# Biogeochemistry of the Kuroshio Large Meander

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#### Abstract

The large meander of the Kuroshio western boundary current is well known to influence the local climate, fisheries, and aquaculture by greatly modulating regional heat transport, but its impacts on biogeochemical processes remain unclear. Using high-resolution numerical ocean modelling and long-term observational datasets, we show that the path of the Kuroshio determines the extent of the shallow nutricline region, where winter convective mixing replenishes nutrient availability for subsequent blooms of phytoplankton during spring. During the large meander phase, this mechanism triggers offshore phytoplankton blooms that are otherwise absent during the non-large meander phase. The large meander also modulates the spatial distributions of primary production, air-sea carbon flux, and export production. These biogeochemical impacts of the Kuroshio large meander exert bottom-up control on regional marine ecosystems that is disproportionate to the thermal effect, and therefore need to be assessed to understand the large meander's overall impacts on fisheries and aquaculture.

#### 1 2

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### 12 Key Points:

- The Kuroshio large meander (LM) expands the nutrient-rich surface water south of Japan
   further offshore during winter.
- During LM, phytoplankton spring blooms increase offshore due to nutrient enrichment
   and decrease nearshore due to nutrient reduction.
- In addition to thermal disturbance, the biogeochemical impacts of the large meander exert
   bottom-up control on higher trophic levels.

#### 19 Abstract

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- 21 local climate, fisheries, and aquaculture by greatly modulating regional heat transport, but its
- 22 impacts on biogeochemical processes remain unclear. Using high-resolution numerical ocean
- 23 modelling and long-term observational datasets, we show that the path of the Kuroshio
- 24 determines the extent of the shallow nutricline region, where winter convective mixing
- 25 replenishes nutrient availability for subsequent blooms of phytoplankton during spring. During
- the large meander phase, this mechanism triggers offshore phytoplankton blooms that are
- otherwise absent during the non-large meander phase. The large meander also modulates the
- 28 spatial distributions of primary production, air-sea carbon flux, and export production. These
- 29 biogeochemical impacts of the Kuroshio large meander exert bottom-up control on regional
- 30 marine ecosystems that is disproportionate to the thermal effect, and therefore need to be
- assessed to understand the large meander's overall impacts on fisheries and aquaculture.

#### 32 Plain Language Summary

33 The Kuroshio is one of the world's most powerful ocean currents that regulates the global

- distribution of heat, salt, and chemical elements by transporting a significant amount of seawater
- from one region to another. The Kuroshio generally travels along the southern coast of Japan, but
- from time to time, it deflects its pathway further south, often by more than 300 km. This
- deflection is known as the Kuroshio large meander, which has been discovered to have impacts
- 38 on the weather, fisheries, and aquaculture in Japan. These impacts have been attributed to the
- <sup>39</sup> large meander's ability to displace the heat distribution. However, the large meander's impact is
- 40 beyond just heat, and so we need to understand what happens to other oceanic properties during
- 41 the large meander, in order to understand its overall impact. In this study, we used a computer
- 42 ocean model to simulate long large meander periods to characterize the impacts of the large
- 43 meander on marine biogeochemistry. The results show that the large meander displaces the
- 44 locations of high and low nutrient, which fuels phytoplankton to bloom in areas where they will
- not be able to otherwise. Understanding such changes is essential for better understanding the
- 46 impacts on fish.

### 47 **1 Introduction**

- 48 The Kuroshio, which means *black current* in Japanese, is one of the strongest currents in the
- 49 ocean that has significant impacts on the global climate system and local marine industries.
- 50 Among the western boundary currents, the Kuroshio is unique in that its main path can be
- characterized by two stable states that it switches between on a timescale of a few years to a few
- 52 decades (Kawabe, 1987). One of the these states takes the path that travels nearshore along the
- southern coast of Japan, which we refer to as the non-large meander. The other stable state,
- 54 which is the main focus of this study, is the path that is deflected offshore south of the Tokai
- region, and is referred to as the large meander. As the Kuroshio is rapid and carries a huge

- amount of water mass along with heat and materials in the ocean, the path of the Kuroshio is
- 57 important for shipping, commercial fishing, and fish farming.

58 Since August 2017, the Kuroshio has been taking the large meander path. In April 2022, this

<sup>59</sup> large meander event has lasted for 4 years and 9 months, which has become the longest ever

60 recorded large meander since a consistent observation by the Japan Meteorological Agency

started in the 1960s (Qiu & Chen, 2021). The ongoing large meander has received much media

attention in Japan, as it has been revealed to trigger extratropical cyclones with extreme rainfall

- 63 (Hirata et al., 2019; Tochimoto & Iizuka, 2022), cause discomfort in summer over the greater
- Tokyo metropolitan area (Sugimoto et al., 2021), and modify the seasonal abundance and
- distribution of commercial fish (Chang et al., 2019; Zhu et al., 2021). All these reported impacts
- have been linked to the large meander's influence on physical conditions such as temperature,
- but obviously the large meander modulates other processes such as biogeochemistry. For
- example, nutrient and phytoplankton abundance can exert bottom-up control on the marine food

69 web, which may have impacts on higher trophic levels such as commercial fish (e.g., Yoneda et

al., 2022). However, such biogeochemical aspects of the larger meander have been explored only

by a few studies (e.g., Lizarbe Barreto et al., 2021; Long et al., 2018), perhaps due to the lack of

- 72 adequate samples to draw robust conclusions.
- 73 In this study, we characterize the biogeochemical impacts of the Kuroshio large meander by
- analyzing the multi-decadal output of a high-resolution global sea ice-ocean model simulation.
- 75 Results reveal robust differences in the spatial distributions of nutrient, phytoplankton, primary
- 76 production, ocean carbon uptake, and export production during the large meander phase
- compared to the non-large meander phase. Using available observations, we show that the
- simulated nutrient results are realistic, which shapes the rest of the biogeochemical quantities.

## 79 **2 Methods**

## 80 2.1 Kuroshio Large Meander Definition

The path of the Kuroshio is considered a large meander when it deflects far south of Japan for a prolonged period. Otherwise, the path is considered non-large meander. There are several indices

to define the large meander, but their time series are generally consistent (Qiu & Chen, 2021).

- 84 Here, the Kuroshio path is defined as a large meander when the southernmost axis of the
- Kuroshio is located south of 32°N in the 136-140°E segment. This definition is one of the two
- criteria for large meander determination used by the Japan Meteorological Agency (Sakajo et al.,
- 87 2022). The other criterion is the sea level difference between Kushimoto and Uragami which is
- disregarded here because these two locations are much closer than the horizontal resolution of
- <sup>89</sup> our model (Section 2.2). The Kuroshio axis is defined as the latitude at which the absolute
- 90 meridional gradient of sea surface height is maximum, which corresponds to the approximate
- 91 location of the fastest zonal geostrophic flow. Using this definition for the Kuroshio axis, we
- 92 define a large meander event when the 13-month central moving average Kuroshio axis is

- 93 located south of 32°N for at least 12 consecutive months. Our definition matches well with the
- past large meander events determined by the Japan Meteorological Agency (Figure A1).
- 95 To assess the model performance in simulating the Kuroshio path variability, we downloaded the
- 96 monthly Kuroshio axis time series produced by the Japan Meteorological Agency
- 97 (<u>https://www.data.jma.go.jp/kaiyou/data/shindan/b\_2/kuroshio\_stream/kuro\_slat.txt;</u> last
- accessed on November 15, 2022). The data provide the southernmost latitude of the Kuroshio in
- the 136-140°E segment from 1961 to 2021 determined based on satellite and hydrographic
- 100 observations (Qiu & Chen, 2021; Sakajo et al., 2022). The data contain several missing values
- 101 during 1961-1968 and 1992-1999 (Figure A1).

### 102 **2.2 Model**

- 103 The global sea ice-ocean coupled numerical model used in this study is the 0.1° version of the
- 104 Australian Community Climate and Earth System Simulator Ocean Model version 2 (ACCESS-
- 105 OM2-01), an updated version of the configuration described by Kiss et al. (2020). The physical
- 106 model is composed of the Modular Ocean Model (MOM) version 5.1 and the Los Alamos sea ice
- 107 model (CICE) version 5.1.2. The biogeochemical model is composed of the Whole Ocean Model
- 108 of Biogeochemistry and Trophic-dynamics (WOMBAT; Oke et al., 2013) and the
- 109 biogeochemistry of CICE (Jeffery et al., 2016). WOMBAT is a phosphorous-based four-
- 110 component (Nutrient-Phytoplankton-Zooplankton-Detritus; NPZD) model with carbonate
- 111 chemistry, dissolved oxygen, and bioavailable dissolved iron (Oke et al., 2013). Phosphate is the
- only macronutrient tracer, and a fixed Redfield ratio of 1:16:106:-172 is assumed with
- 113 phosphorous, nitrogen, carbon, and oxygen. We use the same biogeochemical parameters as
- 114 Ziehn et al. (2020). Although the micronutrient iron can limit the phytoplankton growth, it is not
- 115 the limiting factor for the Kuroshio region (Hayashida et al., 2020), which is supported by
- available observations (Moore et al., 2013). There is no supply of nutrient from river discharge,
- but this effect may be negligible for the nutrient budget in the study region which is further away
- 118 from river mouths (Kuroda et al., 2018).
- In this study, we analyzed the monthly mean output of ACCESS-OM2-01 which was integrated
- 120 for 244 years by prescribing the 61-year (1958-2018) Japanese Atmospheric Reanalysis dataset
- 121 (JRA55-do version 1.4.0; Tsujino et al., 2018) as the surface forcing repeatedly for four times.
- 122 This cyclic procedure follows the protocol of the Ocean Model Intercomparison Project (OMIP;
- 123 Griffies et al., 2016; Tsujino et al., 2020). The ocean model was initialized from rest with zero
- sea level anomaly, and the initial temperature and salinity fields were set to the World Ocean
   Atlas 2013 version 2. The first three cycles were integrated using the physics-only version of
- Atlas 2013 version 2. The first three cycles were integrated using the physics-only version of ACCESS-OM2-01. The biogeochemistry model was incorporated at the beginning of the fourth
- cycle and integrated for 61 years (Years 184-244). The biogeochemical fields were initialized at
- the start of the fourth cycle to the Global Ocean Data Analysis Project version 2 (GLODAPv2;
- Lauvset et al., 2016) for dissolved nitrate (via the Redfield ratio), the multi-model median values
- 130 of the Iron Model Intercomparison Project for dissolved iron (Tagliabue et al., 2016), and an

