Postprint: Relationship Between Chinese White Dolphin Distribution and Environmental Factors in the Western Pearl River Estuary

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Abstract

In 2012, a ship-based line transect survey of Chinese white dolphins (Sousa chinensis) was conducted in the western estuary of the Pearl River, with simultaneous in situ sampling and measurement of fishery resources and environmental factors to analyze the relationship between dolphin spatial distribution and environmental variables. Generalized Additive Models (GAM) were employed to examine the relationships between Chinese white dolphin sighting rates and sea state, water depth, bottom water temperature, salinity, pH, dissolved oxygen, nekton density, prey species density, and distance from shore. The GAM model explained 64.7% of the total deviance in the distribution of Chinese white dolphin sighting rates. Nekton density, water depth, prey species density, distance from shore, and bottom water temperature exerted substantial influences on habitat selection by Chinese white dolphins. Model results indicated that dolphin activity was closely correlated with prey species density; however, the effect on sighting rates diminished when prey density reached a certain threshold, presumably because dolphins spent less time foraging when food was abundant. The preferred water depth for Chinese white dolphins was approximately 10 m, and this simulation result was generally consistent with previous statistical results. Chinese white dolphins exhibited selectivity toward bottom water temperature, with sighting rates decreasing significantly when bottom water temperature exceeded 19.5°C, possibly because bottom water temperature may influence the distribution of prey fish species, thereby affecting dolphin activity. The water area within 3 km from shore represented a preferred habitat for Chinese white dolphins, and this area should therefore be prioritized for protection and management.

Full Text

Relationships Between Environmental Factors and the Distribution of Indo-Pacific Humpback Dolphins (*Sousa chinensis*) in the Western Pearl River Estuary, China

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Abstract

The Indo-Pacific humpback dolphin (*Sousa chinensis*) is a small odontocete species widely distributed throughout inshore waters of the Indian and western Pacific oceans. The species is currently classified as "Near Threatened" by the IUCN Red List of Threatened Species. Effective conservation requires understanding the relationship between populations and their habitats. The Pearl River Estuary contains one of the world' s largest-known populations of this dolphin species; however, commercial development is extensively modifying the surrounding environment. Moreover, the region is densely populated, and the intensity of human activities such as shipping and reclamation is increasing. The habitat of the Indo-Pacific humpback dolphin throughout the Pearl River Estuary is changing, and life for dolphins within it is becoming more complex.

We used data collected during vessel-based line-transect surveys in 2012, augmented by data from nekton sampling by bottom trawls and environmental variables, to identify relationships between the environment and the distribution of dolphins in the western Pearl River Estuary. A total of 200 nekton species belonging to 81 families and 19 orders were collected during the four surveys. On the basis of humpback dolphin encounter rates, generalized additive models (GAM) were used to assess the relationships between dolphin encounters and nine environmental variables: Beaufort Sea state, depth, bottom water temperature, salinity, pH, dissolved oxygen, nekton density, prey species density, and distance to the shore. Nekton density, depth, prey species density, distance to the shore, and bottom water temperature were all significantly associated with dolphin encounter rate, and collectively explained 64.7% of the observed variance.

GAM models revealed the habitat preferences of these dolphins. Along with an increase in nekton density, dolphin encounter rate fluctuated, initially increasing and then decreasing and increasing again. The reason for this observed pattern may be the proportion of dolphin prey in the nekton, indicating that prey density was not positively correlated with nekton density. Humpback dolphin distribution and prey density were closely related, although any effect of prey density decreased above a threshold level, suggesting that foraging time decreases in times of prey abundance. Water depth is considered to be a factor limiting the offshore distribution of humpback dolphins. We noted that humpback dolphins were more frequently observed in water depths of 10 m, and this preference shown by dolphins for a certain water depth is the same as that recorded in other survey years. We also identified a relationship between dolphin encounter rates and bottom water temperature, with the encounter rates decreasing markedly when the bottom water temperature exceeded 19.5°C. It is likely that bottom temperature affects the distribution of prey species, which in turn influences the nature of dolphin distribution. Offshore distance is also an important factor determining dolphin distribution. With an increase in the offshore distance from 0.1 to 3 km, the dolphin encounter rate increased monotonically with increasing distance. Thereafter, the encounter rate decreased monotonically when the offshore distance exceeded 3 km. Because the preferred habitat of humpback dolphins occurs at a distance of less than 3 km offshore, prioritized conservation of this environment would better protect and improve management of this increasingly threatened dolphin species.

