Kuroshio and Oyashio Currents☆

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Introduction

The Kuroshio and Oyashio currents are the western boundary currents in the wind-driven, subtropical, and subarctic circulations of the North Pacific Ocean. Translated from Japanese, Kuroshio literally means black ("kuro") stream ("shio") owing to the blackish—ultramarine to cobalt blue—color of its water. The "blackness" of the Kuroshio Current stems from the fact that the downwelling-dominant subtropical North Pacific Ocean is low in biological productivity and is devoid of detritus and other organic material in the surface water. The subarctic North Pacific Ocean, on the other hand, is dominated by upwelling. The upwelled, nutrient-rich water feeds the Oyashio from the north and leads to its nomenclature, parent ("oya") stream ("shio").

The existence of a western boundary current to compensate for the interior Sverdrup flow is well understood from modern wind-driven ocean circulation theories. Individual western boundary currents, however, can differ greatly in their mean flow and variability characteristics due to different bottom topography, coastline geometry, and surface wind patterns that are involved. For example, the bimodal oscillation of the Kuroshio path south of Japan is a unique phenomenon detected in no other western boundary current of the world oceans. Similarly, interaction with the semienclosed and often ice-covered marginal seas and excessive precipitation over evaporation in the subarctic North Pacific Ocean make the Oyashio Current considerably different from its counterpart in the subarctic North Atlantic Ocean, the Labrador Current.

Because the Kuroshio and Oyashio currents exert a great influence on the fisheries, water properties, and atmospheric circulation of countries surrounding the North Pacific Ocean, they have been the focus of a great amount of observation and research in the past. This article provides a brief review of the dynamical aspects of the observed Kuroshio and Oyashio currents: their origins, their mean flow patterns, and their variability on seasonal-to-decadal time scales. The article consists of two sections, the first focusing on the Kuroshio Current and the second on the Oyashio Current. Due to the vast geographical areas passed by the Kuroshio Current from off the Philippines to far east of Japan (Fig. 1), the first section is divided into three subsections: the region upstream of the Tokara Strait, the region south of Japan, and the Kuroshio Extension region east of the Izu Ridge. As will be become clear, the Kuroshio Current exhibits distinct characteristics in each of these geographical locations owing to the different governing physics.

The Kuroshio Current

Region Upstream of the Tokara Strait

The Kuroshio Current originates east of the Philippine coast where the westward flowing North Equatorial Current (NEC) bifurcates into the northward flowing Kuroshio Current and the southward flowing Mindanao Current. At the sea surface, the NEC bifurcates nominally at 12°N–13°N, although this bifurcation latitude can change interannually from 10°N to 15°N. The NEC's bifurcation tends to migrate to the north in November/December and during El Niño years, and to the south in June/July and during La Niña years. Below the sea surface, the time-mean NEC's bifurcation tends to shift northward with increasing depth. This tendency is due to the fact that the southern limb of the wind-driven subtropical gyre in the North Pacific shifts to the north with increasing depth due to the β-spiral effect.

Branching northward from the NEC as the Kuroshio Current passes across the northern tip of Luzon, it has a mean geostrophic volume transport of ~15 Sv (1 Sverdrup $= 10^6\ \mathrm{m^3\ s^{-1}}$). Seasonally, the Kuroshio transport at this upstream location has a maximum in spring and a minimum in fall. Similar seasonal cycles are also found in the Kuroshio's transports in the East China Sea and across the Tokara Strait.

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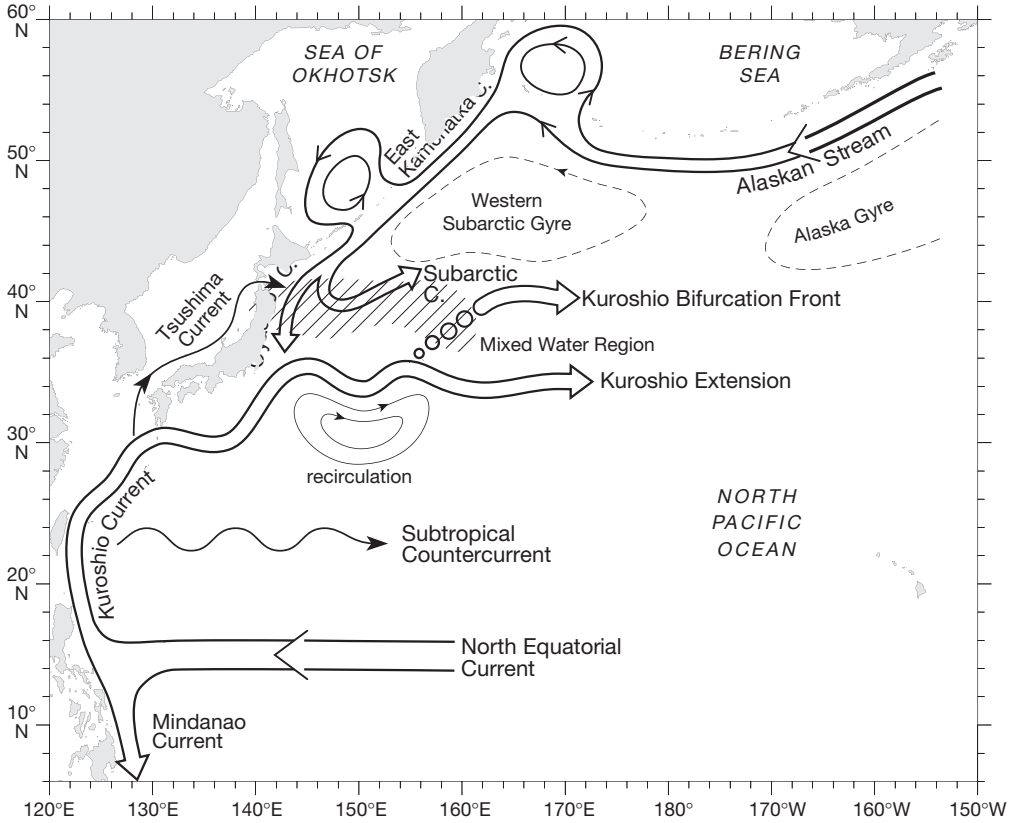

Fig. 1 Schematic current patterns associated with the subtropical and subarctic gyres in the western North Pacific Ocean.

As the Kuroshio Current flows northward passing the Philippine coast, it encounters the Luzon Strait that connects the South China Sea with the open Pacific Ocean (Fig. 2). The Luzon Strait has a width of 350 km and is 2500 m deep at its deepest point. In winter, part of the Kuroshio water has been observed to intrude into the Luzon Strait and form a loop current in the northern South China Sea (see the *dashed line* in Fig. 2). The loop current can reach as far west as 117°E, where it is blocked by the shallow shelf break off the southeast coast of mainland China. The formation of the loop current is likely due to the northeast monsoon, prevailing from November to March, which deflects the surface Kuroshio water into the northern South China Sea. During the summer months from May to September when the southwest monsoon prevails, the Kuroshio Current passes the Luzon Strait without intrusion.

