

Article

Effect of Indian Ocean Dipole signal on freshwater cyanobacterial dynamics

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Abstract

The proliferation of freshwater cyanobacteria is a serious environmental problem that often reduces water quality. In this study, we observed the possible influence of the Indian Ocean Dipole (IOD), represented by the Dipole Mode Index (DMI), on the dynamics of cyanobacterial blooms in a river system (the lower Nakdong River). Korean monsoon rainfall (KMR) was preceded by 5-month moving average DMI of ~1.5 years, and the KMR and DMI were negatively associated ($r^2 = 0.53$, $n = 15$, $p < 0.01$). In turn, a decrease in KMR was responsible for a decrease in total dam discharge ($r^2 = 0.64$, $n = 15$, $p < 0.01$), resulting in an abrupt increase in cyanobacterial cell density at the study site ($r^2 = 0.94$, $n = 15$, $p < 0.01$). We found a strong and significant positive correlation between cyanobacterial density of the Nakdong River and a 5-month moving average DMI ($r^2 = 0.95$, $n = 15$, $p < 0.01$). These correlations suggest that a positive DMI decreased KMR and therefore water discharge, resulting in an excessive proliferation of the cyanobacterial density during the monsoon period. Despite a variety of uncertainties, the presence of the IOD is believed to play a role in triggering freshwater cyanobacterial proliferation through a signal propagation pathway during summer drought occurrence in the monsoon period.

Key words: climate variation, cyanobacterial proliferation, Indian Ocean Dipole, Korean monsoon rainfall

Introduction

Cyanobacterial proliferation has increased in frequency, leading to reduced water quality in eutrophic freshwater ecosystems (Paerl et al. 2001, Paerl and Paul 2012). Many studies have attempted to find a causal relationship between the local environmental characteristics and cyanobacterial blooms, and intensive examinations have revealed several factors, such as high water temperature, excessive nutrient loading, and water stagnancy, that lead to serious proliferation (Kohl and Lampert 1991, Hitzfeld et al. 2000, Elliott 2012, Paerl and Paul 2012). Furthermore, accelerated eutrophication increases cyanobacterial growth, which further deteriorates water quality and ecosystem health.

In addition to local environmental factors, recent studies have revealed relationships between climate variations and cyanobacterial blooms, increasing interest in local cyano-

bacterial dynamics. Paerl and Paul (2012) emphasize that climatic changes (e.g., global warming, hydrologic changes, increased frequencies and intensities of tropical cyclones, and more intense and persistent droughts) strongly affected cyanobacterial growth and bloom potential in not only marine ecosystems, but also in freshwaters. Many studies revealed the impact of increased temperatures and light intensity, related to global climate variations, on prolonging the season of cyanobacteria dominance and increasing biomass (Wagner and Adrian 2009, Markensten et al. 2010, O'Neil et al. 2012, Hense et al. 2013). Studies have also investigated the relationship between the sudden discharge of water and the reduction of cyanobacteria through flushing and/or dilution of algal cell density (Webster et al. 2000, Maier et al. 2001, Hong et al. 2014). This hydrological pattern is especially important in the East Asian region, where the major water source is summer monsoons.

Several hypotheses explain the relationship between East Asian summer rainfall (mostly represented by East Asian summer monsoon) and global climate variations. Wang et al. (2001) emphasized that weak East Asian summer monsoon and enervation of Indian summer monsoon (ISM) was related to the decay of El Niño-Southern Oscillation (ENSO). A Ding and Wang (2005) study of ISM revealed a potential link between ENSO and other regions through circumglobal teleconnection. Despite its importance, however, the process of EASM development is still unknown owing to the large uncertainty surrounding circumglobal teleconnection and ENSO (Ha et al. 2005).

