

Article



Behaviors of the Yukon River Sediment Plume in the Bering Sea: Relations to Glacier-Melt Discharge and Sediment Load

Kazuhisa A. Chikita ^{1,*}, Tomoyuki Wada ², Isao Kudo ³, Sei-Ichi Saitoh ¹, Toru Hirawake ⁴ and Mitsuhiro Toratani ⁵

- ¹ Arctic Research Center, Hokkaido University, Sapporo 001-0021, Japan; ssaitoh@arc.hokudai.ac.jp
- ² Earth System Science, Co., Ltd., Tokyo 160-0022, Japan; wada-tomoyuki@ess-jpn.co.jp
- ³ Faculty of Fisheries Science, Hokkaido University, Hakodate 041-8611, Japan; ikudo@fish.hokudai.ac.jp
- ⁴ National Institute of Polar Research, Tokyo 190-8518, Japan; hirawake.toru@nipr.ac.jp
- ⁵ Department of Optical and Imaging Science and Technology, Tokai University, Hiratsuka 259-1292, Japan; tora@keyaki.cc.u-tokai.ac.jp
- * Correspondence: chikita@sci.hokudai.ac.jp; Tel.: +81-11-772-4292

Abstract: Sediment plumes, released to the Bering Sea from the delta front of the Yukon River, Alaska, are initiated mainly by glacier-melt sediment runoffs in the glacierized regions of the Yukon River drainage basin. The surface sediment plumes are extended around the fan-shaped Yukon River delta, which is followed by the northwestward dispersion. During continuous measurements of the Yukon River discharge and sediment load, behaviors of the sediment plumes were explored by shipboard and coastal observations in the Bering Sea. At the high river sediment load of ca. 2500 kg/s, the plume partially plunged into the sea bottom layer. The plunging probably originated in the nepheloid-layer formation from the flocculation of river-suspended sediment, of which more than 90% wt. is silt and clay (grain size d < 63 μ m). In order to numerically obtain the area of the surface sediment plumes, a satellite image analysis was performed by using three near-infrared bands in MODIS/Aqua or MODIS/Terra. The plume area was significantly correlated (R² = 0.735, *p* < 0.01) to the sediment load averaged for the two days with time lags of 20 days and 21 days to the date of a certain satellite image. Hence, the dispersion of plume-suspended sediment appears to be controlled by the sediment runoff events in the Yukon River rather than the northward "Alaskan Coastal Water".

Keywords: Yukon River; sediment load; surface sediment plume; density underflow; MODIS image

1. Introduction

In the coastal area receiving the river inflow, the river water is mixed with the marine water, accompanied by the dissipation of flow energy. Thereafter, the mixed water (brackish water) departs from the bottom bed to the surface layer and moves offshore as a slow hypopycnal (buoyant) surface plume (flow speed of the 0.1 m order) [1]. The liftoff of the mixed water up to the surface layer is based on the fact that the mixed water density ρ (e.g., $\rho = 1001-1012 \text{ kg/m}^3$ at 25 °C in temperature and 5–20‰ in salinity at water surface) is smaller the marine water density (~1023 kg/m³ at 25 °C and ca. 35‰ at water surface). The offshore movement of such a river plume is accompanied by the dispersion or advective diffusion of terrigenous dissolved and suspended matters, of which the adsorption and deposition can be incorporated into the coastal and marine ecosystems, including carbon and nutrient cycles [2,3].

When the river is rich in suspended sediment, as in the high sediment runoffs by heavy rainfall, snowmelt or glacier-melt, the river sediment plume mostly behaves as a surface sediment plume in the offshore region. This is because the mixed water in the coastal region generally has the suspended sediment concentration (SSC) of much less than ca. 5 g/L, thus being much lighter than the marine water [4,5]. Then, the bulk density



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). ρ_t (kg/m³) of the mixed water at SSC, C (g/L) is obtained by $\rho_t = \rho(1 - C/\sigma) + C$, where σ is particle density (kg/m³). The density σ can vary greatly at 1030–2850 kg m⁻³, depending on the content rate of particulate organic matters [6,7].

Behaviors of such a sediment surface plume can be affected by littoral, tidal and wind-driven currents, and hydrological conditions of the river [5,8,9], of which the dynamical influence changes depending on the turbulent level of the currents and the distance from the estuary. For example, by shipboard observations and satellite images of surface water temperature for the Mackenzie River plumes in the Arctic Ocean (Mackenzie River discharge, 9.8×10^3 m³/s as annual mean), Mulligan et al. [10] showed that the offshore movement of the river plume and the onshore transport of the deeper shelf water are strongly affected by wind-driven currents at 5–10 m/s wind. With respect to the Amazon River (2.0×10^5 m³/s as annual mean), applying the 16-year data of satellite images and river discharge to the Amazon River plumes, Gouveia et al. [11] pointed out that a positive precipitation trend in the western Amazon basin makes the river plumes decrease the ocean salinity on the pathway by increasing the river discharge.

For river plumes of the small scale, with river discharge of $10 \text{ m}^3/\text{s}$ order or less, the effects of tidal and wind-driven currents on the plumes' dispersion are relatively strengthened. For example, by the vertical profiling of water quality on the ship and numerical simulation, Masunaga et al. [12] showed that the mixing of the river plume initiated by river discharge of $3-35 \text{ m}^3/\text{s}$ is dominated by the wind stress and baroclinic tidal flow.

Focusing on sedimentation in the coastal and offshore zones under the influence of river inflow, behaviors of suspended sediment in the mixing zone with decaying flow energy and increasing salinity, and in the offshore zone, accompanied by the surface sediment plume and associated currents, are important to know the sedimentary processes. In the mixing zone, of which the bottom is often gently sloped, the flocculation (or aggregation) of suspended sediment tends to prevail and consequently produce a nepheloid (suspended-sediment rich) layer near the bottom, which can shift to density underflow moving downslope more offshore [13]. The flocculation process of suspended sediment has been explored by field observations, laboratory experiment and numerical models [14–17]. However, the connection of the flocculation process to the subsequent nepheloid layer behaviors is not well known [18,19]. It is because growing the first thin nepheloid layer up to the one thick enough to produce the density underflow on the slope is difficult in the laboratory experiment and numerical simulation.

An objective of this study is to investigate how the river sediment plume dynamically behaves and is dispersed in the coastal and offshore regions, being exemplified by the Yukon River sediment plume. In this paper, the formation of the nepheloid layer ascertained by the outboard observations in the coastal region is connected to offshore behaviors and associated sedimentary process of the Yukon sediment plume obtained by shipboard observations and satellite image analyses.

