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Chapter 20

The Kuroshio - Its Physical Aspect and Roles in Kagoshima's Nature and Culture -

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1. Introduction

The Kuroshio is one of the largest currents in the oceans of the world, and flows northward along the western boundary of the North Pacific Ocean. Along its path, the Kuroshio flows through the coastal seas of Kagoshima Prefecture, which are located at the most upstream stretch of the current as it passes through the waters south of the main islands of Japan. As a result, numerous aspects of Kagoshima's culture and natural environment are closely related to the Kuroshio. For example, coral reef habitats extend northward along the Kuroshio's path as far as the small islands south of Kyushu, where the subtropical seawater it transports from the southern latitudes is warm enough to nurture such reefs, even in the wintertime.

The Kuroshio also sustains Kagoshima's active commercial fishing industry. This is because the warm current transports larvae and fry of numerous fish species (*e.g.*, Japanese mackerel, Japanese spiny lobster and Japanese eel) from their upstream spawning areas into the hospitable nursery and fishing grounds that are associated with complex bottom topography present in the coastal seas of Kagoshima. As for the cultural aspects of Kagoshima, the Kuroshio is responsible for guiding a multitude of foreigners to the shores of the region in previous eras, some of which changed history by planting foreign cultural influences in Japanese soil.

To give just one example, it is well known that firearms were introduced to Japan in 1543 by Portuguese traders whose ship had drifted off course while en route to China - eventually arriving at Tanegashima Is. south of Kyushu because of the influence of the Kuroshio. There are many other instances in which the Kuroshio plays an important role in Kagoshima's nature and culture.

The author wrote this article to provide general and useful information about the Kuroshio to persons without any previous knowledge of the Kuroshio, such as visitors from foreign countries. This first article provides general explanations of the Kuroshio from the physical oceanographic point of view, and then describes regional features of the current in the seas of Kagoshima, such as the spatial patterns, temporal variations, water properties and water colors, before finally focusing on some effects of the Kuroshio on Kagoshima's natural environment, such as the region's ecosystem, fishing industries, and regional climate. A number of historical events that connect the region with the Kuroshio are added as topics in each section.

2. Topographic features of Kagoshima's seas

Kagoshima Prefecture is composed of a mainland area corresponding to the southernmost part of Kyushu, Japan's third largest island, and several other islands that make up the northern part of the Nanseishoto Island chain (Fig. 1a). The western coast of the mainland area faces the northernmost stretch of the Okinawa Trough, which is a deep basin (in some cases deeper than 2,000 m) that follows the continental shelf in the East China Sea. The Okinawa Trough and the North Pacific Ocean (with depths more than 5,000 m) are separated by the Nanseishoto Island chain, which rides a north-south extending ridge with three deep fissures (Fig. 1b). These are the Tokara Strait south of Kyushu, the Kerama Gap south of Okinawa Island, and the Yonaguni-Taiwan Strait (this name is used only for convenience in this text).

Waters within the upper 1,000 m from the surface flow freely between the two basins through those three channels. Therefore, the currents and water properties that mark the coastal seas of Kagoshima are a regional element of the large-scale oceanic circulation system that makes up the North Pacific Ocean. Because of this, the upper-ocean circulation system that governs all of the World Ocean, not only the North Pacific Ocean, will be considered in the next section. The World Ocean is used in this text as a concise word to express the oceans of the world, such as the Atlantic, Pacific and Indian Oceans.

3. The Kuroshio as part of global ocean circulations

Fig. 2 shows an overview of the major surface currents over the World Ocean, which is coherent to a depth of about 1,000 m. You may be surprised to learn that the circulation patterns for the Pacific, Atlantic, and Indian Oceans are very similar to each other. For example similar circulations are present over the mid-latitude oceans in

