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Béchir Béjaoui, Sana Ben Ismail, Achref Othmani, Olfa Ben Abdallah-Ben Hadj Hamida, Cristele Chevalier, et al.. Synthesis review of the Gulf of Gabes (eastern Mediterranean Sea, Tunisia): Morphological, climatic, physical oceanographic, biogeochemical and fisheries features. *Estuarine, Coastal and Shelf Science*, 2019, 219, pp.395-408. 10.1016/j.ecss.2019.01.006 . hal-02062093

HAL Id: hal-02062093

<https://hal.science/hal-02062093v1>

Submitted on 28 Jan 2020

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Synthesis review of the Gulf of Gabes (eastern Mediterranean Sea, Tunisia): Morphological, climatic, physical oceanographic, biogeochemical and fisheries features

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1. Introduction

Several oceanographic surveys have been done in the Gulf of Gabes since the beginning of the twentieth century. The aim of the study by the “*Pourquoi Pas?*” in 1923 was to investigate sea bottom features (Dangeard, 1924). The benthos research began with Le Danois (1925) and Seurat (1924, 1929, 1934), who studied the habitats on the intertidal floor. Later, De Gaillande (1970a, b) and Poizat (1970a, b) studied the benthic sands, the hydrodynamics and sediments of the Gulf, while Ktari-Chakroun and Azouz (1971) focused on the bottom topography to identify areas suitable for trawling. During the same period, Ben Othman (1971) published hydrobiological observations on the southeast Tunisian coast. The potential of pelagic fish exploitation was investigated in the frame of the research and development project of fisheries during three combined hydroacoustic and oceanographic cruises (June–July and September–October 1972 and April–May 1973) that enabled a detailed description of oceanographic properties (Brandhorst and Messaoud, 1977). The latter study could be considered the first of its kind, given the investigated geographical space and the subject matter addressed.

Water circulation highly influences the biological, chemical and sedimentological features in the Gulf of Gabes. Previous studies showed that water circulation in the Gulf is closely associated with the Atlantic waters circulating through the Strait of Gibraltar (Béranger et al., 2004; Ben Ismail et al., 2012, 2014) and with tidal effects (Tsimplis et al., 1995; Gasparini et al., 2004). Tides observed in the Gulf of Gabes are among the highest in the Mediterranean Sea (up to 2 m in height) and

are mostly semidiurnal (Gasparini et al., 2004; Sammari et al., 2006). In addition to tides, anticyclonic winds also drive water circulation (Hattour et al., 2010), bed sediment texture and seagrass density (Ben Brahim et al., 2010).

The Gulf of Gabes is considered highly productive (D’Ortenzio and d’Alcalà, 2009; Ben Brahim et al., 2010), contributing approximately 40% of the national fish production in Tunisia (DGPA, 2015) and thus constituting an anomaly in the eastern Mediterranean Basin, which is known to be oligotrophic, as it is governed by the inflow of usually nutrient-poor Atlantic surface waters coming from Gibraltar (Berman et al., 1984; Krom et al., 2010). The Gulf was recently identified as one of the eleven consensus ecoregions of the Mediterranean and is considered, together with the Venetian shelf region, as a shallow and phytoplankton bloom region (Ayata et al., 2017). Additionally, this area is usually considered an important nursery for several fish species (Hattour et al., 1995; Derbel et al., 2012; Enajjar et al., 2015).

Since the industrialization in 1970, which involves discharge from large-scale phosphate production plants in Sfax and Gabes (Béjaoui et al., 2004; Ghannem et al., 2010), the phosphogypsum discharge (~12000 ton per day) has become the main cause of the disequilibrium of this ecosystem. Recent studies have shown a decrease in fish resources (Zairi and Rouis, 1999; Hamza-Chaffai and Pellerin, 2003); a loss of marine biodiversity (Drira et al., 2008; Barhoumi et al., 2009; Rabaoui et al., 2013) and a degradation of water quality (Bel Hassen et al., 2008; Drira et al., 2014a, b; Ben Salem et al., 2015). The discharges of phosphogypsum led to a drastic decrease in the seagrass areas, as observed for *Posidonia oceanica* assemblages, which were shown to be

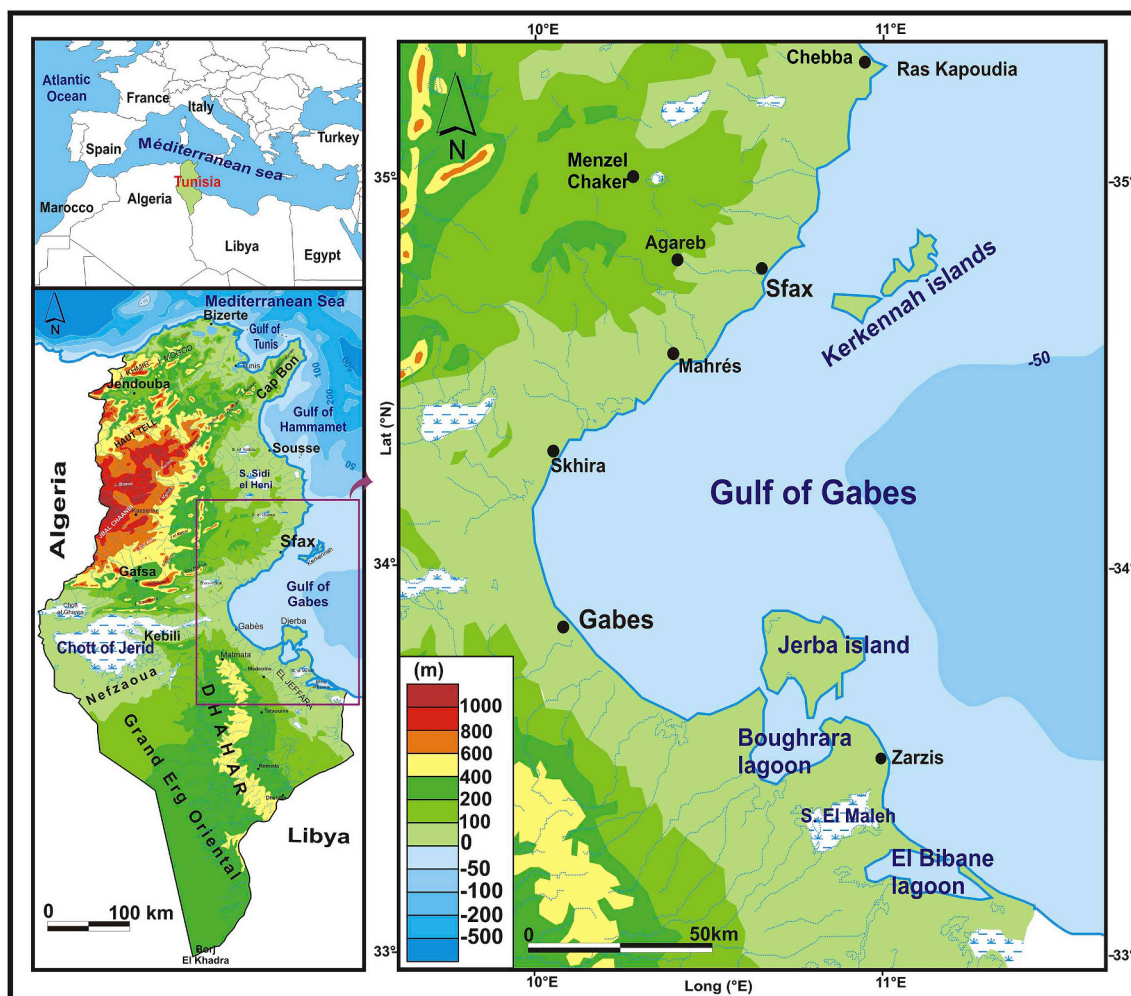


Fig. 1. Localization of the gulf of Gabes.

strongly reduced in the more polluted areas (Béjaoui et al., 2004; Ben Brahim et al., 2010).

