows waves to generally have the following characteristics (Chiu, Feng-Chen. Private communication, National Taiwan University, 2012):

1. The movement of fluid particles as a function of depth beneath surface waves is an exponential function of wavelength attenuation. When depth is half the wavelength, the fluid particles are essentially free of wave interference.
2. The impact of waves on a given depth depend on wavelength rather than wave height. Usually depths of one-half wavelength are not affected. Insufficient depth will result in interference, with interference increasing with wave height.
3. Wavelength and wave period that meet the dispersion law criteria have a set relationship, where wavelength (m) $= 1.56 \times T$ (s) $\times T$ (s). For a wave of a period $T = 10$ s, the wavelength is about 156 m; for a wave of a period of 8 s wave, the wavelength is about 100 m. This varies across waters of different depth, but most of waves occur with a period of 4–6 s.
4. A wave height/length ratio greater than 1/7 makes it difficult to sustain the wave shape, resulting in broken waves. Normally, a wave height/length ratio of 1/20 results in a fairly steep wave with a significant nonlinear phenomenon.

Typhoon-driven waves can reach an average height of 10 m, and the impact of these waves on subsurface waters decreases with depth exponentially. Given a wave height/length ratio of 1/10, being a steep wave, a wavelength of 100 m would have a small impact on turbines placed at a depth of 50 m. However, before a typhoon coming from the Pacific hits Taiwan's east coast, it will exhibit a particularly large fetch which may result in long waves of a period greater than 10 s, potentially making the 50 m depth insufficient to ensure turbine safety. Thus, power plant operations will require the real-time collection and analysis of measured wave spectra during typhoons.

5.4.2 Impact of Earthquake

Earthquakes are caused by collisions between tectonic plates, volcanic eruptions, and meteor impacts. Plate collisions primarily occur in the middle of the ocean, with lava outflows that form the rugged seabed crust. This continuous outpouring of lava pushes the two sides to form a mid-oceanic ridge. When the force of the

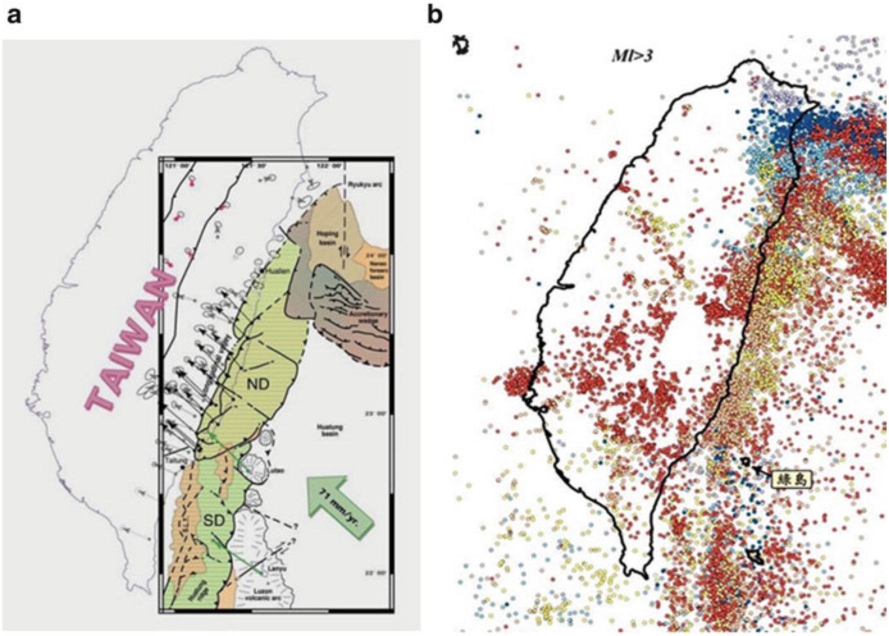

Fig. 5.8 Earthquake epicenters in eastern Taiwan. (**a**) Taiwan's eastern arc—land collision zone structure with GPS displacement volume distribution by year. The Philippine Sea Plate moves northwest towards the Eurasian Plate at an average rate of 71 mm/year. The western edge of the Luzon Arc collides with the eastern edge of the Asian mainland, resulting in crust deformation and orogenesis. The *arrows* in the figure represent annual changes in GPS displacement relative to the Baisha station on Peng-Hu islands. Lu-Dao and Lan-Yu are seen to move northwest at a rate of about 82 mm/year. The *dashed black line* represents the position of the thrust fault. "ND" and "SD," respectively, represent the North Domain and South Domain of the Luzon Arc deformation band [38]. (**b**) Earthquake distribution map of Taiwan based on earthquake data from the Central Weather Bureau. Events are color coded by depth (Courtesy of Prof. Char-Shine Liu 2012)