2. Study Area

The eastern shelf region of the Bering Sea $(2.29 \times 10^6 \text{ km}^2 \text{ in area})$, where the Yukon River plume is mainly dispersed, is 50–70 m deep on average. The region at a distance of less than ca. 170 km off the delta front is shallow at less than 30 m in depth, which is due to sedimentation from sediment load of the Yukon River and the surrounding rivers (Figure 1) [20]. Behaviors of the Yukon sediment plume and the consequent dispersion of the plume-suspended sediment was considered to be controlled by the northern movement of the "Alaskan Coastal Water" [20–22], which was connected to the bottom distribution of clay minerals on the Alaskan-Chukchi margin [23].

Most of the Yukon River drainage basin (area, $8.55 \times 10^5 \text{ km}^2$) is located in the subarctic region south of the Arctic Circle (66°33′ N) and is occupied by 74.8% forest with discontinuous permafrost and 1.1% glacierized area in Alaska Range, Wrangell Mts., St. Elias Mts., etc. [24–27]. Site PLS (Pilot Station) is the lowest gauging station of the

United States Geological Survey (USGS) at ca. 170 km upstream of sites ALK and site EMK, base villages for the coastal observations (Figure 1). The drainage area upstream of site PLS is 3.21×10^5 km², and at site PLS, annual discharge, annual sediment load and annual sediment yield were 1.97×10^2 km³/year, 44.5 Mt/year and 53.5 t/km²/year in 2007 and 2008, respectively [26]. Hence, of the six largest rivers in the subarctic to arctic regions (Mackenzie in Canada, Yukon in USA/Canada, and Amur, Lena, Ob and Yenisei in Russia), the Yukon River is the sixth largest river for annual discharge, but the second largest river for annual sediment load (the top is Mackenzie at 100 Mt/year) and the largest river for annual sediment yield [28].

As a characteristic of suspended and bottom sediments in the Yukon River and its glacial tributaries, the sediments mostly consist of silt and clay, produced by glacial erosion of bedrock in the glacierized headwater regions. Thus, the bed of the Yukon River at site PLS is not gravelly, where the suspended sediment is fine-grained with more than 90% wt. silt and clay [26,27]. By measuring the bedload transport rate in the Tanana River, one of the Yukon's glacial tributaries [29], Burrows et al. [30] showed that the bedload occupies only the 1% order of the suspended load.



Figure 1. (a) Location of observation sites, B42–B53, offshore from the Yukon River delta on 1–2 August 2007 and 2–4 July 2008; (b) clear RGB (red-green-blue color model) satellite images of MODIS/Terra (2250 h, 25 July 2007 and 2315 h, 5 July 2008 in GMT) for the Yukon sediment plume, taken on the dates closest to the observations. The label "PLS" shows the location of the USGS Yukon River gauging station. The "ALK" and "EMK" are base villages for coastal observations (observation sites; three black circles with no name and sites B1–B10) near the Yukon delta front [31].

The Yukon River delta is fan-shaped with branching the Yukon River channel into smaller river channels, and thus the river sediment plume tends to be dispersed around the coastal line of the delta front (Figure 1b).

3. Methods

3.1. Field Observations

In order to explore behaviors of the sediment plume released from the Yukon River delta, observations in the coastal and offshore regions were undertaken by an outboard and a research training ship, the Oshoro-maru (1396 ton in weight), Faculty of Fisheries Sciences, Hokkaido University, respectively (Figure 1).

The observations by the Oshoro-maru were conducted on 1–2 August 2007 and 2–4 July 2008. The observation in 2007 started at site B42 at 1235 h, 1 August and ended at site B53 at 1831 h, 2 August, and that in 2008 started at site B42 at 2320 h, 2 July and ended at site B53 at 0253 h, 4 July. Thus, the observations in 2007 and 2008 took ca. 30 h and ca. 28 h for all the sites, respectively. Here, all the shipboard observation times are denoted by the Alaska Daylight Time (AKDT), since the time series of Yukon River discharge and sediment load at site PLS were acquired at the AKDT.

At eight sites, sites B42 to B53, at less than 172 km northwest of the delta front (Figure 1a), where the surface sediment plume was visually ascertained, vertical profiles of water temperature, electric conductivity at 25 °C (EC25) and water turbidity were obtained every 0.1 m in water depth by a TCTD (turbidity, conductivity, temperature, and depth) profiler (model ASTD687, JFE Advantech, Co., Ltd., Nishinomiya, Japan) [32,33]. While lowering the profiler below water surface by rope (descending speed of 0.5 m/s or less), water temperature, electric conductivity and water turbidity were automatically recorded in the profiler itself, with the pressure sensor responding to the water pressure increasing at the 0.1 m depth interval. Meanwhile, surface water and bottom sediment were sampled by a 2 L Van-Dorn water sampler (URL: https://www.kc-denmark.dk/products/water-sample grab sampler [34], respectively. The undisturbed sediment ca. 0.1 m thick below the bottom surface was then sampled.

The water turbidity, x (ppm) was changed into suspended sediment concentration, y (SSC; mg/L) by using a regression curve, $y = 1.597 \times 0.8119$ at x = 0-160 ppm ($R^2 = 0.932$, p < 0.01). The regression curve was acquired from plots between the turbidity and the SSC of surface water sampled simultaneously on the ship. The regression curve is suitable only for the Yukon River sediment plume, since the turbidity vs. SSC relation can vary water by water, depending on the size, mineralogy and organic content rate of suspended sediment and the optical feature of water under condition of no suspended sediment.

The SSC was obtained by filtering a certain volume of sampled water with the glass filter GF/B (1.0 µm opening) (URL: https://www.cytivalifesciences.com/en/us/about-us/our-brands/whatman (accessed on 25 September 2021)), and weighing the dried filters. In addition, the EC25 values in mS/m were converted into NaCl (‰) water as salinity by the linear relationship (R² = 0.992, *p* < 0.001) between EC25 and salinity. Here, water density $\sigma_{\rm T}$ was calculated by $\sigma_{\rm T} = \rho(S, T, 0) - 1000$, where $\rho(S, T, P)$ is water density (kg/m³) and a function of salinity S (‰), water temperature T (°C) and pressure P (=0 at 1 atm).

During the measurements of the Yukon River discharge and sediment load at site PLS, vertical profiles of water temperature, EC25 and water turbidity were acquired at the three sites (three black circles near site ALK in Figure 1) in coastal regions by using the same profiler on 7 June and 9 September 2008. Then, bottom sediment was also sampled by the grab sampler. At sites B1 to B10 (black circles in the inserted map of Figure 1a), similarly, the profiles and bottom sediment were obtained in September 2009 and June 2010 [31]. These coastal observations were performed to explore relations between the Yukon plume's behavior and the river discharge and sediment load, and to connect them to the observational results at sites B42 to B53. In order to know the sedimentary process by the sediment plume, the grain size of the bottom sediment was related to that of the bottom sediment at sites B42 to B53.

