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CLIMATE CHANGE ON THE WATER COLUMN IN CORSICA

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Abstract

Situated in a hotspot regarding certain climate change projections, the island of Corsica offers great potential to study the impact of climate change (CC) on the water column. The coastal water column is crucial to the marine ecosystem functioning as it supports many physico-chemical and biological processes, including the planktonic dynamics. From an assessment of multi-sourced data acquired in coastal marine environments around Corsica, the climatic causes of water column disturbances and their expected consequences were discussed, this lead to a state of knowledge regarding the evolution of the planktonic ecosystem in relation to the effects of CC (meteorology, winds, temperature, etc.) on the water column (thermocline, pH, sea level, etc.). While the impacts linked to water acidification are not yet perceived, the most impacting climate change-induced alteration observed in the water column dynamics of Corsica are the modification of the winter conditions. Indeed, winters are characterized by increasing temperatures and weakening wind intensity leading to a decrease of the phytoplankton spring bloom. Such situation is ultimately very likely to impact the associated food chain and biogeological fluxes including the carbon pump.

Introduction

The Mediterranean region has been referenced as one of the most responsive regions to climate change (CC) (IPCC, 2014) and was defined as a primary « Hot-spot » (Giorgi, 2006) regarding future CC projections that threaten its ecological richness (Coll et al., 2010). Islands are at the forefront of CC and of the challenges the ocean is facing (Ducrocq, 2017).

Corsica is in the front line of CC since it is located in a sector where, throughout the Mediterranean, most pronounced forecasts were predicted regarding the evolution of air temperature, evapotranspiration, precipitation and soil moisture. Furthermore, with large natural areas and reduced levels of anthropogenic pressure, the island of Corsica is an ideal candidate to understand and to study the effects of CC.

In Oceanography, the marine coastal zone is the interface between land and ocean, it shelters high productive specific ecosystems and it is an area of nutrients and energy flows. It is shallow (0 to 200 meter depth) and influenced by terrestrial influx (natural or anthropogenic).

Marine coastal zones can be strongly affected by climatic events due to their higher reactivity and lower inertia compared to open-ocean waters, making them highly sensitive to environmental forcing fluctuations (Rabalais et al., 2009). Moreover, sheltered ecosystems are subject to the pressures of CC (rising waters, increased storms, changing precipitations, currents, water temperature, acidification, etc.) but also to the pressures related to continental human activity (pollution, exploitation of resources, coastal development, etc.).

The coastal water column supports many physico-chemical and biological processes. It is the cradle of the phytoplanktonic production which generates almost half of global primary production (Field et al., 1998) and is at the origin or supports most of the pelagic food chains but also benthic environments.

This phytoplanktonic production is under the control of physical and chemical limiting factors such as light, temperature and nutrients (nitrogen, phosphorus, silica, iron, etc.) whose availability is largely related to the degree of mixing, the exchanges with the continental environment, the rain, the winds, the thermocline, etc. The blooms are also under influence of biotic factors such as predator-prey interactions (Behrenfeld et al., 2014).

The phytoplanktonic production, resulting from photosynthesis, is significantly converted by the primary (zooplankton) and secondary (mollusks, fish, turtles, cetaceans, etc.) consumers of the pelagic and benthic environments. So phytoplankton is the main actor of the ocean biological pump: through photosynthesis, which allows its growth and development, it consumes large quantities of CO_2 and carbon is thus fixed in organisms and can be exported through the food chains (fecal pellets, dead organisms, etc.) to deeper waters. In addition, most of the benthic organisms that make up the richness of coastal environments have a larval planktonic phase. Benthic organisms are therefore, for a fundamental phase of their life cycle, an integral part of the planktonic ecosystem. The effectiveness of the renewal of benthic populations, through recruitment, is therefore largely dependent on planktonic larval survival and therefore on the state of this ecosystem.

Zooplankton also plays an important role in shaping the extent and pace of climate change. Zooplankton plays a role in the biological pump because much of the CO_2 that is fixed by phytoplankton, then eaten by zooplankton, eventually sinks to the seabed. Much of this carbon can be locked up in sediments and removed from the carbon cycle. Zooplankton also facilitate this process by moving large quantities of carbon from the ocean's surface to deeper layers when they dive each day into the ocean depths to avoid near-surface predatory fish (Richardson, 2008).

