Long-term trends and seasonal variations in environmental conditions in Sesoko Island, Okinawa, Japan

Tanya Singh¹, Frederic Sinniger², Yoshikatsu Nakano¹,², Shigeo Nakamura¹, Shouhei Kadena¹, Mori Jinza¹, Hiroyuki Fujimura³, and Saki Harii¹

¹ Sesoko Station, Tropical Biosphere Research Center, University of the Ryukyus, 3422 Sesoko, Motobu, Okinawa 905-0227, Japan
² Present address: Marine Science Section, Research Support Division, Okinawa Institute of Science and Technology, 1919-1 Tancha, Onna, Okinawa 904-0495, Japan
³ Department of Chemistry, Biology and Marine Science, Faculty of Science, University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan

* Corresponding authors: T. Singh; S. Harii E-mail: tsingh138@gmail.com; sharii@lab.u-ryukyu.ac.jp

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Abstract Knowledge of environmental factors is crucial in understanding biological and ecological processes. Yet information on the environment around Sesoko Island, Okinawa, Japan, one of the main locations for coral reef research in Japan, remains scarce. Data of air and sea surface temperature (SST), wind velocity, wave height, and frequency of typhoons have been manually recorded at Sesoko Station, Tropical Biosphere Research Station, the University of the Ryukyus from September 1990 to November 2021. Here we describe the seasonal and long-term trends in these environmental variables at Sesoko Island. Some of the key findings were that the air temperature and SST fluctuated by ~9–12°C throughout the year. A rise in air temperature and SST between 1990 and 2021 was observed in the winter and autumn season, respectively. The Degree Heating Week (DHW) based on the in-situ data reflected the bleaching observations around Sesoko Station. The DHW exceeded the critical bleaching level of 8°C-week in 1998 and the significant bleaching level of 4°C-week in 2001, 2016, and 2017. Weak southerly winds were dominant in summers, while stronger northeasterly winds were dominant in winters. The frequency of winds between 3.4 to 7.9 m/s and northeastern winds have increased through time. Typhoons generally occur between May and October, and the frequency of typhoons has not increased over the past 30 years. Wave heights never exceeded 0.5 m and were highest between July and September. These findings will provide a reliable baseline of the environment at Sesoko Island for further ecological studies.

Keywords SST, Air temperatures, DHWs, Winds, Currents, Long-term monitoring

Introduction

Local environmental conditions like temperature and light have a crucial influence on several biological and ecological processes. This is especially prevalent for corals that experience fluctuation of these environmental variables at various scales. Sea surface temperature (SST) is one of the most decisive factors influencing coral physiology and coral reef distribution. The relationships between biological processes and temperature are usually parabolic. An increase in temperature raises the rates of the biological processes until it reaches a thermal optimum beyond which these rates decline rapidly (Huey and Stevenson 1979). Similarly, corals may lose their symbiotic algae and bleach when SSTs exceed the local summer maxima by 1°C (Hoegh-Guldberg 1999) or when SST reaches temperatures low enough to induce cold stress (Saxby et al. 2003; Hoegh-Guldberg et al. 2005). Degree Heating Week (DHWs) developed by the National Oceanic and Atmospheric Administration Coral Reef Watch (NOAA CRW) is an index that can represent the cumulative effect of thermal stress (Liu et al. 2003, 2006) and is frequently used as coral bleaching indicator.
Bleached corals are physiologically compromised and susceptible to mortality. Extremely low SSTs can also limit metabolic activity such as calcification, reproduction, larval survival (reviewed in Veron and Minchin 1992).

Wind velocity is another critical factor influencing coral ecology. Wind speeds are often used as a proxy for water movement in studies examining environmental drivers of spawning (van Woesik 2010; Keith et al. 2016). Within one to two months before the full moon of the spawning month, the surface wind speed strongly correlated with spawning day deviations of Acropora corals in Okinawa and Australia (Sakai et al. 2020). High wind speeds near the ocean’s surface immediately before spawning can delay the night of Acropora coral spawning (Sakai et al. 2020). Furthermore, the surface current direction can also influence larval dispersal and potential recruitment rates among coral reefs (Oliver and Willis 1987; Nakamura and Sakai 2010). Increased surface current speed could increase the nutrient supply to shallow corals by increasing the diffusion rates between the corals and the water column (Atkinson and Bilger 1992; Lesser et al. 1994).