Exploitation of marine resources has been a significant component in this historical relationship, and overuse has occurred at different times (Tudela, 2004). Indeed, overfishing caused reductions in fish abundance, biomass and species richness and can disrupt ecosystem functioning, leading to changes in biological assemblages and the degradation of marine ecosystem services (Worm et al., 2006). Mediterranean fisheries are typically multi-species and multi-gear, particularly the demersal fisheries which consist of numerous small to medium-sized boats (Farrugio et al., 1993). This diversity brings additional difficulties to the task of managing fisheries (Papaconstantinou and Farrugio, 2000). Coastal fisheries are particularly important in the southern region of Tunisia, and almost 53% of the national fishing units (which represents approximately 13 000 units, including approximately 400 trawlers) operate in the Gulf of Gabes. Most fishermen along the Gulf coastline are small-scale coastal fishermen (63%). They compete vigorously with large trawlers and sardine boats based out of the Gulf's main port cities, especially as fish stocks continue to decline from overfishing. In the Gulf stocks are already overfished by more than 30% (LRMV, 2011) and biodiversity is declining, coinciding with the reduction in submerged aquatic vegetation.

Invasive species represent an added pressure on ecosystem functioning and fisheries. Among the exotic invasive species recorded in the Mediterranean Sea (Galil, 2000; Zenetos et al., 2005), several have been recorded in Tunisian coastal ecosystems and specifically in the Gulf of Gabes; for example, the green algae *Caulerpa taxifolia* and *C. racemosa*

(Langar et al., 2002), the pearl oyster *Pinctada radiata* (Tlig-Zouari et al., 2009), blue portunid crabs *Portunus segnis* (Rabaoui et al., 2015) and *Callinectes sapidus* (Mancinelli et al., 2017) and the tropical scyphozoan *Rhopilema nomadica* (Daly Yahia et al., 2013) (see Fig. 6.)

The purpose of this paper is to provide an in-depth review on the climatic, geomorphologic, physical, biogeochemical, planktonic and fisheries features of the Gulf of Gabes. It is intended to be used as support for stockholders interested in the Gulf ecosystem.

2. Field location

The Gulf of Gabes, named “Petite Syrte”, is located in the south-eastern part of Tunisia with the town of Chebba in the north and the Tunisian-Libyan border in the south (Fig. 1). It occupies a wide continental shelf area (Morzadec-Kerfourn, 2002) and represents approximately 33% of the Tunisian coastal waters and more than 50% of the 700 km long Tunisian coastline (APAL, 2011). It shelters various islands (Kerkennah, Kneiss and Jerba) and lagoons (Boughrara and El Bibane) and several towns, such as Gabes, Sfax, Jerzis and Jerba.

3. Climate characteristics

The Gulf of Gabes is characterized by a semi-arid Mediterranean climate influenced by both a wet temperate component coming from the north and east and a dry and hot subtropical Saharan component including sand storms coming from the south (Dahech and Beltrando, 2012a). Two main seasons are observed: the summer (June to

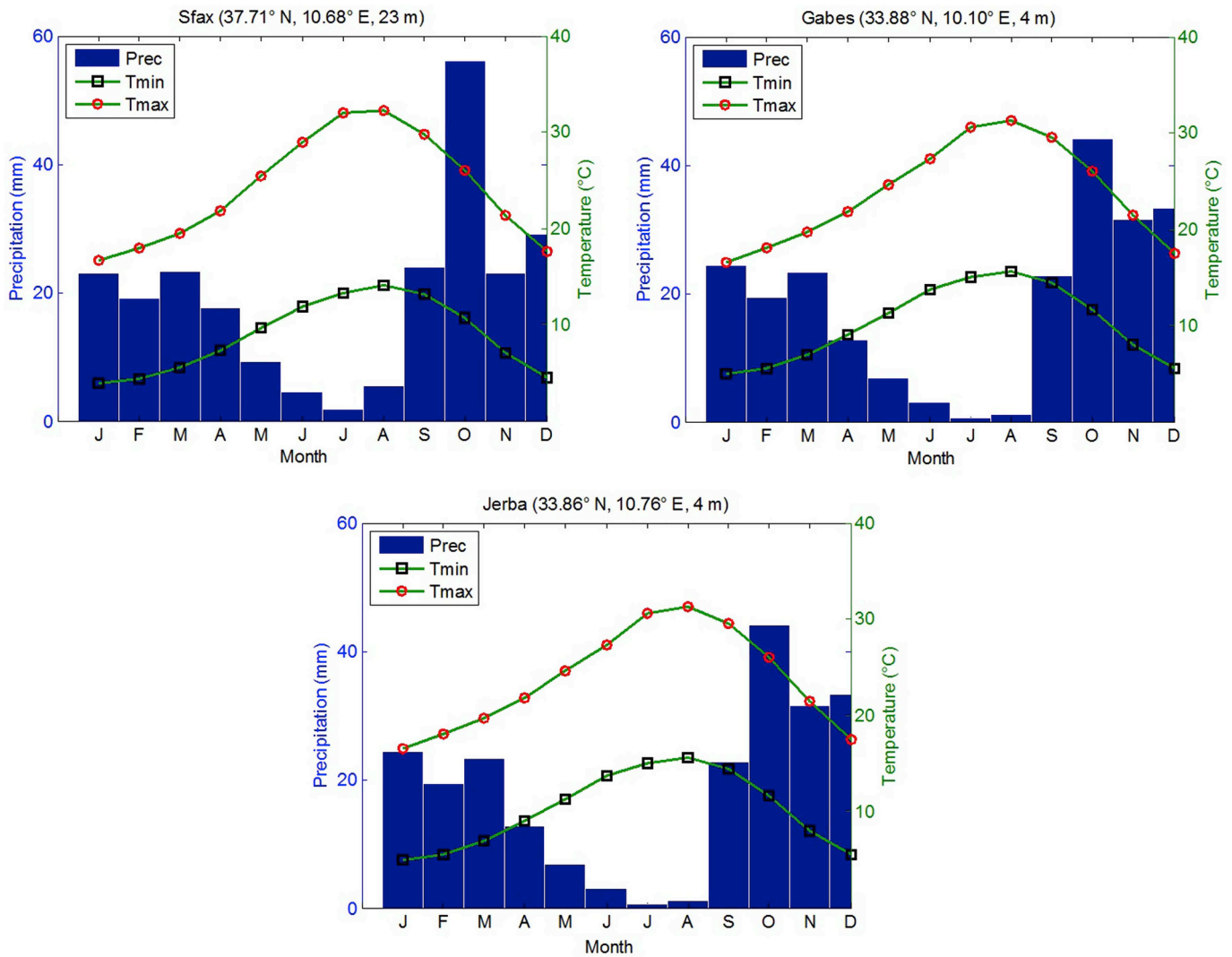


Fig. 2. Mean monthly values of precipitation and temperature for the stations of Sfax (A), Gabes (B) and Jerba (C) (data from National Institute of Meteorology for 1970–2015 period). The total annual precipitations reach 236 mm in Sfax and 234 in Jerba with 110 mm in autumn.

September), which is dry and hot, and the winter (January to March), which is wet and cool (Fig. 2). The hot season extends beyond the summer, and the number of sunny days may reach 64.4% (Amari, 1984). Two intermediate seasons, spring and autumn, may be observed, but the duration depends on the year. The latter is the rainiest season (El Melki, 1996).

The mean temperature is approximately 11 °C in the winter and approximately 23 °C during the summer (Atlas Climatique, 1999). Furthermore, the mitigating effect of the sea can be observed on extreme values and their spatial repartition. In fact, the minimum temperature is +4 °C at Sfax and –3 °C at Gabes, whereas the maximum is +44 °C at Sfax and +50 °C at Gabes (Bechrawi, 1980). The mean temperature in winter is approximately 12 °C and 13 °C in Sfax and Jerba, respectively, whereas during the summer it is 25 °C in Sfax and 26 °C in Jerba (Fig. 2).

The precipitation has a strong annual variability from 120 mm to, exceptionally, > 600 mm a year (Atlas Climatique, 1999), with up to 650 mm recorded in Sfax in 1969 (Daoud and Dahech, 2012). The mean annual precipitation for the period 1970–2015 was 236 mm in Sfax and 234 mm in Jerba. Forty five percent (45%) of precipitation occurs in autumn (from 80 to 110 mm) and 30% in winter (from 60 to 80 mm), whereas the precipitation is < 5 mm in summer (Amari, 1984; Atlas Climatique, 1999) (Fig. 2). Rivers in the gulf of Gabes are intermittent

with annual flow estimated to 80 million m³ year⁻¹ (APAL, 2012). The only continuous inputs in the gulf of Gabes is that of the industrial waste of about 410 million m³ year⁻¹ (Béjaoui et al., 2004).