At site PLS, ca. 170 km upstream of the delta front, time series of hourly and daily mean sediment load were obtained in June 2006–September 2009 by using the suspended sediment concentration (SSC; g/L) converted from water turbidity (ppm) and the river discharge data of USGS (U.S. Geological Survey) (URL: http://waterdata.usgs.gov/nwi s/dv/?site_no=15565447&agency_cd=USGS&referred_module=sw (accessed on 7 May 2021)) [26]. The discharge is acquired by applying the H-Q rating curve from recorded river stage, H (m) and simultaneously measured discharge, Q (m³/s) by USGS, which is updated every year. Hourly and daily mean time series of water temperature were also

obtained at site PLS by a temperature logger (TidbiT v2, Onset Computer, Inc., Bourne, MA, USA) [26].

In order to explore the influence of wind-driven currents on the dispersion of surface sediment plume, the hourly wind velocity data at the airports of site EMK and Nome were utilized (URL: https://www.wunderground.com/history/daily/us/ak/emmonak, URL: https://www.wunderground.com/history/daily/us/ak/nome (accessed on 2 and 10 August 2021)) (Figure 1a). The hourly wind data were then compiled into the data of daily mean wind speed and direction, which were applied to judge if the wind-driven currents promote or suppress the northwestern dispersion of the surface sediment plume.

Relatively clear RGB (red–green–blue color model) composite images of MODIS/Terra from the NASA oceanic web site (URL: http://oceancolor.nasa.gsfc.gov (accessed on 19 and 24 February 2021)) closest to the dates of the marine observations are shown in Figure 1b. The horizontal distributions of the surface sediment plumes on the images indicate that the B50–B53 line was relatively close to the center line of the sediment plume extending northwestward, and that site B53 was located near a farthest margin of the plume.

3.2. Laboratory Experiments

The bottom sediments sampled at sites B42 to B53 and the 13 sites in the coastal region were analyzed for the grain size by the photo-extinction method with a centrifuge for particles of grain size $d \le 44 \ \mu m$ (micrometers) and by the sieving method for $d > 44 \ \mu m$ particles [26]. With respect to the flocculation of suspended sediment in the coastal region, the grain size of suspended and bottom sediments at site PLS was similarly analyzed. Then, using the bottom sediment at site PLS, the salinity effect on the grain size of suspended sediment was explored by increasing the salinity in pure water [31]. Meanwhile, mineralogical analyses were conducted by the XRD (X-ray diffraction) method for suspended sediment in water sampled at site PLS and site B9 (Figure 1a).

3.3. Image Analysis

In order to know hydrological effects of the Yukon River on behaviors of the surface sediment plumes in the Bering Sea, the plumes' area during the monitoring of river stage and turbidity at site PLS was numerically obtained by using the Aqua Level 1 Products from the NASA oceanic web site mentioned before. Three near infrared bands (wavelength; 667, 748 and 869 nm) of MODIS/Aqua or MODIS/Terra (MODIS; Moderate Resolution Imaging Spectroradiometer) were applied to each image for scaling suspended sediment concentration (SSC) of the plume. Here, the satellite observed reflectance L_T for each of wavelengths, 667, 748 and 869 nm is given as follows:

$$L_{\rm T}(667) = L_{\rm M}(667) + L_{\rm A}(667) + t(667)L_{\rm W}(667), \tag{1}$$

$$L_{\rm T}(748) = L_{\rm M}(748) + L_{\rm A}(748) + t(748)L_{\rm W}(748), \tag{2}$$

$$L_{\rm T}(869) = L_{\rm M}(869) + L_{\rm A}(869) + t(869)L_{\rm W}(869), \tag{3}$$

where L_M is the reflectance due to gas molecules, L_A is the reflectance due to aerosol particles, L_W is the reflectance due to water body (our target), and t is the diffuse transmittance between sea surface and satellite on the assumption of single scattering. This assumption requires that neither the single scattering albedo nor the phase function depends on wavelengths. In addition, the reflectance L_A by aerosol particles is supposed to follow the Ångström' law as follows:

$$\mathcal{L}_{\mathcal{A}}(\lambda) \cong \left(\frac{\lambda}{869}\right)^{-\alpha} \frac{F_0(\lambda)}{F_0(869)} \mathcal{L}_{\mathcal{A}}(869),\tag{4}$$

where λ is the wavelength (nm), α is the Ångström exponent, and F₀ is the extraterrestrial solar irradiance. Here, the reflectance L_A at a certain wavelength is assumed to be nearly

equal to that normalized by the parameters at $\lambda = 869$ nm. Then, L_w in Equations (1)–(3) is given in the following:

$$L_{w}(667) = R_{rs}(667) \cdot F_{0}(667) \cdot \cos\theta_{0} \cdot t_{0}(667),$$
(5)

$$L_{w}(748) = R_{rs}(748) \cdot F_{0}(748) \cdot \cos\theta_{0} \cdot t_{0}(748), \tag{6}$$

$$L_{w}(869) = R_{rs}(869) \cdot F_{0}(869) \cdot \cos\theta_{0} \cdot t_{0}(869),$$
(7)

where θ_0 is the solar zenith angle, t_0 (λ) is the diffuse transmittance between the sun and sea surface at a wavelength λ , and R_{rs} (λ) is the remote-sensing reflectance at λ . Here, two parameters, α and $L_A(869)$ in Equation (4) and the relationship between R_{rs} (λ) and SSC (mg/L) at or near water surface in Equations (5)–(7) are unknown. Hence, if certain α and $L_A(869)$ values are given, the relationship between R_{rs} and SSC is obtained for the wavelengths, 667 nm, 748 nm and 869 nm. As a result, following relations were obtained in case of the East China Sea and Yellow Sea [35]:

$$R_{\rm rs}(667) = 0.000561 \cdot C^{1.1156} \ (R^2 = 0.692, \, p < 0.01), \tag{8}$$

$$R_{\rm rs}(748) = 0.0000854 \cdot C^{1.140} \ (R^2 = 0.607, \, p < 0.01), \tag{9}$$

$$R_{\rm rs}(869) = 0.0000763 \cdot C^{0.997} \ (R^2 = 0.849, \, p < 0.01), \tag{10}$$

where C is SSC (mg/L) in situ at or near water surface. Finally, using Equations (8)–(10), the L_W values were calculated from Equations (5)–(7), and then compared with the ship-observed SSC values. In this study, the following relationship was applied:

$$C = 0.657 \cdot C_{sat}^{1.32} \ (R^2 = 0.723, \, p < 0.01), \tag{11}$$

where C_{sat} is SSC (mg/L) at or near water surface from MODIS/Aqua or MODIS/Terra images. Equation (11) is applicable for $C_{sat} < \sim 20$ mg/L. Clear RGB Images in June–September of 2005–2009 were adopted for scaling the SSC of sediment plumes.

