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Research Article

WAKES AND THERMAL ANOMALIES IN THE LESSER ANTILLES SURFACE WATER

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ABSTRACT
The appearance and dynamics of sea surface wakes are documented with observations in the Lesser Antilles and a detailed study of the Dominican wake is presented. Cloud data for the Lesser Antilles indicate that clearing of the atmosphere on the leeward side of the islands expose the areas to increasing solar irradiance on the lee side of the island wakes. However, average sea surface temperatures around the Lesser Antilles show slight cooling. Compared to the global average temperature rise of about 0.018^0C y^{-1}, the slight cooling of sea surface temperature that is observed in the region stays as an anomaly in the Lesser Antilles. Atmospheric anomalies and the islands' thermal variances are not restricted to the near shore region of the Lesser Antilles, rather wakes are impacting the surface water over large areas and increase the surrounding sea surface temperatures. The intensity of warming shows that Guadeloupe, Dominica and Martinique have the major impact on surface warming. The temperature range to identify the wake effect with monthly averaged surface temperature shows that the average recognition temperature is around 0.86^0C but can vary between 0.3^0C and 2.0^0C. The wake temperature goes through a diurnal cycle and night cooling is documented with the difference of day and night measurements. Cooling is especially strong around Guadeloupe and Martinique as indicated by a decrease of about 4^0C at night. Averaged data in the wake of Dominica show that day and night temperatures may reach about 3.5^0C. Both day and night measurements over twenty years do not indicate a warming trend, rather a decrease in sea surface temperature that is estimated to be around -0.004 ^{0}C y^{-1} to -0.002 ^{0}C y^{-1} in the vicinity of Dominica, and the Lesser Antilles region is exposed to a similar anomaly. The analysis of chlorophyll concentrations shows that upwelling around the Lesser Antilles plays not a significant role, although the data in the path of the wake of Dominica exhibits an increase in concentrations compared to the windward side, but in the average, concentration does not exceed 0.2 mg m^{-3}. The most possible explanation for the slight cooling in the Lesser Antilles is due to changes in surface wind speed and precipitation because both show an upward trend during the last decades.

Keywords: *Lesser Antilles, wakes, surface temperature anomalies, chlorophyll, climate change*

INTRODUCTION
Small islands are dominantly coastal areas with a unique and very diversified environment. Sea level rise is considered one of the most widely recognized climate change threat to low-lying coastal areas and it is projected that global mean sea level will be increased by the year 2100 to about 0.35 m to 0.70 m (Nurse *et al.,* 2014). Interannual mean sea level of the Caribbean region seems to be highly correlated with El Niño Southern Oscillation and the seasonal cycle has large variations with peaks around October (Palanisamy *et al.,* 2012), although differences are observed at some Caribbean islands where the trend is around 2mm $y\text{-}^1$ (Torres and Tsimplis, 2012).

The Intergovernmental Panel on Climate Change (IPCC, 2018) showed with high confidence that human activities have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. However, the globally averaged temperature does not fully assess climatic change and its impact at smaller scales. Smaller islands especially have microclimates that deviate from global changes. Temperature increase on the continents, as well as in the oceans, is not evenly distributed and shows that the slope of increase differs from region to region. This is seen with a comparison of observations from The Bahamas and the Philippines, demonstrating that change in sea surface temperature may vary to a high degree between islands (Szekielda and Watson, 2022; Szekielda and Guzman, 2021). Observations also indicate variability that may be a manifestation of decadal oscillations, and the observed variability in sea surface temperature is not an effect of global warming alone, rather a combination of several factors. For instance, research in The Bahamas showed that all seasons have a warming trend although they have a different slope, and the highest predicted increase is for the period September to November at 1.7 ^{0}C, while lowest predicted increase is 1.0 ^{0}C for June to August. Thus, The Bahamas may surpass the temperature increase that was set by the Intergovernmental Panel on Climate Change (IPCC) as a desirable upper limit (Szekielda and Watson, 2021).
Ocean surface temperatures follow closely the global trend, the IPCC having reported for the ocean an increase of about 0.88 °C in 2011–2020 compared to 1850–1900 (IPCC, 2021). This increase is not restricted to the surface, rather the warming reaches the oceans to a depth of about 700 meters that has been warmed at a rate of 0.11^{0}C, 0.07^{0}C and 0.05^{0}C per decade for the Indian, Atlantic and Pacific Oceans, respectively (Hoegh-Guldberg *et al.*, 2018). Larger anomalies are expected to occur on the local level, and in particular, in regions with microclimates typically found in coastal regions and in the vicinity of small islands. Air temperature at land stations on small islands shows strong warming trends but changes in precipitation are less consistent and the trends are generally weak. However, a significant rise of the daily intensity rainfall was observed at the majority of the locations in the Caribbean Sea, (Stephenson *et al.,* 2014).

General oceanographic features in the Caribbean Sea

The origin of the major water masses in the Caribbean is in the North and South Atlantic Ocean that enter through the sills of the Antilles Islands Arc that separate the Caribbean Sea from the Atlantic Ocean. Thus, the geomorphology of the Caribbean regulates the water budget because two major sills control the water inflow from the Anegada Passage between the Virgin Islands and the Lesser Antilles, with sill depths of about 1,950 and 2,350 m, and the Windward Passage that is located between Cuba and Hispaniola with a sill depth of about 1,600 m. As a consequence, the surface water is highly stratified in the upper 1200 m and is directly related to sill depths of the Antilles Islands arc that controls the transport of deep water into the Caribbean (Gordon 1967). However, most of the water entering the Caribbean is carried through the southern Lesser Antilles passages (Johns *et al.*, 2002) and mesoscale variability is observed when anticyclonic rings from the Brazil Current collide with the Lesser Antilles Passages (Johns *et al.*, 1990; Fratantoni *et al.*, 1995; Andrade and Barton 2000; Jochumsen et al.; 2010; Hu *et al.*, 2004). The surface salinity in the Lesser Antilles is strongly influenced by freshened surface water from the Orinoco and Amazon estuaries to the Caribbean Sea with low salinity especially during August to September (Hellweger and Gordon, 2002). By November, the southern part of the Caribbean Sea is seen to receive its freshwater input mainly from the Orinoco plume. It is evident that low-salinity water is also generated through mixing of Orinoco water with water from the Amazon plume. That mixture may occasionally reach the coasts of Hispaniola and Puerto Rico. Water approaching the Lesser Antilles is about 0.3 psu lower in salinity as compared to the western region of the Lesser Antilles. Sea surface temperature anomalies seem to be characteristic of the Caribbean Sea because different temperature trends have been observed in the southern and eastern parts. Warming of about 0.5 ^{0}C has been found in the northwestern corner of the Caribbean. However, the sea surface temperature of the wider Caribbean Sea continues to increase except for the Lesser Antilles that showed cooling (Ped *et al.*, 2016). The Columbia Basin also showed a slight decrease in temperatures for 2011 to 2014 and an increase in salinity. This thermal and salinity anomaly was also recognized with measurements in the vicinity of the Lesser Antilles showing a decrease in temperature of about -0.007 ^{0}C y^{-1} (Szekielda, 2022). As small as this decrease is, it shows that the region at the entrance to the Caribbean Sea did not follow the general global trend in warming. That the climate of small islands does not necessarily follow the global warming trend is also shown with temperature and precipitation trends for the islands Trinidad and Tobago that indicate no significant warming (Dookie *et al.*, 2019). While the climate of the Lesser Antilles is predominantly determined by the almost constant trade winds, the islands are exposed to varying wind strength that is documented in the distinction between the Windward Islands and the Leeward Islands. The Windward Islands include Barbados, the Caribees, Dominica, Martinique, Grenada, Saint Lucia and Saint Vincent. The northern part of the Lesser Antilles includes the Leeward Islands, Antigua and Barbuda, the British Virgin Islands, Montserrat, Saint Kitts and Nevis, and Anguilla. Substantial environmental differences are observed between the windward and the leeward parts of the islands. Anomalies are especially shown in the moisture transport of the winds that bring drier air to the west slope of the islands, but cloud forests on the volcanic slopes of the windward side are getting wetter (Jury, and Bernard, 2019). Thus, a microclimate is generated on those islands that develop strong gradients in temperature and humidity (Richards, *et al.,* 2015).

Sea surface wakes observations

The oceanographic scenario around the islands is complicated by the extraordinary air-sea/mountain interaction and the orographic effect. The high mountains in the Lesser Antilles islands are obstacles to the Trade Winds because they force the approaching airflow to split and generate weak winds downstream while increased wind speed is observed on the flanks of the islands. Rising air over the windward side of the mountains cools adiabatically and water vapor condenses as rainfall in the wind direction. The effect is cloud clearing and the exposure of surface water to higher irradiance at the leeside of an island that results in warmer temperatures. Wakes have been detected to persist over long distances, away from islands, with elevated sea surface temperatures that are higher than the surrounding oceanic waters (Caldeira *et al.*, 2002; Xie *et al.*, 2001; Yang *et al.*, 2008). The water column in wake water is strongly stratified but unstable in its temperature profile, and salinity shows water parcels that may sink and/or rise in response to intense heat flux (Azevedo *et al.*, 2021). Furthermore, the diurnal cycle in irradiance causes changes in evaporation of the ocean surface, and cooling at night leads to stretching of the mixed layer.

Increase in sea surface temperature on the leeward side of islands as a result of wake formation seems to be a common process worldwide because it has been reported for various islands, for instance, offshore Hawaii (Xie *et al.*, 2001; Yang et al.; 2008), the Canary Islands (Van Camp *et al.*, 1991), Lesser Antilles, (Szekielda, 2022) and Madeira (Azevedo *et al.*, 2021). However, research on wakes and their thermal behavior in the Caribbean is rather limited although some rigorous work has been done with observations, models and satellite observations especially on cloud trails in the Lesser Antilles (Kirshbaum and Fairman, 2015) and in the St. Vincent's wake (Smith *et al.,* 1997).