- 131 arbitrary small value globally (0.625 nM phosphorous) for phytoplankton, zooplankton, detritus,
- and calcium carbonate. To expedite the spin-up of dissolved inorganic carbon and total
- alkalinity, these fields were initialized to their end states of the fifth cycle of the OMIP
- 134 simulation using the lower-resolution (1°) ACCESS-OM2 (omip2; Mackallah et al., 2022; Orr et
- al., 2017). Unlike the other biogeochemical fields, dissolved oxygen was initialized to
- 136 GLODAPv2 21 years later (model year 205; forcing year 1979) due to a bug in the initialization
- 137 routine. Dissolved oxygen has no effect on other biogeochemical tracers, and the biogeochemical
- 138 tracers have no effect on the physical state.

### 139 2.3 Observation-based Surface Phosphate Gridded Dataset

- 140 To evaluate the model performance in simulating the nutrient concentration distributions in the
- 141 Kuroshio region, we generated monthly composite maps of observation-based surface phosphate
- 142 concentrations for the large meander and non-large meander phases. This dataset is an updated
- version of the 1° gridded product over the North Pacific based on optimal interpolation of in situ
- 144 measurements from 1961 to 2021 (Yasunaka et al., 2021). The updates incorporate recent
- 145 measurements archived in the World Ocean Database 2018 (Boyer et al., 2018) and the Global
- 146 Ocean Data Analysis Project v2.2022 (Lauvset et al., 2022), which allows us to increase the
- 147 number of samples for the large meander composites. The decorrelation radius for the optimal
- interpolation was set to  $7^{\circ}$  both in the zonal and meridional directions and 1 month in the
- temporal direction. The signal-to-noise ratio was set to 1.7; the interpolated data whose
- 150 interpolation square error ratios are less than 0.9 were used in this study.

## 151 2.4 Long-term Phosphate Monitoring along 137°E

- 152 To evaluate the simulated difference in the nutrient distribution between the large meander and
- non-large meander states, we downloaded the hydrographic transect dataset along 137°E
- 154 provided by the Japan Meteorological Agency
- 155 (<u>https://www.data.jma.go.jp/gmd/kaiyou/db/mar\_env/results/OI/137E\_OI\_e.html</u>; last accessed
- on November 15, 2022). The dataset provides a collection of more than 50 years of ship-based
- 157 oceanographic observations since 1967 (Oka et al., 2018). In this study, we analyzed the
- dissolved phosphate concentrations collected by water sampling annually during winter (between
- late January and early February) from 1997 to 2022, covering 6 large meander years and 20 non-
- large meander years (Figure A2). The measured units of  $\mu$ mol kg<sup>-1</sup> were converted to the units of
- 161 the model output  $(\mu M)$  using the density of the water sample. We used the phosphate samples
- 162 with a quality control flag of 2, which means *acceptable measurement* for water samples

- 163 following the definition of the World Ocean Circulation Experiment (WOCE;
- 164 <u>https://www.ewoce.org/;</u> last accessed on November 15, 2022).

### 165 **3 Results**

### 166 **3.1 Kuroshio Path Variability**

During the 244 years of the model integration, the model simulated 13 large meander events which lasted for 1 to 15 years (Figure 1a). Even though the same 61-year interannual variability was prescribed as the atmospheric forcing repeatedly for four times, the Kuroshio path variability is different among the four cycles of this free-running (i.e., not data-assimilating) model. This finding demonstrates the importance of ocean dynamics in determining the Kuroshio path variability and that the variability is unpredictable from the atmospheric state alone, which is

- consistent with the findings of the previous studies (Qiu & Miao, 2000; Tsujino et al., 2013).
- 174 To evaluate the simulated Kuroshio path variability, the probability density distributions of the
- Kuroshio axis in the model and the observations are compared (Figure 1b-d). Both the model and
- the observations agree that the distributions are skewed to the left of the median. Median values
- are 32-33°N, indicating the dominance of the non-large meander states. The model has a bias in
- simulating the most frequent Kuroshio axis positioned at 32.6-32.8°N (Figure 1b), which is
- about 0.4° south of the most frequent observed axis (Figure 1c). In terms of the distributions
- south of 32°N, the model tends to simulate large meanders positioned at 30.4-30.6°N, as
- indicated by the secondary peak in the histogram (Figure 1b). Furthermore, the model very
- occasionally simulates large meanders that are positioned south of 29°N (Figure 1a,b). Both of



these simulated features are absent in the observations (Figure 1c). The modelled distribution is 183 also much more clearly bimodal than the observed distribution. 184

185

Figure 1. (a) Monthly time series of the Kuroshio axis latitude over the 244 years of the model 186 integration. Green denotes monthly values with the 13-month central moving average indicated 187 by pink. Horizontal black line segments along 32°N denote the large meander events. Vertical 188 purple dashed lines indicate the first year of each cycle for the atmospheric forcing. Shading 189 denotes the large meander and non-large meander events used for biogeochemical model 190 composite analysis. Comparisons of the monthly Kuroshio axis probability density distributions 191 with a latitudinal bin size of  $0.2^{\circ}$  (b) simulated by the model over 244 years with (c) those 192 determined observationally over 1961-2021 by the Japan Meteorological Agency (JMA). In (b-193 c), dots show the median Kuroshio axis with horizontal lines denoting the interquartile range. 194

#### 195 3.2 Nutrient and Phytoplankton

196 In the last 61 years of the model integration during which the biogeochemical model was incorporated, we consider the first 15 years or so as a spin-up phase based on the time series of 197 modelled biogeochemical properties averaged over the Kuroshio region (Figure A3). We 198 therefore characterized the biogeochemical structure of the large meander and non-large meander 199 states based on the last 44 years of the model integration. During this period, the model 200 201 simulated two large meander periods and two non-large meander periods, each of which lasted for between 8 and 15 years (Figure 1a). This resulted in a total of 246 large-meander and 282 202 non-large-meander monthly samples of the model output. From these rich samples, we 203

constructed large meander and non-large meander composites of modelled dissolved phosphate
 concentration and phytoplankton biomass distributions.

For phosphate, the difference between the large meander and non-large meander phases is most

207 prominent during winter (February; Figure 2). The large meander is well known to generate a

- persistent cold-core eddy offshore north of the Kuroshio path at around 137°E (Sugimoto et al.,
   2020). As expected from the general characteristics of cold-core eddies (Chang et al., 2017), our
- results show that this cyclonic eddy is rich in phosphate (Figure 2a). The transect along  $137^{\circ}E$
- shows that the subsurface phosphate is shoaled on the north side of the Kuroshio (Figure 2d). By
- comparing the depths of nutricline (the maximum absolute vertical gradient in nutrient
- concentrations) between the north and south of the Kuroshio, we estimate this shoaling effect to
- 214 be about 400 m.
- 215 During non-large meander phases, the phosphate-rich surface water is limited to nearshore areas,
- and similar to the large meander phases, it is located north of the Kuroshio path (Figure 2b). The
- transect along 137°E illustrates that the shoaling of subsurface nutrient-rich water is narrower but
- stronger than the large meander cases, as depicted by the greater difference in the nutricline
- depth across the Kuroshio (about 500 m; Figure 2e). As a result, the surface phosphate
- 220 concentration difference between the large meander and the non-large meander can be
- 221 characterized by higher offshore concentrations and lower nearshore concentrations during the
- large meanders, and vice versa for the non-large meanders (Figure 2c). This difference is
- controlled by the changes in the extent and strength of the shoaling of the subsurface phosphate-
- rich water determined by the position and strength of the Kuroshio (Figure 2f). Enhanced
- shoaling during the non-large meander states may be related to topographic features (Miyama &
- 226 Miyazawa, 2013).
- 227 The winter phosphate concentration difference between the large meander and non-large
- meander states preconditions the annual bloom of phytoplankton in these typically nutrient-
- 229 limited regions during spring (May; Figure 3). Phytoplankton spring blooms respond positively
- to the offshore nutrient enrichment and negatively to the nearshore nutrient reduction triggered
- by large meanders (Figure 3c), which mirrors the spatial pattern of the winter surface phosphate
- concentration difference (Figure 2c). Phytoplankton biomass within 1-2° south of the Kuroshio is
- 233 generally low.
- The vertical extent of the offshore bloom during the large meander is about 20 m deeper than
- that of the nearshore bloom present in both the large meander and non-large meander states
- 236 (Figure 3d,e). The nearshore bloom is slightly weaker during the large meander. Hence, the

primary difference is that the large meander expands the latitudinal extent of the spring bloom
north of the Kuroshio by as much as 300 km along 137°E.