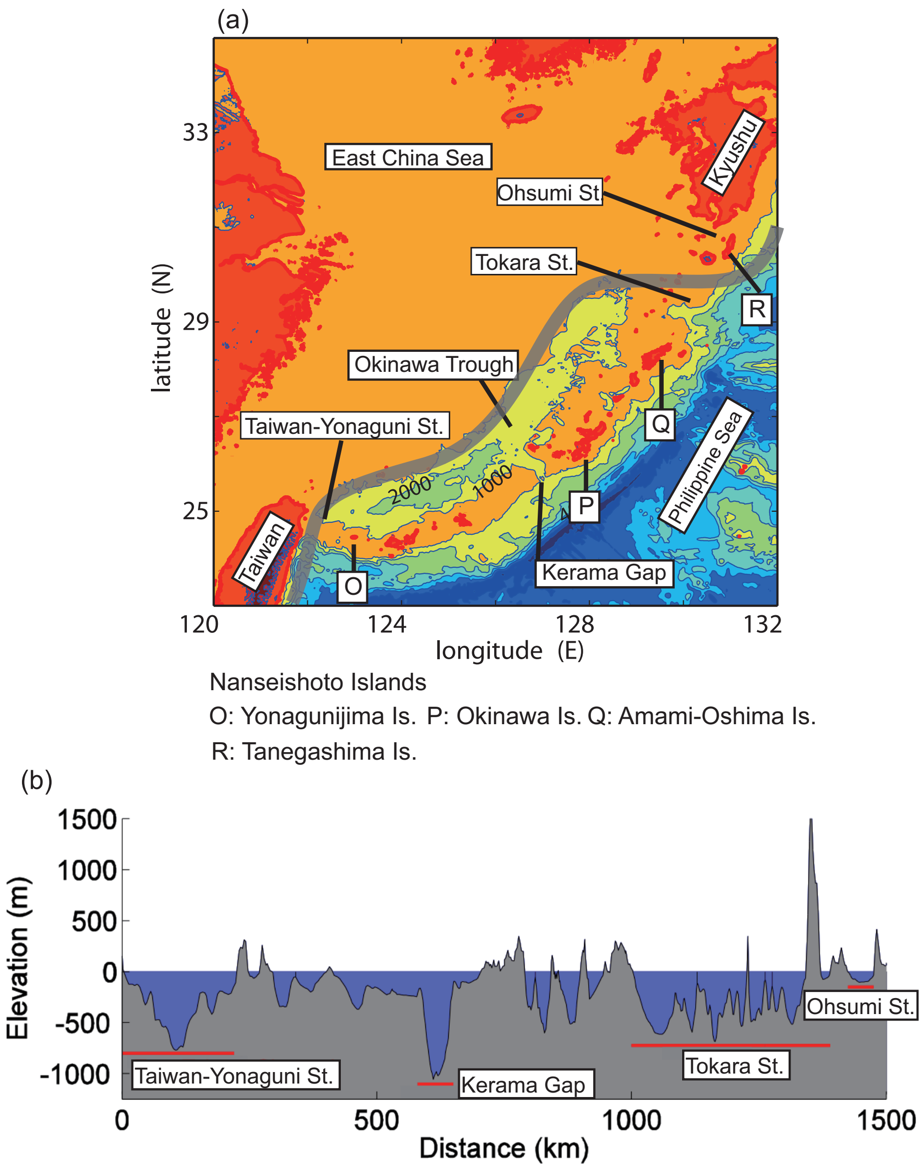

Fig. 1. (a) Bathymetry of the seas around the Nanseishoto Island chain. The bold gray line denotes the Kuroshio path. (b) Cross section of the Nanseishoto Island chain from Taiwan (on the left) to Kyushu, Japan (on the right) (Image courtesy of Jae-Hun Park).

both the Northern and Southern Hemispheres - travelling clockwise in the north and counterclockwise in the south. In oceanographic terms, these mid-latitude, large-scale circulations are known as *subtropical gyres*. The Kuroshio is a northward component of the North Pacific subtropical gyre, while the Gulf Stream is a North Atlantic counterpart of the Kuroshio. The westward intensification of the currents is a distinctive characteristic of all subtropical gyres; this feature is due to the fact that the "center" of this type of circulation is actually located at its western edge. Thus, the Kuroshio and Gulf Stream, which are located at the western boundaries of their respective regions, are much stronger than the California Current and Cannery Current, which are located at the eastern boundaries of their respective regions. In oceanographic terms, the former are generally called *western boundary currents* and latter are known as *eastern boundary currents*. In both the Northern and Southern Hemispheres, the western boundary currents carry warm water poleward while cold high-latitude waters flow eqatorward along the eastern boundary currents.

Fig. 3, which shows a meridional temperature section over the central Pacific Ocean, provides us with information on oceanic motions under the sea surface. Most of the ocean floor is deeper than 5,000 m (the mean depth of the World Ocean is about 3,800 m), and most such deep-sea ocean water is 5 ˚C or less. The warmer water extending from the surface to a depth of about 1,000 m, known as the *thermocline* in oceanographic terms, rides above the colder deep water in the low- and mid-latitude oceans. The subtropical gyre, including the strong western boundary current, is the result of thermocline water being pushed in a horizontal direction by the force of prevailing winds all over the earth. In contrast, the colder deep-water motion is governed by another mechanism, referred to as *thermohaline circulation*.