The annual evaporation varies from 1600 to 2000 mm (Atlas Climatique, 1999) with high temporal and spatial variability; for instance, the monthly evaporation varies from 110 mm during winter to 210 mm during summer at Sfax and from 145 to 184 mm at Gabes. Globally, evaporation (approximately 1790 mm a year) is not balanced by precipitation (approximately 230 mm a year) and river inputs (80 million m³ a year). Consequently, the freshwater budget is estimated to be approximately –1400 mm a year (Bethoux, 1977).

The average annual wind intensity is approximately 3.5 m s⁻¹ (Dahech, 2007) and rarely exceeds 8 m s⁻¹. The dominant wind originates from the eastern sector, corresponding usually to sea breeze (Dahech, 2007). Dust wind, which may cause some damage, comes mainly from the southwest. Its frequency ranges from 12 days year⁻¹ in Sfax to 20 days year⁻¹ in Gabes and 18 days year⁻¹ on Jerba Island (Dahech and Beltrando, 2012b). During the winter, the prevailing wind is from the western sector. Coming from the continent, this wind is often cold and dry. During summer, the prevailing wind is mainly from the eastern sector (Dahech and Beltrando, 2006). Sea breeze circulation is the most frequent (Dexter, 1958; Dahech et al., 2006), and since it comes from the sea, it is humid. This local wind improves the thermal

comfort near the coasts (Dahech, 2015). During autumn and spring, the alternation of unsteady eastern, northern and western winds occur (Dahech, 2007).

The mean annual solar radiation is approximately 208 W m^{-2} , ranging from 292 W m^{-2} during August to 104 W m^{-2} during January (Beltrando, 2004). During the summer, when the day-length is approximately 16 h, the insolation duration reaches 350 h per month in Sfax and Jerba. The duration of insolation decreases in winter to 200 h per month (Atlas Climatique, 1999).

4. Coastal morphology

The coastal morphology of the Gulf shows varied forms (Brahim, 2001; Oueslati, 2004; Kouka, 2015).

Beaches (Fig. 3) are mostly located at the mouth of wadis (e.g., Chaffar beach formed by two spits approximately 8 km long and 40–150 m wide), on the southern coast of Gabes (Miossec and Paskoff, 1979) and at the eastern facades of Jerba Island (from the spit of R'mel to Aghir) and the Zarzis peninsula (Oueslati, 2004; Bourgou and Kassah, 2008). Elsewhere, they are very discontinuous and often take the form of narrow sandy beaches a few meters wide without shorefront dunes (Oueslati, 2004; Bouaziz, 2011), as observed in bays and the downslope of cliffs. Locally, they correspond to undeveloped spits, e.g., Botria spit and Sebket Driaa in the south of Skhira. The large beaches located in tourist areas have suffered irreversible degradation for several decades (Paskoff, 1985; Bourgou and Kassah, 2008). The most significant examples are Chaffar and Teboulbou, characterized by a relatively high erosion rate between 1.5 and 2 m a year (Oueslati, 2004). In addition to sea level rise and land subsidence, this erosion is mainly linked to 1) urban developments, 2) the construction of dams in the catchment areas shortening the sediment supply, and 3) the absence of wadis supplying sediment to intertidal zones, as on the Kerkennah Islands, Jerba and the coast located between Ras Kaboudia (Chebba) and El Awabed north of Sfax (Paskoff, 1985; Bouaziz et al., 2005; Bouaziz, 2011).

Cliffs can exceed 8 m (Oueslati, 2004; Kouka, 2015), as in Jorf and Borj El H'ssar (west coast of Kerkennah), Ouled Gacem (east coast of Kerkennah), Skhira-Nadhour, Ras El Jorf (in front of Jerba) and Karboub in the east of the Gulf of Boughrara (Kouka, 2015) (Fig. 3). They often consist of fragile formations (e.g., sandy clays rich in gypsum and silty sands) (Oueslati, 2004; Kouka, 2015) crossed by numerous ravines. Deep notches are often observed in their bases, evidencing severe and rapid degradation of the coasts, and therefore, large blocks are found at the base of these cliffs. This phenomenon is remarkable, especially at Skhira, Ras El Jorf (facing Jerba Island) and Karboub (eastern sector of Boughrara) (Oueslati, 2004). Elsewhere, the cliffs are between 1 and 5 m high. They are carved in relatively resistant (in particular, marine or wind sandstone of upper Quaternary) or heterogeneous (alternation of Quaternary sandstone, colluvium and alluvium) rocks (Bourgou and Kassah, 2008; Bouaziz, 2011). They are observed along the coast from Ras Kaboudia in Sfax (Melloulèche, Louza, Awabed ...), on the Kerkennah Islands and Jerba (Aghir, Sidi Yati, Guellala ...), on the northern coast of Gourine, on the Zarzis peninsula and in the “slobs” that isolate Bihret El Bibane Sea (Oueslati, 2004).

Wetlands cover a large area (Fig. 3), consisting of sebkhas (salted land without vegetation), chotts (salted land with salt-tolerant vegetation), tidal marshes, and lagoons (Morzadec-Kerfourn, 2002; Bouaziz, 2011). The sebkhas and chotts cover a large part of the Gulf coast and almost 2/3 of the Kerkennah Islands. They are in direct contact with the sea behind the sandy beaches, and they often border the tidal marshes. These dominant landscapes are observed on the coast of Melloulech, Mahres and Quadrane and particularly around the Zarzis peninsula and the El Bibane Lagoon (Oueslati, 1992; Kouka, 2015). The salt marshes are composed of two separated parts: “the slikke” (regularly emerged and submerged part depending on the tide) and “the schorre” (visible part with a halophyte vegetation sometimes crossed by a dense tidal

channel network) (Oueslati, 1992). Their evolution and extension are strengthened by the tide importance as well as by some sheltered coastal areas; thus, they mainly extend in bay beds and estuaries (Oueds Quadrane, El Maleh and Kerkennah) or behind shelter spits (spits of Chaffar, Skhira, Botria and Ras R'mel and the two peninsulas of Lella El Hadhria and El Gastil) (Oueslati, 2004). Lagoons are only found in the southern part of the Gulf, such as the Boughrara and El Bibane Lagoons. Their development is related to morphological evolution since the Versilian transgression (Bouaziz et al., 2003).

Generally, coastal areas have been experiencing significant changes over time, enhanced by climate change and related sea level elevation (Bouaziz, 2011). This phenomenon was revealed by several observations, such as high rates of land salinization and coastal erosion (Oueslati, 1992; Bouaziz, 2011).

5. Physical oceanography

The circulation in the Gulf is mainly influenced by the effects of the tides and anticyclonic winds (Abdennadher et al. 2006; Sammari et al., 2006; Poulain and Zambianchi, 2007). The bottom topography, sediment texture, and relatively high density of seagrass beds (*Zostera*, *Cymodocea* and *Posidonia*) and algae (*Caulerpa*) contribute to the complexity of the hydrodynamic nature of the area.

5.1. Permanent currents

The Atlantic Tunisian Current (ATC) (Sammari et al., 1999), a permanent surface current with an Atlantic origin, is characterized by its minimal salinity as it travels through the Tunisia-Sicily Channel and flows along the Tunisian coast between 0 and 200 m (Sorgente et al., 2011; Ben Ismail et al., 2012). This current is primarily oriented towards the south and is then divided into two branches in front of the Gulf of Gabes: a coastal branch (between the coast and 80 km) facing south, where the Atlantic Water (AW) becomes saltier ($S > 38$) (Ben Ismail et al., 2010), and a less salty branch (S of approximately 37.4–37.7) flowing over 180 km off the coast with a southeast direction along the Libyan shelf (Millot et al., 2006; Ben Ismail et al., 2010). This current was recently identified as the Atlantic Libyan Current (ALC) (Sorgente et al., 2011; Ben Ismail et al., 2015).

The Gulf of Gabes occupies a vast shallow area, making it more sensitive to atmospheric effects (e.g., wind). Its particular bathymetry (less than 50 m to 110 km from the coast and up to 200 m to 400 km from the coast) strongly influences its hydrodynamics, with a general circulation characterized by high mesoscale variability. Several studies have demonstrated the almost permanent presence of an anticyclonic vortex south to 34° N , named “Sydra Gyre” (SG) (Ciappa, 2009; Sorgente et al., 2011). A mainstream of the north-south current accompanies a reverse south-north current (Hattour et al., 2010). These currents are involved in the renewal of the Gulf waters and fuel an anticyclonic circulation (more or less intense according to the season), causing an average elevation of approximately 20 cm in the shallow regions. However, these currents remain low compared to those induced by tides (Fig. 4).