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Figure 2. Comparisons of modelled February composite surface dissolved phosphate

concentration south of Japan during (a) the large meander and (b) the non-large meander, and (c)

their difference. (d-f) Cross-section comparisons in the upper 800 m along 137°E, denoted by
black solid line in (c). Solid lines in (a) and (b) represent the path of the Kuroshio, defined by the

black solid line in (c). Solid lines in (a) and (b) represent the path of the Kuroshio, defined by the sea level contour at which the latitudinal gradient is maximum along 137°E. Dashed and dotted

boxes in (c) define respectively the nearshore and offshore regions used for time series analysis

- in Figure 6. Solid and dashed lines in (d) and (e) represent the nutricline and the zonal velocity contours of 0.2, 0.4 and 0.6 m s<sup>-1</sup> represent the nutricline and the zonal velocity
- contours of 0.2, 0.4, and 0.6 m s<sup>-1</sup>, respectively.



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**Figure 3.** Comparisons of modelled May composite surface phytoplankton phosphorous biomass south of Japan during (a) the large meander and (b) the non-large meander, and (c) their difference. (d-f) Cross-section comparisons in the upper 100 m along 137°E, denoted by black

solid line in (c). Solid lines in (a) and (b) represent the path of the Kuroshio, defined by the sea
level contour at which the latitudinal gradient is maximum along 137°E. Dashed and dotted
boxes in (c) define respectively the nearshore and offshore regions used for time series analysis

in Figure 6.

### **3.2.1 Consistency with Observations**

257 The observation-based surface dissolved phosphate concentration dataset illustrates both the

- offshore enrichment and the nearshore reduction of nutrients during the large meander winters as
- found in the model simulation (Figure 4c). However, the magnitude of the phosphate
- 260 concentration difference is much smaller in the observation-based dataset than the model. The
- observed offshore phosphate enrichment is about 0.05  $\mu$ M (Figure 4c), which is about half of the
- modelled increase (Figure 4f). The observed nearshore phosphate reduction is only about 0.02
- $\mu$ M (Figure 4c), whereas the modelled reduction is close to 0.1  $\mu$ M (Figure 4f). The observation-
- based dataset generally shows much smaller difference across the entire domain, possibly due to

interpolation with smoothing to minimize the error from sparse in-situ data which can result in
 suppressing variability (Yasunaka et al., 2021).

267 To further evaluate the model performance, we used the vertical profiles of dissolved phosphate

concentrations along 137°E observed annually during winter over the last 26 years (Figure 5).

- The vertical profiles are available at every 1° latitude (Figure A2), but our analysis focused on
- the profiles at 29°N, 32°N, and 34°N, which respectively correspond to regions of neutral,
- 271 positive, and negative anomalies in the modelled winter phosphate concentrations during the
- large meander relative to the non-large meander (Figure 2c,f). In general, the model
- 273 underestimates the phosphate concentration below the surface mixed layer.
- 274 The observed profiles show no clear distinction between the large meander and non-large
- meander states at 29°N, which is consistent with the model (Figure 5a). At 32°N, there is a
- robust difference throughout the depth between the two phases (Figure 5b); the observed
- 277 concentrations at every vertical level were always higher during the large meander than those of
- the non-large meander. This robust distinction is also evident from the model simulation. Within
- the surface mixed layer, the observed concentration difference is about 0.1  $\mu$ M. Below the
- surface mixed layer, the observed concentration difference increases with depth up to about 1.8
- $\mu$ M at 400 m, and then decreases (Figure 5b). A very similar concentration difference in terms of
- both the magnitude and the vertical variation is simulated by the model.
- At 34°N, the observed profiles generally show 0.1-0.5 μM lower phosphate concentrations
- during the large meander than the non-large meander in the surface mixed layer (Figure 5c), with
- an exception of one large meander year (2018; Figure A2). Below the surface mixed layer, the
- difference is indistinguishable between the large meander and non-large meander phases. The



model also simulates about 0.1  $\mu$ M lower phosphate concentrations during the large meanders on average, extending from the surface mixed layer to about 400 m.

#### 289

**Figure 4.** Comparison of observation-based January-February composite surface phosphate

concentration south of Japan during (a) the large meander and (b) the non-large meander, and (c)

their difference. Differences between the modelled and observation-based composites during (d)

the large meander and (e) the non-large meander. (f) Difference between the large meander and

non-large meander composites of the model output. Here, the model output is interpolated to the

295 grid of the observation-based dataset.



296

Figure 5. Comparisons of vertical dissolved phosphate concentration profiles in the upper 800 m
between the large (LM; red) and non-large (NLM; blue) meander years at (a) 29°N, (b) 32°N,
and (c) 34°N along 137°E collected between late-January and early-February annually since
1997. Magenta and cyan show the comparable profiles simulated by the model with errorbars
denoting ±1 standard deviations from the January-February averages.

### 302 **3.2.2 Seasonal Cycle**

303 The biogeochemical impacts of the large meander have distinct seasonality as illustrated by the

304 seasonal cycle comparison at the offshore and nearshore regions where the most prominent

differences were identified (Figure 6). Both at the offshore and nearshore regions, the nutrient

306 concentration differences are robust from December to March, meaning that the concentrations

- between the large meander and non-large meander cases do not overlap even within one standard
- deviation ranges around their means (Figure 6a,b). Nutrient concentration differences decrease
   from April and are negligible from June to October, during which the concentrations are close to
- from April and are negligible from June to October, during which the concentrations are clos zero. In contrast, the nutricline depth does not vary seasonally at either location, and the
- differences between the large meanders and the non-large meanders are clear (Figure 6c,d). The
- 312 lack of seasonality in the nutricline depth suggests that the surface nutrient concentration
- differences emerge only during winter because they are driven by winter convective mixing, and
- not processes that do not have specific seasonality such as eddy suction (Chang et al., 2017). The
- large meander enhances the winter nutrient replenishment in the offshore region by shoaling the
- nutricline depth (Figure 6c), thereby yielding higher surface nutrient concentrations compared to
- the non-large meander phases (Figure 6a). In contrast, the nearshore nutrient replenishment is
- 318 stronger during the non-large meander phases when the shoaling effect of the Kuroshio is
- 319 stronger (Figure 6d), resulting in higher surface nutrient concentrations than the large-meander
- case (Figure 6b). The mixed layer depth is always shallower in the offshore region during the
- large meander winters (January-March; Figure 6e), which rules out the possibility that the
- 322 strength of the convective mixing drives the offshore nutrient enrichment. In other words, the
- 323 shoaling effect of the nutricline overwhelms that of the mixed layer.
- 324 The seasonal cycles of modelled surface phytoplankton biomass reveal that the large meander
- 325 changes not only the magnitude, but also the timing of the spring bloom in the offshore region
- 326 (Figure 6g). The increased supply of phosphate during winter enables phytoplankton to form a
- 327 bloom offshore that peaks in May. In the case of the non-large meander, the peak arrives a month
- 328 later in June. In the nearshore region, the seasonality can be characterized by a spring bloom that
- peaks in May, which is common to both the large meander and non-large meander phases
- 330 (Figure 6h). The only difference is that the biomass is consistently higher during the non-large
- meander phases, which is likely caused by the difference in the nutrient availability (Figure 6b).
- 332 The higher biomass during large meanders in the offshore region and during non-large meanders
- in the nearshore region continues even in summer, which indicates the continuous nutrient input



from the subsurface thanks to the shallow nutricline. Surface phosphate concentrations remain

low probably because nutrients are consumed as soon as they are supplied.

336

**Figure 6.** Comparisons of modelled monthly composite seasonal cycles of (a,b) surface dissolved phosphate concentration, (c,d) nutricline depth, (e,f) mixed layer depth, and (g,h) phytoplankton phosphorous biomass averaged over the (a,c) offshore and (b,d) nearshore regions

defined in Figure 2 during the large (red) and non-large (blue) meander phases. Error bars

represent the standard deviations of monthly area-averaged values incorporated into each phase.

### 342 **3.2.3 Latitudinal Distributions and Correlations**

The latitudinal position of the Kuroshio has strong influence on the latitudinal distributions of 343 winter nutrient availability and spring phytoplankton biomass in the Kuroshio region (Figure 344 7a,b). There is a clear pattern that the north of the Kuroshio is always higher in phosphate 345 concentration and phytoplankton biomass than its southern counterparts. However, there are a 346 few exceptions that can be categorized into two groups. First, the phosphate concentration and 347 the phytoplankton biomass 1° north of the Kuroshio are higher but they decrease further north 348 until reaching near the coast in some cases (e.g., Year 239). This pattern emerges when the 349 Kuroshio takes the S-shaped path (Kasai et al., 1993) along 137°N (Figure A4). In this case, it is 350

more appropriate to refer to the position of the phosphate-rich surface water (and hence the

- 352 shallow nutricline area) as being left of the Kuroshio path, rather than the north of the Kuroshio.
- The other exception to the latitudinal distributions relative to the Kuroshio position is the
- presence of higher values further south of the Kuroshio that are especially evident from the
- phytoplankton biomass distribution (e.g., the first 4 years; Figure 7b). This pattern likely reflects
- local blooms south of the Kuroshio path, which would be located further south during the large
- 357 meanders.

