Abstract: The size of phytoplankton (a key primary producer in marine ecosystems) is known to influence the contribution of primary productivity and the upper trophic level of the food web. Therefore, it is essential to identify the dominant sizes of phytoplankton while inferring the responses of marine ecosystems to change in the marine environment. However, there are few studies on the spatio-temporal variations in the dominant sizes of phytoplankton in the littoral sea of Korea. This study utilized a deep learning model as a classification algorithm to identify the dominance of different phytoplankton sizes. To train the deep learning model, we used field measurements of turbidity, water temperature, and phytoplankton size composition (chlorophyll-a) in the littoral sea of Korea from 2018 to 2020. The new classification algorithm from the deep learning model yielded an accuracy of 70%, indicating an improvement compared with the existing classification algorithms. The developed classification algorithm could be substituted in satellite ocean color data. This enabled us to identify spatio-temporal variation in phytoplankton size composition in the littoral sea of Korea. We consider this to be highly effective as fundamental data for identifying the spatio-temporal variation in marine ecosystems in the littoral sea of Korea.

Keywords: phytoplankton; phytoplankton size classes (PSCs); ocean color; deep neural network (DNN)

1. Introduction

Environmental condition (temperature, salinity, nutrients, and light availability) change impacts on the structure and functions of marine ecosystems, especially phytoplankton, which play a critical role as primary producers in the biogeochemical cycles of marine ecosystems [1–3]. Physical and chemical variations in the ocean are known to influence the primary production, photosynthetic properties, and size of phytoplankton [2]. The West, South, and East Seas comprise the littoral sea of Korea. Their surface water temperatures are increasing two to four times faster than global temperatures [4]. Previous studies have continuously reported variations in biological properties, such as the blooming cycle of phytoplankton, community fluctuations, and effects on the upper trophic level [5–8]. In particular, several recent papers have reported that the proportion of small phytoplankton is increasing, owing to warming water temperatures [9–12]. The dominant size distribution of phytoplankton plays a critical role in variations in energy efficiency and primary productivity for upper trophic marine organisms [13–17]. The physiological characteristics of phytoplankton are also highly related to its size; therefore, it plays a crucial role in the identification of the impacts of environmental change on marine ecosystems [17]. Nevertheless, there is inadequate long-term information on the community fluctuations and spatio-temporal distributions of phytoplankton according to
size. A method to identify these long-term spatio-temporal distributions involves chlorophyll-a, using satellite ocean color [18]. However, previous studies have focused on investigations related to the total amount of phytoplankton. Recently, it has been considered more important to identify the impacts of change on variations in the environment and phytoplankton structure [19]. Although studies related to the contributions of the dominant phytoplankton size in the littoral sea of Korea have been reported, research on the long-term spatio-temporal distributions in the littoral sea is inadequate. Therefore, a method to identify the long-term spatio-temporal distributions of dominant phytoplankton size is essential.

The dominant size of phytoplankton is generally divided into three sizes (referred to as phytoplankton size classes (PSCs)): micro-size phytoplankton (>20 µM), nano-size phytoplankton (2–20 µM), and pico-size phytoplankton (<2 µM). Researchers are attempting to perform studies on PSCs using various methods (microscopy, flow-cytometry, filters, pigment analysis). However, it is difficult to identify the long-term spatio-temporal characteristics of variations in PSCs owing to the limitations of data observed in the field [17]. Researchers recently developed a method to identify the spatio-temporal distributions of phytoplankton size compositions using ocean color data [20–22]. There are two commonly used types of PSCs algorithms: spectral-based and abundance-based algorithms [21,23]. Spectral-based algorithms perform estimation using correlations with the properties of PSCs that vary with optical characteristics [24–27]. This method is highly sensitive to optical characteristics and is difficult use in ocean waters with high turbidity [28,29]. Abundance-based algorithms perform estimation using the statistical correlation between total chlorophyll-a concentration and composition according to phytoplankton size [30,31]. This method has difficulty reflecting both regional characteristics and characteristics in ocean waters with a complex environment [17].