Keywords: Humpback dolphin (*Sousa chinensis*); Pearl River Estuary, China; conservation; encounter rates; generalized additive model

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1. Introduction

The Indo-Pacific humpback dolphin (*Sousa chinensis*) is a small coastal and estuarine odontocete cetacean, also known as the Indo-Pacific humpback dolphin (Delphinidae). In 1988, the State Council of China listed it as a first-class nationally protected animal [1], and the IUCN classified it as Near Threatened in 1988 [2]. It is also included in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) as a species prohibited from trade [3]. The species is primarily distributed in coastal waters of the western Pacific and Indian oceans [4], and in Chinese waters mainly in estuarine areas of the southeastern coast [5]. According to published reports, Chinese waters with humpback dolphin distribution include the Pearl River Estuary [6-12], Xiamen [13-17], eastern Zhanjiang waters [18], northern Beibu Gulf [19-22], southwestern Taiwan coast [23-24], Shantou [25], and Li Songhai et al. also discovered humpback dolphins in southwestern Sanya, Hainan [26].

Previous studies on humpback dolphins in Chinese waters have focused primarily on distribution, individual identification, home range, and other basic population biology [15,27]. Research on habitat selection, particularly how environmental factors affect dolphin activities or migration, remains relatively scarce, yet such studies would greatly benefit conservation planning and management of humpback dolphins in Chinese waters. The Pearl River Estuary humpback dolphin population' s range includes both eastern and western estuarine mouths, extending from the Shenzhen-Hong Kong waters of Lingdingyang in the east to the upper and lower Xieyang Islands of Jiangmen City in the west, covering over 3,000 km^2 and representing the largest known population globally [11]. The surrounding coastal cities of this estuary—Guangzhou, Shenzhen, Zhuhai, Macau, and others—are economically developed and densely populated. Human activities such as land reclamation are intensifying, causing environmental changes in humpback dolphin habitat and making their survival environment more complex. Studying the relationship between this population' s distribution or activities and environmental factors can effectively understand humpback dolphin habitat requirements, predict their distribution range and potential important habitats, and provide a basis for conservation management, such as reducing damage to potential habitats and human activity interference, and restoring damaged habitats.

Unlike the semi-enclosed Lingdingyang area, the western Pearl River Estuary is an open-type estuary, which has considerable similarity with habitats of other populations along China' s coast and even worldwide, making it representative for study. Due to their strong mobility, marine cetaceans are difficult to track, and their large activity range makes studying seasonal migration challenging. However, cetacean distribution is related to environmental elements, including geographic and oceanographic factors. Water temperature affects cetacean distribution both directly and indirectly [28-29]. Direct effects are primarily reflected in energy costs for thermoregulation [30], while indirect effects manifest through the distribution of prey such as fish, cephalopods, and zooplankton. Fish and cephalopod distributions are related to oceanographic characteristics and environmental elements, including upwelling and ocean fronts, causing prey organisms to move both horizontally and vertically at different times. This makes it difficult to predict habitat use patterns. At small spatial scales, measuring environmental parameters is more convenient than measuring prey organisms, and environmental parameters can better simulate cetacean habitat preferences at fine scales [31]. Understanding the relationship between humpback dolphin distribution and environmental factors can identify habitat use requirements and distribution patterns, providing detailed information on foraging habits and identifying potential important habitats.

The Generalized Additive Model (GAM) was first proposed by Hastie et al. [32] and is a non-linear relationship model that has been used to analyze relationships between marine economic fish species distribution and geographic/environmental variables [33-36]. Its application in marine cetacean habitat selection analysis is becoming increasingly common [37-38]. In the western Pearl River Estuary, there have been reports on humpback dolphin distribution and seasonal migration trends [12], but no studies have specifically examined the relationship between dolphin distribution and marine environmental factors, including other nekton. This study uses 2012 line-transect dolphin observation data, fishery resources, and environmental element sampling data from the western Pearl River Estuary to: (1) estimate the density distribution of fishery resources; (2) analyze the relationship between humpback dolphin distribution and environmental factors (depth, bottom water temperature, salinity, pH, dissolved oxygen, and offshore distance); and (3) examine the relationship between humpback dolphin distribution and other nekton resources.