The winds driving the upper-ocean circulations prevailing over the mid-latitudes are known as the Westerlies, while the Trade winds - also referred to as Easterlies - prevail over the low-latitudes (Fig. 4a). The wind patterns over the Pacific, Atlantic and Indian Oceans are the roughly similar, although directions are reversed for the Northern and Southern Hemispheres. Winds, therefore, drive the surface water with the same manner in

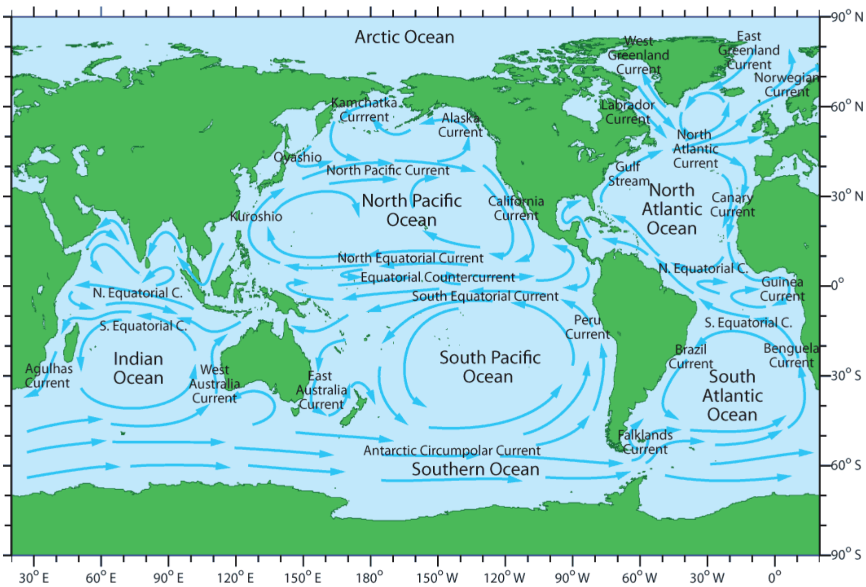

Fig. 2. A schematic view of the major surface currents over the World Ocean extracted from the homepage of the Science Education through Earth Observation for High Schools (SEOS) Project (http://www.seos-project.eu/home.html).

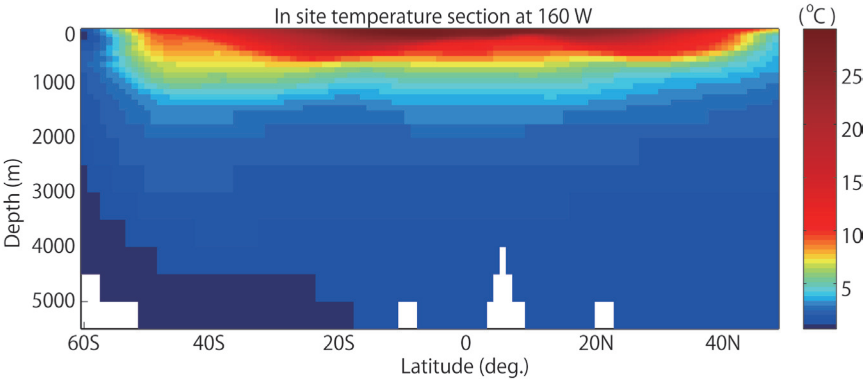

Fig. 3. A meridional temperature section over the central Pacific Ocean. This data is based on an objectively analyzed (1° grid) climatological field of in situ temperatures from the World Ocean Atlas 2001 (WOA01).

each ocean. This is the reason why the upper-ocean circulation patterns are very similar for all oceans.

In both the Northern and Southern Hemispheres, as a result of wind-forced motion, surface water accumulates in the central area of the subtropical gyres, causing the sea level to become higher in those areas than the surrounding seas (Fig. 4b). Here, a scientific question arises; Why does the surface water rotate clockwise in the subtropical gyre of the Northern Hemisphere and counterclockwise in the Southern Hemisphere? This is initially counter-intuitive because the water normally flows from a high to a low sea-level area. The answer is found in a form of motion called a "*geostrophic current*," in which the pressure gradient force is balanced by the Coriolis force, which is a force that influences moving particles on rotating surfaces, such as the earth. We can see analogous phenomena in the atmosphere in the form of typhoons and cyclones.

4. Current structure and water properties of the Kuroshio

4.1. Large-scale features of the entire current

This chapter describes the special distribution and temporal variations of the Kuroshio in detail. Fig. 5 shows a snapshot field of the sea surface velocity recorded on May 9, 2007, based on reanalysis data reproduced using the Japan Coastal Ocean Predictability Experiment (JCOPE) observational-data assimilated numerical model. The Kuroshio, which is recognized as a strip about 100 km wide, originates off the eastern coast of Luzon Island in the Philippines (15°-18° N). From there, it flows northeastward along *the continental slopes* east of Taiwan and in the East China Sea, then along the Japanese main islands of Kyushu and Shikoku, before arriving near the Bōsō Peninsula in mid-Honshu (~35° N) where it finally leaves the coastal area and veers east toward the International Date Line in the central North Pacific.