In the latitudinal band east of Luzon and Taiwan (18°N–25°N), the northward flowing Kuroshio Current has been observed to be highly variable. Repeat hydrographic and moored current meter measurements show that the variability of the Kuroshio path and transport here are dominated by fluctuations with a period of ~100 days. These observed fluctuations are caused by impinging energetic cyclonic and anticyclonic eddies migrating from the east. The 18°N–25°N latitudinal band in the western North Pacific is where one finds the Subtropical Countercurrent (STCC). The STCC, a shallow eastward flowing current, is highly unstable due to its velocity shear with the underlying, westward flowing NEC. The unstable waves generated by the instability of the STCC-NEC system tend to move westward while growing in amplitude. The cyclonic and anticyclonic eddies that impinge upon the Kuroshio east of Luzon–Taiwan are results of these large-amplitude unstable waves. Indeed, satellite measurements of the sea level (Fig. 3) reveals that the Kuroshio east of Luzon–Taiwan has higher eddy variability than either its upstream counterpart along the Philippine coast or its downstream continuation in the East China Sea.

North of 24°N, the Kuroshio Current enters the East China Sea through the passage between Taiwan and Iriomote Island. In the East China Sea, the Kuroshio path follows closely along the steep continental slope. Across the PN-line in the East China Sea (see Fig. 2 for its location), repeat hydrographic surveys have been conducted on the quarterly basis by the Japan Meteorological Agency since mid 1950s. Based on the measurements from 1971 to 2017, the volume transport of the Kuroshio across this section has a mean of 28.0 Sv and a seasonal cycle with 28.3 Sv in winter, 28.5 Sv in spring, 28.3 Sv in summer, and 26.7 Sv in fall, respectively (Fig. 4). In addition to this seasonal signal, large transport changes on longer interannual and decadal timescales are also detected across this section.

Although the main body of the Kuroshio Current in the East China Sea is relatively stable due to the topographic constraint, large-amplitude meanders are frequently observed along the density front of the Kuroshio Current. The density front marks the shoreward edge of the Kuroshio Current and is located nominally along the 200 m isobath in the East China Sea. The frontal meanders commonly originate along the upstream Kuroshio front northeast of Taiwan and evolve rapidly while propagating

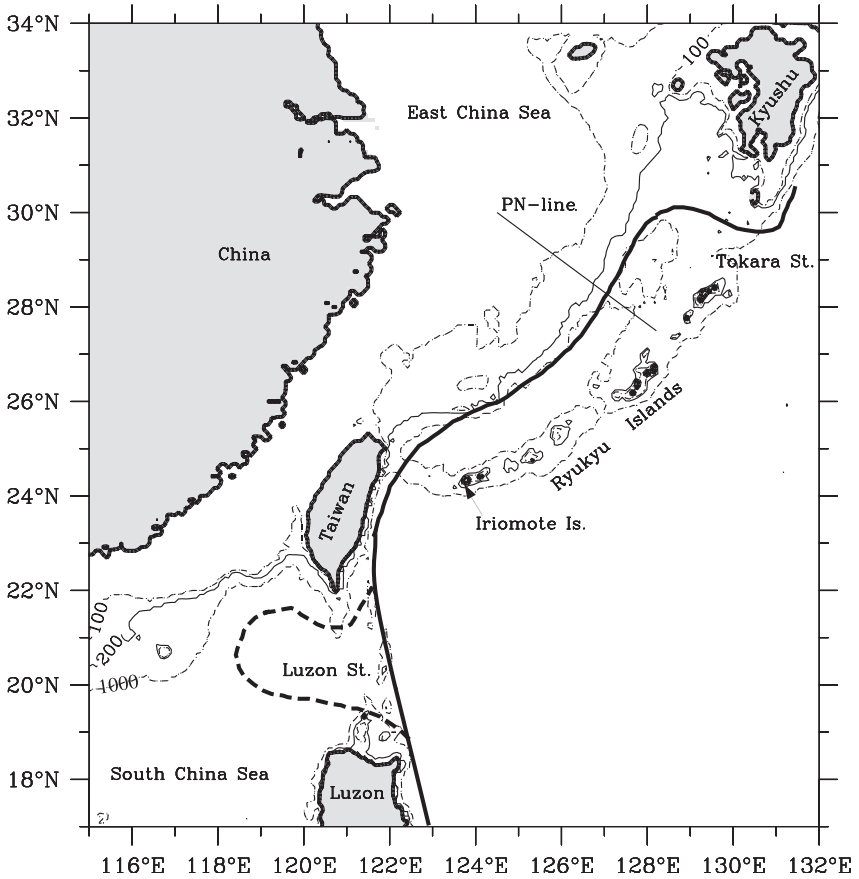

Fig. 2 Schematic of the mean Kuroshio path (the *solid thick line*) along the North Pacific western boundary. The *thick dashed line* south of Taiwan denotes the winter-time branching of the Kuroshio water into the Luzon Strait in the form of a loop current. PN-line denotes the repeat hydrographic section across which long-term Kuroshio volume transport is monitored (Fig. 4). Selective isobaths of 100, 200, and 1000 m are depicted.

downstream. The frontal meanders have typical wavelengths of 200–350 km, wave periods of 10–20 days, and downstream phase speeds of 10–25 cm s^{-1}. When reaching the Tokara Strait, the fully-developed frontal meanders can shift the path of the Kuroshio Current in the strait by as much as 100 km.

Around 128°E–129°E and 30°N, the Kuroshio Current detaches from the continental slope and veers to the east toward the Tokara Strait. This area is where part of the Kuroshio water is observed to intermittently penetrate northward onto the continental shelf to feed the Tsushima Current. The frontal meanders of the Kuroshio, as described above, are important for the mixing and water mass exchanges between the cold, fresh continental shelf water and the warm, saline Kuroshio water along the shelf break of the East China Sea. It is this mixture of the water that forms the origin of the Tsushima Current. The volume transport of the Tsushima Current is estimated at 2 Sv.

Region South of Japan

The Kuroshio Current enters the deep Shikoku Basin through the Tokara Strait. Combined surface current and hydrographic observations show that the Kuroshio's volume transport through the Tokara Strait is about 30 Sv. Inference of transport from the sea level measurements suggests that the Kuroshio's transport across the Tokara Strait is maximum in spring/summer and minimum in fall, a seasonal cycle similar to that found in the upstream Kuroshio Current. Further downstream, offshore of Shikoku, the volume transport of the Kuroshio has a mean value of 55 Sv. This transport increase of the Kuroshio in the deep Shikoku Basin is in part due to the presence of an anticyclonic recirculation gyre south of the Kuroshio. Subtracting the contribution from this recirculation reduces the mean eastward transport to 42 Sv. Notice that this "net" eastward transport of the Kuroshio is still larger than its inflow transport through the Tokara Strait. This increased transport, ~12 Sv, is likely supplied by the northeastward flowing current, known as the Ryukyu Current that has been observed along the eastern flank of the Ryukyu Islands. Near 139°E, the Kuroshio Current encounters the meridionally-oriented Izu Ridge. Due to the shallow northern section of the ridge, the Kuroshio Current exiting the Shikoku Basin is restricted to pass through the Izu Ridge to either around 34°N where there is a deep passage, or south of 33°N where the ridge height drops (see Fig. 5).