5.2. Tides and tidal currents

In the Gulf of Gabes, the tide is predominantly semi-diurnal with diurnal inequality $(O1 + K1)/(M2 + S2) < 0.1$ (Abdennadher et al. 2006; Othmani et al., 2017). The M2 and S2 semidiurnal components are well developed in the Gulf (coastal areas and central part) but are reduced in the offshore regions. The other semidiurnal components, N2 and K2, are of reduced amplitude, $< 3 \text{ cm}$ (Tsimplis et al., 1995; Gasparini et al., 2004; Othmani et al., 2017). The Gulf has the highest tidal range in the Mediterranean Sea (maximum $> 2 \text{ m}$) essentially due to the low slope of the continental shelf and the shallow depth, which maintains its horizontal dimensions close to the resonance condition

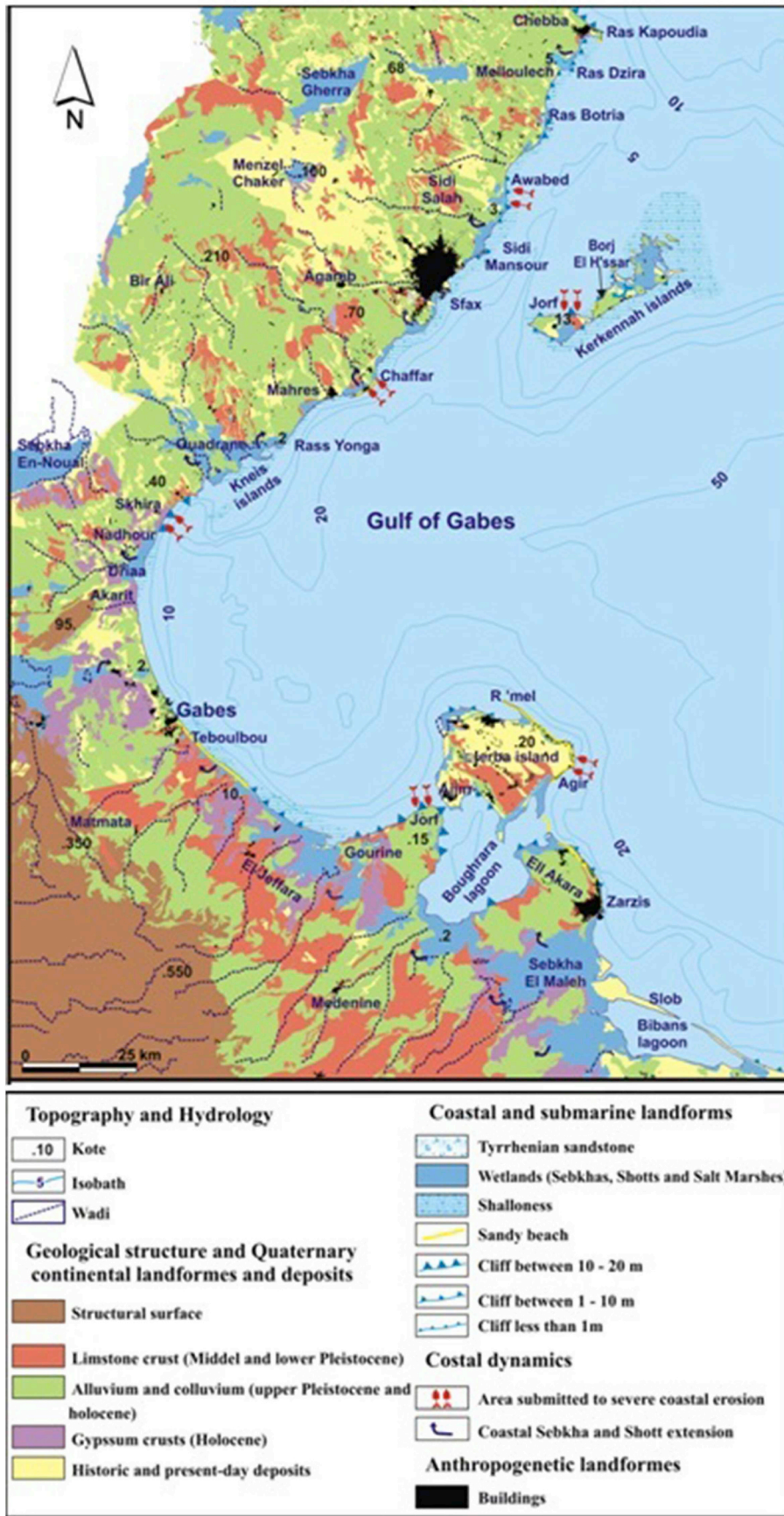


Fig. 3. Geomorphology of the gulf of Gabes.

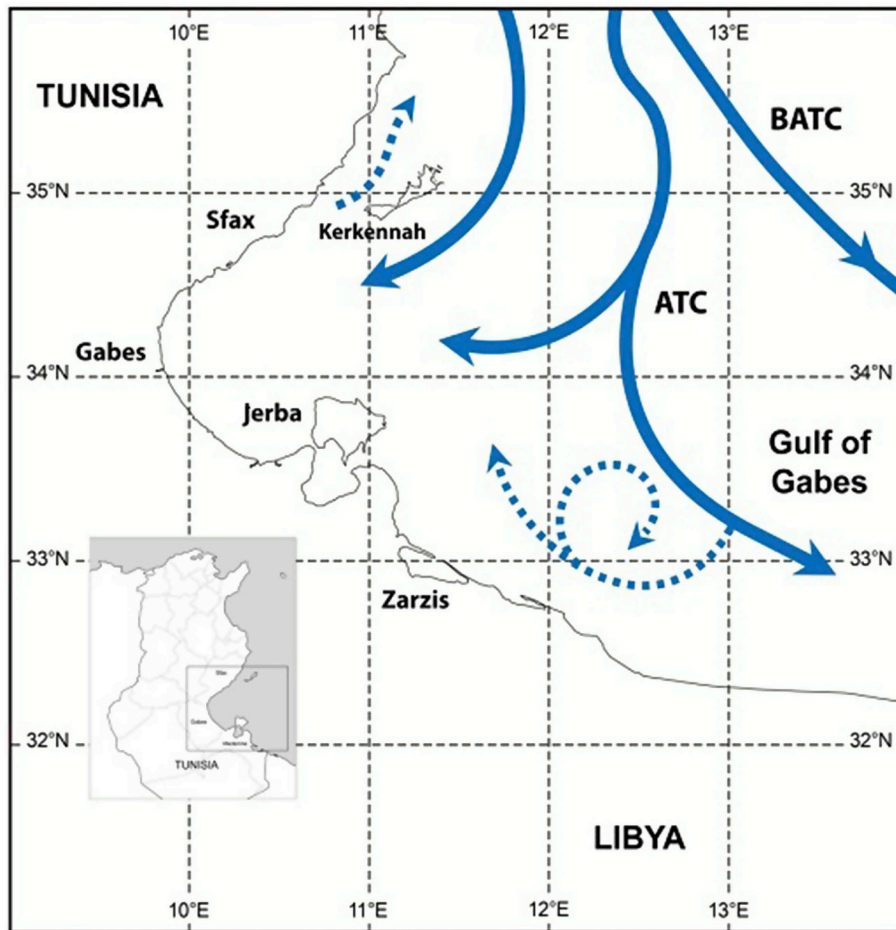


Fig. 4. Schematic illustration of the main pathways of the principal water masses flowing through the Gulf of Gabes: BATC (Bifurcation Atlantic Tunisian Current) and ATC (Atlantic Tunisian Current) (Ben Ismail et al., 2015).

(1/4 of the wavelength of the semi-diurnal tidal wave incidence) (Othmani et al., 2017). The tide produces a stationary wave whose amphidromic points are distributed around the island of Pantelleria and that resonates in the Gulf of Gabes (Sammari et al., 2006). The Gulf is thus a tide amplifier with a greater tidal range in the central part than on the coast. The tidal amplitude reaches 2.3 m in the central part of the Gulf during the spring tide (Sammari et al., 2006) and 0.2 m during the neap tide (Ayari et al., 2008). However, along the coast, the high bottom friction (dissipating 61% of the energy) decreases the tidal amplitude (e.g., 0.8 m in Ras Kaboudia and 1.6 m in Ras Jdir during spring tide) (Sammari et al., 2006) and causes a phase lag exceeding 3 h at the lagoon of Boughrara and 4 h at El Kantara.