Another example of the relationship between ocean-atmosphere interactions and local meteorology can be found in the Indian Ocean Dipole (IOD), a convection movement over the Indian Ocean linked to anomalies in sea surface temperatures (SST; Saji et al. 1999). Researchers discovered a dipole mode (Fig. 1) with anomalously low SST near Sumatra and high SST in the

western Indian Ocean. This anomaly is called a “positive IOD” when warm SST develop enormous moist air masses over the sea surface, and convection from the western Indian Ocean region transfers the moisture to adjacent regions, often resulting in strong rainfall in Eastern Africa and serious drought in the Asian and Australian regions (Fig. 1a). During a “negative IOD” (Fig. 1b), the opposite distribution of SST occurs (i.e., low SST in East Africa and high SST in the western Indian Ocean region), overturning moisture convection direction and leading to strong summer monsoon rainfall over the China–Korea–Japan belt and Australia. During a negative IOD, a 10-month delay usually occurs between the development of the negative IOD and the onset of the East Asian summer rainfall (Kripalani et al. 2010).

We speculate that summer cyanobacterial proliferations in South Korea are related to the IOD pattern, especially positive IOD, that causes drought. South Korea is located between China and Japan and experiences concentrated summer rainfall, known as the Korean monsoon rainfall (KMR), around mid-June to mid-July and several typhoon events around late July to early September. Lack of summer rainfall often (1) decreases river flow (although upriver impoundment somewhat mitigates the problem), (2) increases water temperature (reduced cloudiness enhances irradiation), and (3) concentrates nutrients in the waterbody. In a series of cyanobacterial studies in a regulated river system (the Nakdong River), a clear link was found between cyanobacterial growth and summer rainfall and river flow (Joo and Jeong 2005, Jeong et al. 2010, 2011). Unexpected drought in the summer monsoon period often resulted in an excessive proliferation of cyanobacteria in the river and vice versa (Jeong et al. 2001, 2003, 2007, Kim et al. 2007). Regulation of river flow is a growing strategy for the mitigation and control of cyanobacterial proliferation (Maier et al. 2004, Jeong et al. 2007, Paerl et al. 2011); therefore, a significant relationship between cyanobacteria and IOD will allow prediction of changes in cyanobacterial proliferation by understanding the projected climate variations.

In this study, we investigated the pattern of cyanobacterial changes in relation to IOD. Long-term cyanobacterial density data from the Nakdong River, South Korea (1994–2008; weekly basis), were compared with the Dipole Mode Index (DMI, a representative quantified index for IOD pattern). We first examined interannual variations of DMI and annual KMR over the Nakdong River basin. The response pattern of dam discharge to rainfall during the Korean Monsoon (KM) period was then examined, and cyanobacterial proliferation patterns were related to dam discharge. Finally, we directly compared cyanobacterial density during the KM with DMI and evaluated this sequential relationship.

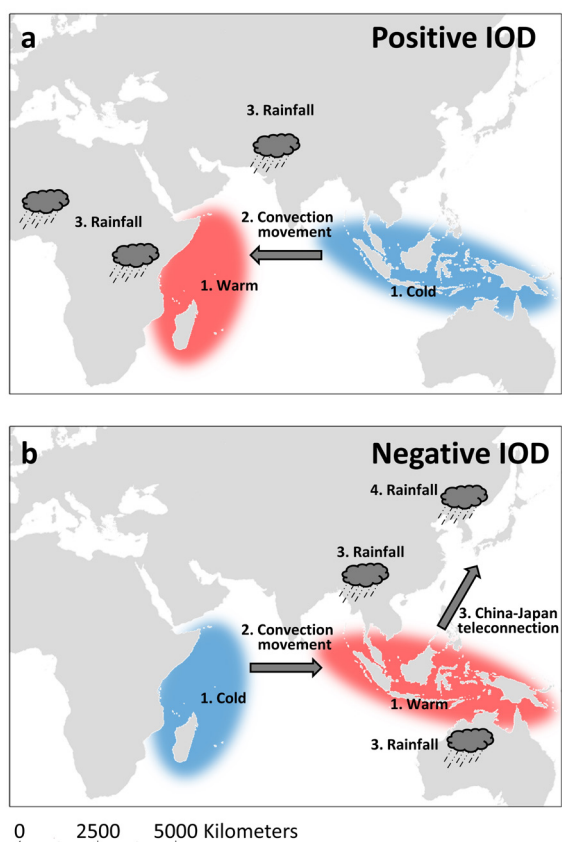


Fig. 1. The relationship between local meteorology and Indian Ocean Dipole, modified from Japan Agency for Marine-Earth Science and Technology (http://www.jamstec.go.jp/frcgc/research/d1/iod/e/iod/about_iod.html). Numbers in each panel indicate the sequence of cascading effect of ocean-atmosphere interactions: (a) positive IOD pattern; (b) negative IOD pattern.