Thus, the three bands were used to solve the simultaneous equations with the three unknowns, i.e., the Ångström exponent, SSC and the aerosol reflectance of 869 nm. The equations hold to remove the effect of aerosol particles from the reflectance of aerosol particles and water body by applying the Ångström' law to the aerosol reflectance and the water body reflectance to SSC.

In Equation (11), there is not the 1:1 correspondence between C and C_{sat} such as in Zang et al. [36], where the SWIR method by Wang et al. [37] and the NIR iterative method in the analysis software, SeaDAS (URL: https://seadas.gsfc.nasa.gov/ (access on 6 May 2021)), were adopted for the atmospheric correction to retrieve SSC at a wide range of the 0.1 to 100 mg/L order. Doxaran et al. [38] obtained the linear relationship between C and C_{sat} from MODIS/Aqua or MODIS/Terra images for the high SSC of 100–2000 mg/L.

4. Results

4.1. Sediment Plume Behaviors by Field Observations

Figure 2 shows cross-sections of SSC, water temperature, salinity and water density σ_T along the B50 to B53 line on 2 August 2007 (Figure 1). The observation along the line took ca. 7 h (1123 h–1831 h in AKDT). Corresponding to the observation date, daily mean values of SSC, discharge, sediment load and water temperature at site PLS were 287 mg/L, 1.06×10^4 m³/s, 3.04×10^3 kg/s and 17.9 °C on 31 July 2007, respectively, where 2 days (equal to the distance, 170 km, divided by rough river flow speed, 1 m/s) were considered as an approximate time needed to flow downstream from site PLS to the delta front. The 21-day values averaged for 11–31 July 2007 at site PLS were 318 mg/L for SSC, 1.04×10^4 m³/s for discharge, 3.33×10^3 kg/s for sediment load and 18.6 °C for water temperature. Here, more 20 days (equal to the distance, 172 km, divided by supposed plume speed, 0.1 m/s) were considered as another approximate time needed to north-



westerly flow from the delta front to site B53, one of the farthest points (Figure 1). There was no large difference (less than 10%) between the daily mean of July 31 and the 21-day mean values.

Figure 2. Cross-sectional distributions of SSC, water temperature, salinity and water density σ_T on the B50–B53 line obtained on 2 August 2007 (see Figure 1).

There was a surface layer at less than 2 m in depth, accompanied by relatively high SSC and low salinity, which clearly depicts the existence of the buoyant surface sediment plume. Meanwhile, a slightly high SSC layer ca. 5 m thick existed just above the bottom, exhibiting the downslope protrusive distribution of 2–3 °C in temperature. This suggests that a turbid density underflow occurred after the plunging of turbid water in the coastal region. In the coastal observations in 2009 and 2010, Chikita et al. [31] revealed that the plunging followed by the underflow occurs at Yukon River sediment load of more than ca. 2500 kg/s (Figure 3). At the boundary shown by the red vertical line in Figure 3, the underflow appears to have coincided with the liftoff to a surface sediment plume [1]. Then, the corresponding sediment load and discharge at site PLS were 2.89 × 10³ kg/s and 7.39 × 10³ m³/s, respectively. The water temperature distribution in Figure 3 indicates that, at such a boundary, the vertical mixing prevails. The river sediment load for the shipboard observation of August 2007 was more than 3000 kg/s. Hence, the separation into sediment surface plume and density underflow in Figure 2 likely occurred in the coastal zone along the delta front.

Originally, the river water density σ_T at site PLS on 31 July 2007 was -1.12 for SSC at 287 mg/L, water temperature at 17.9 °C and salinity at 0.113‰. Thus, the river water should not be heavier than the marine water of $\sigma_T = 25-26$ on 2 August 2007, including if the mixing of river water with marine water occurs in the coastal area. Hence, the turbid underflow in Figure 2 is considered to have been initiated by the nepheloid layer formation [18] from the flocculation of fine-grained (more than 90% wt. silt and clay; grain size d < 0.063 mm) suspended sediment, which was supplied mainly by the glacier-melt sediment runoffs of the Yukon River in June to September [31].



Figure 3. Longitudinal cross-sections of SSC, water temperature, salinity, and water density σ_T by the coastal observation on the B5–B8 line on 6 September 2009 (Figure 1) [31]. The red dotted line in the SSC cross-section shows a boundary of separation into surface sediment plume and density underflow.

The density underflow observed is unlikely to have been produced by the resuspension of bottom sediment by tidal, littoral or wind-driven currents, because, in the coastal region, the high SSC bottom layer followed by the plunging was formed in the relatively deep zone [31]. The wind at site EMK during the observation in Figure 3 was weak at 1.3 m/s northwesterly on average, thus blowing onshore. Hence, the resuspension by wind-driven currents is again probably low because the separation into surface sediment plume and density underflow in Figure 3 appears to have occurred under the flow energy decay in the mixing zone.

There existed a clear thermocline of 4–10 °C at 10–15 m in depth with a small salinity range of 31–32 ‰, which separated the upper warm brackish layer from the lower cold marine water. However, the whole layer, including the thermocline, was pycnally stratified by increasing σ_T from 20 to 25 downward.

Figure 4 show cross-sectional distributions of SSC, water temperature, salinity and water density σ_T on the B42–B50 line for 1235 h, 1 August–1253 h, 2 August 2007 (Figure 1). On the traverse line, the SSC in the lower layer increased toward site B50, suggesting the center of the turbid underflow near site B50 or in more northeastward regions (Figure 1). On the farther traverse B44–B52 line, the SSC zone of 4–6 mg/L in the lower layer became unclear, compared with that on the B42–B50 line. This is probably due to the flow energy dissipation by lateral spreading of the underflow during the downslope movement [39,40]. The thermocline at depths of 10–15 m was still clear on the traverse lines. The cold marine water at water temperature 1–2 °C, salinity ca. 32‰ and $\sigma_T = 25–26$ thus existed consistently in a lower layer under the surface sediment plume.



Figure 4. Cross-sectional distributions of SSC, water temperature, salinity and water density σ_T on the B42–B50 line obtained on 1–2 August 2007 (see Figure 1).