Parallel to the coast, tides induce periodic currents whose intensity can be high in some places, as shown in Fig. 5 (Othmani et al., 2017). Based on the geographic distribution of the maximum amplitude and the phase of the M2 wave (Molines, 1991), Tounsi (1998), the surface current is approximately $10\text{--}30\text{ cm s}^{-1}$ in shallow areas and can reach 50 cm s^{-1} in topographic shallow corridors during spring tides, as confirmed by *in situ* measurements (Sammari et al., 2006; Hattour et al., 2010). Currents are as periodic as tides; during the flood, they flow coastward and fill the Gulf, whereas during the ebb, they flow eastward and empty the Gulf (Othmani et al., 2017). The water masses coming from the Gulf's eastern sector bifurcate into two branches. One is directed to the northern sector, towards the Kerkennah Islands, and the other to the southern sector, towards Jerba Island. In the north, the currents surround the Kerkennah Islands on both the northern and southern sides, meeting in the channels. At the level of Ras Kaboudia,

the current bifurcates into two branches, the first moving northward and the second going towards Sfax Harbor. In the south, the current moves toward the western inlet of the Boughrara Lagoon, where the tidal currents feed the lagoon from both the east and the west (Othmani et al., 2017). The currents follow approximately the same path during flood and ebb tides, but they move in substantially opposite directions and at slightly different intensities.

5.3. Wind currents

The currents induced by winds are often parallel to the coast and may be hampered by the low water level. The currents due to storms can be superimposed onto tidal movements, provoking significant elevations of the sea level (LCHF, 1979). Amari (1984) showed that under the action of local or broader winds, the currents can be 2 to 5 times stronger than the tidal currents, especially in the presence of "marine" winds, whose influence is clearly higher than that of the "earthly" winds (Morellato, 2008).

5.4. Wave currents

The dominant waves in the Gulf of Gabes are NNW and ESE (WAM-DI Group, 1988), with a height varying between 2 and 4.8 m and a period of 10 s (measurements beyond a 20 m depth over a 20-year period; 1974–1994) (Hydrotécnica Portuguesa, 1995). However, the significant height of these waves experienced a slight increase over 50 years. During storms, waves generated offshore are quite unstable and

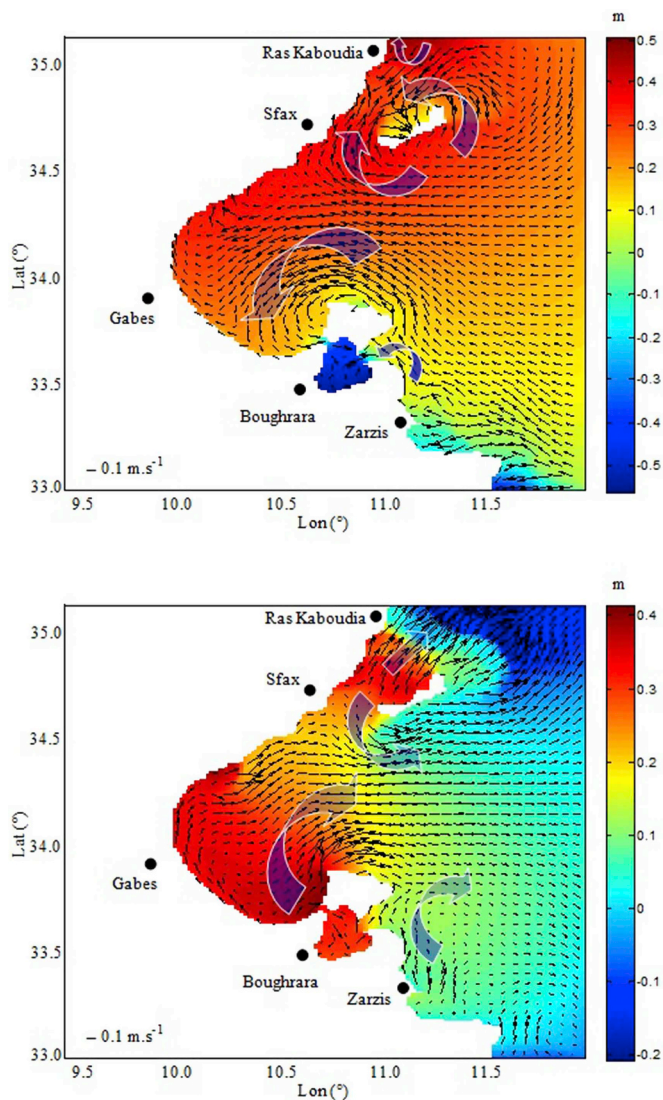


Fig. 5. Simulated surface tidal currents and water level spatial distribution during flood tide (A) and ebb tide (B). Arrows indicate the current directions and colours designate the water level above the mean depth (Othmani et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

spread mainly in the NE, ENE and SE sectors, with significant heights estimated at 5.4 m, 6.3 m and 7.7 m, respectively. They dampen near the coast because of the gradual slope of the ground, shallow depth, and seagrass beds present on the coast. The most significant action of the waves is particularly evident along the Bin El Ouediane coastline by sand spit edification (Ayari et al., 2008).

5.5. Hydrology

The warm climate of Tunisia promotes evaporation and increases the salinity and temperature of water masses. The mean annual salinity and temperature are relatively high, approximately 38.00 and 19.4 °C, respectively (Ben Ismail et al., 2010; Ben Brahim et al., 2013). The seasonal variation of temperature is particularly important in the Gulf of Gabes, varying from 13 °C in the winter to 26 °C in the summer. Seasonal variations of salinity are also observed, particularly in the coastal area of the Gulf, where the salinity may exceed 39.00 in summer (Ben Brahim et al., 2013). The water column is well mixed during the winter, whereas vertical stratification is observed from May to October.

Recent studies show that the stratification varies with depth (Bel Hassen et al., 2008, 2009a, b; Ben Ismail et al., 2010). In deep areas (> 70 m), vertical stratification is more pronounced due to the presence of cold and less salty Atlantic water. In more shallow areas (< 60 m), the water column is well mixed with an average salinity of 37.90 and an average temperature varying between 21.6 °C at the surface and 20.6 °C at the bottom in summer conditions (Ben Othman, 1973; Bel Hassen et al., 2009a, b), when the water mass with an Atlantic origin is more difficult to characterize.

5.6. Present-day and future climate

The Gulf of Gabes is particularly interesting for the study of the impacts of climate change on coastal ecosystems (Rizzi et al., 2016). Indeed, its shallowness and large continental shelf make it specific for the Mediterranean Sea (Morzadec-Kerfourn, 2002). Strong air-sea interactions in such shallow water lead to strong seasonal variations of the water temperature and to very high sensitivity to any change in the weather conditions (Sorgente et al., 2002). The air temperature, a key indicator of climate evolution (Sanchez-Arcilla et al., 2011), strongly increased in the region during the last decades, as illustrated by the high increasing rates of summer maximum daily temperature for the period of 1974–2007: approximately 0.6 °C, 0.7 °C and 0.67 °C per decade in Sfax, Jerba and Gabes, respectively (Hemming et al., 2013). This air warming led to a lengthening of the summer season at a rate of 8 days per decade and stagnation or even a slight decrease in the rainfall amount (Harzallah et al., 2010). Simultaneously with this atmospheric warming, a warming trend of water temperature at a rate of +0.12 °C per decade was observed between 1920 and 2007, although the data set is sparse and limited in amount (Harzallah et al., 2010).

Recently developed coupled atmosphere-ocean regional climate models (RCMs) for the Mediterranean Sea predict an accelerating increase in air and water temperatures during the next decades (Taylor et al., 2012; Goodess, 2013; Gualdi et al., 2013; Jacob et al., 2014). According to these scenarios, the air temperature will increase approximately 1.5 °C in the 2021–2050 period relative to the 1961–1990 one. On the other hand, a marked decrease in rainfall may occur after 2020 (–20 mm between the 2021–2050 and 1961–1990 periods). These changes will likely impact the water properties of the Gulf (Harzallah et al., 2010; Goodess, 2013; Gualdi et al., 2013). A tentative study of the potential impacts of these changes (Sanchez-Arcilla et al., 2011) considered that the water quality of the Gulf may decrease by 20% due to decreased precipitation (through reduced dilution) and by 10–50% due to an increase in the water temperature (through reduced dissolved oxygen content). The warming of the waters would also lead to the appearance of marine alien species. Nearly 40 species have been observed in the Gulf of Gabes between 1966 and 2006 (Agnew et al., 2013). The number of alien species is projected to be approximately 80–100 by 2050 (Goodess, 2013).