Some aspects of the Kuroshio are inherently unstable. For example, the current itself tends to meander over its entire length; emanating *mesoscale eddies* with horizontal scales from several 10 to several 100 km as it travels. This feature is particularly remarkable in the stream east of the Bōsō Peninsula, where there is no continental slope to constrain the current.

The Kuroshio has a current speed exceeding 1 m/s along the current axis near the sea surface. At that speed, a drifter deployed into the Kuroshio will travel downstream about 100 km a day. This estimate means that, if tossed into the water off of Luzon Island (~15° N), the Kuroshio can potentially carry a drifter to the coastal areas of Kagoshima (~30° N) in just a few months - even if the drifter partially escapes from the main stream of the current.

The drift period from Luzon Is. to Kagoshima provides a hint that helps us understand the following interesting historical fact: most of the historical

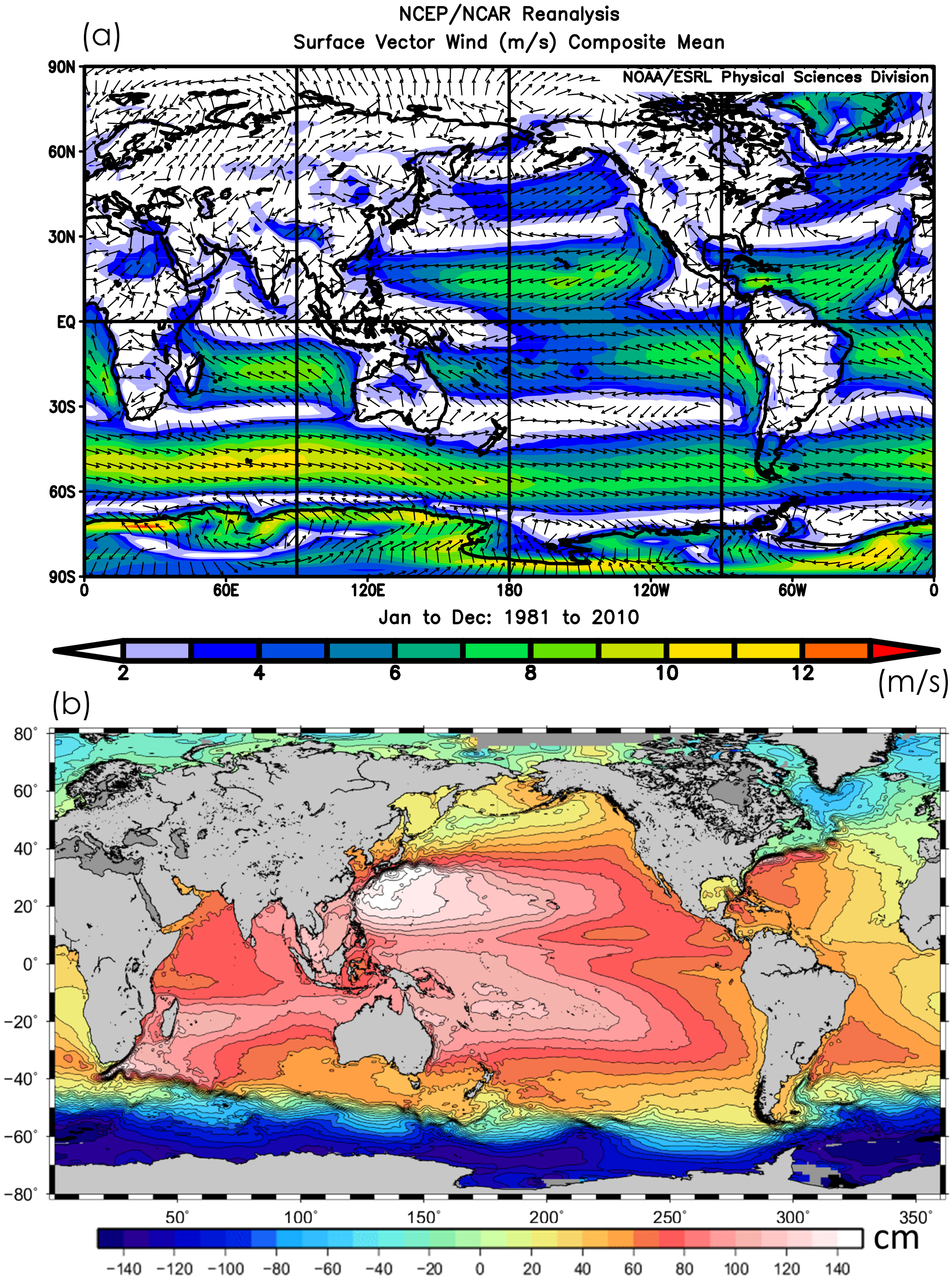

Fig. 4. (a) Long-term mean surface winds, derived from reanalysis data for 1981 to 2010. This image was created with the graphic tool installed on the homepage of NOAA, Earth System Research Laboratory, Physical Sciences Division, located at (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl). (b) Long-term mean dynamic topography, which is physically equivalent to sea level, over the World Ocean. The image was adopted from the Archiving Validation and Interpretation of Satellite Oceanographic data (AVISO) homepage, which is available at: http://www.aviso.oceanobs.com/en/data/products/auxiliary-products/mdt.html.

events involving foreigners arriving off the south coast of Japan occurred in the summer to autumn season. Referring to Kawai (1995), this fact can be explained as follows:

In the days of sail, trade ships passed through the South China Sea from Southeast Asia en route to China in the summer using the prevailing southwesterly winds. Some of these ships suffered damage at sea due to typhoons or tropical cyclones that caused them to drift off course out of control. Drifting ships that passed through the area between Luzon and Taiwan were immediately entrained into the Kuroshio, and thus eventually arrived off the south coast of Japan in the summer or autumn months. Therefore, in the Edo period, it was thought that the Kuroshio originated somewhere in the Southeast Asian waters connected to the South China Sea.

With an amplitude of about 10 % of its mean speed, seasonal changes in the Kuroshio's current speed, as it travels over the East China Sea and south of Japan, are quite small. However, the current's intra-seasonal variations show significant amplitude, about 40 % of its mean value, especially off the south coast of Japan. This is because the mesoscale eddy propagating from the North Pacific interior region impinges into the Kuroshio during a period of about 100 days.

Inter-annual and inter-decadal variations of the current speed are also found with an amplitude between those of the seasonal and intra-seasonal changes. Furthermore, the Kuroshio shows strange temporal path variation behavior, which is distinctive among the western boundary currents in the World Ocean. For example, the Kuroshio path transitions between the large-meander and straight paths off the south coast of Japan, and it is well known that each state is maintained over long pe-

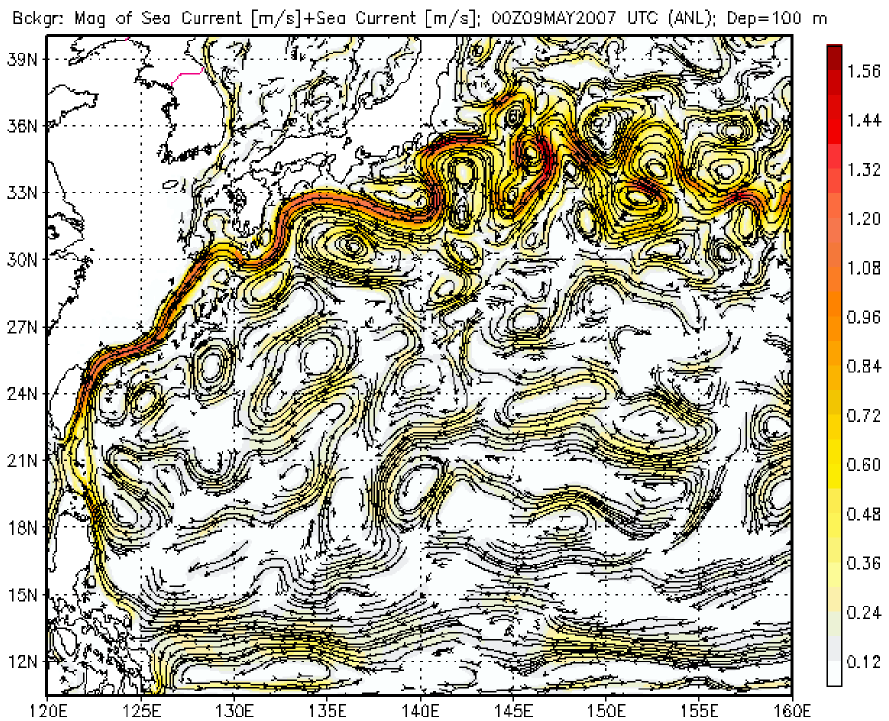

Fig. 5. Near sea-surface current field over the northwestern North Pacific Ocean on May 9, 2007, which is expressed by the stream function, derived from FRA-JCOPE2 17 Years NW Pacific Ocean Re-Analysis data. The image was made with the graphic tool included in the homepage of JCOPE (http://www.jamstec.go.jp/frcgc/jcope/htdocs/e/home.html).

riods, from several months to several years. It is also known that the epochs in which one state is predominant over the other vary on a decadal time scale. It has been suggested that the mechanism governing the path's transition is somehow related to the inter-annual or inter-decadal variations of the Kuroshio's current speed, but details regarding the mechanism been yet to be determined, in spite of the efforts of numerous scientists.