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2. Survey Area and Methods

2.1 Survey Area This survey consisted of dolphin line-transect observations and fixed-point sampling of fishery resources and environmental elements. The survey area was located in the western Pearl River Estuary, extending from the southwest of Hengqin Island in Zhuhai City in the east to the area east of Xiachuan Island in Jiangmen City in the west, covering the four major western estuary mouths of Hengmen, Yamen, Humen, and Yamen. The survey vessel had a draft of 2.5 m. The survey range was 112.67°–113.5°E, 21.5°–22°N, with preset transect lines totaling approximately 440 km.

2.2 Survey Methods **Dolphin observations** were conducted using vessel-based line-transect methods following Jefferson et al. [6-7]. The observation platform was set on the foredeck, with the observation point approximately 4-5 m above water level. Under suitable observation conditions (visibility 1,200 m), the vessel navigated along preset transect lines at 13-15 km/h. A 7×50 IF WP Nikon binocular compass was used by the primary observer, while the secondary observer used naked-eye observation and recorded data. Observation teams consisted of 3-4 people per shift, rotating sequentially. Observation records included transect observation logs and dolphin sighting records. Transect logs primarily included start/end times and positions, visibility, and voyage distance. When dolphins were sighted, one observation series would end, with simultaneous estimation of individual numbers, group composition, and behavior. Sighting records included time of first sighting, position, bearing and angle, group size, composition, and behavior. Voyage speed and distance were recorded by a Magellan Explorist 210 GPS, and bearings were measured by telescope.

Fishery resources and environmental element sampling was synchronized with dolphin transect surveys. Within the dolphin observation transect range, 13 sampling stations were set up in profiles from shallow to deep water areas, distributed longitudinally across different depth gradients. Bottom trawling was conducted on the same day as dolphin surveys, with one trawl per station for 30 minutes using a single-bottom trawl fishing vessel (5-20 m depth). All catches were sampled and analyzed on-site, with total weight, total number, and minimum/maximum body lengths measured for each species. Environmental elements were sampled before trawling, including bottom water temperature, salinity, pH, and dissolved oxygen (DO), measured using a YSI 556 MPS multi-parameter water quality meter.

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3. Data Processing and Analysis

The study area was divided into 4 km × 8 km grids along observation transects to reduce potential autocorrelation issues while establishing connections with environmental elements. This compromise reduced the problem of most grids having no dolphin observation data. The grid system covered the area 112.67° –113.5°E, 21.5°–22°N. For quantitative analysis of dolphin observation data, group sightings were used as the discovery target, introducing group observation effort. Dolphin encounter rate was calculated as sightings per unit effort (SPUE: sightings per 100 km search effort).

Nine environmental variables and potential factors affecting dolphin encounter rate were used in GAM analysis: depth, bottom water temperature, salinity, pH, dissolved oxygen, nekton density, prey species density, and offshore distance. Previous studies in Hong Kong waters showed that among fish families, estuarine fish such as *Johnius grypotus*, *Thryssa hamiltonii*, *Collichthys lucidus*, and others are preferred prey. Prey species density in this study refers to the distribution of these fish species.

When analyzing data, Pearson correlation coefficients were used to determine relationships between variables. When collinearity existed, only one variable was selected as an explanatory variable [40]. The swept-area method was used to assess fishery resource biomass in the study area [41], calculated as:

$$D = \frac{Y}{A(1-E)}$$

where A is the hourly swept area, Y is the average catch rate (kg/h), E is the escape rate (taken as 0.5), and D is the standard resource density (kg/km^2).

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4. Generalized Additive Models (GAM)

The GAM model is a generalized linear model (GLM) extension that provides a flexible, non-linear framework for studying population relationships without restricting variable relationships. The general form is:

$$g(E(Z)) = f_1(X_1) + f_2(X_2) + ... + f_p(X_p)$$

where Z is the dependent variable, X are independent variables, f are smoothing functions (e.g., spline, local smoothing), g is the link function, and p is the number of parameters.