To enhance the estimation accuracy of PSCs, an algorithm needs to be developed that can reflect the variations in phytoplankton communities according to time and environmental transitions by using an abundance-based algorithm that considers physical factors [18,32,33]. Deep learning techniques, distinct from existing methods, are drawing attention as tools to develop the algorithm. Furthermore, the distribution of PSCs in oceans worldwide can be determined by applying physical characteristics and spatiotemporal variations in PSCs and PFTs (Phytoplankton Functional Types) by using actual machine learning techniques [34].

The objective of this study is to develop a PSCs algorithm, which includes environmental factors, using deep learning techniques and lays a foundation for identifying the spatio-temporal distributions of PSCs. We develop a new algorithm to estimate PSCs from satellite ocean color data, which enables spatio-temporal analysis that is missing in observations and may contribute to understanding the variations in marine ecosystems caused by environmental changes.

2. Data and Methods

2.1. Field Observation Data

This study used observation data (2018–2020) from the National Institute of Fisheries Science (NIFS) to develop a new PSCs algorithm applicable to the East, West, South Seas (which comprise the littoral sea of Korea), and the East China Sea. Using the ocean observation data from the main institute and regional research centers of the NIFS, we developed the new algorithm based on data observed at the sea surface at 60 stations (Figure 1) in spring (April–May), summer (August), fall (October–November), and winter (February). Details of the survey stations are shown in Supplementary Table S1.
Figure 1. Locations of field observation stations.

The parameters used to develop the new algorithm were total chlorophyll-a, size-fractionated chlorophyll-a (micro, nano, and pico size), total suspended solids (TSS), and sea surface water temperature (SST). The data were collected and observed using a rosette sampler and CTD (SBE-911, Seabird Electronics Inc., Bellevue, WA, United States) installed on the vessel. To measure the total chlorophyll-a in the collected seawater, it was filtered with a 25 mm GF/F (Whatman) and stored in a freezer (−70 °C). To measure size-fractionated chlorophyll-a (micro, nano, and pico size), the seawater was sequentially filtered on 20 and 2 μm Nuclepore membrane filters (47 mm) and then 47 mm GF/F (pore size: 0.7 μm), and stored in a freezer (−70 °C). Then, chlorophyll-a was extracted in a laboratory with 90% acetone over 24 h using the method specified by Parson et al. [35] and was analyzed using the 10-AU device. The weight before and after filtering was measured using a precombusted 47 mm GF/F to analyze TSS.

2.2. Training and Model Structure

In this study, a deep neural network (DNN) based model was used to construct the new algorithm for phytoplankton size classification, which was station-based. As training data, the above-mentioned parameters (Section 2.1) were used to train the model, which were obtained by field observation. The total chlorophyll-a (total phytoplankton biomass; unit: μg L⁻¹, n = 531), TSS (determination factor of turbidity in study areas; unit: μg L⁻¹, n = 531), and SST (controlling factor of phytoplankton size; unit: °C, n = 531) were used as input variables, whereas the size fractionated chlorophyll-a, obtained in a laboratory using the Parson method [35], was used as ground truth data classifying the three categorical types (micro-size phytoplankton, n = 126; nano-size phytoplankton, n = 99; pico-size phytoplankton, n = 306; Table 1) corresponding with the dominant size. In other words, the ground truth data (dominant size of phytoplankton in each area; unit: character types) were used to train and validate the output layer of the DNN-based model for each input
variable to develop the new algorithm for phytoplankton size classification (Figure 2). Of the total 531 pieces of station dataset input variables: total chlorophyll-a ($n = 531$), TSS ($n = 531$), and SST ($n = 531$); ground truth data: size fractionated chlorophyll-a ($n = 531$), 210 pieces were used for the training dataset, and 30 pieces were used for validation dataset in the model training process. The training and validation datasets were composed of 70 and 10 pieces of each class, respectively, in order to prevent over-fitting to a specific class in the training process. The remaining 291 pieces were used as the test dataset, validating the final trained model.