Although easterly trade winds are steady, they develop over islands an unequal distribution of humidity and diurnal air temperature cycle. This generates a microclimate that is also regulated by the elevation of the islands that may result in large differences across small horizontal distances (Richards *et al.*, 2015). The distribution of clouds in the vicinity of islands is related to two processes: the first one is connected to the daily temperature cycle of the islands, while the second one is related to the seasonal changes, but both result in mechanical lifting as well as differential heating of surface land and seawater because of the unusual high heat capacity of water. The islands' orography adds to the environmental complexity and is responsible for varying wind fields that may be forced due to horizontal momentum and direction, either to ascend or divert around the islands. Mechanical uplifting is directly related to the orography of the islands when the airflow has sufficient horizontal speed. In this case, cumuli may cover the windward slopes, whereas at reduced momentum, winds incline to detour around the islands and initiate convergence zones, upwind and downwind. In addition, thermal uplifting occurs mainly in the afternoon, and the cloud frequency is enhanced in the afternoon because of the accumulated absorbed solar irradiance on an island's surface deposit (Kirshbaum and Fairman 2015). Thus, it is evident that the thermal properties of the major surface deposits on islands and water are the drivers in the atmospheric and surface circulation in the vicinity of islands. Comparison of different surface coverage shows high heat capacity in $Jkg^{-1}K^{-1}$ of water at around 4180 compared to vegetated surfaces with a value of about 830, rocks of about 2000 and dry sand of about 840.

At constant winds, this large difference in heat capacity of different surface deposits leads to a situation where air moving over an island is disconnected from the moisture supply and loss of moisture through precipitation. The east side benefits from the moisture of the trade winds, while the west slope receives drier wind. This generates a microclimate that also depends on elevation, and large differences can occur across small horizontal distances (Richards, *et al.*, 2015). Wake water may be slightly unstable leading to the stretching of the mixed layer as has been observed over a distance of about 100 km close to Madeira, where the sea surface temperature can be 4^0C higher than the surrounding oceanic waters (Azevedo et al, 2021). Increase in surface temperature and greater evaporation also introduces changes in the vertical density profile and may trigger at the surface salinity instability. The wind shadow on the leeside of the island is rather smooth whereas island flanks are characterized by a rougher surface. In addition, wake air is relatively warm and dry (Arístegui *et al.*, 1994). This difference in wind characteristics can be observed especially in orbital imagery due to the different sea state, because a disturbed air-sea interface reflects sunlight differently compared to an undisturbed sea surface.

Impact of wakes are reported downwind of St. Vincent where long areas of smooth sea surface with a length of about 300 km are detected, and it appears that they are not affected by diurnal heating of the island (Smith *et al.*, 1997). However, observations in the vicinity of the Lesser Antilles show the daily cycle of cloud formation is related to the atmospheric wake. The strength of cloud trail building does not only depend on the wind speed but also on the island mountain ridgeline.

The sea surface temperature in the Lesser Antilles shows slight cooling that makes it attractive to investigate further this anomaly with the aim to extract details on wake temperature patterns and the possible impact on chlorophyll concentrations that may serve as an indicator for changes in the ecosystem. Thus, this study will provide information on the specific cloud and wake formations and their relation to sea surface conditions around the islands. The following will focus on the appearance and dynamics of the thermal sea surface wake in the Lesser Antilles, and will show a detailed analysis of the wake at Dominica from which some general conclusions can be drawn.

MATERIALS AND METHODS

The research is based on satellite remotely sensed data that were processed with Giovanni, a system for multidisciplinary research and applications, that can be accessed via https://giovanni.gsfc.nasa.gov/(Acker and Leptoukh, 2007). Data are displayed in different formats as time-series and average maps for time-dependent events. The selected parameters include: a) sea surface daytime and nighttime temperatures as measured at the 11µm atmospheric window at spatial resolution of 4 km; b) chlorophyll concentrations at 4 km ground resolution; c) cloud fraction that is defined as the number of cloudy pixels divided by the total number of pixels; d) wind observation images that are extracted from https://www.meteoblue.com/en/weather/ and e) cloud observations that were obtained from https://www.star.nesdis.noaa.gov as multispectral product (CIRA/NOAA), and Worldview (worldview.earthdata.nasa.gov).

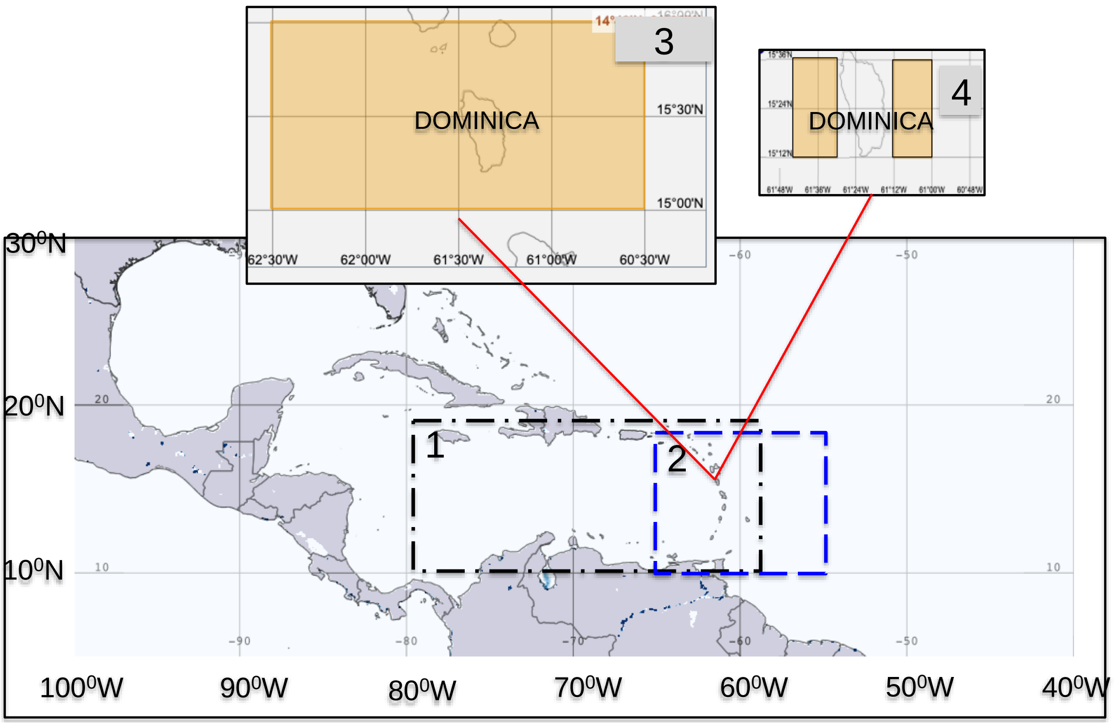

Figure 1: Location of selected test sites.

Figure 1 shows four sites that were selected in order to resolve spatial and temporal thermal surface events that occur in the eastern Caribbean Sea and to analyze wakes around the Lesser Antilles. Site 1 is located between 80^0W, 10^0N and 58^0W, 19^0N and serves to determine the thermal anomalies of the eastern part of the Caribbean Sea, whereas site 2 encompasses mainly the Lesser Antilles region and is located between 65^0W, 10^0N and 55^0W, 18^0N. Dominica is considered as the northernmost island of the Windward Islands and is included in site 3 to identify general changes that may occur around an island due to the formation of oceanic wakes. The area covered is marked with the coordinates between 62.51^0W, 15.01^0N and 60.50^0W 16.01^0N. Site 4 includes two separate areas that were selected to detect differences between the windward and leeward side of the Dominica island in relation to wake location and its performance. The leeward side west of Dominica is located between $61.73W^0$, 15.20^0N and 61.51^0W, 15.60^0N whereas the windward site is located east of Dominica between 61.20^0W,15.20^0N and 61.00^0W, 15.60^0N.

RESULTS AND DISCUSSION

Cloud appearance in the Lesser Antilles

The typical appearance of atmospheric wakes and cloud streaks can be visualized with the images shown in Figure 2 recorded on 7 February 2023. The wake is initiated by wind approaching the island but decreases its velocity over the elevated island terrain and develops wind curls on the flanks of the downstream faces of the wind. Dong *et al.,* (2018) suggested that Ekman pumping connected to the wind curl can lead to local upwelling or downwelling and supports the formation of cyclonic or anticyclonic eddies. However, local cooling due to vertical transport of water from the lower layer of the water column seems to be negligible.

Cloud trails are a common feature in the vicinity of the Lesser Antilles and observations over several months showed that trails are present preferably when steady wind conditions prevail. The trails along the Lesser Antilles develop within a short time in the afternoon and are an effect of diurnal heating over the islands. The trails have a rather limited daily residence time and last only for several hours in the late afternoon. Based on interpretation of cloud images obtained during 2022 and 2023 with GOES East, the trails appear frequently with lengths of approximately 150 to 250 km, but in isolated cases, are observed to reach a length close to 400 km. This range of cloud trails agrees with previous reporting on wake signatures from major islands in the region at approximately 300 km downstream (Nunalee *et al.,* 2015). However, the wake pattern in the Lesser Antilles is considered as a weak one, because of lower wind speed and lower island height as compared, for instance, to the Hawaiian Islands (Smith *et al.,* 1997).