To elucidate the relationship between winter nutrient availability and spring phytoplankton

bloom in the Kuroshio region, we calculated correlations between the two variables at each
 latitude along 137°N (Figure 7c). Correlation coefficients are above 0.6 throughout the latitudes

- latitude along 137°N (Figure 7c). Correlation coefficients are above 0.6 throughout the latitudes
   between 30.7-33.3°N, indicating the strong relationship between winter nutrient availability and
- the subsequent bloom strength on a year-to-year basis. Correlations are weaker north of this
- latitudinal band probably because the phosphate concentration is generally high in the nearshore
- region, and so there must be other processes that drive the interannual variability of the spring
- bloom magnitude. Correlations are generally also weaker south of 30.7°N (except around







**Figure 7.** Latitudinal distributions of (a) February surface dissolved phosphate concentration and

369 (b) May surface phytoplankton phosphorous biomass along 137°E over the last 44 years of the

model integration. Crosses denote the locations of the Kuroshio axis determined from the sea

<sup>371</sup> level gradient along 137°E. (c) Latitudinal distribution of the Pearson's correlation coefficients

between the February surface dissolved phosphate concentration and May surface phytoplankton

biomass along 137°E over the last 44 years of the model integration.

### 374 **3.3 Primary Production, Ocean Carbon Uptake, and Export Production**

375 The spatial anomalies of the highs in the offshore region and the lows in the nearshore region

- during the large meander phase are also present in annual primary production, ocean carbon
- uptake, and export production (Figure 8). This spatial coherence is expected as higher
- 378 phytoplankton biomass leads to increased primary production, which results in greater biological
- carbon uptake and pump. Despite the prominent spatial anomalies, the differences between the



- large meander and non-large meander phases are minimal (<5 % difference) when these 380
- quantities are integrated over the entire study area. 381

382

Figure 8. Spatial comparisons of modelled annual mean (a-c) depth-integrated net primary 383 production, (d-f) air-sea carbon flux (positive means flux into the ocean), and (g-i) vertical 384 detritus export at 100 m during the large meanders (a,d,g) and the non-large meanders (b,e,h), 385 and (c,f,i) their differences. Solid lines in (a,b,d,e,g,h) represent the path of the Kuroshio, defined 386 by the annual mean sea level contour at which the latitudinal gradient is maximum along 137°E. 387

#### **4** Discussion 388

- In this study, we characterized the biogeochemical impacts of the Kuroshio large meander by 389
- generating monthly composites of modelled biogeochemical variables during the large meander 390
- and non-large meander phases from a multi-decadal simulation output of a 0.1° global sea ice-391
- ocean coupled model. Biogeochemical responses in the model correspond well with the 392
- observations even though the Kuroshio axis in the model is generally positioned further south 393
- during large meanders. Our spatial analysis reveals that the large meander enhances winter 394
- nutrient availability offshore south of Japan by extending the shallow nutricline area that is 395
- always positioned on the left side of the Kuroshio path and replenishes the surface water with 396

- 397 nutrients through seasonal convective mixing (Kuroda et al., 2018). The nutrient enrichment in
- this typically nutrient-poor offshore region during the large meander winter allows
- 399 phytoplankton to form a bloom a few months later during spring. This offshore large meander
- 400 bloom arrives a month earlier with a greater magnitude compared to the bloom during the non-
- large meanders, and is also evident from satellite observations (Lizarbe Barreto et al., 2021).
- 402 Such a distinct difference in both the timing and magnitude of the spring bloom may alter the
- 403 spatial distributions of fish abundance and species.
- In contrast to the offshore region, the nutrient concentration and phytoplankton biomass in the nearshore region are lower throughout the year during the large meander. This reduction is
- 406 caused by weakened shoaling effect of the Kuroshio, which makes the subsurface nutrients less
- 407 accessible by winter convective mixing. The phosphate measurements along 137°N indicate that
- 408 our model may have overestimated the magnitude of the nutrient reduction during the large
- 409 meander. On the other hand, the satellite observations suggest that the magnitude of the
- 410 reduction of the nearshore phytoplankton biomass is similar to that of the offshore increase
- 411 (Lizarbe Barreto et al., 2021), which is consistent with our model results. In the nearshore region,
- 412 nutrient availability is important not only for phytoplankton, but also for macroalgae such as
- 413 seaweed, which is an essential seafood product for Japan.
- Essentially, the spatial pattern of the biogeochemical signature of the large meander corresponds
- to the inverse of temperature anomalies (Sugimoto et al., 2020). However, such biogeochemical
- anomalies of the large meander will have an influence on macroalgae and higher trophic levels
- that is disproportionate to the thermal effect. For example, the nearshore warming during the
- large meander has been related to an increase in sardine egg abundance, whereas the egg
- abundance of another fish species (anchovy) was more closely linked to water transparency,
- 420 which is an indicator of food availability (Nakata et al., 2000). Such complexity of fish responses
- to both physical and biogeochemical processes necessitates more thorough assessment of the
- 422 large meander impacts on fisheries and aquaculture, which is possible by combining
- 423 biogeochemical model simulations, satellite ocean color, and in situ monitoring.
- Besides the shoaling effect, the Kuroshio path can determine the regional biogeochemical
- anomalies directly by transporting nutrient-poor waters. It is interesting to note that our model
- shows a slight decrease in phosphate (Figure 2c) and phytoplankton biomass (Figure 3c) in the
- 427 Seto Inland Sea during the large meanders. While this result might not be robust because of the
- limited resolution of the model, previous studies suggested the control of the Kuroshio water
- intrusion on the hydrographic and biogeochemical properties of the Seto Inland Sea (e.g.,
- 430 Kobayashi & Fujiwara, 2008). Such direct impacts of the Kuroshio remain as a subject of future
- 431 studies.
- A strong correlation between winter nutrient availability and spring phytoplankton bloom in the
- 433 offshore region gives prospects for improving predictability of the large meander impacts by

- 434 implementing biogeochemistry into an operational ocean forecasting system (e.g., Miyazawa et
- al., 2017). Furthermore, marine industries may benefit from decadal predictions of
- biogeochemical states, as the decadal variability of the Kuroshio large meander is expected to
- 437 strengthen in the future due to the stronger decadal variability of the Kuroshio Extension (Joh et
- 438 al., 2022) that is closely linked to the large meander occurrence (Usui et al., 2013). Such
- biogeochemical implementation into a decadal ocean prediction system (e.g., Kido et al., 2022)
   has great potential in supporting long-term adaptation planning for future large meanders that
- 441 may last longer than the ongoing record-breaking event, as demonstrated by our model
- 442 simulations.

### 443 Appendix



Figure A1. Monthly time series of the Kuroshio axis latitude over 1961-2021 determined by the
Japan Meteorological Agency. Green denotes monthly values with the 13-month central moving
average indicated by pink. Orange shadings denote the large meander events since 1965.



**Figure A2.** Comparisons of the winter transects of dissolved phosphate concentrations from

- 450 29°N to 34°N along 137°E observed annually during late January-early February by the Japan
- 451 Meteorological Agency since 1997. The large meander years are indicated by bold font in
- 452 subplot titles.





454 **Figure A3.** Monthly anomalies of modelled (a) temperature, (b) phosphate concentration, (c)

455 phytoplankton phosphorous biomass, (d) zooplankton phosphorous biomass, (e) detritus

- 456 phosphorous concentration, and (f) natural dissolved inorganic carbon concentration averaged
- 457 over the upper 1,000 m of the Kuroshio region (129-144°E by 28-36°N). Values represent
- 458 anomalies relative to their monthly climatology and shadings denote  $\pm 3$  standard deviations over
- the last 30 years of the model integration. Vertical lines denote 15 years after the biogeochemical
- 460 model initialization.





462 **Figure A4.** Daily-mean snapshots of modelled (a,c) dissolved phosphate concentration and (b,d)

- 463 phytoplankton phosphorous biomass (a,b) in the surface layer and (c,d) along the 137°E
- latitudinal cross section on May 14 of Year 211. Solid lines in (a) and (b) represent the path of
- the Kuroshio, defined by the sea level contour at which the latitudinal gradient is maximum
- along 137°E. Dotted lines in (c) and (d) denote the Kuroshio axis, defined by the latitude at
- 467 which the latitudinal sea level gradient is maximum along 137°E.

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- 476 conflicts of interest to declare.

