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First Chemical–Physical Measurements by Multi-Parameter Probe in the Blue Hole of Faanu Madugau (Ari Atoll, the Maldives)

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Abstract: Blue holes are submarine karst cavities with chemical and physical characteristics of the water column completely different from those in the surrounding environment. In this study a multi-parameter probe was used, for the first time, to characterise the water column of the Blue Hole of Faanu Madugau (Ari Atoll, Maldives, 3°55.799′ E 72°56.469′ N), the only blue hole described in the Indian Ocean up to date. Measurements of the temperature, salinity, dissolved oxygen, turbidity, chlorophyll-α, photosynthetically active radiation, potential density, pH, and H_2S were obtained with a high detail. Three distinct physical–chemical layers were identified from the surface up to 70 m depth. An intermediate and turbid layer, located between 40 m and 46 m depth, sharply separates the upper layer displaying water characteristics equal to those of the outside environment from the deep and more characteristic layer of the blue hole, where a unique environment can be observed. Waters are oxygenated, warm, and rich in chlorophyll-α in the upper layer, whilst waters are anoxic, colder, denser, and completely dark, with low pH values and high H_2S content in the deep layer. The Blue Hole of the Maldives represents an extreme environment from a geological, oceanographic, biological, and ecological point of view. Further investigations will be thus required to understand the origin of the Blue Hole waters, the mechanisms that keep it isolated from the external environment, the influence of weather and marine forcing on it, and how climate change may impact it.

Keywords: Blue Hole; Maldives; multi-parameter probe; temperature; H_2S; pH; turbidity

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1. Introduction

The term "blue hole" was described as early as the 18th century and has appeared on the sea charts of the Bahamas since the 19th century [1]. The blue hole is an almost vertical karst hole in carbonate rocks, opening underwater and therefore containing marine, fresh, or mixed-chemistry waters, which usually display water characteristics different from the surrounding environment [2–4]. The topography and the occurrence of strong environmental gradients of the blue holes make these karstic cavities structurally and functionally similar to submerged caves. The most well-known marine blue holes are located in the Bahamas (the Middle Caicos Island's Blue Hole and the Dean's Blue Hole), in Belize (the Great Blue Hole), in China (the Sansha Yongle Blue Hole), in Australia (Houtman Abrolhos reef). Some blue holes are also known in the Mediterranean Sea (the Gozo Blue Hole—Malta) and Red Sea (the Dahab Blue Hole—Egypt) [4,5].

Blue holes may have different origins and may have formed as a result of different processes as indicated by [2]: the filling of dissolution sinkholes or shafts created in the vadose zone, the phreatic dissolution along an ascending halocline, the roof collapse over voids produced by dissolution in the phreatic zone, or the bank margin fracture. For example, the Great Blue Hole in the lagoon of Lighthouse Reef Atoll of Belize was generated by subaerial dissolution of the reef limestone (Pleistocene, 2.58 My) during the lowering of the glacial sea-level and the following collapse of the roof; the stalactites found inside it at 40 m depth are the evidence of its subaerial formation [6].

Blue holes are environments with extreme characteristics, as they have a limited water exchange with the surrounding environment, a lack of freshwater injection, and a water column that is characterised by sharp and highly stable physical-chemical gradients. Severe anaerobic conditions with considerable concentrations of hydrogen sulphide (H_2S) can develop, especially in their deep portions due to the presence of an important bacterial component [7–11].

Blue holes thus represent natural laboratories to investigate extreme both chemical and physical characteristics and gradients in aquatic ecosystems, and to evaluate their effect on the biotic component [9]. The wide scientific interest that these unique environments generate is testified by the many studies conducted on the blue holes since their discovery; these studies involved multidisciplinary approaches that integrate geology to define the origin and the geological conformation of blue holes, physical oceanography to characterise stratification in the water masses and external exchanges, biology to investigate composition of the benthic communities (including microbial one), and chemistry to define water composition [11–22].