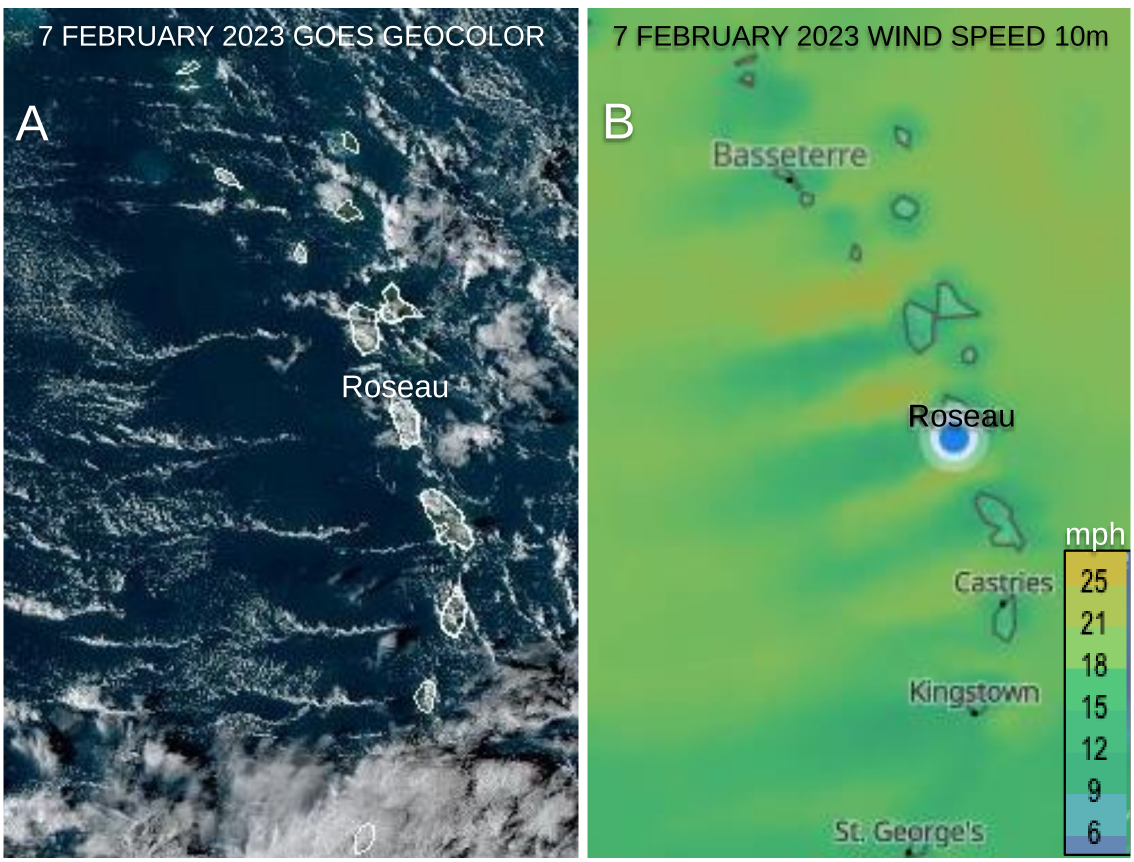

Figure 2: Comparison of cloud patterns and wind speed on 7 February 2023 in the afternoon. Roseau is included as a point of reference. A: Wake appearance and cloud trails reveal the cloud-free region in the lee part of the islands. B: Reduced wind speed shows the location of wakes and the channeling of elevated winds through the island passages. Note that cloud trails and wind are not pointing in the same direction. Source: Meteoblue; the original image was marginally enhanced in order to visualize better the wake extension.

A comparison of statistics showed for the Lesser Antilles that cloud trails developed around 30-40 percent of the day and around 60 percent of days without larger-scale cloudiness (Kirshbaum and Fairman, 2015). The cloud trails have a rather short appearance of less than two hours and develop their narrow alignment according to wind direction and speed. A typical scenario of changes in the direction of cloud trails in the Lesser Antilles is shown in Figure 3 that also shows on the leeside of the islands the lower cloud appearance. This cloud clearance infers that the higher transparency of the atmosphere exposes the sea surface to higher solar irradiance that is responsible for the warmer temperature in wake water.

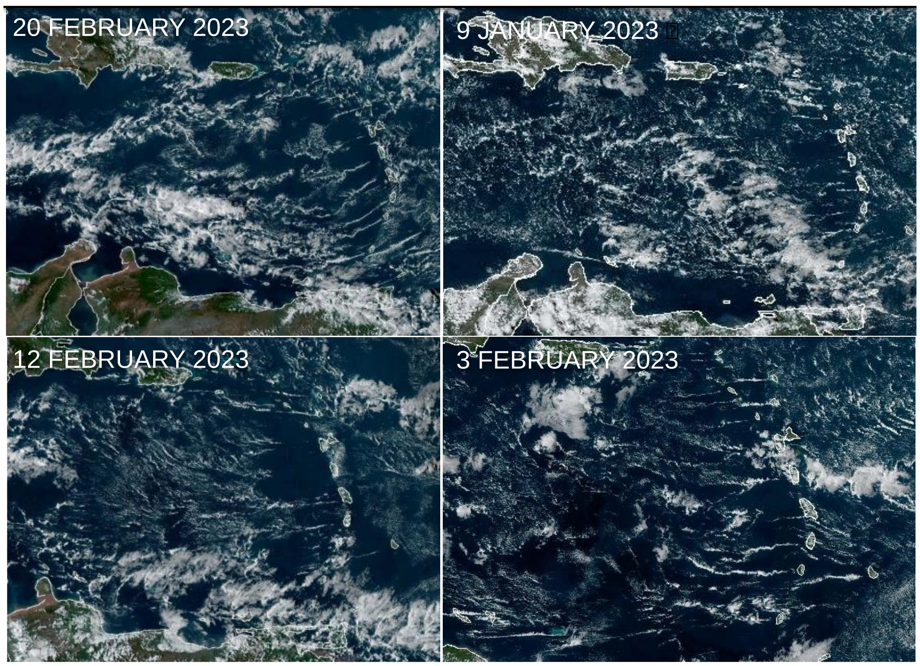

Figure 3: Cloud appearance and building of cloud streaks in the vicinity of the Lesser Antilles as viewed with GOES East, (NOAA NESDIS STAR).

The lower cloud frequency on the leeward side of the islands is shown with the average cloud fraction analysis in Figure 4 with yearly averaged data for 2003 to 2022. Low cloud frequency on the leeside compared to the windward sides is high at the Leeward Islands and the Windward Islands, whereas the region close to Trinidad and Tobago shows a distinctive difference in cloud patterns.

Cloud frequency around the Lesser Antilles shows anomalies that are recognized in 2010/2011 with a high frequency, and a minimum in cloud frequency is observed in 2014 and for 2019 to 2022. However, even during periods of higher cloud coverage, the islands in the Windward Islands still show reduction of cloud frequency at the leeside compared to the windward sides of the islands.

The climatology of cloud fraction in the vicinity of the Lesser Antilles is shown with the average from 2002 to 2022 in Figure 5A. It shows the mean extent of reduced cloud coverage of the southern border in the vicinity of St. Lucia. Figure 5B shows the series of monthly averaged cloud fraction for the same region as shown in Figure 5A. It resolves temporal changes in the cloud field and, aside from the seasonal changes, it is evident that the cloud fraction in the leeward sides of the islands undergoes interannual fluctuations and long time changes that are

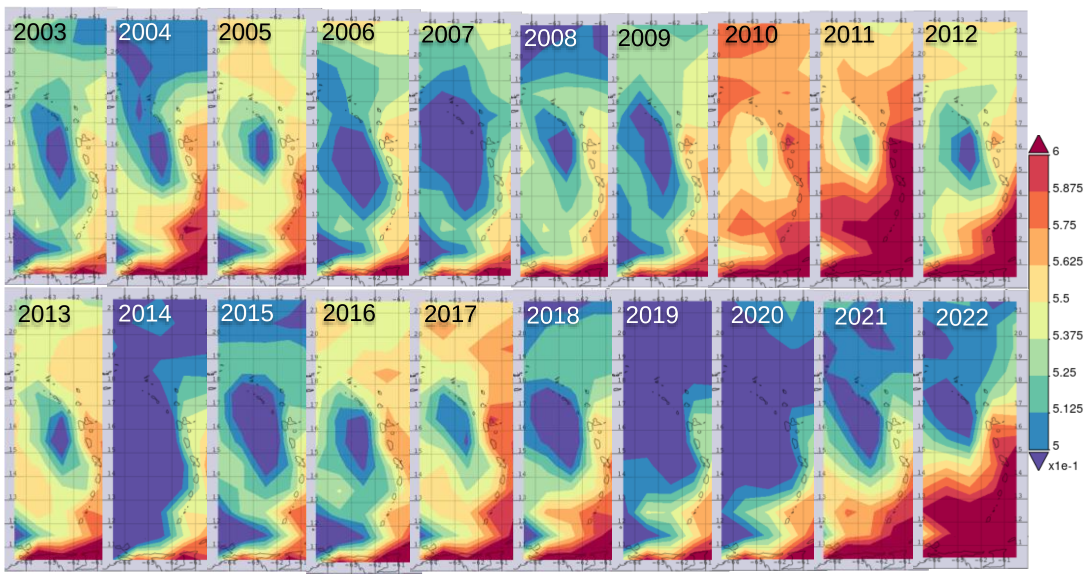

Figure 4: Lesser Antilles yearly averaged maps of cloud fraction 2003 to 2022 based on cloud mask and count of lowest two clear sky confidence levels. The values give the ratio cloudy and partly cloudy/total count mean of monthly one-degree resolution based on MODIS-Aqua product MYD08_M3 v6.1.