Table 1. The number of dominant-sized phytoplankton (ground truth data for training DNN-based model) which appeared at field observation stations in each sea area (East, West, South, and East China Seas) during the study period (2018–2020).

| Microsize phytoplankton (>20 µM) | East Sea | West Sea | South Sea | East China Sea | Sum |
|---------------------------------|----------|----------|-----------|----------------|-----|
| Nanosize phytoplankton (2–20 µM) | 39       | 13       | 21        | 53             | 126 |
| Picosize phytoplankton (0.7–2 µM) | 42       | 39       | 8         | 10             | 99  |
| Total                           | 135      | 167      | 115       | 114            | 531 |

Figure 2 shows the DNN-based model structure of this study. In an input layer, the three input variables (total chlorophyll-a (CHL), total suspended solids (TSS), and sea surface temperature (SST), obtained by field observation, were used as input variables in this model.

Figure 2. Deep learning framework of this study model. As training data, the total chlorophyll-a (CHL), total suspended solids (TSS), and sea surface temperature (SST), obtained by field observation, were used as input variables in this model.
model by densely stacking each layer and solving a non-linearity problem efficiently. Each hidden layer consisted of 20–60 nodes per dense layer. Between the dense layers, the dropout layers were combined to prevent the model over-fitting to a specific class during training. The last layer, the output layer, used the soft-max function to classify the dominant phytoplankton size classes (Equation (3)). In the processing of training, an Adam and a categorical cross-entropy were applied for the model training optimizer and the loss function, respectively. The training epochs and batch size were set to 2000 and 10, respectively, so the weights were configured to update 21 times per epoch. In addition, training was configured to stop early if the loss function value for the validation dataset did not improve within 80 epochs, in order to reduce the over-fitting and the model execution time.

\[
\sigma(x) = \frac{1}{1 + \exp^{-x}} \quad (1)
\]

\[
\tanh(x) = \frac{\exp^x - \exp^{-x}}{\exp^x + \exp^{-x}} \quad (2)
\]

\[
y_k = \frac{\exp(a_k)}{\sum_{i=1}^{n} \exp(a_i)} \quad (3)
\]

2.3. Satellite Data

Using the new algorithm based on the final trained model, this study used satellite ocean color data to identify the spatio-temporal distribution of dominant phytoplankton size classes. The collected satellite data was a VIIRS-SNPP (Visible and Infrared Imager/Radiometer Suite-Suomi National Polar-orbiting Partnership) by the OBPG (Ocean Biology Processing Group) at NASA Goddard Space Flight Center accessed on 9 May 2022 (https://oceandata.sci.gsfc.nasa.gov/VIIRS-SNPP/), and consisted of monthly level-3 data on reflectance of remote sensing at 551 nm (Rrs551), total chlorophyll-a, and SST from 2018 to 2020. TSS, which needs a trained model as an input variable, was estimated using a previously developed algorithm [36] with Rrs551. By assumption, and due to no significant difference between the satellite ocean color data and in-situ data, this study used the satellite data to identify the spatio-temporal distribution of dominant phytoplankton size classes.

3. Results and Discussion

3.1. Results of DNN-Based Model for PSCs

We verified the accuracy of the trained DNN-based model results using classification performance evaluation indicators. Then, the model was analyzed using Equations (4)–(7) with the classification of the confusion matrix in Table 2. According to the confusion matrix, a result is considered true positive (TP) if both prediction and measurement are correct, false positive (FP) if the actual incorrect answer is predicted as correct, false negative (FN) if the actual correct answer is predicted as incorrect, and true negative (TN) if the actual incorrect answer is predicted as incorrect.

| Model results | In Situ Results |   |
|---------------|-----------------|---|
| True          | True Positive (TP) | False Positive (FP) |
| False         | False Negative (FN) | True Negative (TN) |

We used four parameters to verify the model performance: precision (Equation (4)), recall (Equation (5)), accuracy (Equation (6)), and F1-score (Equation (7)). Table 2 lists the results obtained using the equations.
Precision = \frac{TP}{TP+FP} 
(4)

Recall = \frac{TP}{TP+FN} 
(5)

Accuracy = \frac{TP+TN}{TP+FN+FP+TN} 
(6)

F1 - score = 2 \times \frac{Precision \times Recall}{Precision + Recall} 
(7)