Fringing reefs are developed around Sesoko Station, Tropical Biosphere Research Center, University of the Ryukyus, on the southeastern coast of Sesoko Island, Okinawa, Japan (Fig. 1). Several studies examining various aspects of coral biology and ecology like reproduction, climate change response, population, and community dynamics are continuously being conducted here. In contrast, these reefs’ environmental features such as temperature and wind velocity have not been updated recently (Nakano and Nakamura 1993; Hohenegger et al. 1999). However, a dataset on several environmental vari-

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Fig. 1A-D  
A, B Location of Sesoko Island and Sesoko Station’s jetty (red dot). Sesoko Island is connected to Motobu Peninsula on Okinawa Island by a bridge. Numbers on the isobaths indicate the depths and the dashed lines represent the lowest tide level. C, D Coral reefs around Sesoko Island. The island is surrounded by fringing reefs. A well-developed reef with crest is located on the north side. On the east side of the island, a narrow coral reef with high coral cover can be found (C). This reef extends to the southern part of the island where it transitions from high energy (Acropora-dominated) to back reef coral communities (branching Acropora and Porites-dominated) (D). North of the island, a complex assemblage of patch reefs (visible in the dashed lines contours) separates Sesoko from Motobu Peninsula. Data source of B: Japan Coast Guards.
ables at Sesoko Station has been collected from September 1990 onwards. This study describes seasonal and long-term trends in environmental variables at Sesoko Station, collected over 32 years, to provide a reliable baseline for further ecological studies.

**Materials and methods**

**Environmental observations**

Environmental parameters were measured by technical staff at the Sesoko Station of the Tropical Research Center, the University of the Ryukyus at approximately 9:00 and 13:00 almost every working day (Monday to Friday) between September 1990 and November 2021. This dataset is named “Record of coastal observations at the Sesoko Station, Tropical Biosphere Research Center, the University of the Ryukyus”. This dataset is available through the homepage of Sesoko Station (https://tbc.skr.u-ryukyu.ac.jp/sesoko/en/). The air temperature was monitored at the garden of the station (26°38.1929′N, 127°51.9177′E), and sea surface temperature (SST), wave height, wind direction and speed, and weather conditions were recorded at the jetty of the station (26°38.1548′N, 127°51.9217′E) (Fig. 1). The air temperatures were manually measured using a standard thermometer (1-NM-11, Ando Keiki Co., LTD, Japan) placed inside a Stevenson screen. Sea surface water was collected using a 5L bucket from the station’s jetty, and SSTs were manually measured using the same thermometer model as the air temperature measurement.

The wind speed and directions were estimated visually from the station’s jetty. The wind speeds were classified following the Beaufort scale (https://www.rmets.org/resource/beaufort-scale) into the following nine classes: 0 (0–0.2 m/s), 1 (0.3–1.5 m/s), 2 (1.6–3.3 m/s), 3 (3.4–5.4 m/s), 4 (5.5–7.9 m/s), 5 (8.0–10.7 m/s), 6 (10.8–13.8 m/s), 7 (13.9–17.1 m/s), and 8 (17.2–20.7 m/s). Data for the wind speed above 21 m/s was not recorded because the station was closed on those days. The wind direction was classified based on the 16 cardinal points, namely: North (N), North-North East (NNE), North East (NE), East-North East (ENE), East (E), East, East-South East (ESE), South East (SE), South-South East (SSE), South (S), South-South West (SSW), South West (SW), West-South West (WSW), West (W), West-North West (WNW), North West (NW), and North-North West (NNW).