Study site

The Nakdong River basin (35–37°N, 127–179°E; Fig. 2), located in the southeastern part of South Korea, is ~520 km long (catchment area 23 800 km²). More than 10 million basin residents rely on the water from the river; thus, quantity and quality of the river water is crucial. Nutrient loading from point-source and nonpoint sources has gradually caused the river to become eutrophic, resulting in recurrent summer cyanobacterial proliferations since 1992 (Joo et al. 1997).

The basin experiences heavy rainfall in summer (average annual rainfall 1250 mm; >60% in Jun–Sep), mainly owing to the KMR season (~late Jun to mid-Jul; Supplementary Table S1) and several typhoons. Jeong et al. (2007) reported that 30–90% of summer concentrated rainfall was from the KMR. Although the KMR percentage fluctuates interannually, in most cases it is the first concentrated rainfall event of the year (Ha et al. 2005) and causes the first flooding (Park et al. 2002). In a normal year after the summer rainy season (usually Sep), a dry period persists from winter to the following spring (~5–20% of annual rainfall; Jeong et al. 2011). In early June, before the onset of the KMR, water temperatures

gradually increase, with the first summer cyanobacterial proliferation occurring in this month. After the onset of the KMR, flooding caused by the rainfall begins to disrupt the summer cyanobacterial proliferations (Park et al. 2002). Because of this KMR impact, relating the changing pattern of KMR to the IOD may allow us to better understand cyanobacterial proliferations.

In addition to rainfall seasonality, a strong heterogeneity of spatial rainfall distribution occurs, with less rainfall upriver and more rainfall downriver (Chang and Kwon 2007, Park et al. 2011). Owing to the spatial and temporal heterogeneity of the rainfall, as well as an increasing dependence on water from the river, intensive regulation of the river flow has become necessary. Consequently, 4 major multipurpose dams and an estuarine barrage control water flow and impoundment.

The study site (Mulgum), located 27 km upstream from the estuarine barrage (Fig. 2), is situated near a water intake facility (35°18'31"N, 128°58'44"E; maximum depth ~10 m; mean depth 4–5 m; river width 250–350 m). At this site, persistent mixing occurs throughout the water column (Ha et al. 1998), and the site is highly eutrophic (Ha et al. 2002, Jeong et al. 2011, Kim et al. 2011).