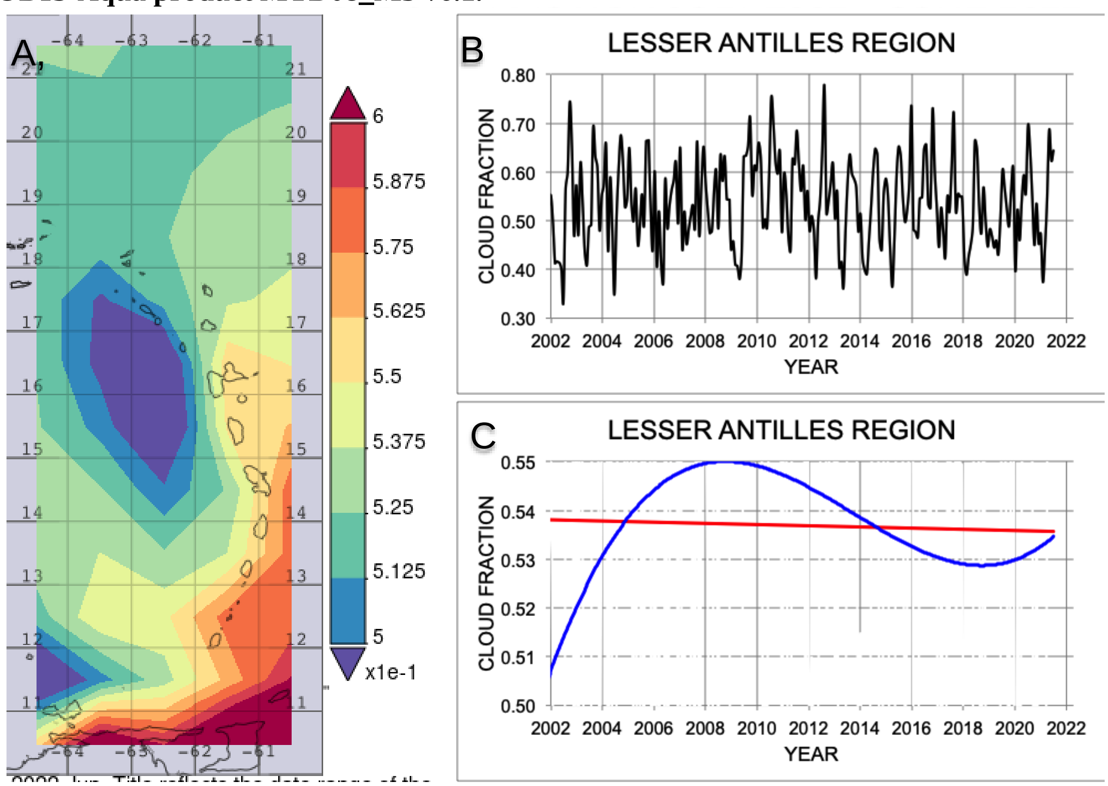

Figure 5: A: Time averaged cloud fraction from 2002 to 2022. The values give the ratio cloudy/total count mean in one-degree resolution based on MODIS-Aqua product MYD08_M3 v6.1. B: Monthly averaged cloud fraction of the region shown in A. Figure C gives the linear regression in red and the 3[rd] polynomial fit in blue.

shown with linear and polynomial regressions in Figure 5C. The polynomial fit for the cloud fraction reveals a maximum in 2009 and a minimum in 2019, whereas the linear regression shows a slight reduction in cloud cover for the investigated period between 2002 and 2022.
The cloud data for the Lesser Antilles indicate that the clearing of the atmosphere on the leeward side of the islands is a common process that can be recognized also around other islands in the Caribbean Sea. The cloud fraction for the larger part of the Caribbean in Figure 6 shows that the Leeward Islands, the Windward Islands and the Leeward Antilles show on their leeward sides well-defined areas of minimized cloud cover. The west cost of Puerto Rico shows likewise the leeward effect of reduced cloud cover. In addition, Hispaniola and Jamaica have in their southwest region their leeward low-cloud field, whereas Cuba has the largest area with reduced cloud cover.

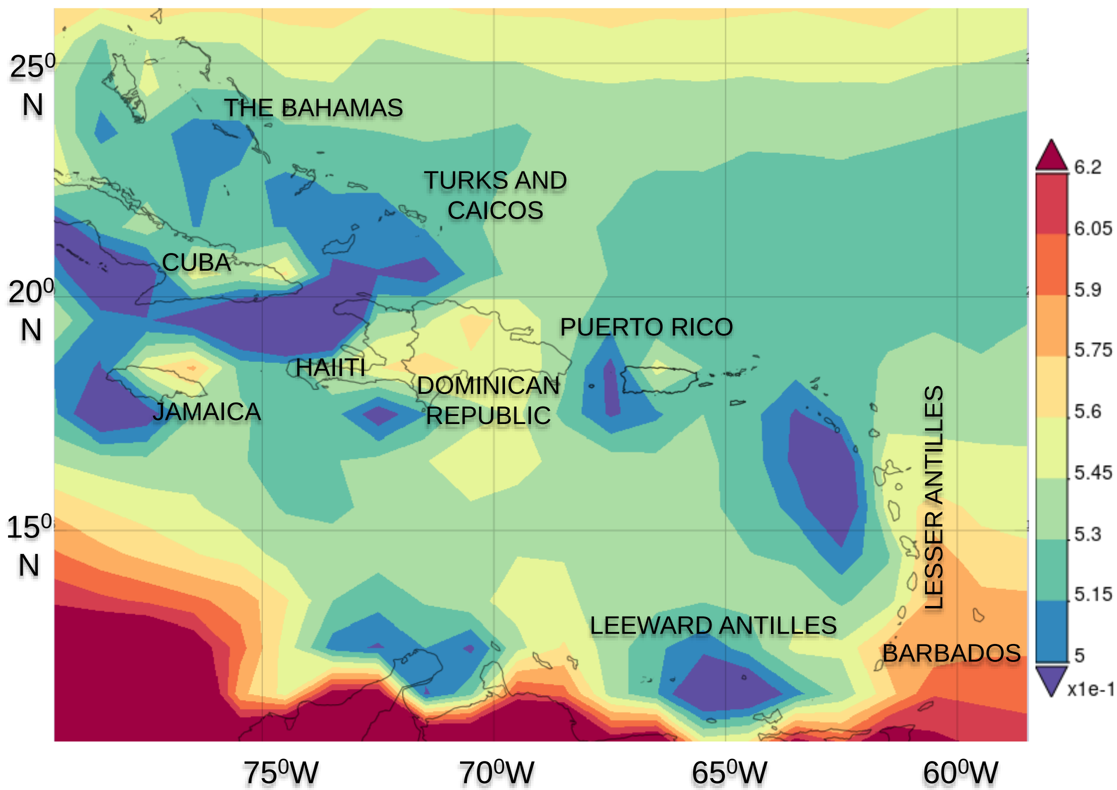

Figure 6: Time averaged cloud fraction for July 2003 to December 2022.

Surface temperature anomalies in the Caribbean Sea

The cloud distribution shows that the Trade Wind region form specific atmospheric conditions that initiate cloud clearing and development of wakes at the leeside. However, atmospheric anomalies and the islands' response to thermal variances are not restricted to the near shore regions of the Lesser Antilles because all islands in the Caribbean show a decrease in cloud fraction and an increase of temperature on their leeside. However the temperature range for wake water, as detected with 4km-resolution data, is rather small and the average temperature to recognize wakes in the Lesser Antilles is only around 0.86^{0}C but can vary between 0.3^{0}C and 2.0^{0}C.

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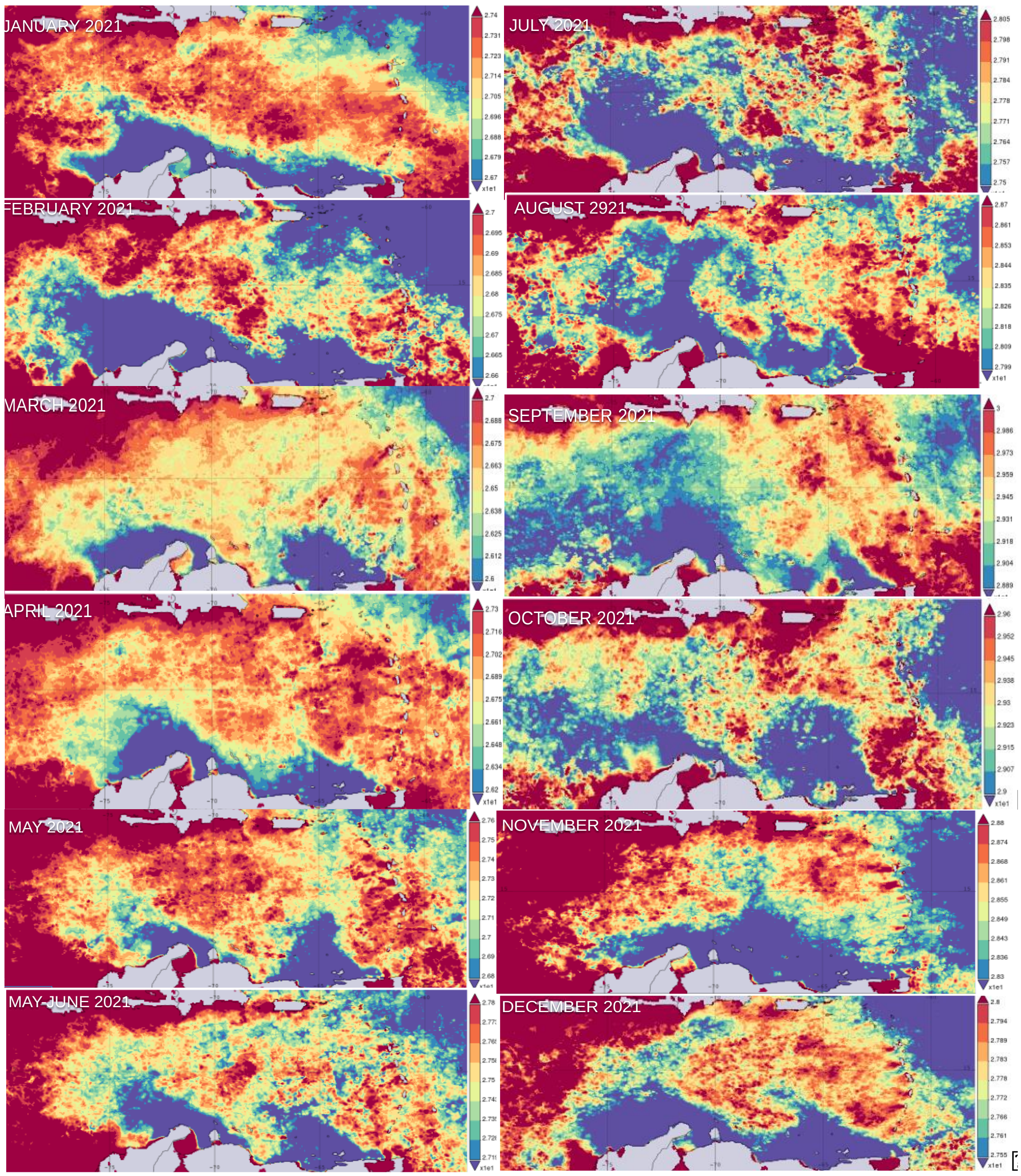

Figure 7: Monthly averaged day-time sea surface temperature (^{0}C) for 2021. Colors were annotated to enhance the best temperature recognition in the vicinity of the Lesser Antilles.