Regarding typhoon occurrence, we used the best track data provided by the Japan Meteorological Agency and compiled as a kml file by the Kitamoto Laboratory of the National Institute of Informatics (http://agora.ex.nii.ac.jp/digital-typhoon/kml/index.html.en). Although the impact on the reef is determined by several parameters, including the size, speed, and direction of the typhoons, here we limited our analyses to the typhoons passing with a 120 km radius of the station with maximum sustained winds over 18 m/s.

Current(s) data were measured at the tip of the jetty from July to September 2004 using an electromagnetic current meter (Compact-EM, JFE-Advantech, Co., Ltd.) (ca. 2 m depth in average). The average wave heights were estimated by eye (trough to crest).

**Calculation of degree heating weeks**

Degree Heating Weeks (DHWs) were calculated to illustrate the thermal stress experienced by the corals around Sesoko Station from 1990 to 2021. DHW over 4°C-weeks can induce coral bleaching and those over 8°C-weeks indicate widespread bleaching and mortality. These DHW threshold values have been validated at several locations including the north-western Pacific and Ryukyus Island (Kayanne 2017; Kayane et al. 2017). NOAA’s products utilize nighttime satellite data (18:00 to 06:00) to calculate DHW to account for the diurnal variations of SST due to ocean surface warming. Since daily temporal variations around Sesoko Station can be as large as 3°C, we only used the morning SST values for calculating DHW (Fig. S2 in Singh et al. 2019). DHW was calculated by subtracting the weekly morning SST from the historical summer maxima (28.6°C) and summing all values ≥ 1°C over the preceding 12 weeks period. The historical summer maxima (MMM<sub>max</sub>) should be calculated using a minimum of seven years between 1985 to 2000, excluding the El Niño years (Donner 2009, 2011).

Therefore, we used the morning SST values from 1991 to 1997 (n = 7) to calculate the MMM<sub>max</sub> by taking the mean of the warmest monthly mean of each year from 1991 to 1997.
Statistical analyses

Statistical analyses were done to test the seasonal (within a year) and annual (between years) variations over 32 years (1990–2021). Temporal variations of temperature and wave height were carried out for their monthly mean values only because these means could represent both seasonal and annual variations. Monthly means were estimated only for days in which both morning and afternoon readings were recorded. Temporal variations in temperature and wave height were tested using generalized additive (GAM) models. Smooth functions of time in months (seasonal trends), time in years (annual trends), and the interaction between the annual and seasonal trends were selected as the explanatory variables for the temperature data. Time in months as factorial variables (seasonal trends) and smooth function of time in years (annual trends) were selected as explanatory variables for the wave height. A significant interaction between the seasonal and annual trends was not observed for the wave height data. We used cubic regression and cyclic cubic regression spline for the time in years and months, respectively. The first-order autoregressive (AR1) correlation structure was incorporated in the temperature models because significant temporal autocorrelations were observed in these models.

Temporal variations in wind speed and directions were tested using a generalized linear model (GLM) with the negative binomial family of distribution and log link function. Most wind velocities belonged to the Beaufort force 1 to 4 and wind directions NNE, NE, ENE, SSE, S, and SSW. Therefore, statistical tests were done only for these force winds and directions. Frequency of readings in a particular wind speed class or directions were selected as the response variable, while time in years and seasons and interaction between year and season were selected as the explanatory variables. The total number of readings in each season/year were taken as weights to account for differences in sampling among years and seasons. Seasons were divided into the following levels: Winter (December-February), Spring (March-May), Summer (June-August), and Autumn (September-November).

Temporal variation in the frequency of typhoons was analyzed by the GLM with the Poisson family of distribution and log link function. The total number of typhoons each year from 1990 to 2021 was employed as response variables, while time in years was selected as the explanatory variable.