Regional current features in the Okinawa Trough and around the Nanseishoto Island chain are characterized by various branches of the Kuroshio. Fig. 6 shows a close-up of this area, along with surface velocity distribution. The Kuroshio bifurcates southwest of Kyushu, at which point the main stream leaves the continental slope and turns clockwise toward the Tokara Strait, while a separate branch current flows northward over the continental shelf and connects with *the Tsushima Warm Current*, which then enters into the Japan Sea through the Tsushima Strait. In Korea, the Tsushima Strait and the Japan Sea are known as the Korea Strait and the East Sea, respectively. Thus, these locations are often referred to as the Tsushima/Korea Strait (or Korea / Tsushima Strait) and the Japan/East Sea (or East / Japan Sea) in international scientific papers.

A weak but organized northward-trending current, known as *the Ryukyu Current*, is found on the eastern side of the Nanseishoto Island chain. This current is very weak or nonexistent near the sea surface, but is strong at intermediate depths (500-1,000 m) where it has a maximum speed of about 0.5 m/s (*e.g.*, Nakamura *et al*. 2007). The name, Ryukyu Current, was given due to its proximity to the Ryukyu Islands, which include the islands between Amami-Oshima and Yonagunijima Is.. Here, note that the Ryukyu Islands are also included in the Nanseishoto Island chain. The Ryukyu Current is generally regarded as a deep branch of the Kuroshio, other portions of which (those deeper than about 800 m) must bifurcate east of Taiwan because they cannot pass through the Yonaguni-Taiwan Strait (which has a maximum sill depth of 770 m) into the East China Sea (See Fig. 1b). One small northern branch of the Kuroshio is *the Osumi Branch Current*, which flows in the Osumi Strait between the Cape Sata and Tanegashima Is.

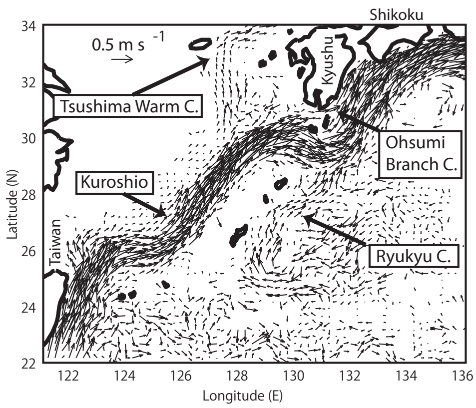

Fig. 6. Mean surface velocity vectors, derived from drifting buoy WOCE data obtained between 1989 and 1996 (Surface Velocity Programme, WOCE Global Data Version 1.0, 1998).

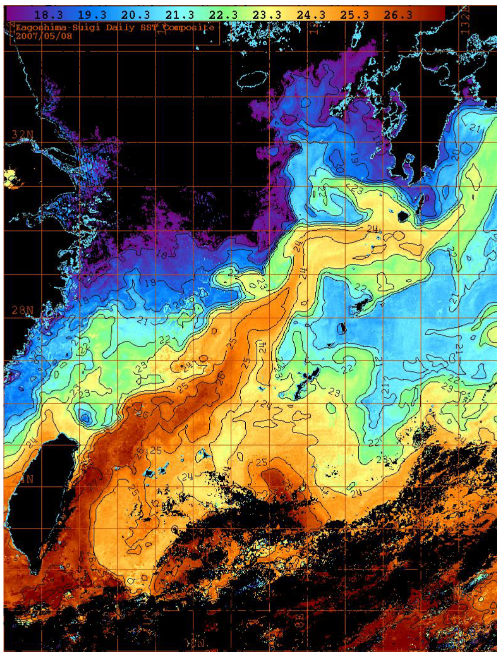

Fig. 7. NOAA sea-surface temperature field on May 9, 2007. The image was made with the tool of the homepage in the Kagoshima Prefectural Fisheries Technology and Development Center (http://kagoshima.suigi.jp/).