Figure 5 shows longitudinal cross-sections of SSC, water temperature, salinity and water density σ_T along the B50 to B53 line in July 2008 (Figure 1). The observation took ca. 7 h (1950 h, 3 July–0253 h, 4 July). Daily mean SSC, discharge, sediment load and water temperature at site PLS were 112 mg/L, 1.18×10^4 m³/s, 1.32×10^3 kg/s and 16.7 °C on 1 July 2008. Similarly, the 21-day averaged values at site PLS were 116 mg/L, 1.37×10^4 m³/s, 1.60×10^3 kg/s and 14.6 °C for 11 June–1 July 2008. The SSC and sediment load were less than half of 31 July 2007 or 10–31 July 2007 (Figure 2), though the discharge was ca. 20% larger. A surface high SSC layer clearly existed as a surface sediment plume, but a near-bottom layer of relatively high SSC was not seen in any cross-sections. Instead, the high SSC zone of 1–5 mg/L was extensively distributed from the surface sediment plume to the lower layer including the cold marine water. This suggests that, at sediment load of less than ca. 2500 kg/s, neither a nepheloid layer nor density underflow is produced in the coastal zone.

The coastal observation on 22 June 2010, when the corresponding sediment load and discharge at site PLS were 2.19×10^3 kg/s and 9.12×10^3 m³/s on 20 June 2010, respectively, did not show any separation into surface plume and density underflow, but the offshore extension of the mixing zone with vertically uniform SSC [31]. In the more offshore region, the formation of surface sediment plume, not accompanied by density underflow, is supposed as in Figure 5.

The dynamical difference shown by Figures 2 and 5 thus leads to a conclusion that, at the Yukon sediment load of more than ca. 2500 kg/s, the nepheloid layer from flocculation of suspended sediment and the separation into surface sediment plume and density underflow could occur in the mixing zone and in the more offshore region, respectively.

B50

0

5

10

15

20

25

30

35

70

0

5

10

15

20

25

30

35

70

80

Water Depth (m)

80

B50

90

0

Water temp. (°C)

100

110

120

Distance (km) from Delta Front

130

140

90

water Depth (m)



=24-22

 σ_T

90

100

110

120

Distance (km) from Delta Front

130

80

Figure 5. Cross-sectional distributions of SSC, water temperature, salinity and water density σ_T on the B50–B53 line obtained on 3-4 July 2008 (see Figure 1).

160

5

10

15

20

25

30

35

70

Water Depth (m)

4.2. Analytical Results for Grain Size of Bottom Sediment

150

s 4.6

Figure 6 shows spatial distributions of mean size and standard deviation in grain size of bottom sediments sampled at sites B42 to B53 and in the coastal regions (three black circles with no label in Figure 1a) in 2008. The grains became gradually fine toward site B50 from the delta front with gradual unsorting (increasing standard deviation). This means that the sediment was deposited following the seaward sediment sorting from the delta front as shown by the gray arrow in Figure 6 [41,42]. This sorting is probably based on the downslope movement of the turbid underflow under condition of the high Yukon sediment load at more than ca. 2500 kg/s. The mean size of the bottom sediment was minimum at 75 µm near site B50 (Figure 6a). Hence, the flowing distance is probably about 90 km (Figure 2) as a limit of northwestward movement of the underflow. The sediment sorting has a southwestern boundary as shown by red dotted lines in Figure 6, probably corresponding to a lateral boundary of the underflow. In the traverse cross-section of Figure 4, the bottom layer of relatively high SSC at $>\sim 4 \text{ mg/L}$ becomes thick toward site B50 from near site B49. This indicates that the underflow's center existed to the northeast of site B49.

=25

150

160

26

140



Figure 6. Spatial distributions of (**a**) mean size (μ m) and (**b**) standard deviation in the grain size of the bottom sediments sampled in 2008. The red dotted lines show southwestern boundaries of the sediment sorting probably by the turbid underflow flowing northwestward (gray arrow) from the coastal region.

4.3. Analytical Results for the Satellite Images

Figure 7 shows an example analyzed for a MODIS/Aqua image of the Yukon surface plume by using the three near infrared bands [35]. The image was taken at 0010 h, 7 July 2008 (GMT), thus being close to the observation date of 2–4 July 2008 (Figure 5). Figure 7 shows (a) the RGB composite image, (b) the distribution of SSC, C = 2-20 mg/L, off the delta front, (c) the two subareas of $20 \ge C > 4 \text{ mg/L}$ (blue) and $4 \ge C \ge 2 \text{ mg/L}$ (red), and (d) the area analyzed (inside the yellow rectangle). Here, it is out of scale for C > 20 mg/L in the coastal region (Figure 7b), and the surface plume area in the area closed by a yellow rectangle in Figure 7d ($6.13 \times 10^4 \text{ km}^2$; lat. $62^\circ 00'00''-64^\circ 32'30''$ N, long. $162^\circ 24'00''-167^\circ 45'00''$ W) was numerically obtained as the Yukon plume area. The black zone in the coastal regions in Figure 7b–d was produced by high reflection intensity at the shallow bottom. The surface plume area was calculated by adding such a black zone to the blue and red zones. Consequently, the surface plume area in Figure 7c was evaluated at 24,670 km².

Table 1 shows a list of surface sediment plume areas obtained from the images of MODIS/Terra or MODIS/Aqua in 2005–2009. Sediment load and discharge at site PLS averaged over 21 days were calculated as those corresponding to each plume area. Here, as in the shipboard observations, two days and 22 days as two approximate times needed to flow downstream from site PLS to the delta, and to northwesterly flow from the delta front to site B53, one of the farthest points, respectively, were considered (Figure 1). For each satellite image of the surface plume, river discharge and sediment load at site PLS were averaged for the time period between the date delayed by 2 days and that delayed by 22 days to the date of the satellite image, e.g., for an image of 24 July, averaged over a period (21 days) between 2 July and 22 July with the time lags of 22 days and 2 days, respectively. Then, the GMT of a satellite image was changed into the Alaska Daylight Time (AKDT; GMT–8 h).



Figure 7. Analytical result for SSC, C (mg/L), from a MODIS/Aqua image (0010 h, 7 July 2008; GMT). (a) RGB (red-green-blue color model) composite image, (b) SSC distribution by the three near-infrared bands, (c) two regions separated by $20 \ge C > 4 \text{ mg/L}$ (blue) and $4 \ge C \ge 2 \text{ mg/L}$ (red), and (d) the area (yellow rectangle) analyzed for the surface sediment plume at $C \ge 2 \text{ mg/L}$ (red zone and black zone near the coastal region).