collision overwhelms the stress tolerance of the rock, the crust can fracture or dislocate, resulting in an earthquake. Taiwan is located at the junction of the Eurasian Plate and the Philippine Sea Plate, formed by the Philippine Sea Plate pushing against the Eurasian plate at a rate of about 72–82 mm per year (see Fig. 5.8a). Taiwan's east coast pushes towards the Central Mountain Range at a similar rate, with the islands Lu-Dao and Lan-Yu moving towards Taiwan also at a similar rate [39, 40]. Taiwan was formed by the collision and lifting of these plates, resulting in the formation of several mountain ranges [41, 42]. On the sea, looking towards the area around Hua-Lien and Tai-Dong, these formations include the Ryukyu Arc, the Luzon Arc, the Hua-Dong Basin, Tai-Dong Canyon, and the Gagua Ridge [43].

Due to the movement of these tectonic plates, Taiwan experiences frequent earthquakes, most frequently in the area between Hua-Lien and Tai-Dong [44]. These earthquakes are all quite shallow (<30 km) [43] and are thus quite destructive. The number of earthquakes in the Tai-Dong area is relatively lower but tend to occur at a shallower depth [40, 43]. Shallower earthquakes have a greater impact on the seabed and land and tend to occur with a higher frequency, thus it is appropriate to discuss the possible impact of very shallow earthquakes on the power plants.

Earthquake data for Taiwan from 2000 to 2012 [45] show a total of 3,548 earthquakes (see Fig. 5.8b), of which 1,046 (30 %) were rated 4 or above. Of these, 732 were very shallow earthquakes, accounting for 70 % of the quakes above a rating of 4, indicating that most of the 4 and above quakes between Hua-Lien and Tai-Dong occurred at very shallow depths. The historical earthquake distribution shown in Fig. 5.8b indicates that, between 2000 and 2012, the majority of 4-and-above very shallow earthquakes occurred near Hsiu-Lin Township in Hua-Lien County and near Hua-Lien City, with the majority of those near Tai-Dong occurring near Cheng-Kung and Dong-He Townships. Most undersea earthquakes also occurred off the coast of these locations as well. In addition, earthquakes also occur frequently in the ocean east of Hua-Lien in an area belonging to the Ryukyu Arc. Vibrations caused by 4-and-above quakes in this area push at seismic faults, resulting in a fractured seabed, and result in a relatively unstable geological structure.

The plate movement results in a dense network of faults under the sea off the east coast of Taiwan, the rugged appearance of the seabed, and the rapid erosion of the mountains extending from Taiwan to Lu-Dao and Lan-Yu, and the ensuing accumulation of sediment. The frequent seismic activity also contributes to ubiquitous seabed landslides. Continuous pressure along the east side of the Luzon Arc results in continuous erosion in the Tai-Dong Canyon to the west. Several normal faults have developed along the central axis of the Tai-Dong Canyon, opening up to the seabed, and the continued activity of these faults indicates that the geological structure is highly unstable.

Both the east side of the Tai-Dong Canyon and the west side of the Luzon Arc feature a major undersea landslide, the sliding surface of which is primarily located along the western edge of the Luzon Arc. The slide has resulted in the accumulation of a large amount of sediment accumulated in many layers from the north or west sides of the canyon [37]. This seabed deformation is caused by earthquake-triggered landslides, and this debris flow is very likely to negatively impact power plant equipment and foundation engineering in the area. Taiwan's eastern submarine telecommunications cable has frequently been damaged by this type of collapse, and the seabed anchoring system for the Kuroshio power plant will unavoidably be vulnerable to similar effects.

5.4.3 Impact of Climate Change

The flow of the Kuroshio can be divided into two types: the first is wind-driven circulation, while the other is caused by uneven distribution of water densities, referred to as thermohaline circulation. Most wind-driven currents take place in the upper layers, where the flow direction and rate are affected by the wind, the Coriolis force, and the Ekman transmission factor. Lower or deeper currents are primarily affected by gravity, only a few of these currents globally can be observed, and most of these currents are identified by speculations of measured temperature and salinity.

The direction and speed of wind-driven currents are mainly determined by the strength and persistent direction of the wind. Therefore, any discussion of such currents requires an understanding of wind-related changes, including changes to temperature and climate. To determine past Kuroshio flow scenarios and explore the effect of change factors, one must first determine whether and how past climate and geological changes have affected the flow direction and rate of the Kuroshio. At the same time, recent research investigations comparing past and present temperature and salinity data provide a more complete perspective on the generation and change of the Kuroshio. Therefore, investigating the change and origins of the Kuroshio entails a highly complex investigation which incorporates climate change from the ice age to the present, recent *El Nino* phenomena and global warming, along with monsoon and typhoon factors [38, 46].