We used 291 pieces of data excluding the training and validation data (46 micro-size phytoplankton (16%), 19 nano-size phytoplankton (6%), and 226 pico-size phytoplankton (78%)) to verify the accuracy of the developed classification model. The precision, recall, and F1-score for micro-size phytoplankton, nano-size phytoplankton, and pico-size phytoplankton are 34.8%, 45.7%, and 39.5%; 42.1%, 17.8%, and 25%; and 80.9%, 85.8%, and 82.8%, respectively. The model yielded an overall accuracy of 70.5% (Table 3). An examination of the test dataset results of the trained DNN-based model revealed that the accuracy of 70% exceeds that of the existing methods for the waters surrounding the Korean Peninsula. However, the accuracy of the training data, validation data, and test data of the DNN-based model differ moderately. With regard to the accuracy of the training set, the precision for pico-size phytoplankton is high. The high accuracy is attributed partially to the large proportion of pico-size phytoplankton in the test dataset at 78%. This is because the model mainly estimates pico-size phytoplankton, which is the dominant phytoplankton size observed in the littoral sea of Korea. Regular acquisition of observations to increase the data would help improve the accuracy of the DNN-based model.

Table 3. Precision, recall, F1-score, and accuracy of training, validation, and test datasets for classification model.

| Data          | Data | Precision (%) | Recall (%) | F1_Score | Accuracy (%) |
|---------------|------|---------------|------------|----------|--------------|
| Training data | 210  | Micro-size phytoplankton (70) | 37.1 | 65.0 | 47.3 | 55.7 |
|               |      | Nano-size phytoplankton (70) | 44.3 | 67.4 | 53.5 |
|               |      | Pico-size phytoplankton (70) | 85.7 | 48.4 | 61.9 |
|               | 30   | Micro-size phytoplankton (10) | 20.0 | 66.7 | 30.8 |
|               |      | Nano-size phytoplankton (10) | 30.0 | 60.0 | 40.0 | 46.7 |
|               |      | Pico-size phytoplankton (10) | 90.0 | 40.9 | 56.3 |
|               |      | Micro-size phytoplankton (46) | 34.8 | 45.7 | 39.5 |
|               |      | Nano-size phytoplankton (19) | 42.1 | 17.8 | 25.0 | 70.5 |
|               |      | Pico-size phytoplankton (226) | 80.1 | 85.8 | 82.8 |

3.2. Estimation of Phytoplankton Size Classes in the Littoral Sea of South Korea Using Satellite

To identify the spatio-temporal distributions of the dominant phytoplankton size in the littoral sea (the purpose of this study), we applied the developed algorithm using a DNN-based model to the satellite ocean color data, and obtained monthly distributions of dominant phytoplankton size from 2018 to 2020. These are shown in Figures 3–5. Although there are marginal spatial differences in the dominant sea areas from 2018 to 2020, the distribution trends of the dominant size are similar. An examination of the distributions of dominant phytoplankton size by sea area revealed that micro-size phytoplankton are dominant in the West Sea from January to March, whereas nano-size phytoplankton are dominant in April and May. In contrast, according to a seasonal survey of the West Sea (2018) by Jang et al. [37], nano-size phytoplankton are dominant in both February (approximately 50%; micro-size: approximately 22%) and April (approximately 42%; micro-size: approximately 37%) during the research period. This was because the contributions of chlorophyll-a according to size, reported by Jang et al. [37], reflected the chlorophyll-a concentrations in the depth of the photic zone, which includes the surface layer. With regard to the phytoplankton community structure in the East Sea, identified using
the algorithm developed in this study, nano-size phytoplankton are dominant from January to April. From May, the dominant sea area of pico-size phytoplankton expands gradually. According to prior research, the key dominant size of phytoplankton communities in spring (March–April) in the East Sea are micro-size diatoms [38–40]. However, previous studies on phytoplankton communities in the East Sea reported differences in the dominant communities depending on the study period and survey station [41–45]. An observation shared among most of these studies is that the size of the key dominant size of the phytoplankton communities tends to decrease as the water temperature increases after spring [41,43–45]. According to the observations of phytoplankton communities in the South Sea and East China Sea from January to May, micro-size phytoplankton are dominant in the west, whereas pico-size phytoplankton are dominant in the central region. Although this spatio-temporal distribution pattern in the East China Sea is similar to those observed in previous studies [46,47], there is insufficient comparable prior research data on variations in phytoplankton communities in the South Sea during this period. From June to September, pico-size phytoplankton showed high distributions in all the sea areas (Figures 3–5). In summer (June–August) when strong stratification develops, pico-size phytoplankton are the dominant size in the littoral sea at surface depths (East, West, South, and East China Seas) [37,44,45,47–49]. However, certain studies conducted in the South Sea observed that the contribution of nano-size phytoplankton or micro-size phytoplankton were high [19,50]. This is likely because the sea area where the studies were conducted is a bay with a high inflow of nutrients from the outside through precipitation [50,51]. From November, sea areas dominant with nano-size phytoplankton gradually begin to appear in the central West Sea and East Sea littoral seas. The dominant sea areas increased until December (Figures 3–5). For the West Sea, comparable prior research results on the spatio-temporal variations in phytoplankton communities during this period are insufficient. In contrast, as mentioned above, the East Sea shows different distribution characteristics depending on the study period and station. However, according to Jo et al. [44], nano-size was the dominant size during September and October after summer, whereas micro-size was dominant in November, followed by nano-size. By substituting the developed PSCs algorithm for all the sea areas of South Korea, the most dominant size in the East, West, South, and East China Seas was observed to be pico-size phytoplankton. Meanwhile, nano-size phytoplankton was dominant in the northern waters of the West Sea, and micro-size phytoplankton in the littoral seas of the West Sea.