The small temperature difference between wake water and the surrounding flank water limits the detection of wakes with coarse resolution data. However, as shown in Figure 7, the leeside of the islands reveal warmer temperatures throughout the year compared to the windward sides, but the general pattern of temperature shows a chaotic distribution. It can be assumed that this is in response to changes in wind direction and strength as well as to the effect of eddy propagation and seasonal influx of the Amazon, Orinocco and Atlantic water from the south. As wakes can be

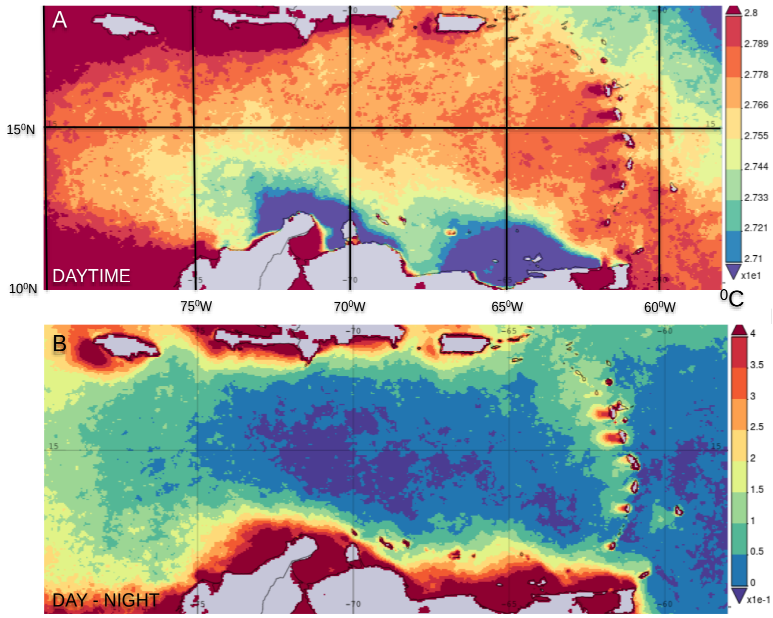

Figure 8: Sea surface temperature (^{0}C) July 2002 to December 2022. A: Daytime measurements (^{0}C); B: Temperature difference of day minus night time measurements.

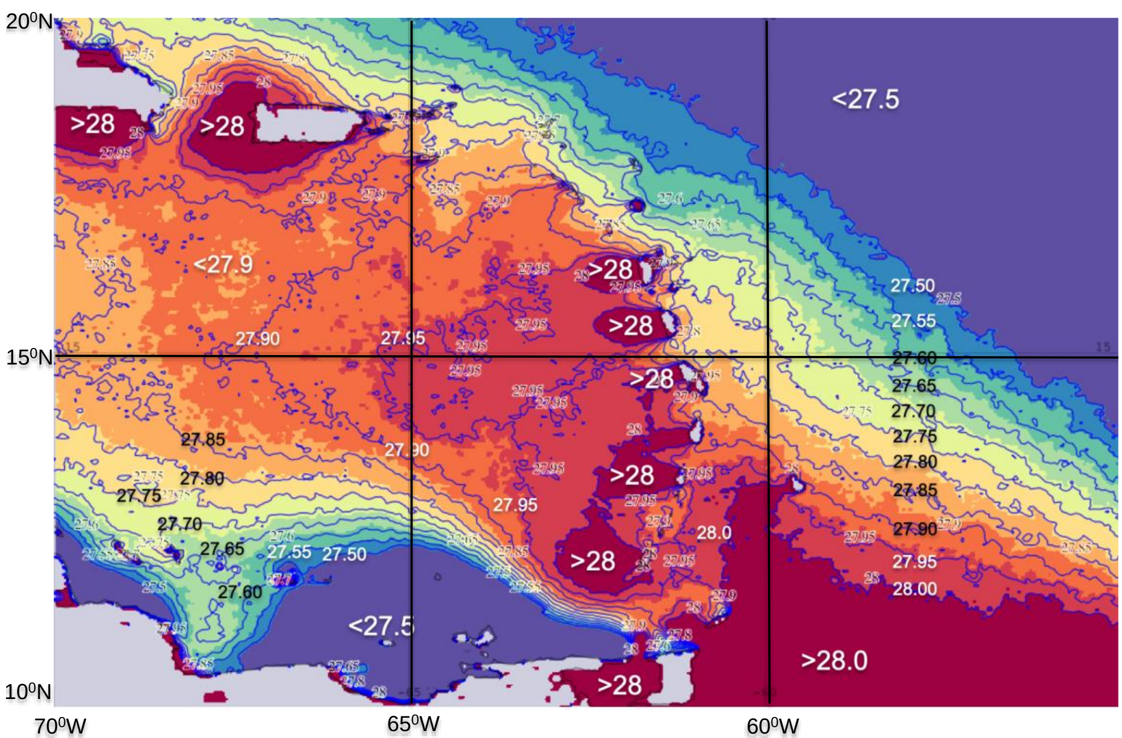

Figure 9: Yearly average daytime sea surface temperature (^{0}C) for 2003.

considered as quasi-stationary features, averaged data over a long-time span would show the more dynamic surface currents and wind stress as background against which wakes would establish stronger signals. This is shown in Figure 8A with the averaged daytime sea surface temperature for 2003, and shows that the yearly averaged data enunciate the temperature gradient between the windward and leeward sides of the islands as caused by wakes.

As shown in Figure 8, with day and night temperature measurements, wake temperatures go through a diurnal cycle as documented with the difference of day and night measurements in Figure 8B. Cooling is especially strong around Guadeloupe and Martinique with a temperature decrease of about 4^0C at night. All other islands show the effect of the day-night cycle, although their night cooling is less pronounced.

The temperature distribution in Figures 8 and 9 identifies the islands and their wakes as additional heat source to the westward-moving surface currents and shows that a large surface area in the vicinity of the Windward Islands is impacted by the wakes' heat accretion. In order to identify any biological response to the thermal anomaly in wakes, a data subset over twenty years was analyzed for chlorophyll concentration and temperature as shown in Figure 10A and B. The remarkable number of averaged measurements allow the extraction of small gradients in temperature and chlorophyll distribution and the identification of fine structures in the surface water. As can be deducted from Figure 10, the northern part of the Lesser Antilles is mainly dominated by incoming Atlantic surface water that is chracterized by low chlorophyll concentrations whereas the southern islands are influenced by the upwelling regime along the Venezuelian coast and water from the Guinea Current that has higher chlorophyll concentrations.

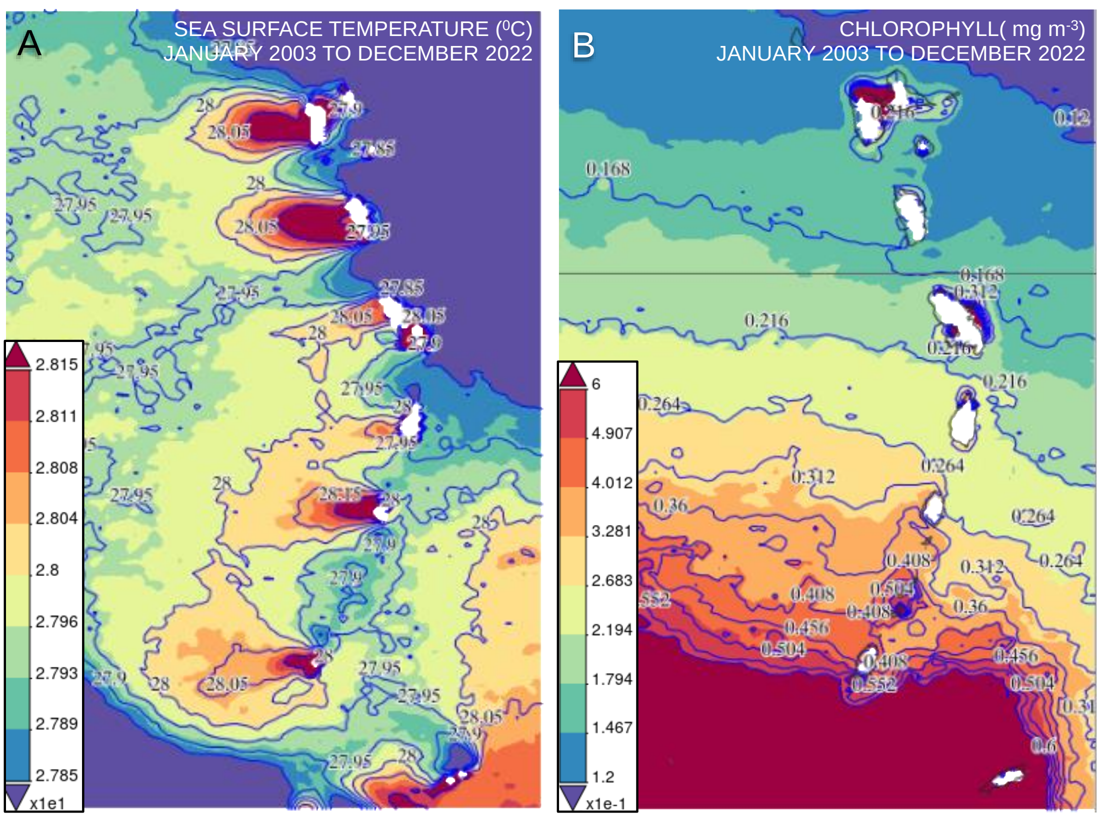

Figure 10: Fine structure of surface temperature (^{0}C) and chlorophyll (mg m^{-3}) distribution based on daytime 4km resolution averaged data from January 2003 to December 2022. The region is located between 64^{0}W, 11^{0}N and 60^{0}W, 17^{0}N.