Today, research on the Kuroshio's ancient flow patterns and changes are based on core samples from the Kuroshio basin, using isotope analysis of foraminifera and algae to determine sea surface temperatures, sediment deposition rates, and types to determine sediment sources. These determinations can help researchers infer the Kuroshio's flow rate at the ancient time, and cross-analysis can be used to determine flow's possible direction and speed, allowing for the possible reconstruction of past climate conditions, along with monsoon change and influence on ocean currents.

Global core samples were used to recreate conditions from 18,000 years ago, indicating that global ocean temperatures today are 2 °C higher but 6 °C higher in the polar areas [47]. Intense solar radiation at the equator from 6,000 to 12,000 years ago generated a strong summer monsoon and also enhanced the flow rate of the North Equatorial Current [48] (see Fig. 1.1) which spread heat to high latitudes. During the last ice age, sea levels dropped by an average of at least 100 m, leaving Taiwan and China high and dry, while Japan's Okinawa Trough and the Ryukyu Islands near Taiwan theoretically should have been located further east due to the Kuroshio. Core data from near Japan also shows that about 7,300 years ago the Kuroshio returned to the Okinawa Trough. Based on changes to oxygen-18 isotope concentrations in foraminifera, our understanding of temperatures and sediment deposit rates for 2,700–4,600 years ago leads to speculation that the Kuroshio at the time had a very weak effect, while the northeast monsoon had a very strong impact [49]. Core research from the Ryukyu Islands indicate that, during the ice age, the

Kuroshio would have been unable to extend to the western edge of the Ryukyu Islands, and must have flowed north along the islands [50].

On the other hand, research along Japan's Nishishichitou Ridge indicates that the Oyashio Current once extended as far as 35N^{o}, meaning that the Kuroshio was located further to the south. Meanwhile, at 7,000–8,000 years ago, strong warming resulted in temperature change, strengthening the North Equatorial Current, thus allowing the warmth from the Kuroshio to reach the Nishishichitou Ridge [51]. The research also indicates that between 18,500 and 17,500 years ago, sea levels off Taiwan's southeast coast reached their lowest point, 150 m lower than current levels. But that sea levels suddenly rose years later, accelerating the Kuroshio's flow. If the sea level rose slowly and the Kuroshio's flow rate fell, the Kuroshio would assume a clear eastward shift [52].

Studies of small-scale annual changes indicate that the Kuroshio followed a significantly different route. From 1959 to 1962, the Kuroshio clearly shifted south from Shikoku in Japan, and then shifted northeast. From 1956 to 1959, and then again in 1963, it flowed directly northeast [53, 54]. The relationship between the Kuroshio and *El Nino* indicates that *El Nino* and the southern oscillation both influence the speed of the Kuroshio, and in *El Nino* years the Kuroshio flows more straight than it does between *El Nino* years [55]. As a result of global warming, temperature rise would enhance the speed and straighten the course of the Kuroshio, exerting a decisive influence on global heat transfer and sea levels [56]. Monsoons and typhoons have a smaller time-scale effect on the Kuroshio's location and flow rate. Given a strong northeast monsoon, the Kuroshio's average flow rate will be relatively low, but a strong southwest monsoon will increase the Kuroshio's flow rate and cause it to take a clearly straightened course [57]. The wind field generated by typhoon Nari slightly offset the Kuroshio's position [58], reduced the sea surface temperature, stirred the subsurface layers, and changed the flow direction [59, 60].

From the above-mentioned studies, one can infer that the flow and direction of the Kuroshio can be influenced by large-scale ice ages, short-term interglacial changes, inter-*El Nino*-years changes, short-term seasonal changes and typhoons. These impacts depend on atmospheric conditions at the time (e.g., the influence of the equatorial trade winds) which are the key driver of the Kuroshio. On the other hand, in high latitudes, the Kuroshio plays an important role in heat transfer globally. In past brief ice ages, this was because ice melt into the North Pacific would pump fresh water into the ocean, forcing the Kuroshio to change direction while reducing the density of the surface seawater and slowing thermohaline circulation. This reduced the northward flow of warm water, with the result that most of northern Asia and North America were covered with ice. This period is referred to as the Younger Dryas, and its effects are recorded in rock cores in the Asian landmass [36]. These changes to the circulation of the North Pacific indicate that the Kuroshio not only is impacted by climate change but also that the Kuroshio's flow direction can also influence climate change in the higher latitudes. Therefore, any deceleration of the Kuroshio or change in its direction is bound to have an impact on the climate in higher latitude areas [61].

In view of that the operating time scale of the Kuroshio power plant is often within a 100 years or less, the Kuroshio flow should not experience any significant difference due to the climate change. On the other hand, while the overall energy of the Kuroshio may be reduced, the scale of the power plants is small enough that the operation of the power plant should not have any significant impact on the Kuroshio's flow momentum.

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