To determine the accuracy and usability of the developed algorithm applied to ocean color, we compared the dominant size estimated via satellite using new PSCs algorithm and the dominant size by sea area (East, West, South, and East China Seas) in the field data, as well as previously developed dominant size estimation algorithms (Table 4). The accuracy was approximately 69.5% according to comparisons of the most dominant phytoplankton size by sea area observed in the field and the most dominant size analyzed through ocean color (the algorithm developed in this study) (Table 4). The dominant distribution of pico-size phytoplankton showed high accuracy in the developed algorithm. One of the main causes of this result is because pico-size phytoplankton are the most dominant size in Korean waters, and were the most prevalent in the sample. With regard to accuracy by sea area, the accuracies for the East, West, South, and East China Seas were 50%, 66.6%, 90%, and 67%, respectively. The lowest was for the East Sea, and the highest was for the East China Sea. To compare the accuracy of the results applied to ocean color using the new algorithm with existing models, we performed a comparison using a dominant size estimation method applying an absorption model ($A_\mu$) [25] and dominant size estimation results using the three components model [52] (Table 4). According to the dominant size results, the $A_\mu$ model yielded an accuracy of approximately 54% in the littoral sea. Meanwhile, the three-component model showed an accuracy of 13%. The previous field observations indicated that pico-size phytoplankton were dominant in most of the sea areas, whereas the three-component model estimated that micro- and nano-size phy-
toplankton were dominant in most of the sea areas. In particular, all the cases were incorrect in the South Sea. The algorithm developed in this study showed a higher accuracy than the existing algorithms in identifying variations in the dominant size in the littoral sea of South Korea. We consider that real AI learning-based algorithms could attain even higher performance if they were continuously trained with new data.

**Figure 3.** Classification based monthly PSCs distribution using L3 mapped VIIRS data in 2018. White color indicates missing area by cloud. Indigo, blue, and green colors indicate micro-size phytoplankton, nano-size phytoplankton, and pico-size phytoplankton, respectively.
Figure 4. Classification based monthly PSCs distribution using L3 mapped VIIRS data in 2019. White color indicates missing area by cloud. Indigo, blue, and green colors indicate micro-size phytoplankton, nano-size phytoplankton, and pico-size phytoplankton, respectively.
Figure 5. Classification based monthly PSCs distribution using L3 mapped VIIRS data in 2020. White color indicates a missing area by the cloud. Indigo, blue, and green colors indicate micro-size phytoplankton, nano-size phytoplankton, and pico-size phytoplankton, respectively.