The surface water that enters the Caribbean Sea through the passages of Guardaloupe, Dominica and Martinique has an average temperature of less than 27.85^{0}C, but farther, toward the southern passages, the temperature increases. The average maximum temperature that characterizes the warm water of the island wakes varies only within a narrow range of 27.95^{0}C at St. Lucia and 28.15^{0}C at St. Vincent. Furthermore, the temperature distribution shows that Guadeloupe, Dominica and Martinique have the major impact of the surface warming.

Interannual changes of sea surface temperature

Compared to the chaotic distribution of temperature recognized in monthly data, the yearly averaged data distinguish better the presence of warm wake water. Therefore, in order to uncover fluctuations on a larger timescale, yearly averaged data were used to follow interannual changes as shown in Figure 11 with a sequence of images between 2007 and 2022. A warming anomaly in the Lesser Antilles reached its maximum above 28.0^{0}C in 2010, but the temperature lowered again in 2011, and the region reached the minimum in 2014. The June 2010 anomaly in sea surface temperature was also documented by Ped *et al.,* (2016) over a large portion of the Caribbean and was about 1.2°C higher than the typical June temperatures.

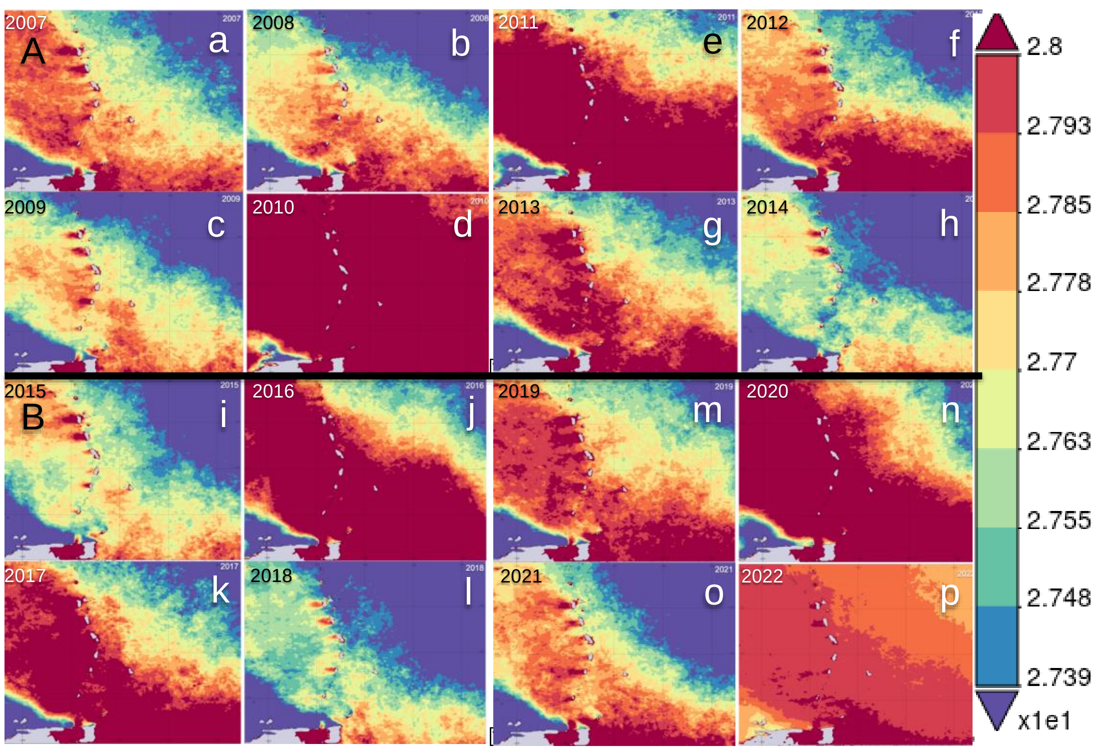

Figure 11: Sea surface temperature (^{0}C) 2007 to 2014 A: (a to h) and B: 2015 to 2022 (i to p). The location of the test site used for this study encompasses the Lesser Antilles region, located between 65^{0}W, 10^{0}N and 55^{0}W, 18^{0}N, and also shown in Figure 1. The same color bar and temperature scale on the right was applied for all images.

A warming period is documented in Figure 12A that shows the temperature distribution for 2003 to 2006 with a range from 27.4 ^{0}C to 28 ^{0}C and 2005 being the warmest year. The temperature gradient between the windward and leeward sides of the islands is well established in 2003 and

2006, while 2004 has the largest warming on the leeside. In 2005, the temperature gradient was not recognized in the Lesser Antilles when the temperature was above 28.0^{0}C, but the temperature lowered again in 2006. This temperature cycling seems to be symptomatic for the region, and in order to achieve better temporal resolution, a Hovmöller analysis was performed covering temperature distribution for 2003 to 2006 as shown in Figure 12B and C and includes a time frame during which warming at the beginning of 2005 was recognized.

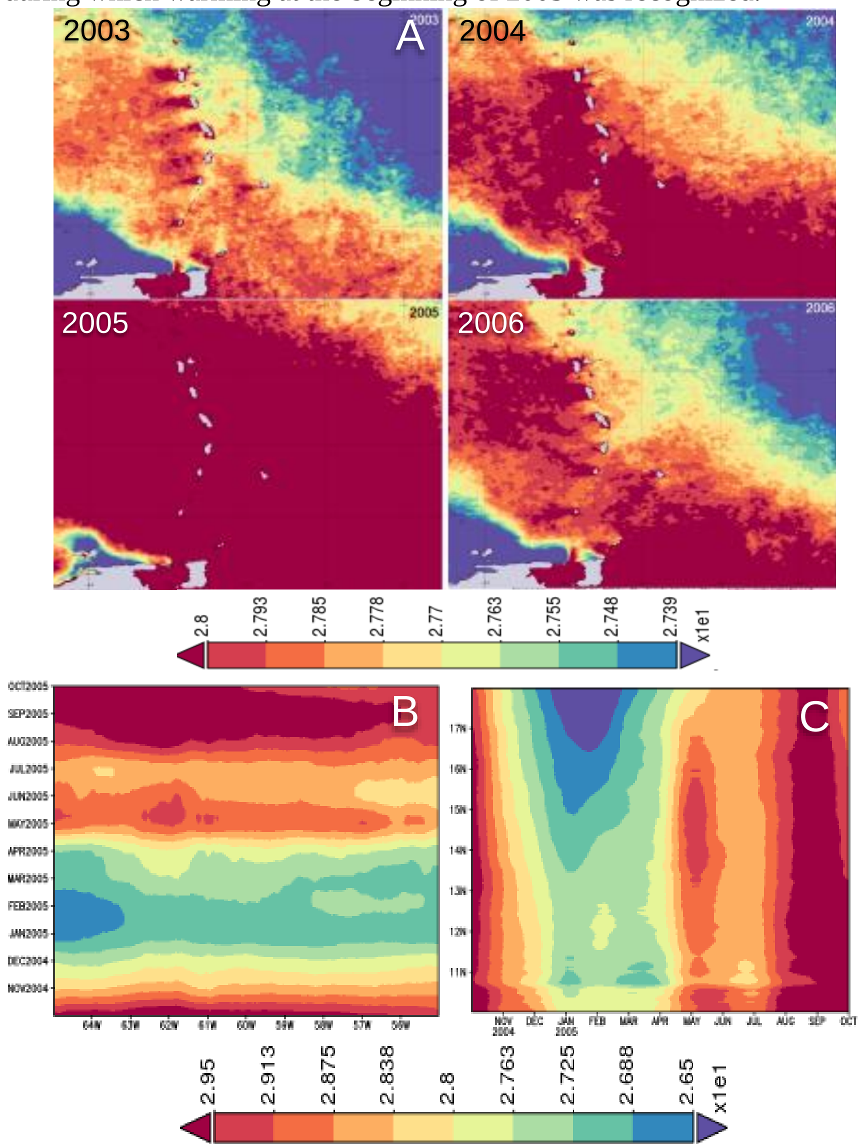

Figure 12: A: Sea surface temperature (^{0}C) from 2003 to 2006. The same color scale was applied for all images shown in A, B and C: Monthly averaged sea surface temperatures for October 2004 to October 2005 applying Hovmöller for latitude averaged temperature (B) and longitude averaged temperature (C).

The temperature distribution documents that the Lesser Antilles, especially Guadeloupe, Dominca and Martinique, build a strong temperature gradient at the entrance to the Caribbean. The wake direction may change from year to year as seen with data for 2003 that show a west-southwest

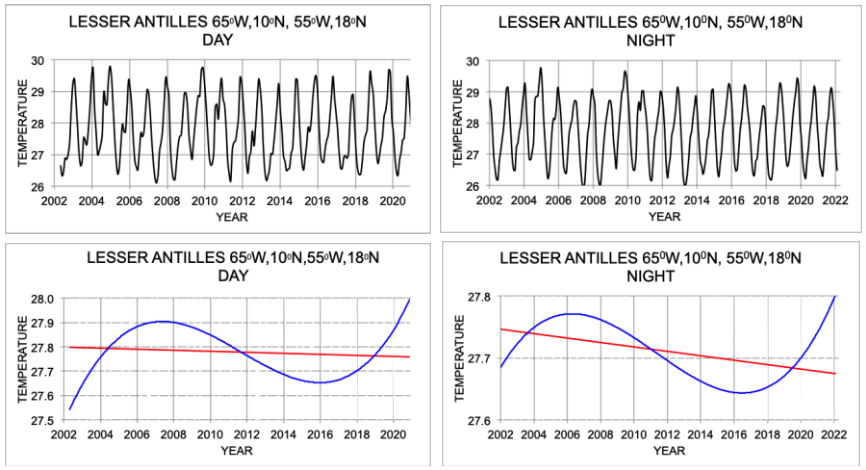

Figure 13: Lesser Antilles day and night temperature (⁰C) trends for 2002 to 2022. Red lines show linear regressions and blue lines are based on 3rd polynomial order. The location of the test site is identified in Figure 1 as box 2.