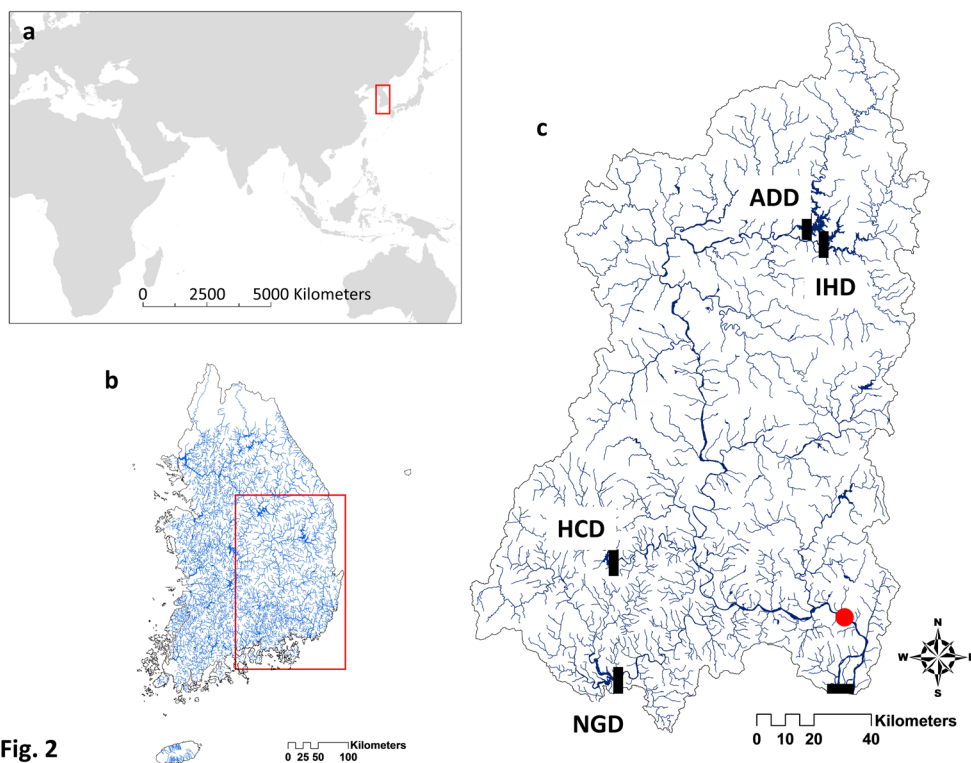


Fig. 2

Fig. 2. Study site: (a) the Asian continent and the location of the Korean Peninsula (red rectangle); (b) stream distribution in South Korea and the approximate region of the Nakdong River system (red rectangle); (c) the Nakdong River basin. ■ indicates multipurpose dams controlling river flow in the basin (abbreviations correspond to dams in Table S1), ■ is the estuarine barrage at the river mouth, and ● is the location of the study site (Mulgum; 27 km upstream from the barrage). Data were cited from (a) ESRI ArcMap 10.0 and (b and c) WAMIS geospatial dataset. ADD = Andong Dam; IHD = Imha Dam; HCD = Hapchon Dam; NGD = Namgang Dam.

Materials and methods

Meteorological data collection and pre-processing

We obtained 3 datasets from relevant administrations. First, the monthly DMI was obtained from the Japan Agency for Marine-Earth Science and Technology (<http://www.jamstec.go.jp/>). The DMI is the anomalous SST gradient between the western equatorial Indian Ocean (50–70°E and 10°S–10°N) and the southeastern equatorial Indian Ocean (90–110°E and 10°S–0°N).

Two types of data related to basin rainfall were supplied by the Korean Meteorological Administration (<http://www.kma.go.kr/>): the KM period for southern Korea (Supplementary Table S1) and daily rainfall (mm) recorded at 21 stations within the river basin. One objective of this study was to investigate the relationship between the DMI and KMR; therefore, for each year from 1994 to 2008, we determined the duration of the KM by simply calculating KM retreat date – KM onset date + 1 (d). We then calculated the daily basin rainfall (mm) by averaging the rainfall data from the 21 recording stations. Finally, for each year, we summed the daily basin rainfall data to get the total KMR (mm) and divided by the corresponding KM duration to obtain the average KMR (mm d^{-1}).

Daily dam discharge data from 4 multipurpose dams were obtained from the Water Management Information System (<http://www.wamis.go.kr/>) of South Korea. First, we considered water travel time from each of the multipurpose dams to the study site, accounting for (1) seasonal differences in flow rates (longer in dry period and shorter in rainy season), and (2) different distances between the study site and each of the multipurpose dams (Supplementary Table S2). Because we focused on the cyanobacterial proliferation during the KM period (typically accompanied by flooding), we consulted several hydrological reports to find water travel time information when flooding occurred: 70–72 h for Andong Dam and Imha Dam, and 40–48 h for Hapchon Dam and Namgang Dam (Lee et al. 2006, Choo et al. 2012). We obtained daily dam discharge data from the 4 multipurpose dams for each KM period and compared the discharge dates to our river monitoring dates. For Andong and Imha discharges, we selected data recorded on the date 3 days prior to every sampling date and 2 days prior for Hapchon and Namgang discharges. Those selected discharge data from the 4 multipurpose dams were summed to calculate the daily total dam discharge (TDD). Finally, for every KM period, we averaged the TDD data to calculate the TDD for the KM period (hereafter, TDD refers to this annual data).