The coasts of the Gulf of Gabes, mainly formed by lowlands, are highly vulnerable to sea level rise (Morzadec-Kerfourn, 2002). At the scale of the Mediterranean Sea, level reconstructions show trends between +0.88 cm and +1 cm per decade for 1960–2000 and between +1.1 and +1.3 cm per decade for the more recent period of 1993–2000 (Calafat et al., 2012; Jordà and Gomis, 2013). These rates are slightly lower than the rate reported at the global scale (+1.8 cm per decade; Ulbrich et al., 2013; Bonaduce et al., 2016) or for the Mediterranean Basin based on altimetry (+2.1 cm per decade for 1992–2005; Criado-Aldeanueva et al., 2008). At the scale of the Gulf of Gabes, the sea level increase is much higher: +2.6 cm per decade for 1998–2009 in Sfax's harbor (Harzallah et al., 2010) based on the Tunisia National Marine data. The scenarios recently provided by the RCMs (e.g., Gualdi et al., 2013) show a rate of +3.1 cm per decade between 2021 and 2050, but this corresponds to the increase due to the steric effects.

6. Biogeochemical and planktonic features

6.1. Nutrients

Contrary to most parts of the eastern Mediterranean Sea (Thingstad et al., 2005; Krom et al., 2010), the Gulf of Gabes does not show a summer nutrient exhaustion, and some seasonal and coastal-to-offshore variations have been already observed (Drira et al., 2010). In coastal areas, the vertical distribution is almost homogeneous throughout the water column and shows a decreasing trend with depth (Drira et al., 2010; Hannachi et al., 2009; Ben Ltaief et al., 2015). The sources of nutrients have not yet been clearly identified since (i) the watershed inputs remain low, (ii) the large continental shelf prevents local nutrient accumulation in deep waters (Bel Hassen et al., 2008) and (iii) the AW flow does not bring significant amounts of nutrients (Bel Hassen et al., 2009a). The observed year-round availability of nutrients may be due to several other factors, such as efficient remineralization and/or nitrogen fixation due to the abundance of diazotrophs (Drira et al., 2016a; Hamza et al., 2016) or high depositions of phosphorus-enriched Saharan dusts (Taieb and Ben Brahim, 2014; Hamza et al., 2016). A recent study revealed that most atmospheric deposition occurred during the wet season, confirming that wet deposition is the main pathway of nutrient deposition in the Gulf (Khammeri et al., 2018). The inorganic nitrogen deposition is low compared to other Mediterranean regions, whereas phosphorus deposition is within the range of observations made in the eastern Mediterranean Basin. High organic nitrogen and phosphorus atmospheric deposition is also observed (Khammeri et al., 2018), corresponding to increases of heterotrophic prokaryote abundances and carbon biomass, suggesting a possible contribution of bacteria to the organic nutrient pool driven by atmospheric deposition (Khammeri et al., 2018).

Nitrate is the major form of dissolved inorganic nitrogen in winter mixing conditions, while the ammonium concentration strongly increases during the summer stratification period (Drira et al., 2008; Bel Hassen et al., 2009b). A putative nitrogen limitation has already been reported during the late-winter and late-spring (Geurmazi et al., 2010; Ben Ltaief et al., 2017). The silica limitation has been associated with the summer oligotrophic conditions highlighted by both low chlorophyll biomasses and high concentrations of particulate organic matter (Bel Hassen et al., 2010). Phosphorous concentrations are low in the open sea compared to the very high concentrations recorded in coastal areas (Drira et al., 2014a, b; Ben Salem et al., 2015). The lowest concentrations are recorded during stratified conditions corresponding to the summer season (July and September), while the maximum concentrations are recorded during the spring season (Bel Hassen et al., 2009b; Drira et al., 2016b).

6.2. Chlorophyll pigments

Along the coast of the Gulf, a high annual variability of chlorophyll is observed (Bel Hassen et al., 2009a). The highest concentrations are recorded close to the coast of Jerba and Kerkennah Islands with concentrations generally below $0.5 \mu\text{g l}^{-1}$, whereas the lowest concentrations about $0.03 \mu\text{g l}^{-1}$ in average are observed in the open sea (Drira et al., 2010). Concerning the vertical distribution of chlorophyll *a*, recent studies confirmed a weak gradient in well mixed coastal areas and in offshore thermally stratified waters (Bel Hassen et al., 2008; Drira et al., 2010).

The variation in phytoplankton pigments and associated community composition were also examined in relation to the water mass properties (Bel Hassen et al., 2008, 2009a; Drira et al. 2009, 2014b; Hannachi et al., 2009). The phytoplankton pigments are generally low year-round with spatial and temporal variations depending on water mass origins and mixing conditions (Bel Hassen et al., 2008, 2009a; Drira et al., 2009, 2014b; Hannachi et al., 2009). Chlorophytes contribute up to 40% of chlorophyll *a* during winter mixing (Bel Hassen et al., 2008,

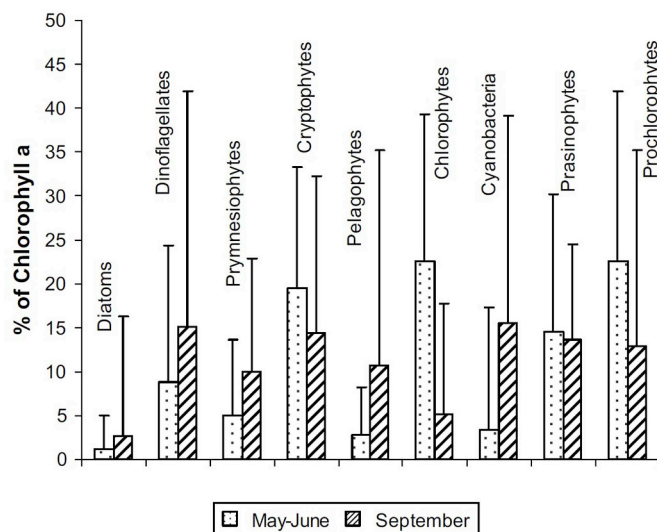


Fig. 6. Mean (plus the standard deviations) relative contributions (%) of phytoplankton classes to chlorophyll *a* biomass (expressed in percentage) calculated by CHEMTAX for May–June and September cruises (Bel Hassen et al., 2009b).

2009a), whereas Bacillariophytes (mainly diatoms) do not exceed 17% (Fig. 6). During the early stratification period, chlorophytes, cryptophytes and prochlorophytes contribute to 65% of total chlorophyll *a*. A significant change occurs during strong stratification, with a decrease in chlorophytes followed by prochlorophytes, while cyanobacteria increase their contribution to the autotrophic biomass (Bel Hassen et al., 2009b; Drira et al., 2016a). The contributions of the autotrophic prokaryotes (cyanobacteria and prochlorophytes) to total chlorophyll *a* are 26% and 28% on average (Bel Hassen et al., 2009b; Drira et al., 2016a), which is in the range of ratios reported for areas of the southern Mediterranean Sea (Barlow et al., 1997). The chlorophyll *a* biomass is dominated by picoplankton and nanoplankton that contribute up to 80% of total chlorophyll *a*. This situation is similar to that reported in the eastern Mediterranean Basin (Vidussi et al., 2001) and in the northwestern Basin (Marty et al., 2008): approximately 87% for these size groups.