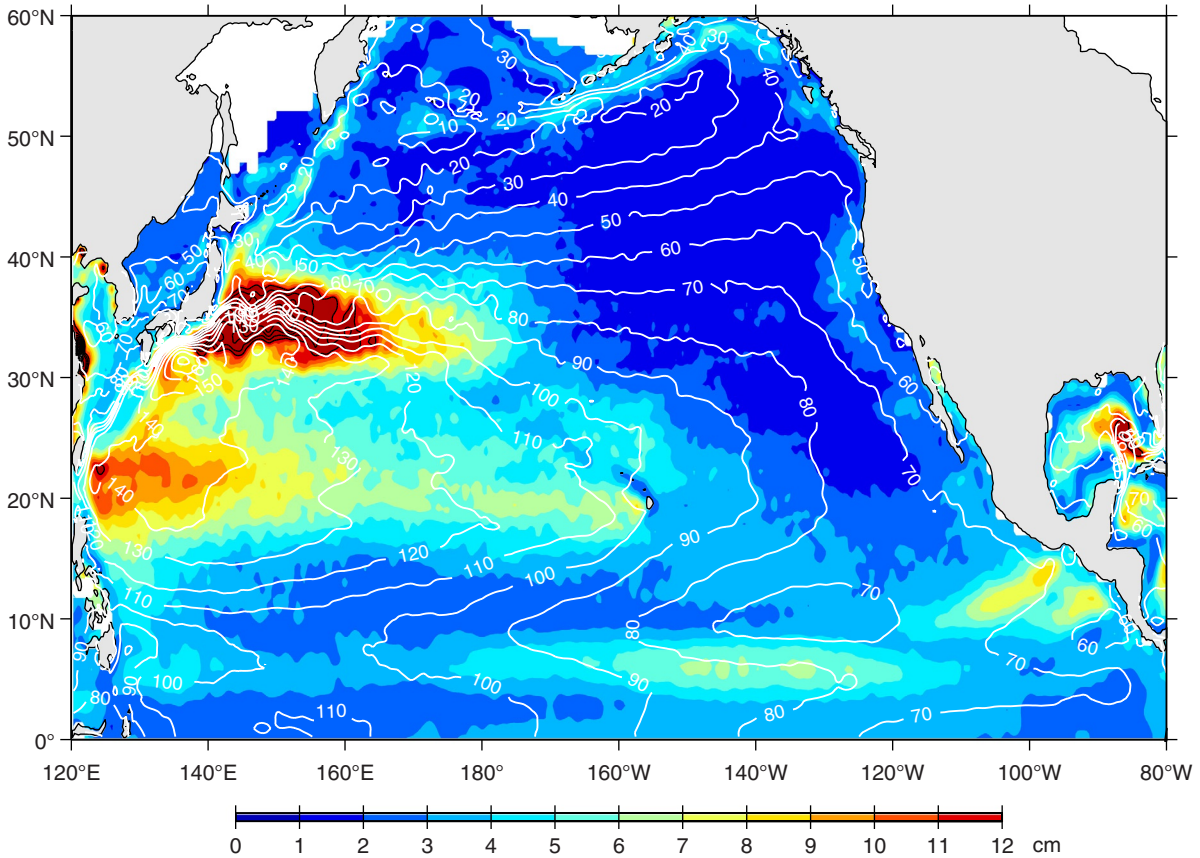

Fig. 3 Map of the root-mean-square sea surface height variability in the North Pacific Ocean, based on satellite altimetric measurements from October 1992 to June 2012. Regions where the rms SSH variability exceeds 12 cm are indicated by *black* contours with a contour interval at 2 cm. *White contours* denote the mean SSH field with unit in centimeter. Adapted with permission from Qiu, B. and Chen, S. (2013). Concurrent decadal mesoscale eddy modulations in the western North Pacific subtropical gyre. *Journal of Physical Oceanography* **43**, 344–358.

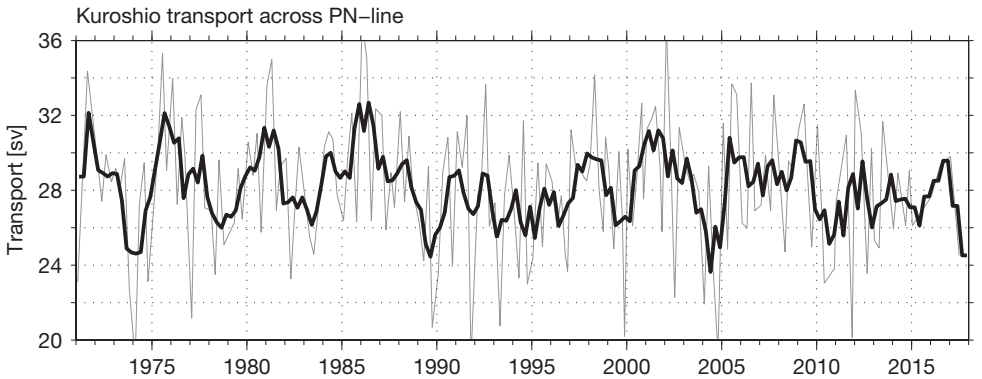

Fig. 4 Time series of the geostrophic volume transport of the Kuroshio across the PN-line in the East China Sea (see Fig. 2 for its location). Here, the volume transport is calculated by integrating northeastward geostrophic flows referenced to 700-dbar depth from 28°42′N, 126°27′E to 27°30′N, 128°15′E. *Solid thick line* shows the low-pass filtered time series after a 12-month running-mean average. Data courtesy of Dr. T. Nakano of Japan Meteorological Agency.

On interannual timescales, the Kuroshio Current south of Japan is known for its bimodal path fluctuations. The "straight path," shown schematically by path A in Fig. 5, denotes when the Kuroshio flows closely along the Japan coast. The "large-meander path," shown by path B in Fig. 5, signifies when the Kuroshio takes a detouring offshore path. In addition to these two stable paths, the Kuroshio may take a third, relatively stable path that loops southward over the Izu Ridge. This path, depicted as path C in Fig. 5, is commonly observed during transitions from a meandering state to a straight-path state. Fig. 6 shows the time series of southernmost