Cyanobacterial data collection

We used water samples collected for 15 years (1994–2008) from the study site, Mulgum station at the lower Nakdong River (Fig. 2), one of the Long-Term Ecological Research sites in the Nakdong River system. Weekly water samples were obtained at a depth of 0.5 m using a 4 L polyethylene bottle. Subsamples for phytoplankton enumeration were prepared in 100 mL polyethylene bottles and immediately preserved with Lugol's solution. Cyanobacteria cell density (cells mL^{-1}) was enumerated using an inverted microscope (ZEISS, 400 \times) by the Utermöhl sedimentation method (Utermöhl 1958).

Data analysis

Data analysis was performed to determine (1) average KMR response to the DMI and (2) relationship among cyanobacteria density, DMI, average KMR, and TDD. KMR response was assessed based on correlation coefficients for the 5-month moving average of the DMI and average KMR from 1994 to 2008. For example, April through August (AMJJA) DMI indicates averaged DMI of 5 months, and we calculated the averages for every year from 1994 to 2008 to obtain 15 AMJJA DMI. Because cyanobacteria abruptly increase in June, we started our comparisons using the 5-month moving average of the DMI with June as the center month (i.e., AMJJA). Next, we shifted the moving average window 1 month earlier (i.e., MAMJJ) and continued until we obtained six 5-month moving averages of the DMI from the current year (year_{*t*}). We continued to calculate the moving averages of the DMI until the third “center January” of 2 previous years (i.e., NDJFM of year_{*t-2*}) was included. In total, we obtained thirty 5-month moving averages of the DMI for the 15 years (1994–2008) and compared each 15-year DMI series with the average KMR using correlation analysis. This approach allowed us to determine any delayed influence of the DMI on the average KMR. Once the strongest correlation was determined, we applied regression analysis to investigate the relationship between the DMI and average KMR. The same protocol was applied to the comparison among the DMI, TDD, and cyanobacterial density.

Results

We determined the annual changes of the DMI, basin rainfall, TDD, and cyanobacterial density (Fig. 3). For 1994–1997, we observed 2 distinct positive DMI peaks; however, in the following years the range of the DMI variation was relatively steady around zero, although small positive or negative peaks repeatedly appeared (Fig.

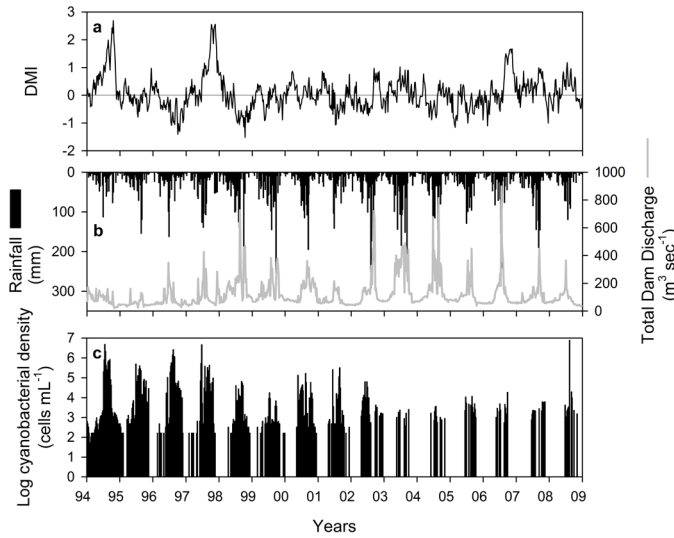


Fig. 3. Changes in (a) Dipole Mode Index (DMI), (b) basin rainfall (black bars) and total dam discharge (TDD; gray line), (c) and cyanobacterial density.