Results

For general annual trends, air temperatures and SSTs were the lowest in January–February and the highest in July–August. The minimum monthly mean air temperature was 15.5±2.9°C (Mean±SD) in February 2000, and the highest monthly mean was 32.1±1.9°C in July 1994 (Fig. 2A). The minimum monthly mean SST was 18.9±0.9°C in February 1995 and the highest monthly mean SST 30.8±0.9°C in August 1998 (Fig. 2B). Significant interaction between annual and seasonal trends were observed for the air and seawater temperature at Sesoko Island (Fig. 3, Table S1, Year x Month: edf=16 and 17, F=151.6 and 158.5, p<0.0001). In other words, the significant rise in air temperature and SST varied among months or seasons. The air temperatures and SST increased from 1990 to 2020 in the winter and autumn, respectively. The monthly mean air temperature in February increased from 17.4±2.9°C (Mean±SD) in 1991 to 19.4±3.2°C in 2021 (Fig. 3A). SST in September and October increased from 27.9±1.2°C and 25.8±1.4°C in 1990 to 29.6±0.9°C and 27.1±1.6°C in 2021, respectively (Fig. 3B).

DHWs exceeded the widespread and critical bleaching level of 8°C-weeks in 1998, and it exceeded the significant bleaching level of 4°C-weeks in 2001, 2016, and 2017 (Fig. 4). The bleaching level DHW values coincided with the bleaching events observed around Sesoko Station. The maximum DHW (DHWmax) in 1998, 2001, 2016, and 2017 were 8.6, 6.5, 6.8, and 4.5°C-weeks, respectively (Fig. 4).

A significant interaction between annual and seasonal trends was observed for wind speed and direction (Fig. 5, Table S2, Year x Season: LRT=51.5–773.5, df=3, p<0.0001). Force 3 (3.4–5.4 m/s) winds were most frequent followed by the force 2 (1.6–3.3 m/s), 4 (5.5–7.9 m/s), and 1 (0.3–1.5 m/s) winds (Fig. 5B). Force 1 winds were generally most frequent in spring and summer, force 2 in spring, force 3 in winter, and force 4 in autumn (Fig. 5B). Southern winds (SSE, S, SSW) winds were domi-
Fig. 2 Temporal variations in daily, 30 days, and 365 days rolling means of (A) air and (B) sea surface temperature at Sesoko station.

Fig. 3 Trends in annual and seasonal variations of monthly means of (A) air and (B) sea surface temperature at Sesoko Station. Raw data are represented by the points, while model predicted values are represented by lines.

nant during the summer season, while northern winds (NNE, NE, ENE) during the winter, spring, and autumn seasons (Fig. 5A, C).

The frequency of force 2 winds decreased significantly from 1990 to 2021, while forces 1, 3 and 4 increased from 1990 to 2021 (Fig. 5B). However, this rate of change varied among seasons (Table S2). The rate of decrease in the frequency of force 2 winds was maximum during the spring, while the increase in the frequencies of forces 1 and 3 winds was highest in winter and force 4 winds in winter and spring seasons (Fig. 5B, Table S3). Significant annual trends in wind directions were also observed, which varied among seasons (Fig. 5C, Table S4). These trends were the strongest for the NE and ENE winds. The frequencies of NE winds have increased significantly from 1990 to 2021, and this effect was strongest during the spring and winter seasons. While the frequencies of ENE winds have markedly decreased from
1990 to 2021, the strongest effect was observed in the spring and autumn season (Fig. 5C).

Typhoons generally approached Sesoko Island from May to October (typhoon season) and peaked in August and September (Fig. 6A). Over the whole period considered, 41 typhoons with maximum sustained winds over 18 m/s passed within 120 km of the station, including one passing by twice with five days intervals (typhoon #16 in...
Four typhoons were tracked within 3 km of the station, with four additional typhoons passing within 10 km. The earliest typhoon passed near the station on the 12th of May 2015, and the latest was recorded on the 28th of October 2017. The temporal variation in frequency of typhoons/year was not significant (Fig. 6B, Table S1, Slope = 0.008, p = 0.66; Pseudo $R^2$ = 2.3%). The frequency of annual typhoons was $2 \pm 0.9$ (Mean $\pm$ SD) and the years 2012 and 2018 experienced four typhoons.

The current in front of the station is generally weak and flows mainly to NE-ENE and SSW-WSW, with a flow velocity of 5 cm/s or lower (Fig. 7). However, the flow velocity is highly affected by the wind speed, and wind speeds above 5 m/s appear to become the main drivers of the surface current in front of the station.