### 477 **Open Research**

- The ACCESS-OM2-01 output is available to download from
- 479 <u>http://dx.doi.org/10.25914/608097cb3433f</u> (last accessed on November 28, 2022). The model
- 480 source code (<u>https://github.com/COSIMA/access-om2</u>; last accessed on November 28, 2022) and
- 481 configuration (<u>https://github.com/COSIMA/01deg\_jra55\_iaf/tree/01deg\_jra55v140\_iaf\_cycle4;</u>
- last accessed on November 28, 2022) are available on github. The hydrographic transect data
  along 137°E
- 484 (https://www.data.jma.go.jp/gmd/kaiyou/db/mar\_env/results/OI/137E\_OI.html#data; last
- accessed on November 28, 2022) and the monthly Kuroshio axis time series
- 486 (https://www.data.jma.go.jp/kaiyou/data/shindan/b\_2/kuroshio\_stream/kuro\_slat.txt; last
- 487 accessed on November 15, 2022) are available to download from the Japan Meteorological
- 488 Agency website. The observation-based nutrient gridded product is available to download from
- 489 <u>http://caos.sakura.ne.jp/sao/north-pacific-surface-nutrients/</u> (last accessed on December 29,
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#### 1 2

# **Biogeochemistry of the Kuroshio Large Meander**

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### 12 Key Points:

- The Kuroshio large meander (LM) expands the nutrient-rich surface water south of Japan
   further offshore during winter.
- During LM, phytoplankton spring blooms increase offshore due to nutrient enrichment
   and decrease nearshore due to nutrient reduction.
- In addition to thermal disturbance, the biogeochemical impacts of the large meander exert
   bottom-up control on higher trophic levels.

#### 19 Abstract

- 20 The large meander of the Kuroshio western boundary current is well known to influence the
- 21 local climate, fisheries, and aquaculture by greatly modulating regional heat transport, but its
- 22 impacts on biogeochemical processes remain unclear. Using high-resolution numerical ocean
- 23 modelling and long-term observational datasets, we show that the path of the Kuroshio
- 24 determines the extent of the shallow nutricline region, where winter convective mixing
- 25 replenishes nutrient availability for subsequent blooms of phytoplankton during spring. During
- the large meander phase, this mechanism triggers offshore phytoplankton blooms that are
- otherwise absent during the non-large meander phase. The large meander also modulates the
- 28 spatial distributions of primary production, air-sea carbon flux, and export production. These
- 29 biogeochemical impacts of the Kuroshio large meander exert bottom-up control on regional
- 30 marine ecosystems that is disproportionate to the thermal effect, and therefore need to be
- assessed to understand the large meander's overall impacts on fisheries and aquaculture.

#### 32 Plain Language Summary

33 The Kuroshio is one of the world's most powerful ocean currents that regulates the global

- distribution of heat, salt, and chemical elements by transporting a significant amount of seawater
- from one region to another. The Kuroshio generally travels along the southern coast of Japan, but
- from time to time, it deflects its pathway further south, often by more than 300 km. This
- deflection is known as the Kuroshio large meander, which has been discovered to have impacts
- 38 on the weather, fisheries, and aquaculture in Japan. These impacts have been attributed to the
- <sup>39</sup> large meander's ability to displace the heat distribution. However, the large meander's impact is
- 40 beyond just heat, and so we need to understand what happens to other oceanic properties during
- 41 the large meander, in order to understand its overall impact. In this study, we used a computer
- 42 ocean model to simulate long large meander periods to characterize the impacts of the large
- 43 meander on marine biogeochemistry. The results show that the large meander displaces the
- 44 locations of high and low nutrient, which fuels phytoplankton to bloom in areas where they will
- not be able to otherwise. Understanding such changes is essential for better understanding the
- 46 impacts on fish.

### 47 **1 Introduction**

- 48 The Kuroshio, which means *black current* in Japanese, is one of the strongest currents in the
- 49 ocean that has significant impacts on the global climate system and local marine industries.
- 50 Among the western boundary currents, the Kuroshio is unique in that its main path can be
- characterized by two stable states that it switches between on a timescale of a few years to a few
- 52 decades (Kawabe, 1987). One of the these states takes the path that travels nearshore along the
- southern coast of Japan, which we refer to as the non-large meander. The other stable state,
- 54 which is the main focus of this study, is the path that is deflected offshore south of the Tokai
- region, and is referred to as the large meander. As the Kuroshio is rapid and carries a huge

- amount of water mass along with heat and materials in the ocean, the path of the Kuroshio is
- 57 important for shipping, commercial fishing, and fish farming.

58 Since August 2017, the Kuroshio has been taking the large meander path. In April 2022, this

<sup>59</sup> large meander event has lasted for 4 years and 9 months, which has become the longest ever

60 recorded large meander since a consistent observation by the Japan Meteorological Agency

started in the 1960s (Qiu & Chen, 2021). The ongoing large meander has received much media

attention in Japan, as it has been revealed to trigger extratropical cyclones with extreme rainfall

- 63 (Hirata et al., 2019; Tochimoto & Iizuka, 2022), cause discomfort in summer over the greater
- Tokyo metropolitan area (Sugimoto et al., 2021), and modify the seasonal abundance and
- distribution of commercial fish (Chang et al., 2019; Zhu et al., 2021). All these reported impacts
- have been linked to the large meander's influence on physical conditions such as temperature,
- but obviously the large meander modulates other processes such as biogeochemistry. For
- example, nutrient and phytoplankton abundance can exert bottom-up control on the marine food

69 web, which may have impacts on higher trophic levels such as commercial fish (e.g., Yoneda et

al., 2022). However, such biogeochemical aspects of the larger meander have been explored only

by a few studies (e.g., Lizarbe Barreto et al., 2021; Long et al., 2018), perhaps due to the lack of

- 72 adequate samples to draw robust conclusions.
- 73 In this study, we characterize the biogeochemical impacts of the Kuroshio large meander by
- analyzing the multi-decadal output of a high-resolution global sea ice-ocean model simulation.
- 75 Results reveal robust differences in the spatial distributions of nutrient, phytoplankton, primary
- 76 production, ocean carbon uptake, and export production during the large meander phase
- compared to the non-large meander phase. Using available observations, we show that the
- simulated nutrient results are realistic, which shapes the rest of the biogeochemical quantities.

## 79 **2 Methods**

## 80 2.1 Kuroshio Large Meander Definition

The path of the Kuroshio is considered a large meander when it deflects far south of Japan for a prolonged period. Otherwise, the path is considered non-large meander. There are several indices

to define the large meander, but their time series are generally consistent (Qiu & Chen, 2021).

- 84 Here, the Kuroshio path is defined as a large meander when the southernmost axis of the
- Kuroshio is located south of 32°N in the 136-140°E segment. This definition is one of the two
- criteria for large meander determination used by the Japan Meteorological Agency (Sakajo et al.,
- 87 2022). The other criterion is the sea level difference between Kushimoto and Uragami which is
- disregarded here because these two locations are much closer than the horizontal resolution of
- <sup>89</sup> our model (Section 2.2). The Kuroshio axis is defined as the latitude at which the absolute
- 90 meridional gradient of sea surface height is maximum, which corresponds to the approximate
- 91 location of the fastest zonal geostrophic flow. Using this definition for the Kuroshio axis, we
- 92 define a large meander event when the 13-month central moving average Kuroshio axis is

- 93 located south of 32°N for at least 12 consecutive months. Our definition matches well with the
- past large meander events determined by the Japan Meteorological Agency (Figure A1).
- 95 To assess the model performance in simulating the Kuroshio path variability, we downloaded the
- 96 monthly Kuroshio axis time series produced by the Japan Meteorological Agency
- 97 (<u>https://www.data.jma.go.jp/kaiyou/data/shindan/b\_2/kuroshio\_stream/kuro\_slat.txt;</u> last
- accessed on November 15, 2022). The data provide the southernmost latitude of the Kuroshio in
- the 136-140°E segment from 1961 to 2021 determined based on satellite and hydrographic
- 100 observations (Qiu & Chen, 2021; Sakajo et al., 2022). The data contain several missing values
- 101 during 1961-1968 and 1992-1999 (Figure A1).

### 102 **2.2 Model**

- 103 The global sea ice-ocean coupled numerical model used in this study is the 0.1° version of the
- 104 Australian Community Climate and Earth System Simulator Ocean Model version 2 (ACCESS-
- 105 OM2-01), an updated version of the configuration described by Kiss et al. (2020). The physical
- 106 model is composed of the Modular Ocean Model (MOM) version 5.1 and the Los Alamos sea ice
- 107 model (CICE) version 5.1.2. The biogeochemical model is composed of the Whole Ocean Model
- 108 of Biogeochemistry and Trophic-dynamics (WOMBAT; Oke et al., 2013) and the
- 109 biogeochemistry of CICE (Jeffery et al., 2016). WOMBAT is a phosphorous-based four-
- 110 component (Nutrient-Phytoplankton-Zooplankton-Detritus; NPZD) model with carbonate
- 111 chemistry, dissolved oxygen, and bioavailable dissolved iron (Oke et al., 2013). Phosphate is the
- only macronutrient tracer, and a fixed Redfield ratio of 1:16:106:-172 is assumed with
- 113 phosphorous, nitrogen, carbon, and oxygen. We use the same biogeochemical parameters as
- 114 Ziehn et al. (2020). Although the micronutrient iron can limit the phytoplankton growth, it is not
- the limiting factor for the Kuroshio region (Hayashida et al., 2020), which is supported by
- available observations (Moore et al., 2013). There is no supply of nutrient from river discharge,
- but this effect may be negligible for the nutrient budget in the study region which is further away
- 118 from river mouths (Kuroda et al., 2018).
- In this study, we analyzed the monthly mean output of ACCESS-OM2-01 which was integrated
- 120 for 244 years by prescribing the 61-year (1958-2018) Japanese Atmospheric Reanalysis dataset
- 121 (JRA55-do version 1.4.0; Tsujino et al., 2018) as the surface forcing repeatedly for four times.
- 122 This cyclic procedure follows the protocol of the Ocean Model Intercomparison Project (OMIP;
- 123 Griffies et al., 2016; Tsujino et al., 2020). The ocean model was initialized from rest with zero
- sea level anomaly, and the initial temperature and salinity fields were set to the World Ocean
   Atlas 2013 version 2. The first three cycles were integrated using the physics-only version of
- Atlas 2013 version 2. The first three cycles were integrated using the physics-only version of ACCESS-OM2-01. The biogeochemistry model was incorporated at the beginning of the fourth
- cycle and integrated for 61 years (Years 184-244). The biogeochemical fields were initialized at
- the start of the fourth cycle to the Global Ocean Data Analysis Project version 2 (GLODAPv2;
- Lauvset et al., 2016) for dissolved nitrate (via the Redfield ratio), the multi-model median values
- 130 of the Iron Model Intercomparison Project for dissolved iron (Tagliabue et al., 2016), and an