On May 2022, physical–chemical characteristics of the water column in the Blue Hole of Faanu Madugau (internal east side of Ari Atoll, the Maldives, 3°55.799′ E 72°56.469′ N; Figure 1) were measured using a multi-parameter probe dropped, for the first time, into the cavity from the surface down to 70 m depth. To date, the Faanu Madugau Blue Hole in the Maldives is the only one known in the Indian Ocean and its recent discovery (April 2000) makes it an environment that still needs to be studied in detail to determine its formation and maintenance mechanisms. Measurements have been used to characterise the distinct layers in the water column of the Maldivian Blue Hole and to highlight its peculiarities from the point of view of chemical and physical parameters. Moreover, the morphology of the Maldivian Blue Hole and the distribution of parameters along its water column were compared with those of the other best known and most studied blue holes in the world to highlight the differences and similarities in water stratification and try to find support for what we found with this our first investigation.

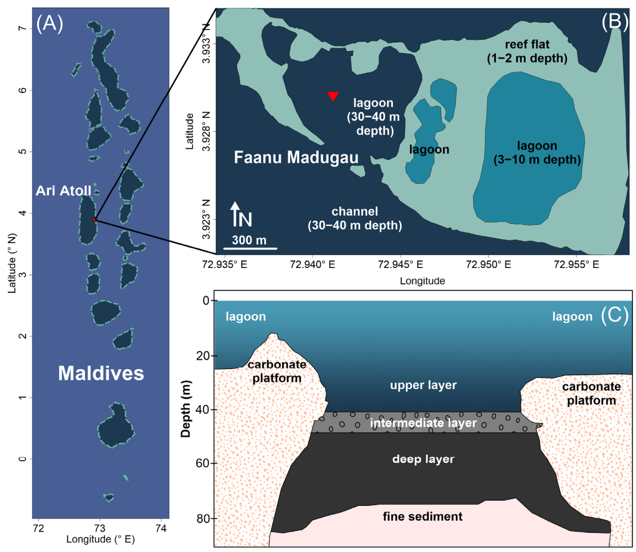

Figure 1. (**A**) Map of the Maldivian Archipelago with the Ari Atoll; (**B**) Faanu Madugau lagoon in the east side of the Ari Atoll, showing the location of the blue hole (red triangle) and the main

characteristics of the lagoon (the different colours correspond to the different depth of the Faanu Madugau lagoon: dark blue corresponds to depths of about 30–40 m, light blue to the reef flat at about 1–2 m depth, and the intermediate blue depths between 3 to 10 m); (**C**) schematic SSE–NNW section of the Blue Hole of Faanu Madugau (modified from [23]) with the entrance of 70 m diameter.

2. Study Area

The Maldives is an archipelago of 27 atolls with around 1192 small coral islands distributed over an 860 km long and 130 km wide isolated carbonate platform North–South oriented, from 7° N to 0.4° S, located in the tropical northern equatorial Indian Ocean [24,25]. More than 99% of the Maldives territory is covered by sea and the land area is less than 1 m high above the mean sea level [24,26,27].

The Maldivian archipelago comprises a double row of atolls, which in turn enclose an inner hemipelagic basin called the Inner Sea, with a maximum depth of 300–350 m in the South and 550 m in the North, while inside each atoll the bottom of the lagoon reaches about 40–60 m depth [24,28].

The region is strongly influenced by the South Asian Monsoon and, therefore, the Maldivian weather is characterised by two monsoons per year, from April to November (the southwest monsoon than brings overcast sky, rain and strong wind) and from January to March (the northeast monsoon that brings clear skies and clear waters) [27]. The alternation of monsoons also affects the ocean current regime, and, therefore, the Inner Sea is affected by sea-surface currents with periodic direction reversals: currents flow to the east during the southwest monsoon and to the west during the northeast monsoon [24,28].

Sea currents are dominated by wind and also by tidal forcing in the first 100 m of the water column, while they are more homogeneous at greater depths. Along the oceanic margins of atolls, in the channels between the atolls and through atoll openings, the sea currents are strongly dominated by the combined action of tides and wind and can exceed 2 m s^{-1} of velocity [29]. Semi-diurnal tides range between 0.7 m in the northern part of the Maldivian archipelago to 1 m in the southern part [30]. Sea surface temperature (at 10 m depth) in the Inner Sea typically varies in a very narrow range between a minimum of 28.27 °C in October–December and a maximum of 29.38 °C in April–June [28]. In the water column, a pronounced thermocline is present at a depth of 100–150 m with a temperature drop of about 15 °C [30]. Salinity in the surface layer (first 100 m of the water column) generally has values around 35.8, while in deeper waters it settles around 35.3 [24].