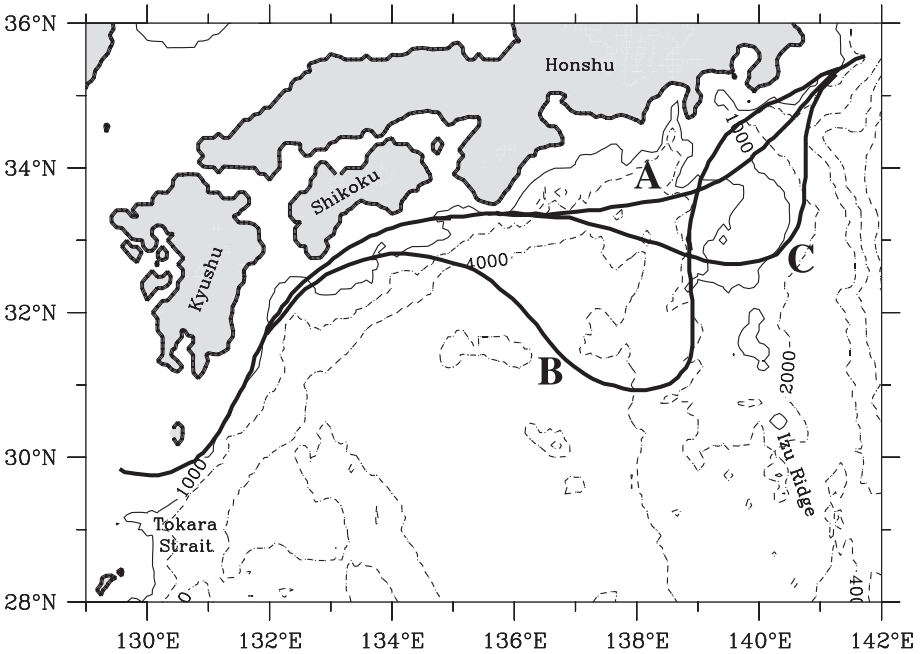

Fig. 5 Schematic stable paths of the Kuroshio Current south of Japan. Selective isobaths of 1000, 2000, 4000, 6000, and 8000 m are included. Adapted with permission from Kawabe, M. (1985). Sea level variations at the Izu Islands and typical stable paths of the Kuroshio. *Journal of the Oceanography Society of Japan* **41**, 307–326.

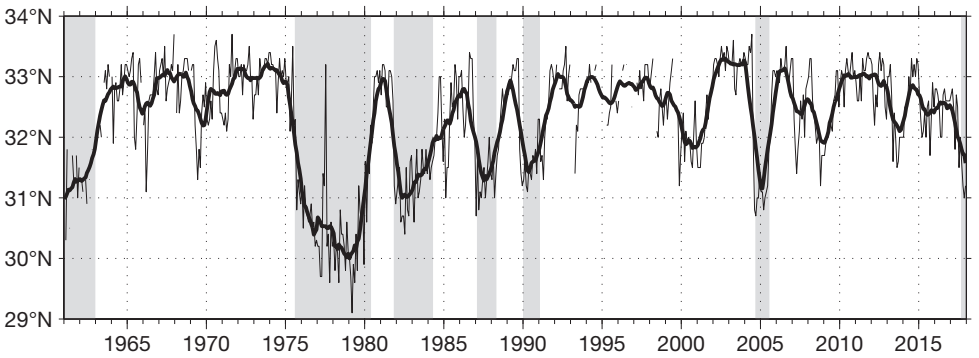

Fig. 6 Time series of the monthly averaged southernmost latitude of the Kuroshio Current south of Japan compiled by Japan Meteorological Agency. *Solid thick line* shows the low-pass filtered time series after a 13-month running-mean average. *Shaded periods* with latitude <32.2°N denote the large meander state of the Kuroshio south of Japan.

latitude of the Kuroshio path between 136°E and 140°E south of Japan. A low (high) value in Fig. 6 denotes an offshore large-meander path (a straight path) of the Kuroshio. From 1961 to 2017, the Kuroshio large-meanders occurred in 1961–62, 1975–79, 1982–83, 1987–88, 1990, and 2004–05. After a dormant period of 12 years, a new large-meander is currently underway since August 2017. Clearly, the large-meanders occurrence is highly aperiodic. Once formed, the meander state can persist over a period ranging from 1 to 5 years. In contrast, transitions between the meander and straight-path states are rapid, often completed over a period of several months. It is worth noting that development of the large-meanders is often preceded by the appearance of a small meander south of Kyushu, which migrates eastward and becomes stationary after reaching 136°E.

Several mechanisms have been proposed to explain the bimodal path variability of the Kuroshio south of Japan. Most studies have examined the relationship between the Kuroshio's path pattern and the changes in magnitude of the Kuroshio's upstream transport. Earlier studies of the Kuroshio path bimodality interpreted the meandering path as a stationary Rossby lee wave generated by the protruding coastline of Kyushu. With this interpretation, the Kuroshio takes a meander (straight) path when the upstream transport is small (large). By taking into account the realistic inclination of the Japan coast from due east, more recent studies have provided the following explanation. When the upstream transport is small, the straight path is stable as a result of the planetary vorticity acquired by the northeastward flowing Kuroshio being balanced by the eddy dissipation along the coast. When the

upstream transport is large, positive vorticity is excessively generated along the Japan coast, inducing the meander path to develop downstream. In the intermediate transport range, the Kuroshio is in a multiple equilibrium state in which meandering and straight paths coexist. Transitions between the two paths in this case are determined by perturbations in the upstream transport (e.g., transition from a straight to meandering path requires an increased upstream transport).

A comparison between the Kuroshio path variation (Fig. 6) and the Kuroshio's transport in the upstream East China Sea (Fig. 4) shows that the 1975–79 large-meander event does correspond to a large upstream transport. This correspondence, however, becomes less obvious after 1980, as there were times when the upstream transport was large, but no large-meander was present (e.g., 1980–81 and 1985–86). Assuming that the upstream Kuroshio transport after 1980 is in the multiple equilibrium regime, the correspondence between the path transition and the temporal change in the upstream transport (e.g., the required transport increase for the transition from a straight to meandering path) is also inconclusive from the time series presented in Figs. 4 and 6. Given the turbulent and irregular nature of the Kuroshio path changes, future studies based on longer transport measurements are needed to further clarify the physics underlying the Kuroshio path bimodality.

Downstream Extension Region

After separating from the Japan coast at 140°E and 35°N, the Kuroshio enters the open basin of the North Pacific Ocean where it is renamed the Kuroshio Extension (KE). Free from the constraint of coastal boundaries, the KE has been observed to be an eastward-flowing inertial jet accompanied by large-amplitude meanders and energetic pinched-off eddies. Fig. 7 shows the mean temperature map at the 300 m depth, in which the axis of the KE is well represented by the 12°C isotherm. An interesting feature of the KE east of Japan is the existence of two quasistationary meanders with their ridges located at 144°E and 150°E, respectively. The presence of these meanders along the mean KE path has been interpreted as standing Rossby lee-waves generated by the presence of the Izu Ridge. A competing theory also exists that regards the quasistationary meanders as being steered by the eddy-driven abyssal mean flows resulting from instability of the KE jet.

Near 159°E, the KE encounters the Shatsky Rise where it often bifurcates. The main body of the KE continues eastward, and a secondary branch, commonly known as the Kuroshio Bifurcation Front (Fig. 1), tends to extend northeastward to 40°N, where it joins the eastward moving Subarctic Current. After overriding the Emperor Seamounts along 170°E, the mean path of the KE becomes broadened and instantaneous flow patterns often show a multiple-jet structure associated with the eastward flowing KE. East of the dateline, the distinction between the KE and the Subarctic Current is no longer clear, and together they form the broad, eastward moving North Pacific Current.