- 131 arbitrary small value globally (0.625 nM phosphorous) for phytoplankton, zooplankton, detritus,
- and calcium carbonate. To expedite the spin-up of dissolved inorganic carbon and total
- alkalinity, these fields were initialized to their end states of the fifth cycle of the OMIP
- 134 simulation using the lower-resolution (1°) ACCESS-OM2 (omip2; Mackallah et al., 2022; Orr et
- al., 2017). Unlike the other biogeochemical fields, dissolved oxygen was initialized to
- 136 GLODAPv2 21 years later (model year 205; forcing year 1979) due to a bug in the initialization
- 137 routine. Dissolved oxygen has no effect on other biogeochemical tracers, and the biogeochemical
- 138 tracers have no effect on the physical state.

### 139 2.3 Observation-based Surface Phosphate Gridded Dataset

- 140 To evaluate the model performance in simulating the nutrient concentration distributions in the
- 141 Kuroshio region, we generated monthly composite maps of observation-based surface phosphate
- 142 concentrations for the large meander and non-large meander phases. This dataset is an updated
- version of the 1° gridded product over the North Pacific based on optimal interpolation of in situ
- 144 measurements from 1961 to 2021 (Yasunaka et al., 2021). The updates incorporate recent
- 145 measurements archived in the World Ocean Database 2018 (Boyer et al., 2018) and the Global
- 146 Ocean Data Analysis Project v2.2022 (Lauvset et al., 2022), which allows us to increase the
- 147 number of samples for the large meander composites. The decorrelation radius for the optimal
- interpolation was set to  $7^{\circ}$  both in the zonal and meridional directions and 1 month in the
- temporal direction. The signal-to-noise ratio was set to 1.7; the interpolated data whose
- 150 interpolation square error ratios are less than 0.9 were used in this study.

## 151 2.4 Long-term Phosphate Monitoring along 137°E

- 152 To evaluate the simulated difference in the nutrient distribution between the large meander and
- non-large meander states, we downloaded the hydrographic transect dataset along 137°E
- 154 provided by the Japan Meteorological Agency
- 155 (<u>https://www.data.jma.go.jp/gmd/kaiyou/db/mar\_env/results/OI/137E\_OI\_e.html</u>; last accessed
- on November 15, 2022). The dataset provides a collection of more than 50 years of ship-based
- 157 oceanographic observations since 1967 (Oka et al., 2018). In this study, we analyzed the
- dissolved phosphate concentrations collected by water sampling annually during winter (between
- late January and early February) from 1997 to 2022, covering 6 large meander years and 20 non-
- large meander years (Figure A2). The measured units of  $\mu$ mol kg<sup>-1</sup> were converted to the units of
- 161 the model output  $(\mu M)$  using the density of the water sample. We used the phosphate samples
- 162 with a quality control flag of 2, which means *acceptable measurement* for water samples

- 163 following the definition of the World Ocean Circulation Experiment (WOCE;
- 164 <u>https://www.ewoce.org/;</u> last accessed on November 15, 2022).

### 165 **3 Results**

### 166 **3.1 Kuroshio Path Variability**

During the 244 years of the model integration, the model simulated 13 large meander events which lasted for 1 to 15 years (Figure 1a). Even though the same 61-year interannual variability was prescribed as the atmospheric forcing repeatedly for four times, the Kuroshio path variability is different among the four cycles of this free-running (i.e., not data-assimilating) model. This finding demonstrates the importance of ocean dynamics in determining the Kuroshio path variability and that the variability is unpredictable from the atmospheric state alone, which is

- consistent with the findings of the previous studies (Qiu & Miao, 2000; Tsujino et al., 2013).
- 174 To evaluate the simulated Kuroshio path variability, the probability density distributions of the
- Kuroshio axis in the model and the observations are compared (Figure 1b-d). Both the model and
- the observations agree that the distributions are skewed to the left of the median. Median values
- are 32-33°N, indicating the dominance of the non-large meander states. The model has a bias in
- simulating the most frequent Kuroshio axis positioned at 32.6-32.8°N (Figure 1b), which is
- about 0.4° south of the most frequent observed axis (Figure 1c). In terms of the distributions
- south of 32°N, the model tends to simulate large meanders positioned at 30.4-30.6°N, as
- indicated by the secondary peak in the histogram (Figure 1b). Furthermore, the model very
- occasionally simulates large meanders that are positioned south of 29°N (Figure 1a,b). Both of



these simulated features are absent in the observations (Figure 1c). The modelled distribution is 183 also much more clearly bimodal than the observed distribution. 184

185

Figure 1. (a) Monthly time series of the Kuroshio axis latitude over the 244 years of the model 186 integration. Green denotes monthly values with the 13-month central moving average indicated 187 by pink. Horizontal black line segments along 32°N denote the large meander events. Vertical 188 purple dashed lines indicate the first year of each cycle for the atmospheric forcing. Shading 189 denotes the large meander and non-large meander events used for biogeochemical model 190 composite analysis. Comparisons of the monthly Kuroshio axis probability density distributions 191 with a latitudinal bin size of  $0.2^{\circ}$  (b) simulated by the model over 244 years with (c) those 192 determined observationally over 1961-2021 by the Japan Meteorological Agency (JMA). In (b-193 c), dots show the median Kuroshio axis with horizontal lines denoting the interquartile range. 194

#### 195 3.2 Nutrient and Phytoplankton

196 In the last 61 years of the model integration during which the biogeochemical model was incorporated, we consider the first 15 years or so as a spin-up phase based on the time series of 197 modelled biogeochemical properties averaged over the Kuroshio region (Figure A3). We 198 therefore characterized the biogeochemical structure of the large meander and non-large meander 199 states based on the last 44 years of the model integration. During this period, the model 200 201 simulated two large meander periods and two non-large meander periods, each of which lasted for between 8 and 15 years (Figure 1a). This resulted in a total of 246 large-meander and 282 202 non-large-meander monthly samples of the model output. From these rich samples, we 203

constructed large meander and non-large meander composites of modelled dissolved phosphate
 concentration and phytoplankton biomass distributions.

For phosphate, the difference between the large meander and non-large meander phases is most

207 prominent during winter (February; Figure 2). The large meander is well known to generate a

- persistent cold-core eddy offshore north of the Kuroshio path at around 137°E (Sugimoto et al.,
   2020). As expected from the general characteristics of cold-core eddies (Chang et al., 2017), our
- results show that this cyclonic eddy is rich in phosphate (Figure 2a). The transect along  $137^{\circ}E$
- shows that the subsurface phosphate is shoaled on the north side of the Kuroshio (Figure 2d). By
- comparing the depths of nutricline (the maximum absolute vertical gradient in nutrient
- concentrations) between the north and south of the Kuroshio, we estimate this shoaling effect to
- 214 be about 400 m.
- 215 During non-large meander phases, the phosphate-rich surface water is limited to nearshore areas,
- and similar to the large meander phases, it is located north of the Kuroshio path (Figure 2b). The
- transect along 137°E illustrates that the shoaling of subsurface nutrient-rich water is narrower but
- stronger than the large meander cases, as depicted by the greater difference in the nutricline
- depth across the Kuroshio (about 500 m; Figure 2e). As a result, the surface phosphate
- 220 concentration difference between the large meander and the non-large meander can be
- 221 characterized by higher offshore concentrations and lower nearshore concentrations during the
- large meanders, and vice versa for the non-large meanders (Figure 2c). This difference is
- controlled by the changes in the extent and strength of the shoaling of the subsurface phosphate-
- rich water determined by the position and strength of the Kuroshio (Figure 2f). Enhanced
- shoaling during the non-large meander states may be related to topographic features (Miyama &
- 226 Miyazawa, 2013).
- 227 The winter phosphate concentration difference between the large meander and non-large
- meander states preconditions the annual bloom of phytoplankton in these typically nutrient-
- 229 limited regions during spring (May; Figure 3). Phytoplankton spring blooms respond positively
- to the offshore nutrient enrichment and negatively to the nearshore nutrient reduction triggered
- by large meanders (Figure 3c), which mirrors the spatial pattern of the winter surface phosphate
- concentration difference (Figure 2c). Phytoplankton biomass within 1-2° south of the Kuroshio is
- 233 generally low.
- The vertical extent of the offshore bloom during the large meander is about 20 m deeper than
- that of the nearshore bloom present in both the large meander and non-large meander states
- 236 (Figure 3d,e). The nearshore bloom is slightly weaker during the large meander. Hence, the

primary difference is that the large meander expands the latitudinal extent of the spring bloom
north of the Kuroshio by as much as 300 km along 137°E.