The chlorophyll *a* concentrations observed in the Gulf of Gabes ($< 0.5 \mu\text{g l}^{-1}$) are in the lower range of values currently reported for the Mediterranean Sea, e.g., on the eastern Mediterranean Sea coasts ($0.40 \mu\text{g l}^{-1}$) (Berman et al., 1986; Gitelson et al., 1996; Yacobi et al., 1995), in the Alboran Sea (Corsini et al., 2002; D'Ortenzio et al. 2002) and the Gulf of Lions ($0.06\text{--}1.7 \mu\text{g l}^{-1}$) (Bosc et al., 2004; Harmelin-Vivien et al., 2008), in the Levantine Basin of the eastern Mediterranean Sea ($< 0.2 \mu\text{g l}^{-1}$) (Bosc et al., 2004; Ignatiades et al., 2009; Berman-Frank and Rahav, 2012), and in the northwestern coastal zone ($0.50 \mu\text{g l}^{-1}$) (Thingstad et al., 1998; D'Ortenzio et al. 2002). These rather low concentrations highlight the oligotrophic character of the Gulf of Gabes (Bel Hassen et al., 2009a, b; Drira et al., 2010; Ben Ltaief et al., 2015). The maximum concentrations are measured during the late spring at the beginning of the stratification period, while the lowest concentrations are found during the summer when the stratification is the strongest (Bel Hassen et al., 2008, 2009b; Drira et al., 2009; Ben Ltaief et al., 2017).

6.3. Phytoplankton

In the Gulf of Gabes, the coastal area shows signs of eutrophication (Ayari et al., 2008; Katlane et al., 2013). Five main classes of phytoplankton are reported in the open sea area, including dinoflagellates (25%), diatoms (16%), cyanobacteria (17%), dictyochophytes (41%), and euglenophytes (1%) (Drira et al., 2009, 2010; Hannachi et al.,

2011). In the coastal area, the phytoplankton community includes Dinophyceae (108 taxa), Bacillariophyceae (58 taxa), Cyanobacteria (5 taxa), and other groups, such as Dictyochophyceae, Euglenophyceae, Coccolithophoridae, and Chlorophyceae represented by only one species (Feki-Sahnoun et al. 2014, 2018a). Among the recorded species, five were declared as toxic: *Alexandrium minutum*, *Coolia monotis*, *Karenia selliformis*, *Protoceratium reticulatum* (Feki-Sahnoun et al. 2017, 2018b) and *Ostreopsis cf. ovata* (Abdennadher et al., 2016). The cyanobacteria grow throughout the water column with a high density recorded at the thermocline and are associated with the presence of *Trichodesmium erythraeum* and *Pseudanabaena galeata*, which contribute to 41 and 50%, respectively, of the total cyanobacteria abundance (Drira et al., 2009, 2010; 2016a). The abundance of cyanobacteria was found to be positively correlated with inorganic nitrogen (Drira et al., 2008). Blooms of *Trichodesmium erythraeum* were first detected in July 1988 (Hamza and Ben Maiz, 1990), and since this date, a survey program has been set up to report any water discoloration linked to this species. Hamza et al. (2016) analyzed this long-term series, showing that these blooms occurred on average 2.11 times per year over the period of 1988–2013 and that their development is mainly linked to Saharan dust deposition events prior to the blooms.

The ultraphytoplankton (cells up to 10 µm), studied using flow cytometry, were resolved into five cell groups, *Prochlorococcus*, *Synechococcus*, picoeukaryotes, nanoeukaryotes and a group of unidentified cells characterized by a low fluorescence signal (Hamdi et al., 2015). The low ultraphytoplankton abundance was explained by the heterotrophic nanoflagellates feeding on picoplankton, suggesting a tight top-down control of the picoplankton community (Hamdi et al., 2015). More recently, the distribution and phylogenetic diversity of picoeukaryote assemblages was studied by Bellaaj Zouari et al. (2018) using biomolecular techniques. They showed the strong impact of both physical and chemical factors on this community and the clear association of some species with water mass properties (e.g., *Acantharia* and *Polycystinea* with Levantine water).

6.4. Zooplankton

The high protozooplankton abundance reported in the Gulf is characterized by an important ciliate community with 61 taxa identified along the coast and in the open sea (Hannachi et al., 2009) and 56 species with important populations of tintinnids identified along the coastline (Kchaou et al., 2009). Abundances of hetero-nanoflagellates were also recently reported to be a choanoflagellate (Hamdi et al., 2015) and low fluorescence nanoflagellates (Rekik et al., 2014; Hamdi et al., 2015) based on flow cytometry analyses.

Within metazooplankton, copepods represented the dominant group (69–83% of total abundance), including fourteen (14) families, with *Acartiidae* (mainly *Acartia clausi*) and *Oithonidae* (mainly *Oithona nana*) being dominant in summer along the coast and near the 50 m depth (Drira et al., 2010). Small planktonic copepods, including pollution-tolerant species (e.g., *Oithona nana*, *Paracalanus parvus*, *Harpacticus littoralis* and *Tisbe battagliai*), proliferate in coastal areas characterized by high anthropogenic inputs (Drira et al., 2017). The seasonal zooplankton distribution is characterized by maximum abundance during September under strong summer stratification (Drira et al., 2010). The reproductive strategy (dominance of egg-carrying species allowing preservation of egg viability after predation; see Saint-Jean and Pagano, 1995) and eclecticism in trophic behavior may explain the summer dominance of small copepods (Ben Ltaief et al., 2015). Drira et al. (2010) showed that the spatial distribution of a dominant species was dependent on salinity, suggesting that these species probably escaped the high coastal salinity (38.00) in order to exploit a wide range of food resources, including phytoplankton or animal prey. More generally, Ben Ltaief et al. (2017) suggested that temperature-salinity conditions and the intensity of thermal stratification should explain the space and time successions of zooplankton communities and of key species. Annelid

larvae and coastal copepods (*Euterpina acutifrons*, *Oithona nana*, *Acartia tonsa*, etc.) are associated with high salinity shallow mixed and microplankton-rich coastal water, whereas Euphausiids, Amphipods, doliolids, and oceanic copepods (*Anomelocera patersoni*, *Sapphirina darwinii*, *Candacia bipinnata*, etc.) are associated with highly stratified and microplankton-poor waters.

7. Fisheries and resources

The Gulf of Gabes is one of the most important fisheries in Tunisia. It accounts for 39.3% of national production and remains a crucial nursery ecosystem for the Mediterranean.

The Gulf encompasses two important coastal ecosystems that are crucial from a biodiversity standpoint, serving as a nursery for a number of fish species: the Boughrara and El Bibane Lagoons. Boughrara is the largest lagoon in Tunisia, covering approximately 50000 ha and harboring 72 species of fauna (DGPA, 2015), including some 30 fish species. Seventy-eight percent of Tunisia's lagoon fishermen are based here. El Bibane Lagoon, located near the border with Libya, covers 30000 ha (Medhioub and Perthuisot, 1977) and houses approximately 60 fish species distributed among 31 families, with the dominance of the Sparidae family (Djabou, 2006). In 2015, 67 fishing net licenses were issued in the lagoon (DGPA, 2015).

The number of animal species reported in the Gulf of Gabes is 667 (Bradai, 2010), distributed mainly between pisces (227 species), molluscs (171 species), sponges (108 species). The Gulf of Gabes houses 255 of the 348 fish species of Tunisia, with 49 species recorded only in this Gulf (Bradai, 2010). Its biodiversity also consists of 46 species of echinoderms, 6 species of cnidarians, 57 species of bryozoa, 11 species of annelids, 24 species of crustaceans, 17 species of ascidians, 108 species of sponges, and 171 species of molluscs (Afli et al., 2005). Most of the benthic communities in the Mediterranean Sea are present in the Gulf of Gabes, with a benthic fauna characterized by the dominance of invertebrates, such as the bivalves *Aloidis gibba*, *Ruditapes decussatus* and *Pinctada radiata*, the sea urchin *Paracentrotus lividus* (echinoderm) and the sponges *Spongia officinalis* and *Hippospongia communis* (Bradai, 2000).

A defining characteristic of the Gulf of Gabes is the seagrass meadows of *Posidonia oceanica*, which is the most important across the Mediterranean and one of the largest in the world (Batisse and Jeudy de Grissac, 1998). The meadows are perfect spawning grounds for all marine organisms and a nursery for juvenile fish (Hattour et al., 1995).

The Gulf of Gabes is likely one of the most important areas for marine turtles in the entire Mediterranean (Laurent et al., 1990; Laurent and Lescure, 1994). Three marine turtle species are observed in the Gulf: the rare green turtle *Chelonia mydas*, the leatherback turtle *Dermochelys coriacea*, which is regularly observed, and the loggerhead *Caretta caretta*, which is the most common. In the southeastern coasts, the cetaceans *Balaenoptera physalus*, *Stenella caeruleo-alba*, *Grampus griseus* (Risso's dolphin) and *Tursiops truncatus* are mentioned (Karaa et al., 2012).