The Blue Hole of Faanu Madugau is located in the east side of the Ari Atoll (the Maldives, 3°55.507′ N, 72°56.559′ E; Figure 1A). It opens in the Faanu Madugau lagoon (Figure 1B) at the bottom of a large bowl-shaped depression at about 30 m depth, with an oval entrance of 70 m diameter, and descends to 85 m depth (Figure 1C) where the bottom is covered by fine carbonate sediments. Along its vertical to overhanging walls at 50 m depth there are speleothems (i.e., stalactites and stalagmites), a proof of the karstic origin of the cavity [23,31]. This cave system has undergone a development sequence with phases of sub-aerial exposure and marine water flooding during the last Holocene marine transgression [23]. The cave originated during the sea level low stand; then, the sea level rose according to the climatic amelioration and caused the collapse of the cave roof, of which elements accumulated on the bottom of the blue hole.

3. Materials and Methods

Physical–chemical measurements in the Blue Hole of Faanu Madugau were carried out on 11 and 12 May 2022 (at 3 p.m. and 7 a.m., respectively) during the XXV Scientific Expedition annually organised by the University of Genoa, the International School for Scientific Diving and the Albatros Top Boat. The measurements were made at the beginning of the rainy season with the onset of the southwest monsoon [32], under the conditions of strong west winds, extremely variable skies (with heavy rains interspersed with brief periods of clear sky), and rough seas outside and slight seas inside the atolls.

Vertical profiles of the temperature (°C), conductivity (mS), salinity, density (kg m^{-3}), dissolved oxygen (%), pH, chlorophyll-α (mg m^{-3}), Photosynthetically Active Radiation (PAR, μM m^{-2} s^{-1}), and turbidity (FTU) were obtained using a IdromArmbiente conductivity–temperature–depth (CTD) probe with added sensors. An amperometric sensor (AMT Anlysenmesstechnik GmbH, Rostock, Germany), also mounted on the CTD probe, was used to evaluate the amount of H_2S inside the Blue Hole of Faanu Madugau. As we did not have the possibility of sampling seawater and analysing it in our laboratories, the values measured by the H_2S sensor were taken as a percentage variation of the values obtained starting from the average of the first 40 m of the water column (taken as the starting reference value). Similarly, as we could not sample water and apply the Winkler's method of post-calibration with measurements on water samples for the determination of dissolved oxygen in mg L^{-1} [33], we considered the percentage oxygen value returned by the probe as an indicative result of the variability in the dissolved oxygen level in the water column. All sensors were calibrated by the manufacturer prior to the oceanographic campaign.

Two repetitions of the measurements were made per day inside the blue hole from 0 m to about 70 m depth to verify the consistency of the measured data and, therefore, the ranges or minimum and maximum values shown in the results correspond to the ranges and minimums and maximums among all the data acquired with the different CTD probe measurements. Likewise, two further water profiles (from 0 m to 26 m depth) were collected inside the lagoon of Faanu Madugau to characterise the water mass surrounding the blue hole.

4. Results

The physical–chemical characteristics of the water column at the Blue Hole of Faanu Magudau are shown in Figure 2; only a vertical profile is shown to simplify data visualisation. Significant variations along the depth gradient are visible and three distinct layers can be recognised.