Table 1. Surface sediment plume area obtained from the MODIS/Terra or MODIS/Aqua images and sediment load and discharge at site PLS averaged over the corresponding period (totally 21 days) between the dates delayed by 2 days and 22 days to the date of each image.

No.	Terra (T) or Aqua (A)	Time & Date (AKDT)	Plume Area (km ²)	21-Day Period	Discharge (m ³ /s)	Sediment Load (kg/s)
1	Т	14:25,7/5/2005	22,829	6/13-7/3,2005	17,193	2569
2	А	14:35,7/5/2005	23,903	6/13-7/3,2005	17,193	2569
3	Т	13:55,7/5/2006	29,062	6/13-7/3,2006	13,343	2594
4	Т	15:30,7/5/2006	29,791	6/13-7/3,2006	13,343	2594
5	А	15:45,7/5/2006	29,625	6/13-7/3,2006	13,343	2594
6	Т	14:25, 6/9/2007	21,940	5/18-6/7,2007	8028	953
7	А	14:40, 6/9/2007	22,644	5/18-6/7,2007	8028	953
8	А	16:15, 6/9/2007	22,644	5/18-6/7,2007	8028	953
9	Т	14:55, 6/12/2007	21,206	5/21-6/10,2007	8679	1024
10	А	15:10, 6/12/2007	20,907	5/21-6/10,2007	8679	1024
11	Т	15:00,7/5/2007	22,492	6/13-7/3,2007	12,062	1813
12	Т	15:20,7/10/2007	20,149	6/18-7/8,2007	11,524	1935
13	А	14:50, 7/25/2007	20,394	7/3-7/23,2007	10,116	2931
14	А	14:55, 8/17/2007	26,142	7/26-8/15,2007	10,837	3637
15	А	16:35, 8/17/2007	26,139	7/26-8/15,2007	10,837	3637
16	Т	13:35,7/5/2008	23,863	6/13-7/3,2008	13,054	1506
17	А	15:15,7/5/2008	23,825	6/13-7/3,2008	13,054	1506
18	Т	14:20,7/6/2008	23,524	6/14-7/4,2008	12,907	1498
19	А	16:10,7/6/2008	24,670	6/14-7/4,2008	12,907	1498
20	Т	14:30, 8/21/2008	22,520	7/30-8/19,2008	12,958	4474

No.	Terra (T) or Aqua (A)	Time & Date (AKDT)	Plume Area (km ²)	21-Day Period	Discharge (m ³ /s)	Sediment Load (kg/s)
21	А	14:45, 8/21/2008	23,404	7/30-8/19,2008	12,958	4474
22	А	16:25, 8/21/2008	24,344	7/30-8/19,2008	12,958	4474
23	Т	15:15, 8/22/2008	25,454	7/31-8/20,2008	13,042	4745
24	А	15:30, 8/22/2008	24,783	7/31-8/20,2008	13,042	4745
25	Т	14:20, 8/23/2008	26,392	8/1-8/21,2008	12,997	4352
26	А	14:35, 8/23/2008	28,191	8/1-8/21,2008	12,997	4352
27	А	16:10, 8/23/2008	28,231	8/1-8/21,2008	12,997	4352
28	Т	15:00, 8/24/2008	26,240	8/2-8/22,2008	12,996	4253
29	А	15:15, 8/24/2008	25,808	8/2-8/22,2008	12,996	4253
30	Т	14:05, 9/10/2008	21,907	8/19-9/8,2008	11,260	2221
31	А	16:00,9/10/2008	22,488	8/19-9/8,2008	11,260	2221
32	Т	13:55, 6/11/2009	29,654	5/20-6/9,2009	21,150	5338
33	Т	15:30, 6/11/2009	31,219	5/20-6/9,2009	21,150	5338
34	А	15:50, 6/11/2009	30,338	5/20-6/9,2009	21,150	5338
35	А	15:00, 7/21/2009	24,565	6/29-7/19,2009	14,187	2797
36	Т	14:10,9/20/2009	24,189	8/29-9/18,2009	7757	3872
37	А	14:30, 9/20/2009	26,029	8/29-9/18, 2009	7757	3872

Table 1. Cont.

Of the 37 images in Table 1, the sediment load at site PLS was over 2500 kg/s for 26 images, which included the large snowmelt sediment runoff as in the period of 21 May– 9 June 2009. Only 14 images had the periods differing by more than a day, since the shooting time between Terra and Aqua is close at 10–20 min or their orbital cycle is 99 min. The error of plume area between Terra and Aqua for the consecutive shooting time of 99 min or less ranges over 2.9–7.1%. Of the 14 images, the 8 images correspond to sediment load at more than 2500 kg/s. Then, the sediment plume could be accompanied by density underflow as in Figure 2.

Figure 8 shows relations between the surface plume area and (a) 21-day mean discharge or (b) 21-day mean sediment load at site PLS, given in Figure 1. The correlation is not that high at $R^2 = 0.3610$ and 0.3676 for the discharge and sediment load, respectively. The low correlation suggests that the suspended sediment dispersion in the plume is not controlled by such mean discharge and sediment load.

Figure 9 shows temporal variations of the plume area and daily mean discharge and daily mean sediment load at site PLS in 2007–2009. Here, the plume area values for the satellite images at AKDT in Table 1 are plotted. Although data plots of the plume area are sporadic because of the limited number of the clear satellite images, the plume area appears to respond more strongly to the daily mean sediment load than the daily mean discharge. Especially, the high response to the sediment load is seen in the great variation of plume area in July–September 2008, and in the similar plume areas in July and September 2009, which correspond to the temporal variation of sediment load rather than that of discharge. Thus, the suspended sediment dispersion in the plume is probably dominated by relatively large sediment load recorded in a short time period. The shipboard observations at all the eight sites took more 24 h (ca. 30 h in 2007 and ca. 28 h in 2008). Hence, 2-day mean values of discharge and sediment load at site PLS were applied for investigating relations between the plume area and hydrological conditions of the Yukon River. Here, by changing the time lag between the plume area date and the dates of 2-day mean discharge or 2-day mean sediment load, it was explored how the plume area responds to the discharge and sediment load.



Figure 8. Relations between the plume area and (**a**) 21-day mean discharge or (**b**) 21-day mean sediment load at site PLS, given in Table 1.



Figure 9. Temporal variations of plume area, daily mean discharge and daily mean sediment load at site PLS in 2007–2009.