This study used GAMs to establish relationships between dolphin encounter rate in each grid and environmental factors. Variable selection used stepwise regression based on Akaike Information Criterion (AIC) and variable significance [43]. The Poisson distribution with natural log link function was used.

After analysis, variables with collinearity were eliminated: bottom water temperature and dissolved oxygen had correlation coefficients >0.7, so only bottom water temperature was retained. The final model included five variables: depth, bottom water temperature, prey species density, nekton density, and offshore distance.

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5. Results

5.1 Fishery Resources Survey Results The swept-area method estimated nekton resource density in the study area. During the dry season, nekton density ranged from 667.88–2,679.94 kg/km², while during the wet season it ranged from 227.03–4,085.22 kg/km². Station-specific densities are shown in Table 1.

5.2 Relationships Between Dolphin Encounter Rate and Environmental Factors A total of 144 dolphin encounter records were obtained. Pearson correlation analysis identified relationships among explanatory variables. When collinearity existed, only one variable was selected. The correlation coefficient between prey species density and nekton density was >0.7. As prey species are the direct food source and potentially less affected by external fluctuations, only prey species density was retained for analysis. The final model selected depth, bottom water temperature, prey species density, and offshore distance.

All five explanatory variables in the GAM model were highly significant ($P < 0.001$), collectively explaining 64.7% of the total deviance in dolphin encounter rate distribution (Table 2). The relationships were:

- **Depth**: Dolphin encounter rate increased monotonically with depth in the 5-10 m range. When depth exceeded 10-15 m, the encounter rate decreased monotonically. The depth range with maximum encounter rates was 5-10 m.
- **Offshore distance**: When offshore distance ranged 0.1-3 km, dolphin encounter rate increased monotonically with distance. When distance exceeded 3 km, encounter rate decreased monotonically.
- **Bottom water temperature**: When temperature ranged 17-19.5°C, encounter rates showed minor fluctuations. When temperature exceeded 19.5°C, encounter rates decreased markedly.
- **Sea state**: Dolphin encounter rate decreased monotonically with increasing sea state, approximately linearly.
- **Nekton density**: A non-linear relationship existed. When nekton density was 850-1,250 kg/km², encounter rate increased with density. At 1,250-2,000 kg/km², encounter rate decreased with increasing density. When density exceeded 2,000 kg/km², encounter rate increased again.

- **Prey species density**: When prey density was 38-250 kg/km², encounter rate increased monotonically. At 250-850 kg/km², the curve flattened. When prey density was 850-1,250 kg/km², encounter rate increased again with prey density.

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6. Discussion

6.1 Dolphin Encounter Rate and Nekton/Prey Density GAM models are suitable for studying humpback dolphins in the western Pearl River Estuary as most potential relationships are non-linear, providing a flexible framework without restricting variable relationships. Marine cetaceans are selective about habitat and environmental changes [44]. In high-productivity areas such as mesoscale ocean fronts and upwelling regions, relationships between mid-trophic level predators and environmental factors have been studied, with cetacean abundance correlated with chlorophyll concentration [45-46].

This study recorded 81 nekton species, including preferred prey fish such as *Clupanodon punctatus*, *Ilisha elongata*, *Thryssa hamiltonii*, *Collichthys lucidus*, and others. A non-linear relationship existed between dolphin encounter rate and nekton density. When nekton density was 850-1,250 kg/km², encounter rate increased with density; at 1,250-2,000 kg/km², encounter rate decreased; and when density exceeded 2,000 kg/km², encounter rate increased again. This fluctuating pattern may relate to the proportion of dolphin prey in the nekton assemblage. In this survey, the proportion of dolphin prey in nekton catches ranged from 1.9% to 63.3%, indicating that prey density was not positively correlated with overall nekton density, likely causing the observed fluctuations in encounter rate.

To eliminate interference from non-prey nekton, we examined the relationship between dolphin encounter rate and prey species density specifically. When prey density was 38-250 kg/km², encounter rate increased monotonically with prey density. When prey density exceeded 250 kg/km², the curve flattened. This suggests that dolphin activity is closely related to prey density: when food is scarce, dolphins must spend more time foraging in food-rich areas, creating a strong positive effect on encounter rates; when food is abundant, dolphins can obtain sufficient food quickly, reducing time spent in any particular area and weakening the positive effect of food density on encounter rates.