An upper layer occurs between 0 and 40 m depth, with homogeneous features and slightly variable values of temperature (29.11–29.54 °C), salinity (34.26–34.43), density (21.38–21.78 kg m^{-3}), and pH (8.21–8.29). Since H_2S also showed a constant trend in the first 40 m, without any variations, the average value of H_2S measured in the first 40 m was taken as a reference value (and fixed to 0%) to assess the percentage variations in the underlying layers. Only turbidity, dissolved oxygen and chlorophyll-α showed variations in the upper layer and had a relatively wider range than the other parameters (0.3–2.3 FTU, 95–111%, and 0.4–2.5 mg m^{-3}, respectively). The PAR, depending strongly on sky cover conditions, sea state, and position of the sun during the day, showed the maximum surface value of only 123 μM m^{-2} s^{-1} due to the cloudy days, and gradually decreased in the water column reaching the minimum of 12 μM m^{-2} s^{-1} at 40 m depth.

The values measured in the lagoon (up to 26 m depth) showed very similar values and distribution in the water column to those measured in the first 26 m along the vertical profiles made above the Blue Hole, demonstrating the homogeneity of the water mass in the first layer inside the lagoon and the absence of interaction with the actual Blue Hole waters. The temperature was in the range 29.43–29.55 °C, salinity in the range 34.32–34.42, density in 21.39–21.59 kg m^{-3}, pH 8.24–8.26, turbidity 0.4–1.1 FTU, chlorophyll-α 1.2–2.4 mg m^{-3}, dissolved oxygen 100–104%, and PAR 84 (at surface)-16 (at the bottom) μM m^{-2} s^{-1}.

A transition zone (chemocline) occurs between 43 m to 46 m depth, where all the parameters abruptly changed. In this intermediate layer, the temperature decreased to the minimum of 26.04 °C, pH decreased 7.52, and the dissolved oxygen collapsed to complete anoxia (1%). The salinity and density increased to 35.06 and 23.24 kg m^{-3}, respectively. Turbidity and chlorophyll-α reached their highest values (4.4 FTU and 2.6 mg m^{-3}, respectively) at 43.5 m depth, in the middle of this transition zone. In this layer, H_2S showed a strong percentage decrease, that reached −10% compared to the reference value of the layer above. The PAR values showed a progressive decrease to the minimum of 8–10 μM m^{-2} s^{-1} (minimum sensor response value).