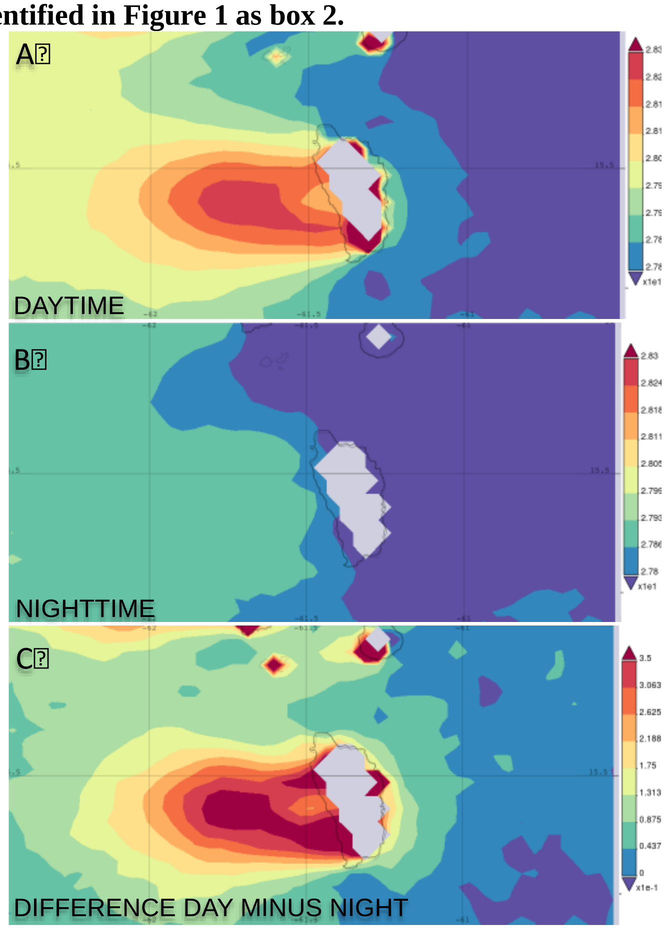

Figure 14: Averaged sea surface temperature (⁰C) analysis for July 2002-October 2022. A: Daytime temperature; B: Nighttime temperature and C: Temperature difference (day minus night). Note that the color annotations in Figures A and B have the same data range and the same color bar for annotations.

direction, and for 2006, a west-northwest direction. 2004 shows an intense warming that extends to a larger area than in the previous year and in 2005, the investigated region underwent a warming period.

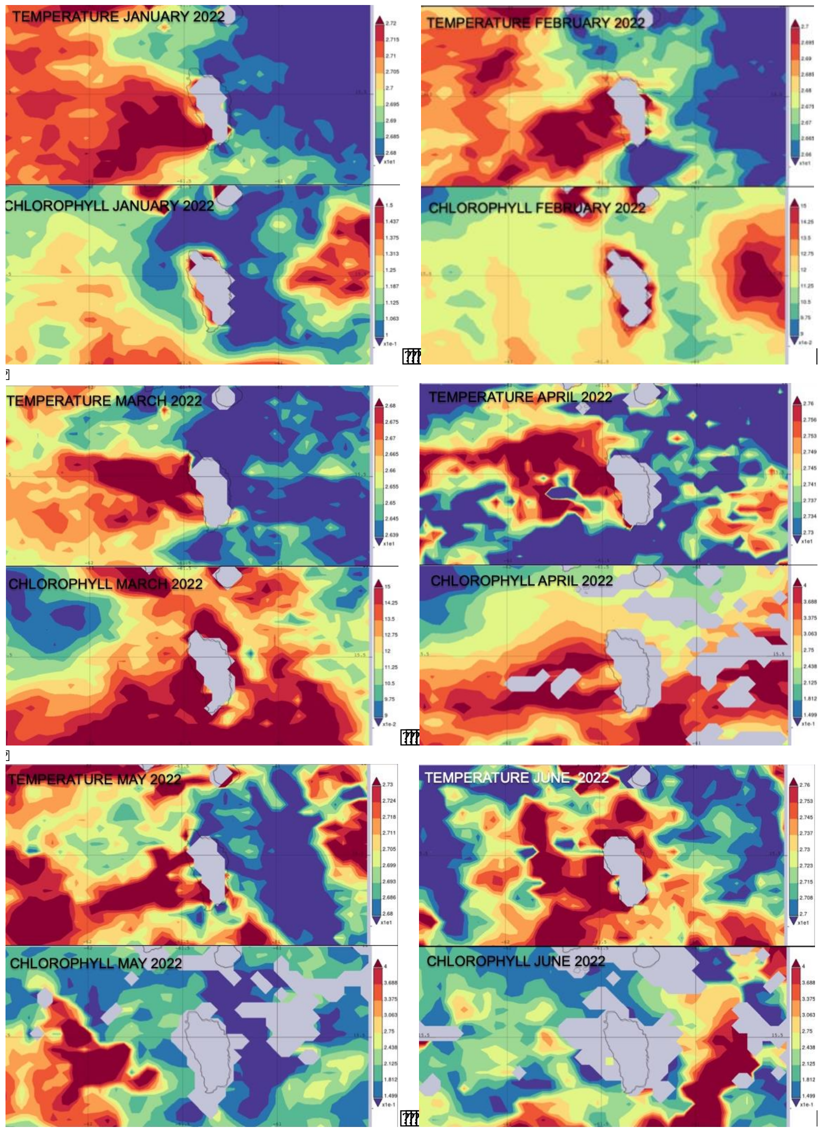

Figure 15: Temperature (^{0}C) and chlorophyll concentrations (mg m^{-3}) in the vicinity of Dominica for January to May 2022.

The fluctuations in temperature show that changes appear at various temporal scales, and in order to estimate the trends in temperature around the Lesser Antilles, day and night time series of monthly averaged data were analyzed and are shown with linear and polynomial fits in Figure 13. Both day and night measurements do not indicate warming with the linear regression. However, the polynomial fits imply a change in slope for 2007 and 2016, and a rather modest decrease in temperature is recorded that confirms previous observations that a slight cooling exists around the Lesser Antilles. Although the temperature decrease is less than 0.01^{0}C, this deviation from global

warming, along with the increase in temperature in other regions of the Caribbean, shows an unusual condition around the Lesser Antilles. To address this issue further, the area around Dominica was selected where the wake was analyzed at a smaller spatial and temporal scale.
As seen in Figure 14, the warming during daytime and the effect of cooling at night establishes a significant day-night difference that reaches at the average about 3.5^0C. Figure 14 A and C show that close to the shore, a slight decrease in temperature is observed. However it appears that local upwelling within the wake plays a minor role, although upwelling in the core of a wake was suggested at the tip of an island (Wolanski *et al.*, 1984). Figure 14 B demonstrates the impact of the daily temperature cycle showing that a wake disseminates the daily stored energy rather quickly at night.

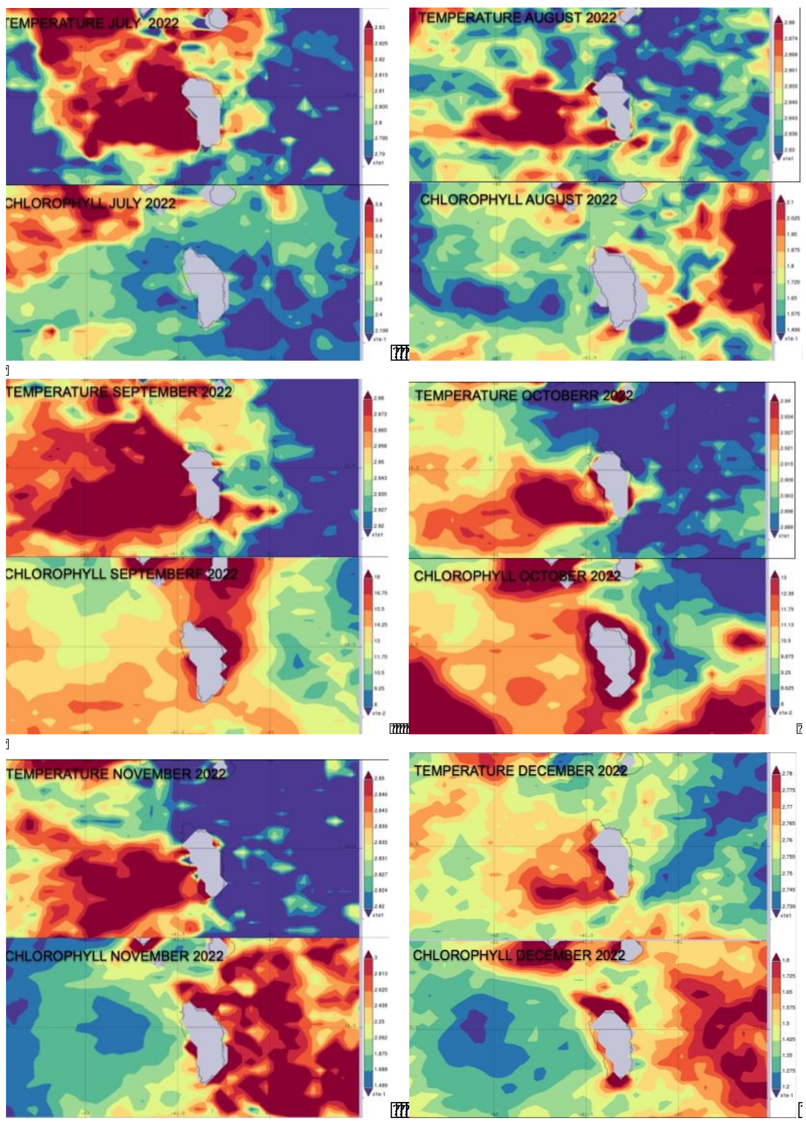

Figure 15 continued: Temperature (^{0}C) and chlorophyll concentrations (mg m^{-3}) in the vicinity of Dominica for July to December 2022.

To further investigate the surface dynamics of the wake water and its possible effects on the bio-system, monthly temperature and chlorophyll data were analyzed and are shown in Figure 15. The distribution of monthly averaged temperature and chlorophyll data in the wake is rather patchy and the complexity in the distribution is most possibly the response to changes in strength and direction of the local wind and current system.