As demonstrated in Fig. 3, the KE region has the highest level of eddy variability in the North Pacific Ocean. From the viewpoint of wind-driven ocean circulation, this high eddy variability is to be expected. Being a return flow compensating for the wind-driven subtropical interior circulation, the Kuroshio originates at a southern latitude where the ambient potential vorticity (PV) is relatively low. For the Kuroshio to smoothly rejoin the Sverdrup interior flow at the higher latitude, the low PV acquired by the Kuroshio in the south has to be removed by either dissipative or nonlinear forces along its western boundary path. For the narrow and swift Kuroshio Current, the dissipative force is insufficient to remove the low PV anomalies. The Kuroshio's inability to effectively diffuse the PV anomalies along its path results in the accumulation of low PV water in its extension region, which generates an anticyclonic recirculation gyre and provides an energy source for flow instability. Due to the presence of the recirculation gyre, the eastward volume transport of the KE can reach as high as 130 Sv southeast of Japan. This is more than twice the maximum Sverdrup transport of about 60 Sv in the subtropical North Pacific.

In addition to the high mesoscale eddy variability, the KE also exhibits dynamical state changes on decadal timescales. Fig. 8 shows the semimonthly KE paths from 1993 to 2016 based on satellite altimeter measurements. The KE paths were relatively stable in 1993–95, 2002–05, and 2010–16. In contrast, spatially convoluted paths prevailed during 1996–2001 and 2006–09. When the KE jet is in a stable dynamical state, satellite altimeter data further reveal that its eastward transport and latitudinal position tend to

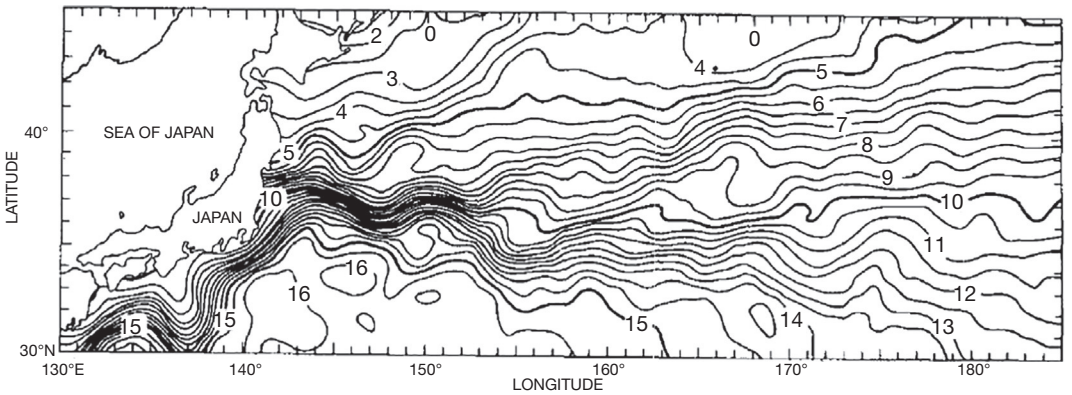

Fig. 7 Mean temperature map (°C) at the 300 m depth from 1976 to 1980. Adapted with permission from Mizuno, K. and White, W.B. (1983). Annual and interannual variability in the Kuroshio Current System. *Journal of Physical Oceanography* **13**, 1847–1867.

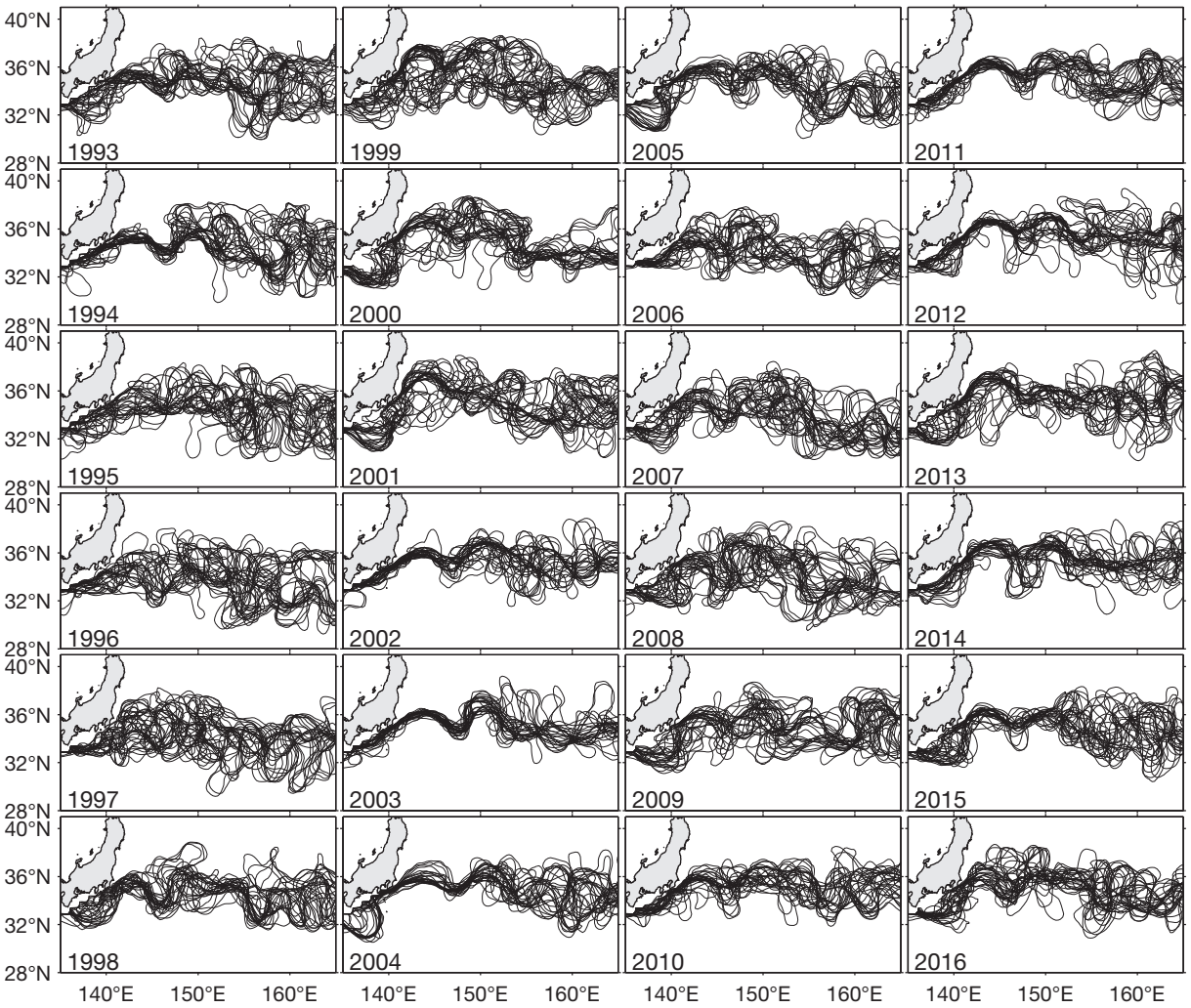

Fig. 8 Yearly Kuroshio and Kuroshio Extension paths from 1993 to 2016 based on multimission satellite altimetry measurements. Paths are plotted every 14 days. Adapted with permission from Qiu, B. and Chen, S. (1995). Variability of the Kuroshio Extension jet, recirculation gyre and mesoscale eddies on decadal timescales. *Journal of Physical Oceanography* **35**, 2090–2103.