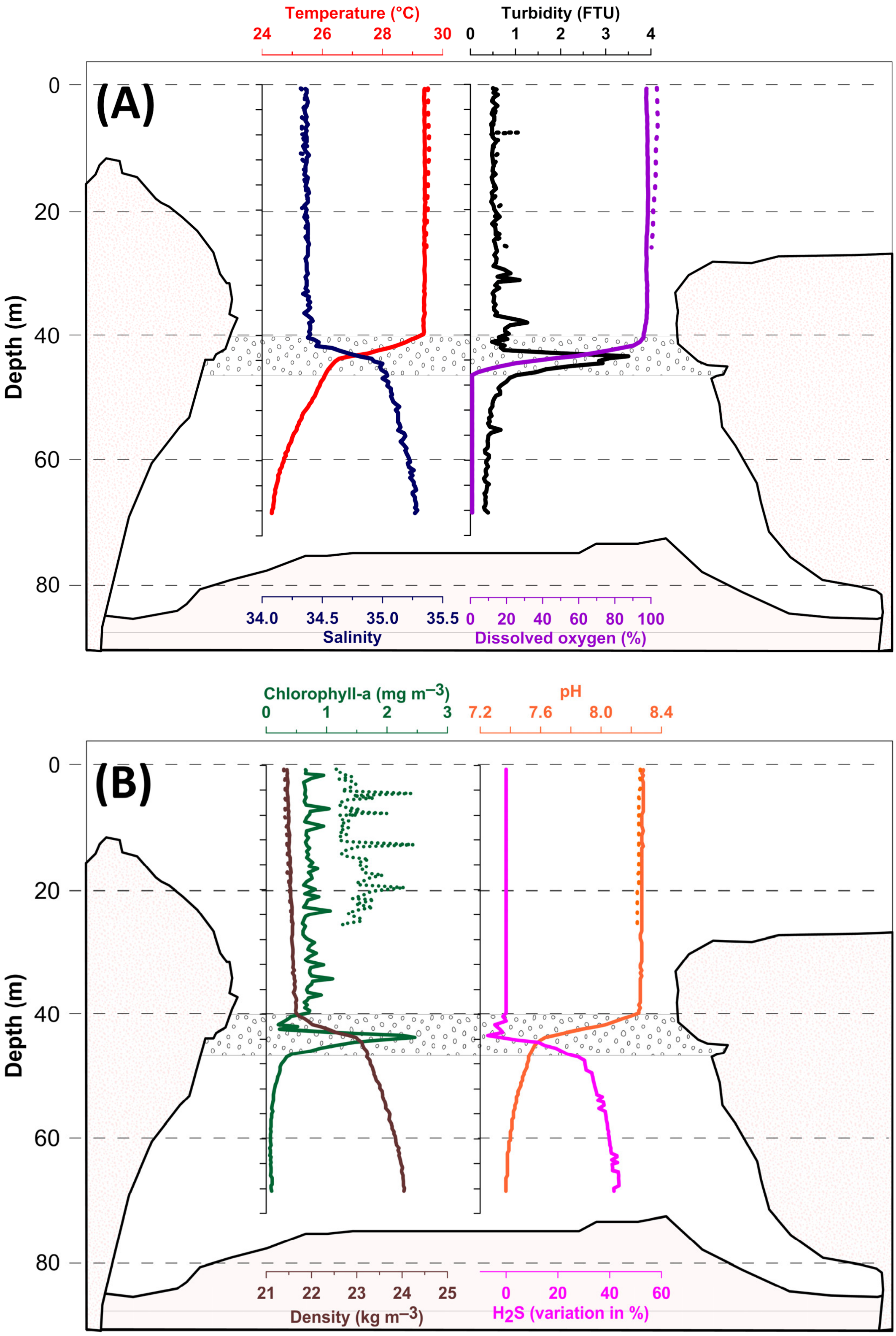

Figure 2. *Cont.*

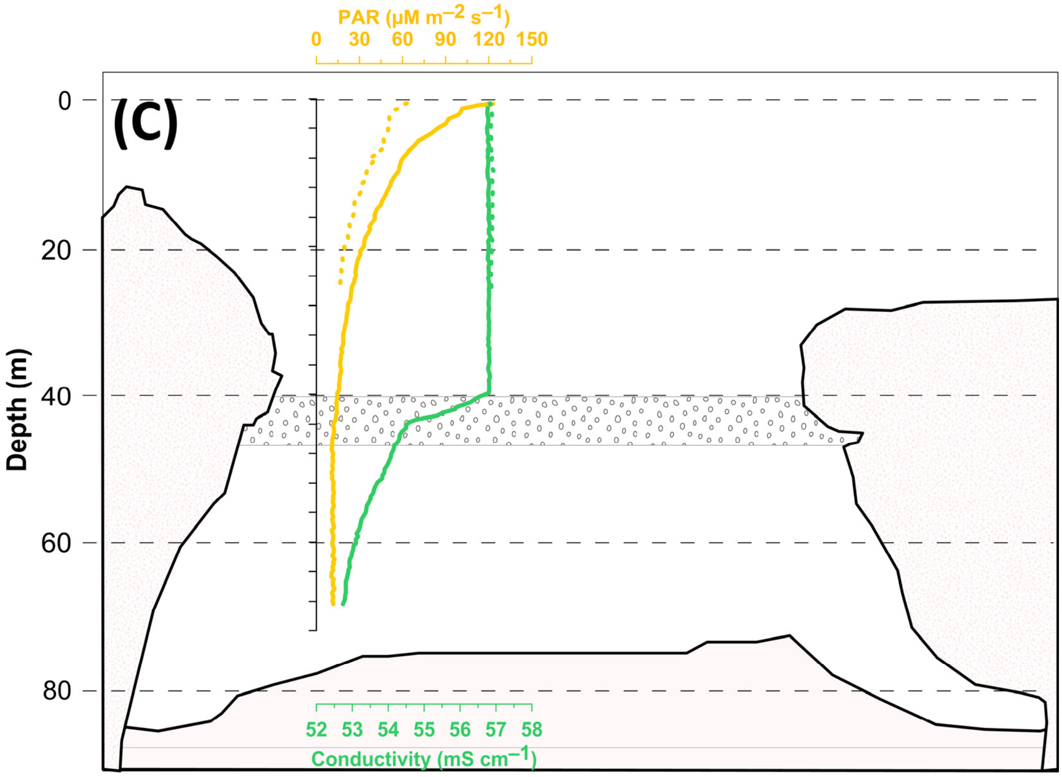

Figure 2. Vertical profiles of the chemical–physical parameters in the Blue Hole of Faanu Madugau (solid lines) with the overlaid vertical profiles collected in the lagoon (0–26 m depth; dotted lines) external of the Blue Hole opening. (**A**) Temperature (red line), salinity (blue line), turbidity (black line), and dissolved oxygen (violet line); (**B**) chlorophyll-α (dark green line), density (brown line), pH (orange line), and H_2S (purple line); (**C**) PAR (yellow) and conductivity (light green). Given the constancy of the investigated parameters in all the vertical profiles carried out in the Blue Hole, only one profile is shown in the figure. The intermediate layer (transition zone) is shown starting from the 40 m depth (bubble symbol).

Below 46 m depth, some parameters continued to change, while others remained stable such as dissolved oxygen, which was fixed at completely anoxic values. The lowest values of temperature and pH (24.21 °C and 7.34, respectively) and the highest values of salinity and density (35.32 and 24.13 kg m^{-3}, respectively) were reached near the bottom. Turbidity and chlorophyll-α decreased, reaching their lowest values on the bottom (0.24 FTU and 0.06 mg m^{-3}, respectively), indicative of extremely clear waters with an absence of phytoplanktonic activity due to the total absence of light. The darkness in this layer was indeed total, as witnessed by the PAR sensor, which marked the lowest value (Figure 2), and also by the direct testimony of divers who have dived to the bottom of the Blue Hole.

5. Discussion

The first difference between the Blue Hole of Faanu Madugau in the Maldives and the other well-known marine blue holes is that the former has its opening at about 30 m depth (Figure 1), while all the other blue holes open at shallower waters, as described hereafter. The depth of its opening, the frequent rippling of the sea surface due to strong winds and currents, and the characteristics of the first part of the water column (for example, the chlorophyll-α and plankton richness) cause the Maldivian Blue Hole to have the peculiarity of not being visible from the sea surface (Figure 3), a factor that contributed to it only being recently discovered (April 2000).