It is evident that the largest area coverage of the warm wake water appears in September. The windward side of the island shows, for all the months, colder water compared to the leeside of the island, but upwelling is absent along the leeside, or at least not recognized in this analysis throughout the year. In general, the wake is flanked by water with lower temperatures that enter through the passages north and south of the island. This is especially well recognized with the January and October observations of temperature and chlorophyll concentrations. During most months, the wake water is low in chlorophyll concentrations, except for March-April when higher concentrations were observed, although the temperature shows typical warm wake water but no upwelling is recognized in the surface water.

The comparison of chlorophyll concentration and surface temperature demonstrates that frequently Atlantic water with low chlorophyll concentrations are detected in the northeast while slightly elevated chlorophyll concentrations are observed in the southwest of Dominica, but the average concentration does not exceed 0.2 mg m^{-3}. While the chlorophyll gradients are small, they indicate two separate ecological zones although upwelling is not recognized in the temperature data, and there is likelihood that eutrophication through anthropological nutrient discharge from the island may cause an increase of chlorophyll concentrations. This finding has been further substantiated with observations close to the windward and leeward sides of Dominica by comparing temperature and chlorophyll concentrations over the temporal range of twenty years. The comparison of both sides of the island is shown in Figure 16 with a temperature time series and the corresponding regressions.

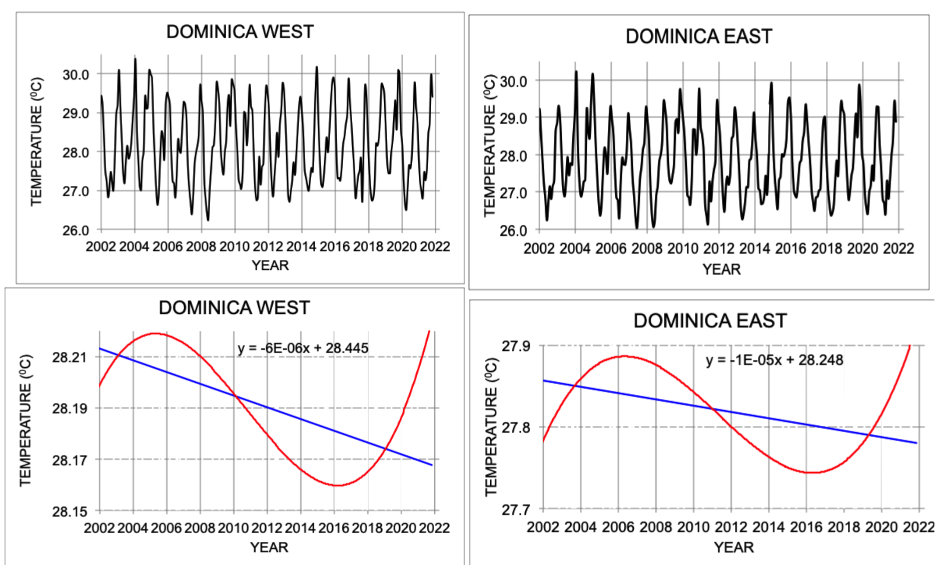

Figure 16: Comparison of monthly averaged sea surface temperature (^{0}C) in the leeward and windward sides of Dominica. The blue lines represent the linear regression and the red lines polynomial 3rd-order fits. Dominica west is the leeside and Dominica east is the windward side. The locations of the two test sites are indicated in Figure 1 as site number four.

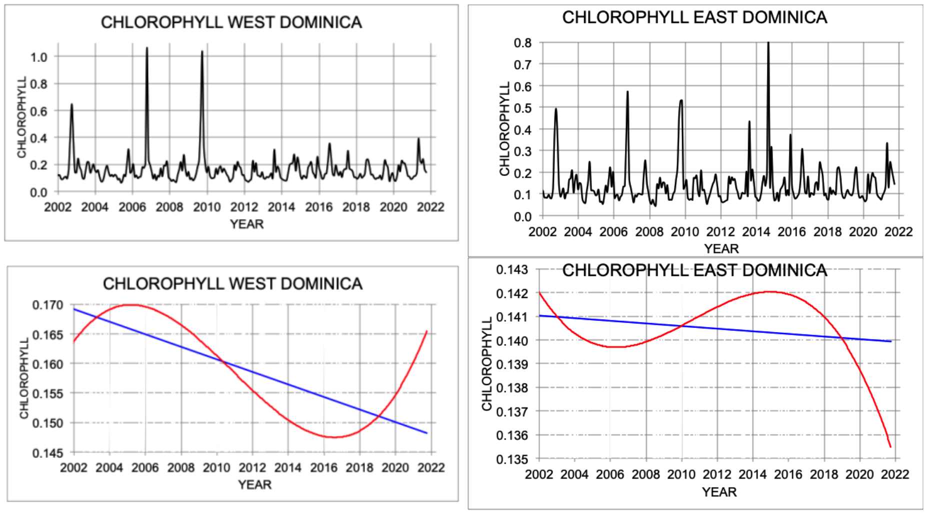

Figure 17: Comparison of monthly averaged chlorophyll concentrations (mg m^{-3}) on the leeward and windward sides of Dominica. Dominica west is the leeside and Dominica east is the windward side. The locations of the two test sites are indicated in Figure 1 as site number four.

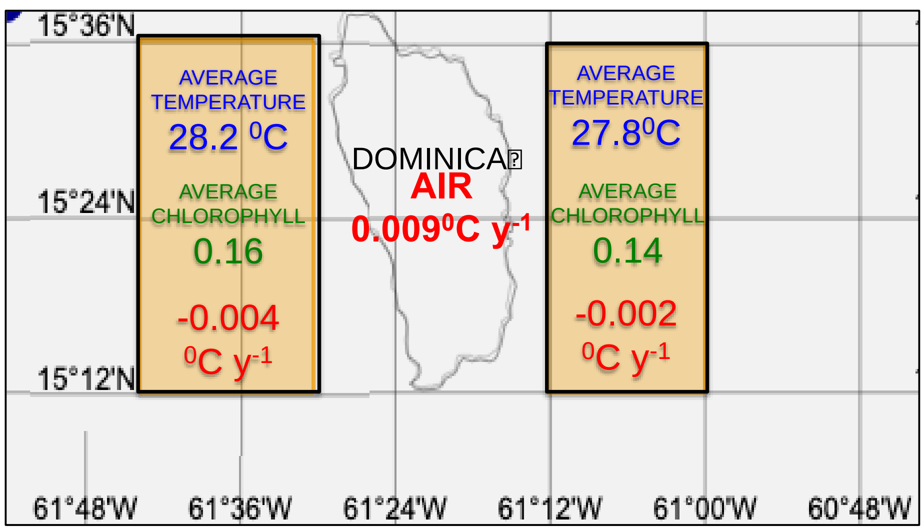

Figure 18: Comparison of averaged data on the leeward and windward sides of Dominica for sea surface temperatures (^{0}C) and chlorophyll concentrations (mg m^{-3}), and air temperature at Roseau (15.30°N, 61.39°W).

Temperatures in Figure 16 show the typical yearly cycle that is superimposed by long-term fluctuations that are similar for the windward and leeward sides of the island. Both sides also show with linear regression the previously observed negative temperature changes in the region, although their slopes are slightly different. The corresponding chlorophyll concentrations in Figure 17 show a` downward trend, but a higher loss is found on the leeside. The polynomial fit

indicates that on the leeside of the island, the maximum concentrations coincide with maximum temperatures, and the minimum concentrations in 2016 fall together with minimum temperatures. However, the windward side shows an opposite trend with the polynomial fit that is mainly a result of the increased chlorophyll concentrations between 2013 and 2017. The time series of temperature and chlorophyll concentrations show slightly different and higher trends for the windward and leeward sides of the island as shown by averaged data in Figure 18.
The water temperature difference between the windward and leeward sides of Dominica is at the average 0.4^0C on the leeside compared to the windward side, and the chlorophyll concentrations are slightly elevated by 0.02 mg m^{-3} on the leeside. The estimated cooling of the sea surface temperature for Dominica is estimated to be around -0.004 ^{0}C y^{-1} and for the leeward side of the island at around -0.002 ^{0}C y^{-1}. The Lesser Antilles region is exposed to the same anomaly in temperature as has been documented in an earlier reporting (Szekielda, 2022). For comparison, the average air temperature over Dominica has a positive change of about 0.009^0C y^{-1}. However, the rate of change varies; for example, recordings at Roseau show from 1979-2021 an increase of about 0.0095 ^{0}C y^{-1} for 1979-2007, a change of about 0.0107 ^{0}C y^{-1}, and for the time frame 1901-2021, an increase of about 0.0078 ^{0}C y^{-1}. Regarding the yearly air temperature and precipitation changes in Dominica, it is obvious that both parameters show an upward trend with anomalies being well pronounced during the last decades (Climate Change Roseau–meteoblue). Observations by Di Napoli *et al.*, (2021; 2023) with the Universal Thermal Climate Index (UTCI) showed that the Lesser Antilles actually witness the greatest upward rates of about 0.045^0C y^{-1}. Considering also the global average temperature rise of about 0.018^0C y^{-1}, the slight cooling of sea surface temperature that is observed in the region appears as an anomaly in the Lesser Antilles. The most possible explanation for the discrepancy between the slight cooling in the Lesser Antilles and the global and regional warming trend may be explained by changes in surface wind speed. Based on modeling by Bustos Usta and Parra (2022), an increase in temperature in the eastern Caribbean is likely, with a decrease in the northern Cayman Sea, due to significant changes in wind direction. Larger trends are even expected in the 2015–2100 period with further increasing wind speed in the Caribbean. Although the wind direction in the eastern part of the Caribbean Sea does not show significant variation, it is observed that wind intensification would decrease the cloud frequency and temperature increase would be expected. However, higher wind speed also induces additional turbulence in the upper water column that would dissimilate incoming energy more rapidly and thus, would prevent a further increase or result even in a decrease of sea surface temperature.

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