Figure 10 shows relations between the plume area and (a) discharge or (b) sediment load averaged for the two days delayed by 20 and 21 days to the image dates. There is a significant correlation ($R^2 = 0.7349$, p < 0.01) with the sediment load. The correlation with the discharge was not consistently significant ($R^2 = 0.3581$ at maximum in case of lag times of 17 and 18 days) ($R^2 = 0.1430$ in Figure 10a). Hence, the dispersion of suspended sediment in the Yukon River plume appears to be controlled by sediment runoff events of the Yukon River (Figure 9), which is initiated mainly by glacier melt in mountainous regions in June–August [26,27]. Nelson and Creager [20] pointed out that sedimentation by the Yukon sediment plume is affected by the strong circulation of northward "Alaskan Coastal Water". However, the high correlation between the plume area and the Yukon sediment load suggests that the dispersion of the whole sediment plume is dominated by the sediment runoff events in the Yukon River.



Figure 10. Relations between the plume area and (**a**) discharge or (**b**) sediment load averaged for the two days delayed by 20 days and 21 days to the image dates.

Here, the influence of wind-driven currents on the northwestward dispersion of the surface sediment plume was explored. If the southeast wind is stronger than the northwest wind during the dispersion, the plume area could increase by the net southeast wind speed. Figure 11 shows relations between the plume area and the net southeast wind (positive) speed averaged over 20 days from each date of satellite images at (a) Nome and (b) site EMK (Figure 1a). If the net wind speed is positive, the southeast wind is stronger than northwest wind, thus probably increasing the plume area. The net wind speed in Figure 11 is mostly negative, and thus the northwest wind prevails during the dispersion rather than the southeast wind. In addition, the correlation is low at 0.286 or 0.0993. Hence, the wind-driven currents appear not to affect the northwestward dispersion of the surface sediment plume.



Figure 11. Relations between the plume area and the net southeast wind (positive) or the net northwest wind (negative) averaged over 20 days from each date of satellite images at (**a**) Nome and (**b**) site EMK (Figure 1a).

5. Discussion

5.1. Dynamic Conditions of Yukon Sediment Plume from Field Observations

As shown by the satellite images in Figures Figures 1b and 7, the Yukon River sediment plume tends to extend northwestward from the Yukon delta. The B50 to B53 line in the shipboard observations was located near the center line of the sediment plume, where the turbid underflow was also observed in the lower layer at relatively high sediment load of the Yukon River (Figures 2 and 3). A hydrodynamic condition of the underflow in Figures 2 and 3 is two-dimensionally judged by using the densimetric Froude number F_d and Reynolds number R_e in the following:

$$F_d = U/(g'D)^{1/2}$$
, (12)

$$R_e = UD/\nu, \tag{13}$$

where U is the underflow's velocity (m/s), D is the thickness (m) of the underflow, g' = g ($\rho - \rho_0$)/ ρ_0 (g: acceleration due to gravity in m/s², ρ : underflow's density in kg/m³, ρ_0 : ambient water density in kg/m³), and ν is the kinematic viscosity (m²/s). From the σ_T distribution in Figure 2, $\rho = 1025 \text{ kg/m}^3$, $\rho_0 = 1022 \text{ kg/m}^3$, D = 7.5 m and $\nu = 1.59 \times 10^{-6} \text{ m}^2/\text{s}$ for salinity 31‰ and water temperature 4 °C were given to Equations (12) and (13). Then, if U = 0.01–0.1 m/s, F_d = 0.067–0.67 and R_e = 4.7 × 10⁴– 4.7 × 10⁵. Thus, the underflow is subcritical and turbulent, indicating relatively low entrainment at the upper boundary [43]. This suggests that the underflow flows down in a relatively long travel distance. This dynamic condition is similar to that of the density underflow in Figure 3 [31], where $F_d = 0.017$ –0.17 and $R_e = 5.7 \times 10^4 - 5.7 \times 10^5$ at U = 0.01–0.1 m/s, $\rho = 1025 \text{ kg/m}^3$, $\rho_0 = 1020 \text{ kg/m}^3$, D = 7.5 m, and $\nu = 1.32 \times 10^{-6} \text{ m}^2/\text{s}$ for salinity at 25‰ and water temperature at 10.6 °C. Thus, dynamic condition of the underflow appears to be consistent over a distance of ca. 100 km since its initiation in the mixing zone.

In order to know the Coriolis effect on behaviors of the whole Yukon River surface plume, Kelvin number K for the sediment plume was calculated by the following [44,45]:

$$K = W/R_d, \tag{14}$$

where W is the plume width (m), and R_d is the baroclinic Rossby radius of deformation (m) as follows:

$$R_{\rm d} = (g'H)^{1/2}/f,$$
(15)

where H is the water depth (m) at a lift-off point into a surface plume, f is the Coriolis parameter (=2 $\omega \sin\varphi$), ω is the earth's rotation rate (=7.29 × 10⁻⁵ rad/s), and φ is the latitude. Here, using the observational result in Figure 2, H = 11 m (thermocline depth), $\rho_0 = 1025 \text{ kg/m}^3$, $\rho = 1020 \text{ kg/m}^3$, and $\varphi = 63.50^\circ$ give f = 1.30×10^{-4} rad/s and $R_d = 5.56 \times 10^3$ m. The location of the liftoff point at the thermocline depth in the coastal region was presumed by extrapolating the bottom slope at the B50–B53 line. The plume width W~100 km is given at the liftoff point from the RGB images in Figure 1b. Thus, K = 1.8×10 was obtained, which indicates that the flow has the large scale on which the plume length far exceeds the width and that the flow dynamics is linear [44].

5.2. Behaviors of the Yukon River Sediment Plume Controlled by River Sediment Load

Figure 12 shows (a) cumulative grain size distributions of suspended sediment and (b) a relation between mean size of the suspended sediment and suspended sediment concentration (SSC) at site PLS in the glacier-melt season of 2009 (Figure 9). Of the seven distributions (Figure 12a) and the seven plots (Figure 12b), those on 22 August provide the smallest median size at 5.21 μ m and the largest SSC at 596 mg/L, respectively. The highly negative correlation (R² = 0.653, *p* < 0.1) in Figure 12b means that, as the glacier-melt sediment runoff increases with high SSC, the suspended sediment becomes more fine-grained.