increase and migrate northward, its southern recirculation gyre tends to strengthen, and the regional eddy kinetic energy level tends to decrease. The reverse is true when the KE jet switches to an unstable dynamical state. In fact, the time-varying dynamical state of the Kuroshio Extension system can be well represented by the KE index, defined by the average of the variance-normalized time series of the southern recirculation gyre intensity, the KE jet intensity, its latitudinal position, and negative of its path length. Fig. 9A shows the KE index time series in the 1993–2017 period; here, a positive KE index indicates a stable dynamical state and a negative KE index, an unstable dynamical state. Consistent with Fig. 8, it is easy to discern from Fig. 9A the dominance of decadal oscillations between the two dynamical states of the KE system.

Transitions between the KE's dynamical states are caused by the basin-scale wind stress curl forcing in the eastern North Pacific related to the Pacific decadal oscillations (PDOs). Specifically, when the central North Pacific wind stress curl anomalies are positive during the positive PDO phase (Fig. 9C), enhanced Ekman flux divergence generates negative local sea surface height (SSH) anomalies in 170°W–150°W along the southern RG latitude of 32°N–34°N. As these wind-induced negative SSH anomalies propagate westward as baroclinic Rossby waves into the KE region after a delay of 3–4 years (Fig. 9B), they weaken the zonal KE jet, leading to an unstable (i.e., negative index) state of the KE system with a reduced recirculation gyre and an active eddy kinetic energy field. Negative anomalous wind stress curl forcing during the negative PDO phase, on the other hand, generates positive SSH anomalies through the Ekman flux convergence in the eastern North Pacific. After propagating into the KE region in the west, these anomalies stabilize the KE system by increasing the KE transport and by shifting its position northward, leading to a positive index state.

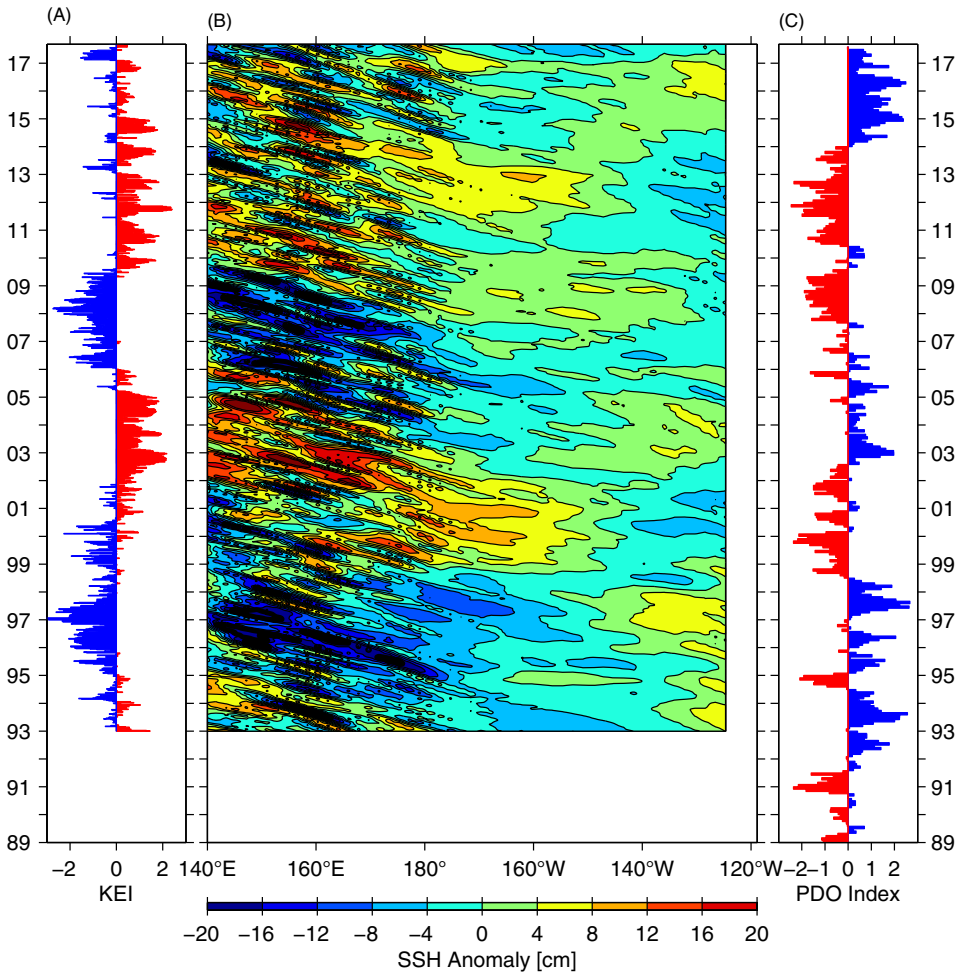

Fig. 9 (A) Time series of the Kuroshio Extension index; available at http://www.soest.hawaii.edu/oceanography/bo/KE_index.asc. (B) Sea surface height anomalies along the zonal band of 32°N–34°N from satellite altimetry measurements. (C) Time series of the Pacific Decadal Oscillation (PDO) index from http://jisao.washington.edu/pdo/PDO.latest.

The Oyashio Current

Due to the southward protrusion of the Aleutian Islands, the wind-driven subarctic circulation in the North Pacific Ocean can be largely divided into two cyclonic subgyres: the Alaska Gyre to the east of the dateline and the Western Subarctic Gyre to the west (Fig. 1). To the north, these two subgyres are connected by the Alaskan Stream, which flows southwestward along the Aleutian Islands as the western boundary current of the Alaska Gyre. Near the dateline, the baroclinic volume transport of the Alaskan Stream in the upper 3000 m layer is estimated at about 15–20 Sv. As the Alaskan Stream flows further westward, the deep passages between 168°E and 172°E along the western Aleutian Islands allow part of the Alaskan Stream to enter the Bering Sea. In the deep part of the Bering Sea, the intruding Alaskan Stream circulates cyclonically and forms the Bering Sea Gyre. The western limb of the Bering Sea Gyre becomes the East Kamchatka Current, which flows southwestward along the east coast of the Kamchatka Peninsula. The remaining part of the Alaskan Stream continues westward along the southern side of the Aleutian Islands and upon reaching the Kamchatka Peninsula, it rejoins the East Kamchatka Current as the latter exits the Bering Sea.