Significant annual and seasonal variations in monthly mean wave height was observed during the study period (Fig. S1, Table S1, Year: edf = 7.2, p < 0.0001, Month: LRT = 22.6, p < 0.0001). Annual mean wave height ranged from 0.02 $\pm$ 0.1 m to 0.41 $\pm$ 0.3 m (Mean $\pm$ SD) throughout the study period, while annual mean wave height of most of the years fell between 0.16 $\pm$ 0.1 m to 0.25 $\pm$ 0.2 m ($n$ = 23). Monthly mean wave heights were highest in June–September and ranged from 0.23 $\pm$ 0.2 m to 0.26 $\pm$ 0.2 m (Fig. S1, Table S1, p = 0.03–0.0001).
Monthly mean wave heights in other months ranged from $0.20 \pm 0.1 \text{ m}$ to $0.22 \pm 0.2 \text{ m}$.

**Discussion**

This study described the seasonal and long-term variations in SST, air temperature, wind velocity, frequency of typhoons, and wave height around Sesoko Station. The seasonal patterns in water temperature and wind velocity observed in this study were similar to those described previously in 1991 and 1996 at Sesoko Station (Nakano and Nakamura 1993; Hohenegger et al. 1999). The water temperature varies by $\sim 10°C$, is maximum in July–August and minimum in January–February, while north-easterly winds dominate from autumn to winter and strong southerly winds in summer. In addition, we compiled over three decades of data to show long-term annual variations in environmental factors around Sesoko Station. In particular, the water and air temperatures in water and air temperature have been rising since the 1990s and the frequency of the north-easterly winds has also been increasing since the 1990s.

The data measured at Sesoko Station represent well the environmental context of this subtropical region influenced by both the cold northern winds and warm Kuroshio current. Air and water temperatures at Sesoko Island can fluctuate by as much as $12–15°C$ throughout the year. Temperatures at Sesoko Station (26.64°N) compared to other locations at similar latitudes are generally lower during the winters and warmer during the summers. For example, the monthly mean SST at our study location ranged from $20.3\pm1.3°C$ to $29.2\pm1.3°C$ (Fig. S2). While the monthly mean SSTs recorded at similar hours as our study site at Layasan Island (25.78°N; 2008–2012) and Lisianski Island (25.98°N; 2011–2013) located in the Northwestern Hawaiian Islands (NWHI) range from $22.5\pm0.9°C$ to $27.8\pm0.6°C$ and $23.1\pm0.9°C$ to $28.2\pm0.6°C$ respectively (Fig. S2) (Pacific Islands Fisheries Science Center 2022). Monthly mean minimum and maximum SSTs at Northern Bahamas (26.5°N) were $22.8\pm0.7°C$ and $29.8\pm0.5°C$ from 1985 to 1997 respectively (Fig. S2) (NOAA Coral Reef Watch 2019). The warmer summer at Sesoko Station compared to NWHI, despite its higher latitude, could be due to the warm Kuroshio current, which flows from southwest to north-east and passes on the west side of Okinawa Island (Gallagher et al. 2015). Like Okinawa, the Bahamas are also located between two warm currents, the Florida and Antillean currents. However, the SST in winter at Sesoko Station is much colder than those in the Bahamas and the NWHI. This can be due to the effect of the cold wind flowing from Siberia in Sesoko, as this region is known to be an area of significant heat transfer from the ocean to the atmosphere during wintertime (Agee and Howley 1977). These southwestward winds blowing against the Kuroshio current off Okinawa have been hypothesized to cause upwelling of the cooler deep water by Ekman transport on the west coast of Okinawa and decrease the current speed during the winter season (Ikema et al. 2013; Nakamura et al. 2015). In addition, Sesoko Island is not located in the main path of the Kuroshio current. Thus, the effect of the current is likely attenuated by the distance. These factors may explain the lower temperatures at our study site than in the Bahamas, which is also influenced by the warm Florida and Antillean currents.