239

Figure 2. Comparisons of modelled February composite surface dissolved phosphate

concentration south of Japan during (a) the large meander and (b) the non-large meander, and (c)

their difference. (d-f) Cross-section comparisons in the upper 800 m along 137°E, denoted by
black solid line in (c). Solid lines in (a) and (b) represent the path of the Kuroshio, defined by the

black solid line in (c). Solid lines in (a) and (b) represent the path of the Kuroshio, defined by the sea level contour at which the latitudinal gradient is maximum along 137°E. Dashed and dotted

boxes in (c) define respectively the nearshore and offshore regions used for time series analysis

- in Figure 6. Solid and dashed lines in (d) and (e) represent the nutricline and the zonal velocity contours of 0.2, 0.4 and 0.6 m s<sup>-1</sup> represent the nutricline and the zonal velocity
- contours of 0.2, 0.4, and 0.6 m s<sup>-1</sup>, respectively.



248

**Figure 3.** Comparisons of modelled May composite surface phytoplankton phosphorous biomass south of Japan during (a) the large meander and (b) the non-large meander, and (c) their difference. (d-f) Cross-section comparisons in the upper 100 m along 137°E, denoted by black

solid line in (c). Solid lines in (a) and (b) represent the path of the Kuroshio, defined by the sea
level contour at which the latitudinal gradient is maximum along 137°E. Dashed and dotted
boxes in (c) define respectively the nearshore and offshore regions used for time series analysis

in Figure 6.

### **3.2.1 Consistency with Observations**

257 The observation-based surface dissolved phosphate concentration dataset illustrates both the

- offshore enrichment and the nearshore reduction of nutrients during the large meander winters as
- found in the model simulation (Figure 4c). However, the magnitude of the phosphate
- 260 concentration difference is much smaller in the observation-based dataset than the model. The
- observed offshore phosphate enrichment is about 0.05  $\mu$ M (Figure 4c), which is about half of the
- modelled increase (Figure 4f). The observed nearshore phosphate reduction is only about 0.02
- $\mu$ M (Figure 4c), whereas the modelled reduction is close to 0.1  $\mu$ M (Figure 4f). The observation-
- based dataset generally shows much smaller difference across the entire domain, possibly due to

interpolation with smoothing to minimize the error from sparse in-situ data which can result in
 suppressing variability (Yasunaka et al., 2021).

267 To further evaluate the model performance, we used the vertical profiles of dissolved phosphate

concentrations along 137°E observed annually during winter over the last 26 years (Figure 5).

- The vertical profiles are available at every 1° latitude (Figure A2), but our analysis focused on
- the profiles at 29°N, 32°N, and 34°N, which respectively correspond to regions of neutral,
- 271 positive, and negative anomalies in the modelled winter phosphate concentrations during the
- large meander relative to the non-large meander (Figure 2c,f). In general, the model
- 273 underestimates the phosphate concentration below the surface mixed layer.
- 274 The observed profiles show no clear distinction between the large meander and non-large
- meander states at 29°N, which is consistent with the model (Figure 5a). At 32°N, there is a
- robust difference throughout the depth between the two phases (Figure 5b); the observed
- 277 concentrations at every vertical level were always higher during the large meander than those of
- the non-large meander. This robust distinction is also evident from the model simulation. Within
- the surface mixed layer, the observed concentration difference is about 0.1  $\mu$ M. Below the
- surface mixed layer, the observed concentration difference increases with depth up to about 1.8
- $\mu$ M at 400 m, and then decreases (Figure 5b). A very similar concentration difference in terms of
- both the magnitude and the vertical variation is simulated by the model.
- At 34°N, the observed profiles generally show 0.1-0.5 μM lower phosphate concentrations
- during the large meander than the non-large meander in the surface mixed layer (Figure 5c), with
- an exception of one large meander year (2018; Figure A2). Below the surface mixed layer, the
- difference is indistinguishable between the large meander and non-large meander phases. The



model also simulates about 0.1  $\mu$ M lower phosphate concentrations during the large meanders on average, extending from the surface mixed layer to about 400 m.

#### 289

**Figure 4.** Comparison of observation-based January-February composite surface phosphate

concentration south of Japan during (a) the large meander and (b) the non-large meander, and (c)

their difference. Differences between the modelled and observation-based composites during (d)

the large meander and (e) the non-large meander. (f) Difference between the large meander and

non-large meander composites of the model output. Here, the model output is interpolated to the

295 grid of the observation-based dataset.



296

Figure 5. Comparisons of vertical dissolved phosphate concentration profiles in the upper 800 m
between the large (LM; red) and non-large (NLM; blue) meander years at (a) 29°N, (b) 32°N,
and (c) 34°N along 137°E collected between late-January and early-February annually since
1997. Magenta and cyan show the comparable profiles simulated by the model with errorbars
denoting ±1 standard deviations from the January-February averages.

### 302 **3.2.2 Seasonal Cycle**

303 The biogeochemical impacts of the large meander have distinct seasonality as illustrated by the

304 seasonal cycle comparison at the offshore and nearshore regions where the most prominent

differences were identified (Figure 6). Both at the offshore and nearshore regions, the nutrient

306 concentration differences are robust from December to March, meaning that the concentrations

- between the large meander and non-large meander cases do not overlap even within one standard
- deviation ranges around their means (Figure 6a,b). Nutrient concentration differences decrease
   from April and are negligible from June to October, during which the concentrations are close to
- from April and are negligible from June to October, during which the concentrations are clos zero. In contrast, the nutricline depth does not vary seasonally at either location, and the
- differences between the large meanders and the non-large meanders are clear (Figure 6c,d). The
- 312 lack of seasonality in the nutricline depth suggests that the surface nutrient concentration
- differences emerge only during winter because they are driven by winter convective mixing, and
- not processes that do not have specific seasonality such as eddy suction (Chang et al., 2017). The
- large meander enhances the winter nutrient replenishment in the offshore region by shoaling the
- nutricline depth (Figure 6c), thereby yielding higher surface nutrient concentrations compared to
- the non-large meander phases (Figure 6a). In contrast, the nearshore nutrient replenishment is
- 318 stronger during the non-large meander phases when the shoaling effect of the Kuroshio is
- 319 stronger (Figure 6d), resulting in higher surface nutrient concentrations than the large-meander
- case (Figure 6b). The mixed layer depth is always shallower in the offshore region during the
- large meander winters (January-March; Figure 6e), which rules out the possibility that the
- 322 strength of the convective mixing drives the offshore nutrient enrichment. In other words, the
- 323 shoaling effect of the nutricline overwhelms that of the mixed layer.
- 324 The seasonal cycles of modelled surface phytoplankton biomass reveal that the large meander
- 325 changes not only the magnitude, but also the timing of the spring bloom in the offshore region
- 326 (Figure 6g). The increased supply of phosphate during winter enables phytoplankton to form a
- 327 bloom offshore that peaks in May. In the case of the non-large meander, the peak arrives a month
- 328 later in June. In the nearshore region, the seasonality can be characterized by a spring bloom that
- peaks in May, which is common to both the large meander and non-large meander phases
- 330 (Figure 6h). The only difference is that the biomass is consistently higher during the non-large
- meander phases, which is likely caused by the difference in the nutrient availability (Figure 6b).
- 332 The higher biomass during large meanders in the offshore region and during non-large meanders
- in the nearshore region continues even in summer, which indicates the continuous nutrient input



from the subsurface thanks to the shallow nutricline. Surface phosphate concentrations remain

low probably because nutrients are consumed as soon as they are supplied.

336

**Figure 6.** Comparisons of modelled monthly composite seasonal cycles of (a,b) surface dissolved phosphate concentration, (c,d) nutricline depth, (e,f) mixed layer depth, and (g,h) phytoplankton phosphorous biomass averaged over the (a,c) offshore and (b,d) nearshore regions

defined in Figure 2 during the large (red) and non-large (blue) meander phases. Error bars

represent the standard deviations of monthly area-averaged values incorporated into each phase.

### 342 **3.2.3 Latitudinal Distributions and Correlations**

The latitudinal position of the Kuroshio has strong influence on the latitudinal distributions of 343 winter nutrient availability and spring phytoplankton biomass in the Kuroshio region (Figure 344 7a,b). There is a clear pattern that the north of the Kuroshio is always higher in phosphate 345 concentration and phytoplankton biomass than its southern counterparts. However, there are a 346 few exceptions that can be categorized into two groups. First, the phosphate concentration and 347 the phytoplankton biomass 1° north of the Kuroshio are higher but they decrease further north 348 until reaching near the coast in some cases (e.g., Year 239). This pattern emerges when the 349 Kuroshio takes the S-shaped path (Kasai et al., 1993) along 137°N (Figure A4). In this case, it is 350

more appropriate to refer to the position of the phosphate-rich surface water (and hence the

- 352 shallow nutricline area) as being left of the Kuroshio path, rather than the north of the Kuroshio.
- The other exception to the latitudinal distributions relative to the Kuroshio position is the
- presence of higher values further south of the Kuroshio that are especially evident from the
- phytoplankton biomass distribution (e.g., the first 4 years; Figure 7b). This pattern likely reflects
- local blooms south of the Kuroshio path, which would be located further south during the large
- 357 meanders.