As the East Kamchatka Current continues southwestward and passes along the northern Kuril Islands, some of its water permeates into the Sea of Okhotsk. Inside the deep Kuril Basin in the Sea of Okhotsk, the intruding East Kamchatka Current water circulates in a cyclonic gyre. Much of this intruding water moves out of the Sea of Okhotsk through the Bussol Strait (46.5°N, 151.5°E), where it rejoins the rest of the southwestward flowing East Kamchatka Current. The East Kamchatka Current is renamed the Oyashio Current south of the Bussol Strait. Because of the intrusion in the Sea of Okhotsk, the water properties of the Oyashio Current are different from those in the upstream East Kamchatka Current. For example, the mesothermal water present in the East Kamchatka Current (i.e., the subsurface maximum temperature water appearing in the halocline at a depth of 150–200 m) is no

longer observable in the Oyashio. While high dissolved oxygen content is confined to above the halocline in the upstream East Kamchatka Current, elevated dissolved oxygen values can be found throughout the upper 700 m depth of the Oyashio water.

The baroclinic volume transport of the Oyashio Current along the southern Kuril Islands and off Hokkaido has been estimated at 5–10 Sv from the geostrophic calculation with a reference level of no-motion at 1000 or 1500 m. Combining moored current meter and CTD (conductivity-temperature-depth) measurements, more recent observations along the continental slope southeast of Hokkaido show that the Oyashio Current has a well-defined annual cycle: the flow tends to be strong, reaching from surface to bottom, in winter/spring, and it is weaker and confined to the layer shallower than 2000 m in summer and fall. The total (baroclinic + barotropic) volume transport reaches 20–30 Sv in winter and spring, whereas it is only 3–4 Sv in summer and fall. This annual signal in the Oyashio's total transport is in agreement with the annual signal in the Sverdrup transport of the wind-driven North Pacific subarctic gyre.

After flowing southwestward along the coast of Hokkaido, the Oyashio Current splits into two paths. One path veers offshoreward and contributes to the east-northeastward flowing Subarctic Current. This path can be recognized in Fig. 7 by the eastward-veering isotherms along 40°N southeast of Hokkaido. Because the Oyashio Current brings subarctic-origin water southward, the Subarctic Current is accompanied by a distinct temperature-salinity front between cold, fresher water to the north and warm, saltier subtropical-origin water to the south. This water mass front, referred to as the Oyashio Front or the Subarctic Front, has indicative temperature and salinity values of 5°C and 33.8 psu at the 100 m depth.

The second path of the Oyashio Current continues southward along the east coast of Honshu and is commonly known as the first Oyashio intrusion. Averaged seasonally, the first Oyashio intrusion as defined by the 5°C isotherms at 100 m depth, reaches its southernmost latitude of 38.5°N in April and retreats to its northernmost latitude of 41.5°N in December. This seasonal migration is likely controlled by the seasonally fluctuating Aleutian Low pressure system via barotropic adjustment across the subarctic North Pacific Ocean. In contrast to this climatological seasonal migration, the first Oyashio intrusion east of Honshu can also change drastically on the interannual and longer timescales. For example, Fig. 10 shows that the first Oyashio intrusion in April 1984 penetrated to a latitude as far south as 36.5°N; in comparison to this anomalous southward intrusion, the 5°C Oyashio water barely reached 39°N in April 1990.

Fig. 11 shows the long-term time series of the first Oyashio intrusion from 1971 to 2017 compiled by the Japan Meteorological Agency. Large-amplitude fluctuations with multiple timescales are clearly discernible. In particular, a poleward-shifting linear trend at 0.029°lat./year stands out. For the cause of low-frequency changes of the first Oyashio intrusion, it has been sought traditionally in the intensity and position changes in the Aleutian Low pressure system. For example, it has been argued that the intensification of the Aleutian Low pressure system and its southward shift have resulted in an anomalous southward intrusion by the Oyashio from the 1970s to 1980s. After 1990s, the first Oyashio intrusion exhibits interestingly more variance on the decadal timescales (Fig. 11). These decadal variations are likely related to the changes in the dynamical state of the Kuroshio Extension system. Specifically, when the KE system is in its unstable state with a negative KE index in Fig. 9A, increased poleward heat transport carried by the unstable KE jet and mesoscale eddies can work to mitigate the southward intrusion by the Oyashio. The reverse is true when the KE system switches to a stable state. It is worth noting that the anomalous southward intrusion of the Oyashio Current not only influences the hydrographic conditions east of Honshu, it also affects the environmental conditions in the fishing ground and the regional climate; for example, an anomalous southward intrusion tends to decrease the air temperature over eastern Japan.

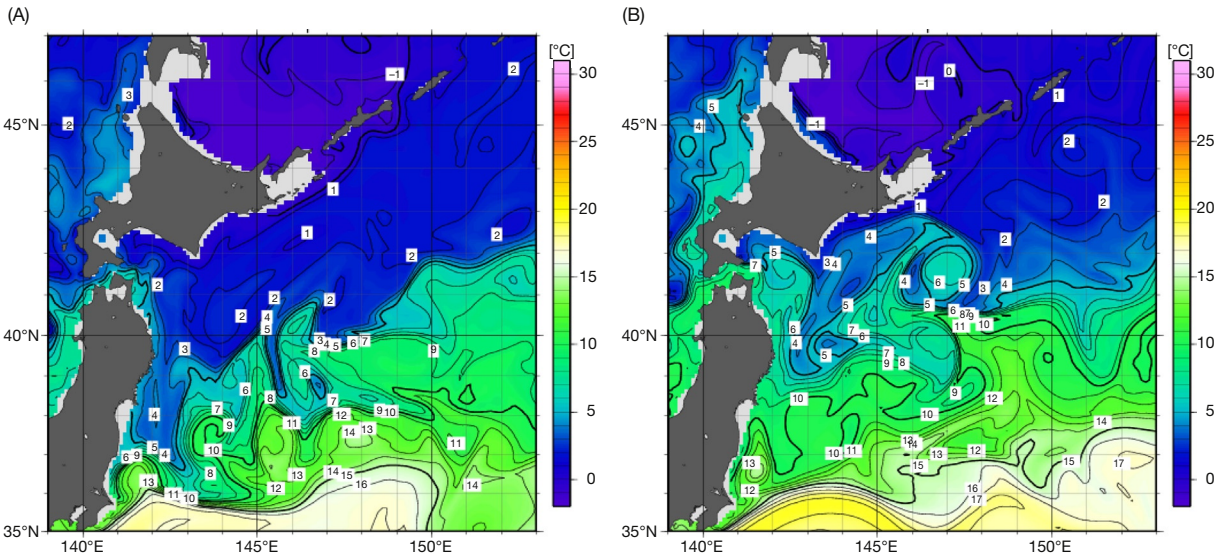

Fig. 10 Water temperature maps at the 100 m depth on (A) 1–10 April 1984 versus (B) 1–10 April 1990 compiled by the Japan Meteorological Agency. Contour interval is 1°C. The first Oyashio intrusion is represented by the 5°C isotherms east of Honshu.