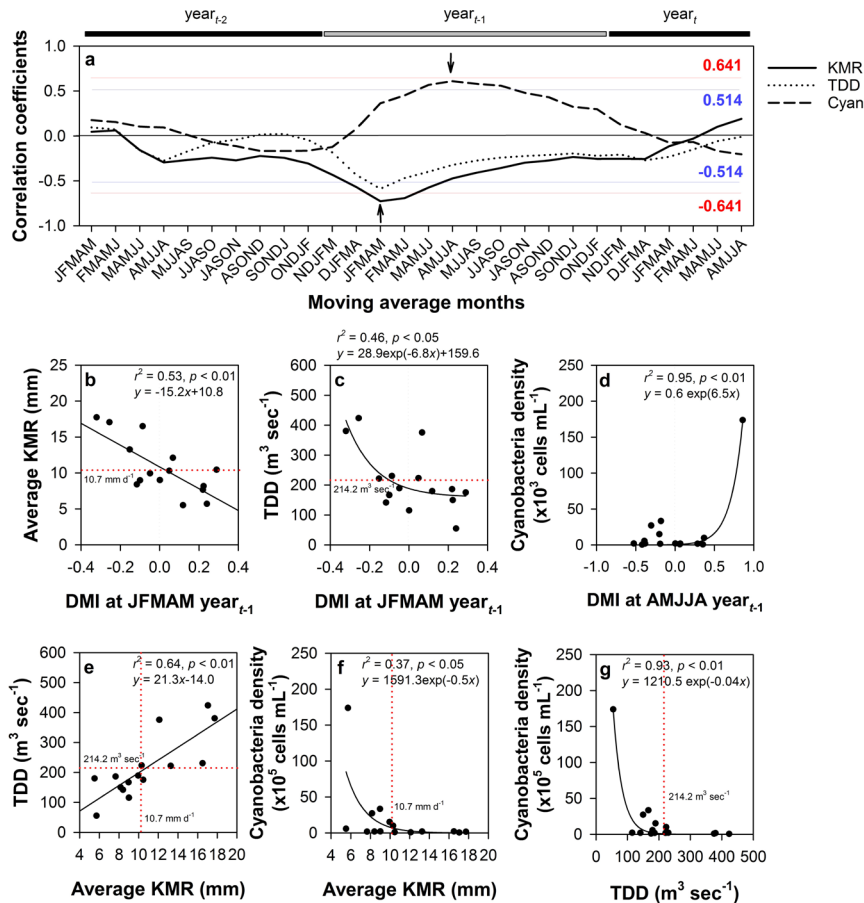


Fig. 4. Relationship between Dipole Mode Index (DMI), Korean monsoon rainfall (KMR), average total dam discharge (TDD), and cyanobacterial density in KM period ($n = 15$). (a) changes of correlation coefficients between DMI from various 5-month moving averages, average KMR (indicated as KMR), TDD, and cyanobacterial density (Cyan); (b) relationship between JFMAM DMI in year_{t-1} and average KMR; (c) relationship between JFMAM DMI in year_{t-1} and TDD; (d) relationship between AMJJA DMI in year_{t-1} and cyanobacterial density; (e) average KMR and TDD in year_t; (f) average KMR and cyanobacterial density in year_t; and (g) TDD and cyanobacterial density in year_t. Four horizontal guidelines in panel a indicate significance at $p = 0.05$ and 0.01 Red dotted lines in panels b, c, and e–g indicate annual averages of average KMR and TDD, respectively.

3a). In years with strong positive DMI peaks, the amount of basin rainfall and the TDD were relatively lower than the following years (Fig. 3b). Among the cyanobacterial density data ($n = 784$; Fig. 3c), high cyanobacterial density was associated with strong positive DMI peaks, scarce basin rainfall, and low TDD (i.e., 1994–1997). During the 15 years, the highest cyanobacteria densities were in 1994, 1997, and 2008.