Corals around Sesoko Island have observed multiple bleaching events. The DHW$_{\text{max}}$ values calculated based on the in-situ data supported the bleaching observations (Fig. 4). Severe mass bleaching events in 1998 and more recently from 2015 to 2017 were observed across the globe, including Okinawa (Loya et al. 2001; van Woesik et al. 2011; Sakai et al. 2019; Singh et al. 2019). Following the mass bleaching event in 1998, soft and hard coral cover decreased by 85% and species density by 65%, with branching corals like *Acropora*, *Pocillopora*, *Seriatopora* being most severely affected (Loya et al. 2001). Despite another thermal stress event in 2001, the coral community had recovered by 2010, dominated by the vulnerable *Acropora* corals (van Woesik et al. 2011). The bleaching event in 2016 around Sesoko Station was comparatively moderate since the thermal anomaly in 2016 was lower than those in 1998 (DHW$_{\text{max}}$ 8.6°C-week in 1998 vs 6.8°C-week in 2016, Fig. 4). During the 2016 bleaching event, 100% of *Acropora* had bleached; however, approximately 60% survived even after remaining bleached for weeks (Sakai et al. 2019). Both rapid recovery of the coral community after catastrophic mortality in 1998 and the recovery of heat vulnerable *Acropora* species from bleaching demonstrate the resilience potential
of corals around Sesoko Station.

Temperatures at Sesoko Station have increased over the past 30 years during the autumn and winter seasons (Figs. 2, 3). This trend of warmer autumn-winter can have several ecological implications. For instance, the growth rates of corals may increase in response to warm winters. A parabolic relationship between coral growth rates (calcification, linear extension) and the temperature has been observed in the subtropical regions (Jokiel and Coles 1990; Castillo et al. 2014; Silbiger et al. 2019). These rates generally peak at temperatures close to their local summer maxima (Jokiel 2004). A decrease in growth rates from the summer to winter has been observed for several species of corals in subtropical regions (Shinn 1966; Kurihara et al. 2019). Therefore, a warmer winter could potentially result in higher growth rates. In addition, *Acropora* corals spawn earlier than usual under warm conditions (Paxton et al. 2015). Considering that gametogenesis of corals takes several months, warmer SST during the autumn season could also affect the timing of coral spawning. Although most of the corals at Sesoko spawn from May–June, some corals like fungoids or brooding species (*Pocillopora, Stylophora, and Seriatopora*) can also spawn or release larvae from late August to September (Heyward et al. 1987; Loya et al. 2008; Isomura and Fukami 2018; Baird et al. 2022). Thus, the warmer temperature in September could also affect the spawning cycles of late spawners at Sesoko Station.

Warmer winter and autumn seasons may affect poleward range shifts or expansions to Sesoko Island as shown in temperate regions (Yamano et al. 2011). However, all species which reach the temperate region may not necessarily establish their populations in the new regions (Mizerek et al. 2021). Several physical and biological factors limit species range expansion by influencing key demographic processes such as dispersal, settlement, growth, and reproduction (Abrego et al. 2021). Cold stress is one of the major limitations, and several studies have shown that minimum winter temperature may limit tropical species from establishing themselves in temperate and subtropical regions. Warmer winter or autumn in Sesoko may allow corals to migrate from further south to Okinawa. Although there are no studies that have examined if any species has expanded its range from Southeast Asia to Okinawa, the temperature data indicate that Okinawa could potentially be a stepping stone site for tropical species to migrate further north.

The warmer autumn or winter could also influence the dynamics of coral diseases. Most of the disease outbreaks are also controlled by temperature, and several coral diseases show a seasonal pattern, where they peak during summer-autumn and decline in winter (Kuta and Richardson 2002; Miller and Richardson 2015; Chen et al. 2017; Sato et al. 2009, 2016; Howells et al. 2020). In Okinawa (including Sesoko Island), the Black Band Disease (BBD) prevalence is maximum during the summer and autumn and almost disappear once the SST declines below 18°C. The daily progression rates of the BBD in corals at Sesoko Island peak when the SST rises above 29°C and decreases once the SST falls below 27°C (Das et al. 2022). Therefore, an increase in temperature in autumn and winter can potentially increase the length of disease outbreaks and interfere with the coral disease dynamics. However, a study on the Great Barrier Reef showed that the white syndrome outbreak significantly decreased following a warmer winter, potentially due to increased disease resistance of the coral host (Heron et al. 2010). Some anecdotal observations state that the number of coral diseases has increased from the 1970s to the 1990s around Sesoko Island and Okinawa. Several coral diseases were reported for the first time in the 2000s (Yamashiro 2004; Weil et al. 2012). However, no study quantified how the prevalence of coral diseases has changed through time around Okinawa.