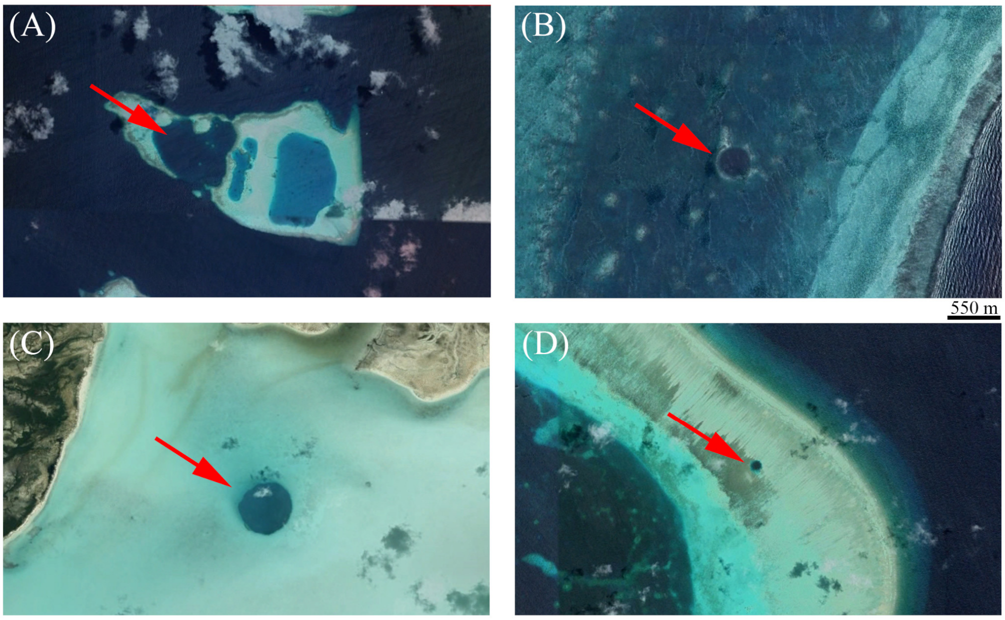

Figure 3. Satellite images of (**A**) the Blue Hole of Faanu Madugau (the Maldives) and of the other and most investigated blue holes: Belize (**B**); Caicos Island (Bahamas) (**C**); Sansha Yongle Atoll (China) (**D**). The red arrows indicate the position of the Blue Hole opening. Images taken from Google Earth Pro (v. 7.3.4.8573) at the same altitude of 9 km and represented at the same scale for comparison. Note that the Blue Hole of Faanu Madugau is the only one not visible from the surface.

The Great Blue Hole in Belize (Figure 3B), with a diameter of 320 m and a maximum depth of 125 m, is considered to be the largest blue hole [34]. It has a cylindrical shape that originates from the roof collapse. Its opening is shallow (5 m depth), with walls inclined by 30° and covered by coarse sediments. At 10 m depth, the walls become almost vertical. Water conditions below 90 m depth are anoxic. Temperature, conductivity, and salinity profiles show three negative steps at 17 m, 60 m, and 80 m. Below 100 m depth, water is rich in H_2S and HCO_3^- reaches high concentrations, probably due to the sulphate reduction [8].

The blue hole of the Middle Caicos Island in Bahamas (Figure 3C) is the largest blue hole, with a 500 m diameter and a 60 m depth. The surrounding shallow lagoon is 0–2 m deep. CTD measurements indicated well-defined thermocline and halocline at 30 m depth, with anoxic to dysoxic conditions at the bottom. Parameter profiles were seasonally dependent [10].

The Sansha Yongle Blue Hole in China (Figure 3D) is 162.3 m wide and is the deepest blue hole reaching 301.2 m depth [35–37]. The surrounding reef is on average 0.5 m deep. The Chinese Blue Hole is strongly stratified, and its water column is divided into five distinct layers. The water column up to 20 m depth is characterised by seasonal variations in temperature; the seasonal thermocline is located between 13 m and 20 m with temperatures that range from 30 to 26 °C, to which correspond a salinity increase from 33.4 to 33.7. At 70–150 m depth there is a permanent thermocline where the temperature decreases from 24.2 to 15.7 °C and the salinity increases from 33.9 to 34.5. Dissolved oxygen becomes undetectable at 90 m depth, indicating anoxic conditions, while sulphide concentration shows a strong increase below 100 m depth. Below 150 m depth, the water column becomes almost homogeneous [11,36,37].

The cylindrical shape of the Maldivian Blue Hole, similar to that of the Belizean Great Blue Hole, may support the hypothesis of its origin resulting from the collapse of the roof. The presence of a turbid layer (or turbid layers) is often a feature reported in descriptions of other blue holes, but with some differences typical of each individual blue hole. For example, ref. [37] mention high concentrations of suspended particulate matter and high values of turbidity at different depths in the Sansha Bule Hole, with the maximum in the chemocline. A similar situation to the Maldivian blue hole was found in the Cousteau Blue Hole [38], which is an inland, non-oceanic blue hole in the Bahamas. This inland blue hole showed an upper layer with oxygenated freshwater, an intermediate layer characterised by a strong halocline and high-water turbidity, and a deep layer with anoxic and H_2S-rich saline waters. The intermediate layer consists of inorganic and organic material coming from the shallower portions of the water column, which remains trapped in the halocline due to the strong density gradient. In this layer, there is an active anoxygenic phototrophs bacterial community decomposing the organic matter [38]. A similar situation can also be found in the marine Blue Hole of Faanu Madugau, but the actual composition of the suspended material will have to be defined in future studies. Future studies will also have to determine the cause of the high chlorophyll-α values measured in the turbid layer. A visibly turbid zone was also described in the King Kong Cavern, the oceanic blue hole of the Andros Island (Bahamas), by [14], but this layer contains off-white turbidity and mucoid filaments due only to the presence of bacteria and is not constant because it is affected by the strong action of the tidal currents. The fact that, on the contrary, the turbid layer is constant and stable in the intermediate layer of the Maldivian Blue Hole may support the idea that currents and tides, even if they can be strong (velocity higher than 2 m s^{-1}) [29], have no effect on the blue hole due to its deep location and the lack of communication of internal waters with the external environment of the blue hole (on the bottom). Given the stability of the turbid intermediate layer (and the protection provided by the surrounding lagoon), it can be assumed that even higher energy events like sea storms are unable to influence the blue hole, but long-term investigations are required to confirm this.