Strong negative correlations were found between the 5-month moving average DMI and the average KMR as well as the cyanobacterial density during the KM period (Fig. 4), and an even stronger correlation between them ~ 1 year earlier. The strongest correlation was observed between JFMAM DMI in year_{*t*-1} and the average KMR ($r = -0.73$, $n = 15$, $p < 0.01$; Fig. 4a). Similar to the average KMR, TDD was also significantly correlated with the JFMAM DMI in year_{*t*-1} ($r = -0.59$, $n = 15$, $p < 0.05$; Fig. 4b), but the correlation coefficient was slightly lower than that of the DMI compared to the average KMR. A significant relationship was also found between the DMI and cyanobacteria density during the monsoon period (Fig. 4a), but the pattern was in contrast to the average KMR and TDD. The highest correlation coefficient was found with the AMJJA DMI in year_{*t*-1} ($r = 0.61$, $n = 15$, $p < 0.01$), 3 months later than the JFMAM DMI in year_{*t*-1}.

The clear relationship between DMI versus average KMR and DMI versus cyanobacterial density (Fig. 4b–d) illustrates that the average KMR was reduced as JFMAM DMI in year_{*t*-1} became positive, a finding that also applied to the TDD changes. Cyanobacterial density was well explained by the DMI variation when we applied an exponential fitting curve. Further comparisons among average KMR, TDD, and cyanobacterial density in year_{*t*} (Fig. 4e–g) show a linear relationship from the average KMR and TDD as increased rainfall increased dam discharge. Furthermore, as rainfall increased, cyanobacterial density decreased. An increase in TDD was negatively associated with cyanobacterial density.

Discussion

The ocean–atmosphere interaction factor (IOD) is assumed to affect summer cyanobacterial density changes through a sequential process, the climate–local meteorology–hydrology–ecosystem response. In particular, a positive IOD that results in drought over the Nakdong River was significantly related with summer cyanobacterial proliferation. Since Saji et al. (1999) discovered the pattern of IOD and its impact on regional rainfall distribution, many studies have focused on the role of IOD in Asian rainfall patterns (Kim et al. 2002, Kripalani and Kumar 2004, Yuan et al. 2008, Kripalani et al. 2010, Pillai and Mohankumar 2010, Tamura et al. 2011). Their common conclusion is

that a negative relationship exists between IOD and Asian rainfall. Mostly they emphasized transportation of accumulated moisture (via the teleconnection process) over the eastern part of the Indian Ocean toward the East Asian region. Yoon (2015) concluded that a negative IOD pattern was responsible for the increase in summer concentrated rainfall over the Korean Peninsula, which in turn increased river flow; however, Guan and Yamagata (2003) emphasized that a strong positive IOD pattern was responsible for a serious drought occurrence in 1994. Our findings also suggest that a strong positive IOD pattern causes drought conditions (i.e., reduced rainfall and low dam discharges), and this in turn results in the proliferation of cyanobacteria. Based on these findings, we concluded that positive IOD patterns (leading to drought) should be the focus to explain cyanobacterial proliferation in the Nakdong River.

We observed that an increase in cyanobacteria density responded sensitively to strong positive IOD peaks. Furthermore, cyanobacterial proliferation intensified if drought occurred more than 1 year consecutively. Lack of KMR due to positive IOD will decrease impoundment in upriver dams, leading to higher probability of TDD decrease. Increase of water resource demand in the following dry seasons (i.e., winter to the following spring) also causes TDD decrease (Jeong et al. 2011). Insufficient summer rainfall for several consecutive years (e.g., 1994–1997) caused serious water resource deficiency, and upriver dam storage gradually decreased (Jeong et al. 2007), leading to decrease TDD. By comparison, the first year of the consecutive dry years would not be strongly affected unless the summer of previous year was dry (Jeong et al. 2007, 2011). We can therefore summarize that positive IOD for >1 year would increase the probability of cyanobacterial proliferation in the river system.