Most shallow water corals have positively buoyant eggs, which are often dispersed passively by wind-driven surface currents (Oliver and Willis 1987; Black 1993). For example, recruitment rates around Iriomote Island could be explained by spatial-temporal variations in wind-driven surface currents (Nakamura and Sakai 2010). Thus, seasonal patterns in wind direction, with southern winds (SSW and S to NW and N) generally dominating during the coral spawning season, may influence larval dispersal and recruitment rates around Sesoko Island. However, wind directions may also fluctuate on a scale of a few days. Furthermore, several other hydrodynamics forcings also influence larval dispersal, such as
tidal currents that are often observed around the Sesoko Station, wave action, horizontal and vertical mixing of the water, etc. The current data obtained in the summer of 2004 suggests that the water flows parallel to the shore (to NE-ENE or to SSW-WSW). This could imply that the reefs located at the NE of Sesoko Island are a potential source for the reef at Sesoko Station, although not an ideal source as most of the area located NE of the station is heavily affected by construction. However, little can be inferred based on single-point data and a wider range of current data would be needed to understand better the potential sources of larvae for the reef in front of Sesoko Station.

The frequency of north-easterly winds has increased through time during spring, autumn, and winter. Changes in climate conditions and small-scale variability can alter spatial and temporal wind patterns (Pryor and Barthelmie 2010). Such changes in wind patterns may have an impact on coral communities (Dollar 1982; Toda et al. 2007) and reef development (Yamano et al. 2003). Although the coral reefs near Sesoko Station might be protected from the north-easterly winds, the patch reefs further north are directly exposed to this increase in north-easterly winds. Stronger north-easterly winds are observed during the autumn and winter seasons (September–March). Wave height around Sesoko Station peaks in September, corresponding to the peak of typhoon activity. Therefore, coral reefs around Sesoko, especially those located north of the island, might experience substantial physical disturbance during the autumn seasons causing whole or partial mortality to the corals. On the other hand, stronger water flow can enhance the diffusion rates between the corals and the water column thereby mitigating bleaching stress by either supplying nutrients or removing the toxic reactive oxygen species from corals (Atkinson and Bilger 1992; Lesser et al. 1994; Nakamura and van Woesik 2001; Nakamura et al. 2003). Therefore, stronger winds may be beneficial in autumn when corals recover from thermal stress and bleaching.

Several theoretical and empirical studies have shown that the frequency and intensities of typhoons are increasing in several parts of the world like North Pacific, Indian, and Southwest Pacific oceans (Webster et al. 2005; Elsner et al. 2008; Mei et al. 2015) In the current study, the frequency of damaging typhoons has remained stable since 1990 at Sesoko Station (Fig. 6B, Table S1). However, to accurately examine if the typhoons are getting stronger through time, we should consider several additional indices such as return period (time between two typhoons), the intensity, precipitation, track, and associated storm activity with the typhoons. This study quantified just one of these indices (frequency of annual typhoons) occurring near northern Okinawa (Sesoko Station). Further research is required to test if typhoons have indeed not been getting stronger around Sesoko and Okinawa.

In conclusion, our study emphasizes the importance of environmental data in explaining several biological and ecological processes. Such long-term monitoring of environmental variables in the field will hopefully contribute to better understanding the future of coral reefs around Sesoko and the world.

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Compliance
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**Electronic supplementary material**

ESM Table S1-S4 and ESM Figs. S1-S2 can be downloaded from the J-STAGE website: https://doi.org/10.3755/galaxea.G2021_S14O

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