4.2 Local features south of Kyushu

Because the Kuroshio is a warm current, its water temperature is higher than the surrounding coastal and offshore waters. Fig. 7 shows the sea surface temperature over the East China Sea on May 9, 2007 as observed by a US National Oceanic and Atmospheric Association (NOAA) satellite. Here, redder colors indicate warmer water while bluish colors depict cooler water. As previously mentioned, the path of the Kuroshio extends along the continental slope of the East China Sea, carrying with it subtropical water from near 20˚ N latitude and keeping the sea surface temperature within the Kuroshio above 20 ˚C, even in winter. It also results in a clear temperature front, which is often called *the Kuroshio front*, near the sea surface between the cooler coastal and warmer Kuroshio waters in the colder months of the year. However, the Kuroshio front on the sea surface disappears in the summer and autumn periods because the sea surface temperature increases to about 28 ˚C due to surface heating, thus becoming roughly uniform over the entire East China Sea. Salinity near the sea surface is also higher within the Kuroshio (maximum: ~3.48 % near the 200 m depth) than the surrounding areas. High salinity water (>3.50 %) is fed over *the North Equatorial Current*, which is a source of Kuroshio water, by an excess of evaporation over precipitation caused by the subtropical high atmospheric pressure zone over the central North Pacific Ocean. In contrast, salinity on the continental shelf edge of the East China Sea is very low (~3.40 % in winter and < 3.30 % in summer) primarily because of fresh water discharge from the large rivers of China such as the Changjiang (Yangtze River). Both the high and low salinity waters mix strongly along the Kuroshio front because of the front's disturbances, which will be discussed in the following paragraphs.

The Kuroshio front disturbances develop as the current meanders along the continental shelf (see Fig. 7). According to NAKAMURA *et al*. (2003), the spatial and temporal scales of the initial deviation are about 200 km in wavelength, with periods of about 20 days. The period scales are dynamically determined based on the crosscurrent density and velocity structures of the Kuroshio on the continental slope. A counterclockwise eddy ("cyclonic eddy" is generally used as a technical term) emanates from such a meander on the inshore side of the current and propagates downstream along the continental slope. When that counterclockwise eddy enters the Okinawa Trough southwest of Kyushu, the main path of the Kuroshio makes a sudden dip in the southern direction before turning northward again. Although the northern direction is persistent, the southern dip is found to increase and recede intermittently, every one to a few months, in association with changes to the counterclockwise eddy.

This type of Kuroshio front development tends to occur during the winter-spring period, and then diminish in the summer-autumn period, when the Kuroshio is stabilized. NAKAMURA *et al*. (2010) indicates that recent studies indicate that the seasonal changes to the stability of the Kuroshio are probably caused by seasonal changes in the winds prevailing over the East China Sea.

5. Roles of the Kuroshio on Kagoshima's nature

5.1. Water color of the Kuroshio and biological activity

In Japanese, the word "Kuroshio" can be broken down into "kuro" which means "black" and "shio" which means "current." Hence, the English name, "Black Current." According to KAWAI (1995), the earliest recorded appearance of this name is found in a 1752 (the 150th year of the Edo Period) map showing the Izushoto Island chain, which extends southward from the Izu Peninsula southwest of Tokyo. The document attached to the map refers to the presence of a rapid stream named the "Kurosegawa" in the sea between the Izu Peninsula and Hachijojima Is. "Segawa" is another Japanese word for current, so "Kuro-segawa" and "Kuro-shio" have identical meanings. Based on this fact, we know that Japanese people of previous eras also considered the sea surface color over the Kuroshio region to be black.

The color of seawater near the surface depends on sunlight penetration of water particles themselves, and on the microscale particles, such as phytoplankton, suspended in the water. Clear water appears dark blue in color, while seawater that contains large amounts of phytoplankton tends to be greenish. Therefore, the black color of the Kuroshio indicates clear water, in which phytoplankton amounts (and hence biological activity) are low.

The reason for the current's low productivity is as follows: Phytoplankton growth (called *primary production* in oceanographic terms), requires nutrients such as nitrates, phosphates and silicates dissolved in seawater, in addition to the sunlight energy required for photosynthesis. Nutrients near the sea surface in the open ocean are generally brought from the deep layer by *upwelling*. Phytoplankton amounts near the sea surface, therefore, are high in upwelling regions and low in the downwelling regions. Because the interior region of a subtropical gyre is typically a downwelling region, such areas are often called "deserts in the ocean."

Despite the limited amounts of phytoplankton within the near sea-surface water of the Kuroshio itself, fishing industries are extremely active in the coastal seas of Kagoshima, which is adjacent to the Kuroshio. This is due to the convergence zone that marks the Kuroshio front, which forms an area where plankton and micronekton grow in profusion, which attracts larger predators, thus creating good fishing grounds. Furthermore, upwellings that occur within the counterclockwise eddy emanating from the Kuroshio-front meander play an important role in supplying nutrient-rich water from the deep ocean to the near sea-surface.