This high biodiversity is threatened by unsustainable fishing, pollution, and exotic species. First, fishing and, particularly, bottom trawling cause a progressive but systematic destruction of *Posidonia* meadows (Ben Abdallah-Ben Hadj Hamida, 2012). Second, the Gulf of Gabes is facing severe pollution problems, especially from the phosphate industry (Béjaoui et al., 2004). Large areas of *Posidonia* have disappeared, *Cymodocea nodosa* is scarce and *Caulerpa prolifera* has almost completely disappeared. Third, the Gulf of Gabes is being invaded by alien species. Several species, mainly of Indo-Pacific origin, have emerged, such as the bivalve *Pinctada radiata* currently abundant in the Gulf (Bradai, 2000); the shrimps *Metapenaeus monoceros* and *Trachypenaeus curvirostris* that strongly compete with the native shrimps *Penaeus kerathurus* (Missaoui et al., 1995), *Metapenaeus stebbingsi* (Ben Hadj Hamida-Ben Abdallah et al., 2006) and *Rimopenaeus similis* (Ben Hadj Hamida-Ben Abdallah et al., 2009); the green alga *Caulerpa racemosa*

(Ben Alaya, 1972); the marine phanerogam *Halophila stipulacea* (Missaoui et al., 2003); the brachyura *Eucreta crenata* (Zaouali, 1992); and the macroura *Portunus segnis* (Rabaoui et al., 2015), which have become very abundant. There are also approximately 20 exotic fish species, including *Siganus luridus* (Ktari and Ktari, 1974), *Siganus rivulatus* (Ktari and Ktari, 1974), *Stephanolepis diaspros* (Chakroun, 1966), *Parexocoetus mento* (Ben Souissi et al., 2004; Bradai et al., 2004), *Pempheris vanicolensis* (Bradai et al., 2004), *Sphyræna chrysotaenia* (Bradai et al., 2002), *Fistularia commersonii* (Ben Souissi et al., 2004), *Hemiramphus far* (Ben Souissi et al., 2005b), *Saurida undosquamis* (Ben Souissi et al., 2005b), *Atherinomorus lacunosus* (Ben Souissi et al., 2006), *Upeneus pori* (Ben Souissi et al., 2005a), *Lagocephalus scleratus* (Jribi and Bradai, 2012), and *Rhinobatos halavi* (Ben Souissi et al., 2007), originated from the Indo-Pacific, as well as *Seriola fasciata* (Bradai, 2000), *Pisodonophis semicinctus* (Bradai et al., 2004), *Sphaeroides pachygaster* (Bradai et al., 1993), *Solea sinegalensis* (Zouari-Ktari, 2008), *Carcharhinus falciformis* (Bradai et al., 2002), *Cheilopogon furcatus* (Ben Souissi et al., 2005c), and *Lagocephalus lagocephalus* (Bradai et al., 2004) from the Atlantic.

In 2015, the area of the Gulf of Gabes contained approximately 53% of the Tunisian fishing fleet and landed approximately 33% of the national fish production. The number of fishing boats recorded in this area is approximately 6800, constituted mainly of coastal boats, which represent 94% of the fleet (DGPA, 2015). The trawler fleet is made up of 270 vessels targeting mainly shrimp, cephalopods (mostly *Sepia officinalis*), and benthic fish. Approximately 98% of the trawler fleet operating in the Gulf of Gabes is connected to the port of Sfax (DGPA, 2015). These trawlers have a three-month closed season (trawling is forbidden from July to September), which corresponds to a biological resting period. The fishing sector employs an average of 31,428 sailors, of whom 60% are employed in coastal fisheries and 12% in trawlers. In 2015, total landings in the Gulf of Gabes were approximately 43,000 tons, representing approximately 33% of the Tunisian total landings, and were provided mainly by the coastal fishing boats, purse seine boats, and trawlers, which contributed 41%, 30% and 24%, respectively (Fig. 7). The contributions of these fishing gears to the Tunisian total landings were approximately 55%, 24% and 38%, respectively.

8. Conclusions

Based on previous studies, this review describes the main characteristics of the Gulf of Gabes and highlights the different specificities of this ecosystem in order to understand its functioning. It could be

interpreted as a reference synthesis and could be used as a support for further investigations.

Several factors interact together to influence the functioning of the Gulf of Gabes ecosystem. The climate, which is pre-Saharan and arid to semiarid, strongly influences the ecosystem functioning, mainly through impacts on physical and biogeochemical features.

The water circulation is primarily influenced by the topography, bottom texture, and meteorological conditions. It is recognized that the tide is particularly strong for the Mediterranean Basin (due to the particular topography characterized by a shallow and flat bottom) and is the most important driver for water circulation in the Gulf.

Compared to other Mediterranean systems, the water temperature and salinity in the Gulf are characterized by some important seasonal variations with relatively high annual means, and the vertical stratification varies with depth and season.

Despite its oligotrophic characteristics, the Gulf of Gabes maintains high productivity. Several studies indicated that Saharan dust enrichment could be considered the most efficient source of nutrients in the Gulf of Gabes. The phytoplankton biomass is dominated by pico- and nanoplanktonic organisms, whereas heterotrophic flagellates and ciliates are important components of the protozooplankton. A high protozoa abundance was reported in the Gulf, as they are the main grazers of the pico- and nanophytoplankton size classes; the microbial food web is likely to be the prevalent trophic pathway in the Gulf of Gabes. The metazooplankton, which constitutes an important link between lower and higher trophic levels, is dominated by small copepods and displays high abundance and biomass compared to other Mediterranean coastal sites.

The Gulf of Gabes, a Mediterranean zone with important biological resources and rich coastal, marine, and freshwater ecosystems is particularly exposed to anthropogenic factors altering its natural features. The stocks are already overfished, and biodiversity is declining, paralleling reductions in submerged aquatic vegetation. Invasive species represent an added pressure on fisheries.

The direct impacts of climate change on fisheries are not well understood. However, it is clear that the Gulf's ecosystems, which act as natural nurseries, may affect marine biodiversity, leading to a decline in traditional fishery species along coastal areas.

Based on a cumulative index of warming, overfishing and pollution effects, the Gulf of Gabes was recently identified as a "Hot Spot" of anthropogenic pressures (Reygondeau et al., 2014) and thus future research should address these issues at regional, Mediterranean and global scales.

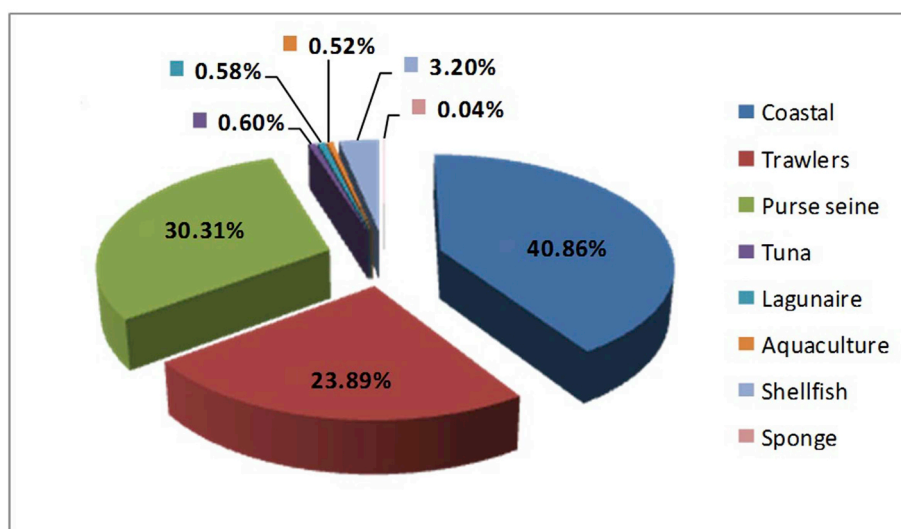


Fig. 7. Distribution of the production by fishing type in the Gulf of Gabes during 2015.

Acknowledgment

This review was carried out in part within the framework of the research projects of the Institut National des Sciences et Technologies de la Mer (INSTM), the INCOMMET project (FP7-INCO-2011-6, contract 295009) and the BISTROMED project (funded by MISTRALS-ENVIMED Program) for the period 2012–2014. We thank the IRD for supporting the Elsevier Language Editing Services.

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