Figure 13 shows relations between the mean size and (a) river discharge or (b) sediment load at site PLS in July–September 2009 (Figure 12). There is a highly negative correlation between the mean size and sediment load ($R^2 = 0.561$, p < 0.1), while there is no significant correlation ($\mathbb{R}^2 = 0.270$, p < 0.1) between the mean size and discharge. The significant correlation in Figure 13b results from the high correlation between the mean size and SSC (Figure 12b). Figures 12b and 13b indicate that, at the SSC of more than ca. 300 mg/L and the sediment load of more than ca. 2500 kg/s, the mean size decreased from ca. 15 to ca. 10 µm. Hence, the formation of the nepheloid layer at sediment load of more than ca. 2500 kg/s (Figure 3) is judged to be due to both the gravitational settling of coarsegrained sediment (medium sand to coarse silt; $31 \le d < 250 \mu m$, where d is the grain size) (Figure 12a) and the differential settling from the flocculation of more amount of fine-grained sediment (medium silt to clay; $d < 31 \mu m$) (URL: https://www.planetary.org/ space-images/wentworth-1922-grain-size (accessed on 14 September 2021)) [15]. In the grain size distribution of 22 August in Figure 12a, clay particles (d < 4 μ m) occupy ca. 42% in weight, where plenty of clay minerals such as kaolinite, chlorite, smectite, etc. could more easily produce the flocs [31,46].



Figure 12. (**a**) Cumulative grain size distributions (wt.%) of suspended sediment and (**b**) a relation between mean size of the suspended sediment and SSC at site PLS in July–September 2009.



Figure 13. Relations between the mean size of suspended sediment and (**a**) discharge or (**b**) sediment load at site PLS in July–September 2009 (Figures 9 and 12a).

Figure 14 shows schematic diagrams about behaviors of the Yukon River sediment plume designed on the base of the offshore and coastal observations and the grain size analysis. At the sediment load, L > ca. 2500 kg/s, the nepheloid layer is formed near the bottom in the mixing zone under condition of the decaying shear, which is produced mainly from the flocculation of suspended silt and clay particles. When the density of the nepheloid layer becomes larger than the lower saline water, the nepheloid layer goes down on the gentle slope in the mixing zone, and changes into density underflow on the relatively steep slope, which flows down in more offshore regions [18]. Meanwhile, as a normal phenomenon of the turbid river water, the liftoff of the mixed turbid water into the surface sediment plume occurs in the mixing zone, followed by the offshore dispersion (Figure 3) [1]. Sedimentation by the surface plume could then occur through the gravitational settling of flocs [16]. As revealed in the satellite image analysis, the sediment dispersion intensity reflected by the surface plume area is controlled by the magnitude of sediment runoff events of the Yukon River (Figures 9 and 10b).



Figure 14. Schematic diagrams of behaviors of the Yukon River plume, based on the coastal and offshore observations, the satellite image analysis and the grain size analysis.

At L < ca. 2500 kg/s, the flocculation enough to produce the nepheloid layer does not occur because of the less amount of fine-grained suspended sediment. Thus, the density underflow is not produced, because the mixed water is not heavier than the lower saline water. Meanwhile, the liftoff of mixed turbid water into the surface sediment plume is produced in the mixing zone, extending more offshore. Sedimentation by the sediment plume then occurs extensively through the gravitational settling from the flocculation of suspended medium silt to clay (d < 31 μ m) (Figures 5 and 12a).

The formation of the nepheloid layer and its transition to density underflow are schematically shown as one of dynamic behaviors of the mixed water in the coastal region receiving the river inflow [18]. However, our study appeals to the need for investigating relations between the nepheloid layer formation and the flocculation process of suspended sediment, and for exploring the mechanism of the transition to underflow on the slope, by focusing on the grain size distribution and mineralogy of suspended sediment. In addition, it is needed to explore behaviors of the nepheloid layer on the slope, related to the transition into density underflow.

6. Conclusions

Behaviors of the sediment plume formed in the Bering Sea by the Yukon River sediment load were explored by shipboard and coastal observations in the glacier-melt seasons of 2007–2010. The following results were acquired:

- (1) The shipboard observation in 2007 suggested that, at the river sediment load of ca. 3000 kg/s, the turbid water in the coastal mixing zone is separated into the surface sediment plume and density underflow. Meanwhile, by the coastal observation in 2008, it was found out that, at the sediment load of ca. 2500 kg/s, the coastal mixed water is separated into the surface sediment plume and turbid density underflow. The separation into the surface plume and underflow could thus occur at the sediment load of more than ca. 2500 kg/s.
- (2) In the shipboard observation in 2008, when the Yukon sediment load was 1600 kg/s on average, such a separation in (1) was not seen, and instead, sedimentation from the

surface sediment plume prevailed in the lower whole layer. In the coastal observation in 2010, where the sediment load was ca. 2200 kg/s, neither a nepheloid layer nor density underflow was seen, and instead, the vertical mixing of turbid water prevailed extensively, showing the vertical uniform SSC and water temperature. Thus, the sediment load value at 2500 kg/s could be regarded as a criterion for changing the sedimentation in the coastal and offshore regions.

(3) Grain size distributions of bottom sediment in the coastal to offshore regions suggest that the sediment sorting by the turbid underflow shown in the above (1) occurred.

The satellite image analysis for obtaining the area of the surface sediment plume was performed by using the three near infrared bands of MODIS/Aqua or MODIS/Terra, and the following results were acquired:

- (4) There was a significant linear relationship ($R^2 = 0.735$, p < 0.01) between the plume area and the sediment load averaged for two days delayed by 20 days and 21 days to the image dates. This suggests that the dispersion of surface sediment plumes in the Bering Sea is controlled by sediment runoff events of the Yukon River rather than "Alaskan Coastal Water".
- (5) The dispersion of the surface plume is probably unaffected by the wind-driven currents because there is no significant correlation between the plume area and the net southeast wind or the net northwest wind in the corresponding periods.

There was a significant negative correlation ($R^2 = 0.561$, p < 0.1) between the sediment load and the grain size of river-suspended sediment, indicating a decrease of 15 to 10 µm in mean size for the sediment load of more than 2500 kg/s. Hence, the following interpretation is possible for the above (1) and (3) results about behaviors of the Yukon sediment plume. The nepheloid layer in the above (1) is probably formed by the gravitational settling of relatively coarse-grained particles (medium sand to coarse silt) and the differential settling from the flocculation of fine-grained particles (fine silt to clay). That the nepheloid layer is formed on the gentle slope is important for the growth of the nepheloid layer and its subsequent transition into density underflow, producing the sediment sorting as in the above (3). In the future, as one of the laboratory experiments, the nepheloid layer formation from the flocculation should be explored by changing the grain size and mineralogy of suspended sediment and the gradient of the slope.

Author Contributions: K.A.C., T.W. and I.K. participated in the field surveys to set and manage field instruments; K.A.C. wrote the paper; S.-I.S. participated in the shipboard observations and conceived and designed the Yukon River—Bering Sea research project; T.H. participated in the shipboard observations; M.T. analyzed all the images of MODIS/Terra or MODIS/Aqua. All authors have read and agreed to the published version of the manuscript.

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