A slight difference was observed in the response pattern of average KMR and TDD of the Nakdong River to DMI changes. Although both were negatively associated with DMI changes, TDD did not increase instantly when DMI became more negative because of the conversion process from rainfall to discharge. Considering that cyanobacterial density would respond more readily to TDD than KMR, IOD–TDD–cyanobacteria relationships should be further examined. Here, we must consider the TDD management strategy in response to the IOD and KMR pattern. In the Nakdong River, Ha et al. (1998) reported that cyanobacteria did not proliferate in 1993 because of higher summer rainfall; however, increased dam water in summer 1993 should be discharged in spring 1994 to impound the next summer rainfall. Thus, the decreasing rate of upriver dam storage and dam discharge rate in that season was greater than that during other years (see Jeong et al. 2007). Because of the positive IOD effect,

summer 1994 was exceptionally dry across the Asian (Guan and Yamagata 2003) and Australian (Cai et al. 2009, Ummenhofer et al. 2009) regions, and average KMR of 1994 was also low, resulting in cyanobacterial proliferation. Furthermore, the average KMR in 1995 was the lowest throughout the study period, exacerbating water resource management problems. We therefore surmise that consecutive positive IOD patterns are responsible for summer cyanobacterial proliferation in Asian region.

A noteworthy finding was a strongly positive exponential growth pattern of cyanobacteria under DMI in previous years. Although a linear relationship between DMI and KMR was observed, cyanobacterial density was not linearly related with DMI and hydrological characteristics because of the growth pattern of cyanobacteria (Reynolds 2006). Cyanobacterial density explosively increased when a stable water environment persisted in the river (Jeong et al. 2003, Kim et al. 2007). Lack of KMR was related with positive IOD, and low flow rates helped cyanobacteria increase abruptly, thus explaining the higher sensitivity of cyanobacteria to positive IOD.

The clear relationship between IOD and cyanobacterial density may provide useful information for developing a forecasting model for cyanobacterial proliferations. In many previous studies regarding cyanobacterial proliferation and basin rainfall (Maier et al. 1998, Webster et al. 2000, Jeong et al. 2006), a dilution or flushing effect caused by highly increased flow rate (i.e., flooding) was emphasized. Despite this significance, when we consider higher sensitivity of cyanobacterial density to dry conditions (i.e., smaller average KMR and TDD; Fig. 4), inhibition of proliferation by disturbing the stable impact of drought is more important for control or mitigation of cyanobacteria. In addition to the adoption of rainfall and its derivatives into the modeling process, drought-related parameters provided useful information for understanding phytoplankton dynamics (Hong et al. 2014). Although enormous uncertainty surrounds the teleconnection mechanism, the strong significant correlation between IOD, drought, and cyanobacterial proliferation may encourage others to consider this relationship.

Monsoon rainfall is a natural driver of the structure and functions in ecosystems (Silva and Davis 1987, Svensson and Berndtsson 1996, Brewin et al. 2000, Kim et al. 2000, An and Park 2002, Dudgeon 2002, Park et al. 2002, Azami et al. 2004, Madhu et al. 2007). Thus, understanding climate–hydrology–ecosystem behavior via the monsoon pattern will help develop more efficient summer water quality and quantity management strategies. Recent advances in remote sensing and computational infrastructure will improve the accuracy of predictions and connect climatology and hydroecology to produce short-term predictions (e.g., 1 year) that support decision-making.

Adaptation to global climate change and local environmental management will be possible by understanding this climate–ecosystem connectivity.

Conclusion

A statistically significant correlation was found for the 15-year interannual variation of cyanobacterial density in the monsoon period compared with the IOD pattern. The average KMR, TDD, and cyanobacterial density in the KM period was largely related to the DMI, with a positive DMI inducing a decrease in the average KMR and TDD and an explosive increase in cyanobacteria density. Based on this relationship, we assume that the IOD pattern is largely responsible for the proliferation of cyanobacteria. Despite various uncertainties, the development of the IOD is believed to play a role in regulating freshwater phytoplankton assemblage through a signal propagation pathway.

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Supplementary information

Tables S1 and S2 are available for download via the Inland Waters website, <https://www.fba.org.uk/journals/index.php/IW/issue/view/128>