6.2 Dolphin Encounter Rate and Depth Depth affects dolphin encounter rates. In the 5-10 m depth range, encounter rates increased with depth. When depth exceeded 10-15 m, encounter rates decreased monotonically. Depth is considered a factor limiting offshore distribution of humpback dolphins. In South African waters, the 10 m isobath was identified as a critical depth limiting offshore distribution [47]. Previous surveys suggested the 10-15 m isobath might be the offshore distribution boundary for humpback dolphins in the western Pearl

River Estuary, with 5-10 m as the main distribution area [12]. Our simulation results are consistent with Chen et al.’ s earlier statistical analysis, indicating that depth selection by dolphins in this region has remained relatively stable across years, with preferred depths in the 5-10 m range.

6.3 Dolphin Encounter Rate and Offshore Distance Offshore distance significantly affects dolphin encounter rates. When distance ranged 0.1-3 km, encounter rates increased monotonically with distance; when distance exceeded 3 km, encounter rates decreased monotonically. This indicates that Pearl River Estuary humpback dolphins primarily inhabit nearshore waters within 3 km of shore. Waters within 3 km are also where human disturbance is most intense. Karczmarski et al. [48] reported that in northeastern Queensland, Australia, dolphin sightings occurred mostly within 1 km of shore, while Parra [47] found dolphins in South African Algoa Bay distributed 200-400 m from shore. These differences likely reflect varying topography and environments among regions. The critical offshore depth for western Pearl River Estuary dolphins is less than in South African waters, but their offshore distribution distance is greater than in South Africa yet smaller than in northeastern Australia.

6.4 Dolphin Encounter Rate and Water Temperature Water temperature affects humpback dolphin habitat preference and distribution. Previous studies using surface water temperature found no significant effects [15,27]. This study used bottom water temperature, which has smaller fluctuations than surface temperature. The Pearl River Estuary is a typical estuarine bay where bottom temperature is less affected by air temperature. In this study, when bottom temperature ranged 17-19.5°C, encounter rates showed minor fluctuations; when bottom temperature exceeded 19.5°C, encounter rates decreased markedly. As mammals, dolphins are less directly affected by water temperature than fish, but temperature changes directly affect prey fish distribution, thereby influencing dolphin distribution. Bottom temperatures >19.5°C were mainly found near the 10-15 m isobath at survey edges, suggesting bottom temperature may be a primary limiting factor affecting prey distribution and thus dolphin offshore distribution. In other areas like the eastern Pearl River Estuary’ s Lingdingyang, the Dachong Channel between Lantau and Guishan Islands exceeds 20 m depth but remains a high-use area for humpback dolphins [6], possibly because bottom temperatures there remain suitable for prey species. This phenomenon provides reference for determining offshore distribution boundaries of humpback dolphins in other Chinese coastal regions.

6.5 Dolphin Encounter Rate and Sea State The relationship between sea state and dolphin group encounter rate shows a monotonic decrease approximately linearly with increasing sea state. Jefferson et al. [6] reported in Hong Kong waters that dolphin group encounter rates decreased significantly with increasing sea state, a result confirmed by this study. When sea state exceeds level 3, assessment results become significantly biased. Therefore, level 1-2 observation data are typically used for dolphin population assessment to avoid underestimation, as whitecaps at higher sea states interfere with observation effectiveness.

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7. Conservation Recommendations

This study shows that western Pearl River Estuary humpback dolphins primarily use waters within 3 km of shore, which are also the main areas for bottom trawling and coastal reclamation. Coastal reclamation and fishing activities have enormous impacts on the dolphin population, causing loss of important habitat and food resources. Fishing operations can also accidentally capture or injure dolphins through net entanglement. Therefore, coastal reclamation should be carefully managed, fishing vessel numbers using gillnets should be limited, and artificial reef deployment and stock enhancement should be implemented to ensure adequate food resources for dolphins. Additionally, areas damaged by reclamation should undergo ecological restoration to effectively protect this flagship species of the estuarine ecosystem.

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