To elucidate the relationship between winter nutrient availability and spring phytoplankton

bloom in the Kuroshio region, we calculated correlations between the two variables at each
 latitude along 137°N (Figure 7c). Correlation coefficients are above 0.6 throughout the latitudes

- latitude along 137°N (Figure 7c). Correlation coefficients are above 0.6 throughout the latitudes
   between 30.7-33.3°N, indicating the strong relationship between winter nutrient availability and
- the subsequent bloom strength on a year-to-year basis. Correlations are weaker north of this
- latitudinal band probably because the phosphate concentration is generally high in the nearshore
- region, and so there must be other processes that drive the interannual variability of the spring
- bloom magnitude. Correlations are generally also weaker south of 30.7°N (except around







**Figure 7.** Latitudinal distributions of (a) February surface dissolved phosphate concentration and

369 (b) May surface phytoplankton phosphorous biomass along 137°E over the last 44 years of the

model integration. Crosses denote the locations of the Kuroshio axis determined from the sea

<sup>371</sup> level gradient along 137°E. (c) Latitudinal distribution of the Pearson's correlation coefficients

between the February surface dissolved phosphate concentration and May surface phytoplankton

biomass along 137°E over the last 44 years of the model integration.

### 374 **3.3 Primary Production, Ocean Carbon Uptake, and Export Production**

375 The spatial anomalies of the highs in the offshore region and the lows in the nearshore region

- during the large meander phase are also present in annual primary production, ocean carbon
- uptake, and export production (Figure 8). This spatial coherence is expected as higher
- 378 phytoplankton biomass leads to increased primary production, which results in greater biological
- carbon uptake and pump. Despite the prominent spatial anomalies, the differences between the



- large meander and non-large meander phases are minimal (<5 % difference) when these 380
- quantities are integrated over the entire study area. 381

382

Figure 8. Spatial comparisons of modelled annual mean (a-c) depth-integrated net primary 383 production, (d-f) air-sea carbon flux (positive means flux into the ocean), and (g-i) vertical 384 detritus export at 100 m during the large meanders (a,d,g) and the non-large meanders (b,e,h), 385 and (c,f,i) their differences. Solid lines in (a,b,d,e,g,h) represent the path of the Kuroshio, defined 386 by the annual mean sea level contour at which the latitudinal gradient is maximum along 137°E. 387

#### **4** Discussion 388

- In this study, we characterized the biogeochemical impacts of the Kuroshio large meander by 389
- generating monthly composites of modelled biogeochemical variables during the large meander 390
- and non-large meander phases from a multi-decadal simulation output of a 0.1° global sea ice-391
- ocean coupled model. Biogeochemical responses in the model correspond well with the 392
- observations even though the Kuroshio axis in the model is generally positioned further south 393
- during large meanders. Our spatial analysis reveals that the large meander enhances winter 394
- nutrient availability offshore south of Japan by extending the shallow nutricline area that is 395
- always positioned on the left side of the Kuroshio path and replenishes the surface water with 396

- 397 nutrients through seasonal convective mixing (Kuroda et al., 2018). The nutrient enrichment in
- this typically nutrient-poor offshore region during the large meander winter allows
- 399 phytoplankton to form a bloom a few months later during spring. This offshore large meander
- 400 bloom arrives a month earlier with a greater magnitude compared to the bloom during the non-
- large meanders, and is also evident from satellite observations (Lizarbe Barreto et al., 2021).
- 402 Such a distinct difference in both the timing and magnitude of the spring bloom may alter the
- 403 spatial distributions of fish abundance and species.
- In contrast to the offshore region, the nutrient concentration and phytoplankton biomass in the nearshore region are lower throughout the year during the large meander. This reduction is
- 406 caused by weakened shoaling effect of the Kuroshio, which makes the subsurface nutrients less
- 407 accessible by winter convective mixing. The phosphate measurements along 137°N indicate that
- 408 our model may have overestimated the magnitude of the nutrient reduction during the large
- 409 meander. On the other hand, the satellite observations suggest that the magnitude of the
- 410 reduction of the nearshore phytoplankton biomass is similar to that of the offshore increase
- 411 (Lizarbe Barreto et al., 2021), which is consistent with our model results. In the nearshore region,
- 412 nutrient availability is important not only for phytoplankton, but also for macroalgae such as
- 413 seaweed, which is an essential seafood product for Japan.
- Essentially, the spatial pattern of the biogeochemical signature of the large meander corresponds
- to the inverse of temperature anomalies (Sugimoto et al., 2020). However, such biogeochemical
- anomalies of the large meander will have an influence on macroalgae and higher trophic levels
- that is disproportionate to the thermal effect. For example, the nearshore warming during the
- large meander has been related to an increase in sardine egg abundance, whereas the egg
- abundance of another fish species (anchovy) was more closely linked to water transparency,
- 420 which is an indicator of food availability (Nakata et al., 2000). Such complexity of fish responses
- to both physical and biogeochemical processes necessitates more thorough assessment of the
- 422 large meander impacts on fisheries and aquaculture, which is possible by combining
- 423 biogeochemical model simulations, satellite ocean color, and in situ monitoring.
- Besides the shoaling effect, the Kuroshio path can determine the regional biogeochemical
- anomalies directly by transporting nutrient-poor waters. It is interesting to note that our model
- shows a slight decrease in phosphate (Figure 2c) and phytoplankton biomass (Figure 3c) in the
- 427 Seto Inland Sea during the large meanders. While this result might not be robust because of the
- limited resolution of the model, previous studies suggested the control of the Kuroshio water
- intrusion on the hydrographic and biogeochemical properties of the Seto Inland Sea (e.g.,
- 430 Kobayashi & Fujiwara, 2008). Such direct impacts of the Kuroshio remain as a subject of future
- 431 studies.
- A strong correlation between winter nutrient availability and spring phytoplankton bloom in the
- 433 offshore region gives prospects for improving predictability of the large meander impacts by

- 434 implementing biogeochemistry into an operational ocean forecasting system (e.g., Miyazawa et
- al., 2017). Furthermore, marine industries may benefit from decadal predictions of
- biogeochemical states, as the decadal variability of the Kuroshio large meander is expected to
- 437 strengthen in the future due to the stronger decadal variability of the Kuroshio Extension (Joh et
- 438 al., 2022) that is closely linked to the large meander occurrence (Usui et al., 2013). Such
- biogeochemical implementation into a decadal ocean prediction system (e.g., Kido et al., 2022)
   has great potential in supporting long-term adaptation planning for future large meanders that
- 441 may last longer than the ongoing record-breaking event, as demonstrated by our model
- 442 simulations.

### 443 Appendix



Figure A1. Monthly time series of the Kuroshio axis latitude over 1961-2021 determined by the
Japan Meteorological Agency. Green denotes monthly values with the 13-month central moving
average indicated by pink. Orange shadings denote the large meander events since 1965.



**Figure A2.** Comparisons of the winter transects of dissolved phosphate concentrations from

- 450 29°N to 34°N along 137°E observed annually during late January-early February by the Japan
- 451 Meteorological Agency since 1997. The large meander years are indicated by bold font in
- 452 subplot titles.





454 **Figure A3.** Monthly anomalies of modelled (a) temperature, (b) phosphate concentration, (c)

455 phytoplankton phosphorous biomass, (d) zooplankton phosphorous biomass, (e) detritus

- 456 phosphorous concentration, and (f) natural dissolved inorganic carbon concentration averaged
- 457 over the upper 1,000 m of the Kuroshio region (129-144°E by 28-36°N). Values represent
- 458 anomalies relative to their monthly climatology and shadings denote  $\pm 3$  standard deviations over
- the last 30 years of the model integration. Vertical lines denote 15 years after the biogeochemical
- 460 model initialization.





462 **Figure A4.** Daily-mean snapshots of modelled (a,c) dissolved phosphate concentration and (b,d)

- 463 phytoplankton phosphorous biomass (a,b) in the surface layer and (c,d) along the 137°E
- latitudinal cross section on May 14 of Year 211. Solid lines in (a) and (b) represent the path of
- the Kuroshio, defined by the sea level contour at which the latitudinal gradient is maximum
- along 137°E. Dotted lines in (c) and (d) denote the Kuroshio axis, defined by the latitude at
- 467 which the latitudinal sea level gradient is maximum along 137°E.

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- 476 conflicts of interest to declare.

### 477 **Open Research**

- The ACCESS-OM2-01 output is available to download from
- 479 <u>http://dx.doi.org/10.25914/608097cb3433f</u> (last accessed on November 28, 2022). The model
- 480 source code (<u>https://github.com/COSIMA/access-om2</u>; last accessed on November 28, 2022) and
- 481 configuration (<u>https://github.com/COSIMA/01deg\_jra55\_iaf/tree/01deg\_jra55v140\_iaf\_cycle4;</u>
- last accessed on November 28, 2022) are available on github. The hydrographic transect data
  along 137°E
- 484 (https://www.data.jma.go.jp/gmd/kaiyou/db/mar\_env/results/OI/137E\_OI.html#data; last
- accessed on November 28, 2022) and the monthly Kuroshio axis time series
- 486 (https://www.data.jma.go.jp/kaiyou/data/shindan/b\_2/kuroshio\_stream/kuro\_slat.txt; last
- 487 accessed on November 15, 2022) are available to download from the Japan Meteorological
- 488 Agency website. The observation-based nutrient gridded product is available to download from
- 489 <u>http://caos.sakura.ne.jp/sao/north-pacific-surface-nutrients/</u> (last accessed on December 29,
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