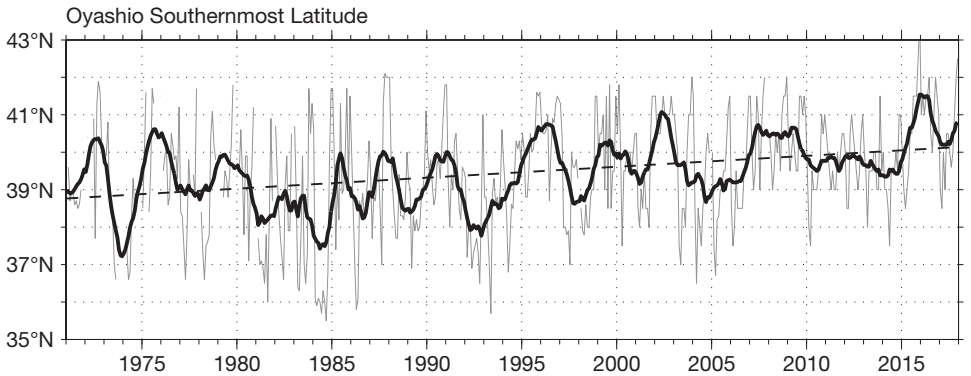

Fig. 11 Time series of the monthly averaged southernmost latitude of the first Oyashio intrusion east of Honshu. The southernmost latitude is defined by the 5°C isotherm south of 43°N and west of 148°E. *Solid thick line* shows the low-pass filtered time series after a 12-month running-mean average and *black dashed line* show the linear poleward-shifting trend of 0.029° lat./year. Data courtesy of Dr. T. Nakano of Japan Meteorological Agency.

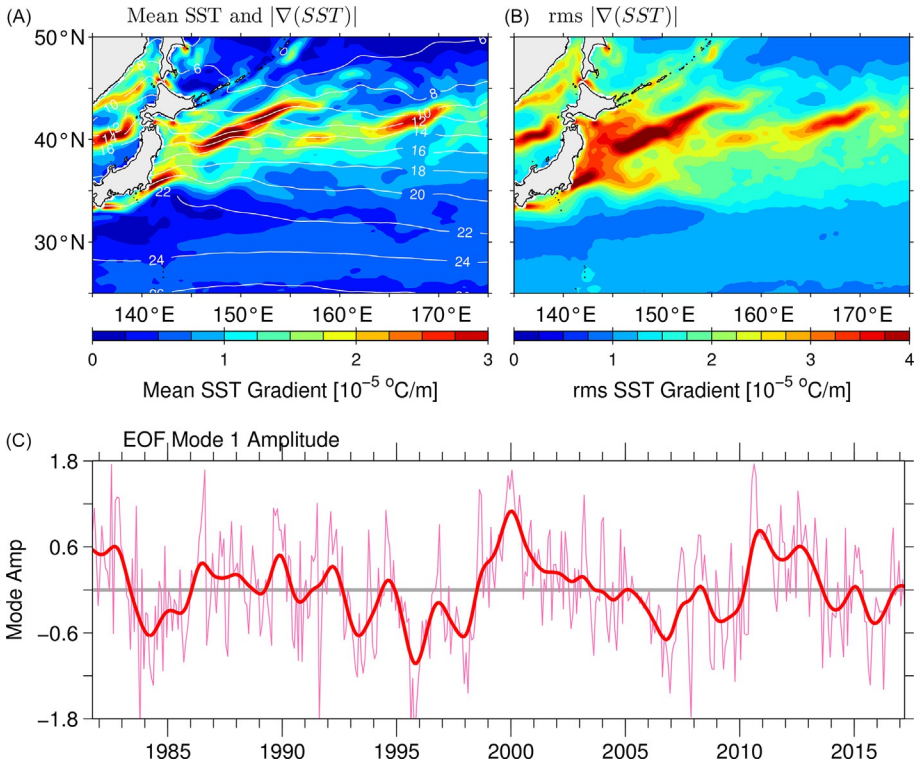

Fig. 12 (A) Mean sea surface temperature (SST) field (*white* contours) surrounding the Kuroshio and Oyoshio Extension region in 1982–2016. *Color shades* indicate magnitude of the horizonal SST gradient. (B) Root-mean-squared amplitude of the time-varying SST gradient during 1982–2016. (C) Time variability in latitudinal position of the maximum SST gradient between 153°E–173°E. *Thin line* denotes the monthly time series and *thick line*, the time series after a Gaussian low-pass filtering that has half-power at 4 months. Adapted with permission from Qiu, B., Chen, S. and Schneider, N. (2017). Dynamical links between the decadal variability of the Oyashio and Kuroshio Extensions. *Journal of Climate* **30**, 9591–9605.

After the Oyashio Current veers east-northeastward to feed the Subarctic Current near 150°E, its temperature front deviates from due east. Within the 38°N–43°N band off Japan, Fig. 7 reveals that another strengthened temperature front emerges east of 153°E. This downstream subarctic temperature front is aligned east-northeastward, parallel to the Subarctic Current. A look at the regional sea surface temperature (SST) gradient and its variance maps east of Japan (Fig. 12A and B) indicates that these two parallel temperature fronts have their respective, locally enhanced fluctuations. Dynamically, the downstream subarctic temperature front is connected to the Kuroshio Bifurcation Front and extends zonally to beyond 170°E. Fig. 12C shows the dominant changes from 1982 to 2017 in the meridional position of the downstream subarctic front based on an empirical orthogonal function (EOF) analysis. A positive value in Fig. 12C indicates a northward-migrated and intensified temperature front. The prominent decadal

changes seen in Fig. 12C are caused in part by the decadal dynamical state changes of the KE system. When the KE system is in a stable (unstable) phase, its increased (decreased) zonal transport and northerly (southerly) position favor a poleward (equatorward) shift of the Kuroshio Bifurcation Front and, by continuation, the downstream subarctic front. In addition to the influence from the KE of the subtropical origin, the decadal downstream subarctic front changes in Fig. 12C are equally affected by the circulation changes forced remotely by the surface wind forcing within the North Pacific subarctic gyre. For the decadal timescale variability, it can be shown that the influences from the KE and the subarctic gyre wind forcing reinforce each other and generate in-phase fluctuations along the downstream subarctic front.

Concluding Remarks

Because the Kuroshio and Oyashio currents transport large amounts of water and heat efficiently in the meridional direction, there is a heightened interest in recent years in understanding the dynamic roles played by the time-varying Kuroshio and Oyashio currents in influencing the midlatitude air-sea interaction and atmospheric storm-tracks through sea surface temperature anomalies. Indeed, outside the eastern equatorial Pacific Ocean, the largest SST variability on the interannual-to-decadal timescales in the North Pacific resides in the Kuroshio Extension and the Oyashio outflow regions. Large-scale changes in the Kuroshio and Oyashio current systems can affect the sea surface temperature anomaly field through warm/cold water advection, upwelling through the base of mixed layer, and changes in the current paths and level of mesoscale eddy variability. At present, much of our understanding about the Kuroshio and Oyashio variability was based on sustained observations of the past three decades. With the accumulation of forth-coming observations, we can expect improved description of the Kuroshio and Oyashio current systems, especially of their roles in the mid-latitude ocean-atmosphere interaction and the long-term climate variability.

Further Reading

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