Frontal effects like these, together with the effect of complex bottom topography of the region, create conditions that make the coastal seas of Kagoshima excellent breeding grounds for various species of fish. The larvae and juveniles of several fish species, such as anchovy, mackerel and Pacific bluefin tuna, are transported from their upstream spawning areas to the coastal area west of Kyushu by the Kuroshio. The water transport factor resulting from the Kuroshio, which occurs intermittently due to the spatially growing counterclockwise eddy southwest of Kyushu (see section 4.2), plays an important role in transporting these species into the coastal area west of Kyushu, and thus has a significant effect on the amounts caught.

5.2. Effects on regional climates

The Kuroshio transports large amounts of heat from lower latitudes to mid-latitudes. Therefore, the winter sea surface temperature of the Kuroshio is significantly higher than those of coastal waters outside the current flow. Because of this, the wintertime weather of the coastal areas of Kagoshima is warmer than its inland areas. This effect also has a substantial impact on synoptic-scale weather in the winter season. For example, extratropical cyclones frequently develop over the Kuroshio flowing in the East China Sea and south of Japan. Cyclones of this type, often referred to as *south-coast cyclones*, are important to Japanese society because they sometimes develop explosively and cause dangerous sea conditions that sometimes result in maritime disasters. They also tend to bring snow to the Kanto district, which is home to the Japanese capital city of Tokyo and its population of more than 13 million people.

Nakamura *et al*. (2012) has recently reported an interesting phenomenon concerning the relationship between the Kuroshio and south-coast cyclones. That is, the tracks and development rates of cyclones that advance along the south coast of Japan vary substantially in association with the large-meander and straight path states of the Kuroshio south of Japan.

In contrast to the colder months, the effect of the Kuroshio on synoptic-scale weather is weak in the summer because the strong sunlight (shortwave radiation) of the season heats sea surface temperatures over the entire East China Sea and south of Japan to tropical temperatures. As a result, typhoons, for example, develop or maintain their intensity by drawing heat from the sea surface everywhere, not just areas limited to the Kuroshio.

However, the situation in the early summer is somewhat different from that of the mid-summer period. There is observational evidence that the seasonal rain front (called the *Baiu Front*), which extends from the southwest to the northeast over the East China Sea in June, is strengthened on the Kuroshio, where the sea surface temperature tends to remain higher than the surrounding areas. Every early summer, Kagoshima endures severe rainfall due to the Baiu Front, which often results in severe damage from floods and landslides. Thus, accurate prediction and associated warnings related to the strong rains spawned by the Baiu Front are needed in Kagoshima to prevent such damage.

In April 2009, a five-year joint research project involving Japanese meteorologists and physical oceanographers began examining the ocean-atmosphere interaction over monsoonal Asia. The nickname of this project, "Hot Spot in Climate System," refers to the fact that the mid-latitude North Pacific climate system is basically maintained by huge amounts of heat drawn from the Kuroshio, which is the most distinct hot spot in the world, into the atmosphere.

6. Summary

In this article, the author has explained the physical aspects of the Kuroshio, which is one of the western boundary currents of the World Ocean. Readers who would like to obtain more advanced knowledge of the western boundary currents may refer to general textbooks of physical oceanography such as Pickard and Emery (1990), and Knauss (1996). The author also attempted to provide information about the Kuroshio that would be useful in understanding Kagoshima's culture and natural environment. Portions of the contents of this section are the result of the author's studies. Readers who are interested in more detailed explanations may refer to author's scientific papers, which are listed in the references.

Before closing this article, the author would like to point out one negative impact of the Kuroshio on human lives in countries adjacent to the North Pacific Ocean. As explained previously, the Kuroshio transports waters gathered from the Philippine, China and Taiwan coasts to the coastal seas of Japan, while also carrying the coastal waters south of Japan further toward the downstream side. Over a scale of several years, these waters eventually spread over the mid-latitude North Pacific. This process has recently given rise to serious environmental problems in countries adjacent to the North Pacific Ocean. For example, large amounts of waste from foreign countries wash ashore on Japanese coasts upstream of the Kuroshio, and Japan itself inflicts huge amounts of waste, via the Kuroshio and the subtropical gyre, onto islands in the North Pacific Ocean and the western coast of North America. The reader may remember that large amounts of debris were swept from the Tohoku area of Japan into the North Pacific Ocean by *the Tsunami* associated with the Great East Japan Earthquake on March 11, 2010. This debris was eventually inflicted on the coastal environments of islands in the North Pacific Ocean and the western coast of North America.

Thus, the Kuroshio and the subtropical gyre are a serious topic of international concern in discussions related to environmental conservation on coasts adjacent to the North Pacific Ocean, and international coastal management corporations will be needed to remove wastes on local beaches and conserve the natural environments there.

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