The values of temperature (29.11–29.54 °C) found in the upper layer (0–40 m depth) above the Blue Hole of Faanu Madugau correspond to the mean surface temperatures of the Inner Sea during summer (29.38 °C) [24]. The salinity values measured (34.26–34.43) were lower than the mean annual value (35.8) [24] due to the fact that the measurements were made during the onset of the southwest monsoon (and the beginning of the rainy season) that make May a typically rainy month [32]. Chaudhuri et al. [39] analysed the meteorological characteristics (precipitation, atmospheric pressure, air temperature, and relative humidity) of the Maldives during the period 2000–2015 and found that an average of more than 200 mm rain falls in May. Chaudhuri et al. [39] found that the weather characteristics of the Maldives are almost constant throughout the year and that the differences over time are minimal, with practically no seasonality pattern in the monthly behaviour. This is due to the location of the Maldives Archipelago, which is crossed by the Equator and is therefore characterised by a fairly stable tropical climate throughout the year.

The stability of meteorological parameters implies the relative stability of the parameters in the water column. The stability of the parameters in the upper layer (0–40 m depth) in turn plays an important role in maintaining the constant environment of the Blue Hole. In fact, the seasonal variation in temperature in shallow waters (up to 10 m depth) is rather small in the Maldives, ranging between 28.27 and 29.38 °C during the year [28]. These seasonal differences are even smaller (less than 0.5 °C) at 50 m depth [28]. On the contrary, in all the other blue holes there are strong seasonal variations in temperature and salinity in shallow waters, due to changes in weather and sea conditions. For example, Belize has a sub-tropical climate with trade winds blowing from the East for most of the year and is characterised by a sea surface temperature in the 23–29 °C range, and a sea surface salinity ranging from 37–41 depending on tropical cyclones and high summer–fall precipitations [8].

The presence of the thermocline at a depth of 40–46 m and the 5 °C gradient in temperatures between the surface and the bottom in the Blue Hole deviate greatly from the temperature characteristics of the water column of the Maldivian Inner Sea [30], demonstrating that the Blue Hole is a peculiar environment that differs greatly from its surroundings.

The condition of anoxia and sulphide richness is common to deep blue hole environments, and, in fact, all the four described blue holes show deep sulphide-rich and anoxic waters, albeit from different depths. The total anoxia starts from 90 m depth in the Sansha Yongle and the Belize blue holes, while it starts from 46 m depth in the Maldivian Blue Hole and, finally, above 30 m depth in the Bahamas one.

6. Conclusions

The results of this first survey conducted with a multi-parameter probe showed that the Blue Hole of Faanu Madugau, the only known blue hole to date in the Indian Ocean, has a characteristic vertical gradient in the physical–chemical parameters investigated along the water column. The deep layer (anoxic and dark with low pH, turbidity, conductivity, and temperature values and high H_2S values) shows completely different features from the upper layer and from the surrounding waters of the lagoon (oxygenated, chlorophyll-rich with high pH, temperature, and conductivity values), and is divided from the latter by a turbid intermediate layer in which the parameters undergo an abrupt change. The Maldivian Blue Hole shows some differences from the other well-known marine blue holes but has some analogies with an inland and freshwater blue hole described from the Bahamas. This evidence is indicative of the unique environment of the Blue Hole of Faanu Madugau, which deserves further investigations with multidisciplinary approaches to understand the mechanisms that isolate deep water from surface water, the influence of weather and marine forcings on it, and to evaluate its resilience in view of water warming or rising sea levels due to global climate change.

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