Table 4. Matched percent between field measurement Chl-a size fractionated with New AI algorithm (this study), Apb algorithm, and three-component model derived from satellite data.

| Field Measurements | New AI Algorithm (This Study) | Apb Algorithm | Three-Component Model |
|--------------------|-------------------------------|---------------|-----------------------|
| Study area         | 67.3%                         | 54.3%         | 13.4%                 |
| East Sea           | 50.0%                         | 41.7%         | 16.7%                 |
| West Sea           | 66.7%                         | 41.7%         | 33.3%                 |
| South Sea          | 90%                           | 90%           | 0%                    |
| East China sea     | 66.7%                         | 50%           | 0%                    |
4. Summary and Conclusion

It is crucial to identify the spatio-temporal distributions of dominant phytoplankton size to understand the variations in coastal marine ecosystems occurring alongside environmental change. The PSCs classification models in prior studies have limited usability owing to their low accuracy in sea areas surrounding the Korean Peninsula. Accordingly, this study attempted to develop a DNN-based PSCs classification algorithm suitable for sea areas around the Korean Peninsula by utilizing data collected from continuous observations as training data for the DNN model.

For this purpose, we collected data observed at the sea surface at 60 stations in spring (April–May), summer (August), fall (October–November), and winter (February) over three years (2018–2020), from the ocean observation data obtained from the NIFS main institute and regional research centers. Data on total chlorophyll-a, size-fractionated chlorophyll-a, TSS, and SST were collected and observed using a rosette sampler and CTD (SBE-911) installed on the vessel. The collected data were used as training data for the DNN-based model.

The available data was collected at different times and locations, and is not continuous. Therefore, the DNN-based model was used for development of new PSCs algorithm. To prevent biased learning owing to imbalanced data, we acquired 70 samples of each class from the data by plankton size for the training process. In addition, we selected four sea areas (the West, South, East, and East China Seas) according to the characteristics of waters around the Korean Peninsula, and configured the ratios of data identically for each sea area. The developed DNN-based PSCs algorithm achieved an accuracy of 70%, which exceeds that of the existing algorithms. However, the high accuracy is partially attributed to the large proportion of pico-size phytoplankton in the test dataset, at 78%. This aspect of the model must be improved by securing additional data in the future.

To examine the distribution characteristics of PSCs in the sea areas surrounding the Korean Peninsula through the developed DNN-based PSCs algorithm, we input satellite data to express spatio-temporal distribution characteristics. Monthly averages and three-year averages of the satellite water temperature, turbidity (i.e., TSS), and total chlorophyll were applied as input values to the new algorithm. The results verified that micro-size phytoplankton were dominant on the West Sea coast, nano-size phytoplankton in the northern East Sea, and pico-size phytoplankton in the South and East China Seas (Figure 6). By season, micro-size phytoplankton and nano-size phytoplankton are dominant in winter and spring in the East, West, and South Seas. From summer, pico-size phytoplankton are dominant throughout the littoral sea of Korea (Figures 3–5).
This study developed a DNN-based PSCs algorithm that classifies the phytoplankton in the littoral sea of Korea into three size levels for the first time. In addition, it presented results on the spatio-temporal distribution of the dominant size based on satellite data. Based on these results, we consider that it can be made capable of producing important data for understanding the variations in coastal marine ecosystems occurring alongside environmental change. However, continuous improvement of the DNN-based PSCs algorithm accuracy through comparison with in situ data is necessary for more precise satellite observations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse10101450/s1, Table S1: Marine ecosystem survey stations of NIFS; Table S1: Dominant phytoplankton size (micro: M, nano: N, and pico: P) in the littoral water of Korea from field measurements, new algorithm (this study), Aph algorithm, and three-component model.

Author Contributions: Conceptualization, H.J. and Y.P.; methodology, H.J. and E.K.; validation, Y.P. and J.D.H.; formal analysis, J.J.K. and H.J.O.; investigation, H.J., H.J.O., J.J.K., E.K., and J.D.H.; data curation, H.J.; writing—original draft preparation, H.J. and J.J.K.; writing—review and editing, J.J.K.; S.-H.Y.; E.K.; visualization, H.J. and E.K.; supervision, J.D.H.; project administration, J.D.H. and H.J.O.; funding acquisition, S.-H.Y. and H.J.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Institute of Fisheries and Science (‘Development of marine ecological forecasting system for Korean waters’; R2022075).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by the National Institute of Fisheries Science (NIFS) grant (‘Development of marine ecological forecasting system for Korean waters’; R2022075) funded by the ministry of oceans and fisheries, republic of Korea.

Conflicts of Interest: The authors declare no conflict of interest.
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