In fact, some evidence suggests that plankton are sensitive indicators of CC for example, unlike other marine groups, such as fish and many intertidal organisms, plankton are generally not commercially exploited, so studies of long-term trends in response to environmental change are generally not confounded with trends in exploitation.

The exploration and awareness of the importance of the marine coastal environment is recent and few physico-chemical parameters of the water column measured together with studies on planktonic ecosystems, have been assessed, *in situ*, continuously, over very long periods of time. Taking inspiration from works accomplished by the International Union for Conservation of Nature (IUCN) with support from the French Agency for Biodiversity (AFB), this paper makes, from an assessment of the data acquired in coastal marine environments around Corsica, a description of the overall functioning of the planktonic ecosystem. On the basis of these measurements, it also presents the state of knowledge on the long-term evolution of this ecosystem in relation to the effects of CC (meteorology, winds, temperature, etc.) on the water column (thermocline, pH, sea level, etc.).

Material and methods

The planktonic ecosystem has been studied by measurements focus on biomass, abundance and on the composition of phytoplankton and zooplankton, at the surface and on vertical and/or horizontal profiles, since the 1970s, on the Northwestern coast, from the marine station STARESO into the Bay of Calvi and along a transect from Calvi in the direction of Nice across the Liguro-Provencal Front (Collignon, 2014; Dauby, 1980, 1985; Goffart et al., 2015, etc.). Since 2002, phyto and zooplankton have also been monitored on a weekly basis in the Bay of Calvi and the near offshore (Michel et al., 2012; Richir et al., 2014; Fontaine et al., 2016; Leduc et al., 2017; etc.).

Furthermore, since 2010, the eastern shore of the island has also been the subject of studies investigating phytoplankton, zooplankton and their modeling (Garrido et al., 2014; Kroek et al., 2015; etc.).

Since the 1970s, physico-chemical measurements are carried out in the water column (salinity, temperature, currents, etc.) in the Bay of Calvi and the near offshore. Two automatic meteorological stations installed near STARESO, register high frequency measurements of wind (speed, direction), temperature, humidity, hygrometry, rainfall and solar radiation (Binard et al., 2008; Binard, 2017; Coste et al., 1972) (http://www.gitan.ulg.ac.be/cms/index.php?page=donnees-de-stareso). A campaign to measure water body acidity and associated effects (Gazeau et al., 2016) has been launched.

Very recently, salinity and temperature campaigns on vertical profiles in front of Bastia were carried out as part of the development of the Stella Mare platform.

Sea level in Corsica was already measured back then around the 1850s in several ports (http://refmar.shom.fr/en/mesures-maregraphiques/french-historic-tide-gauges-data-in-non-digital-form#Ajaccio). Yet, these recordings only lasted one or two years. While the longest and most continuous sea level time series in Corsica was registered in Ajaccio (1980-2016), only a limited part is complete (2002-2016) and thus statistically usable (see: https://www.sonel.org/?page=maregraphe&idStation=1719). It has also been monitored in Calvi Bay (STARESO) since 2005 (Binard, 2017).

For the north-western Mediterranean, to our knowledge, the exploitable datasets of seawater temperature are (1) for surface waters, those of Marseille (France), beginning in 1895, those of STARESO since 1985 and of Villefranche since 1974 and (2) for in-depth data: those from the Estartit (Spain) and the T-Mednet.org networks (http://www.t-mednet.org) initiated in 1999, and MEDCHANGE project, both including Corsica.

Finally, we interface the analyses carried out on the planktonic ecosystem with physico-chemical measurements carried out in the water column (with more than 8 millions of data in the Bay of Calvi and the near offshore (Binard, 2017)).

Results and discussion

Current state of data and knowledge

Sea Surface water temperature: The exploitable series all confirm the same trend and the emergence of a currently occurring net warming of surface waters (Binard et al., 2008; Romano and Lugrezi, 2007; Romano et al., 2010) estimated to + 0.668°C over the century, and + 0.768°C when only the warmest months (June to September) are taken into account (Romano and Lugrezi, 2007; Romano et al., 2010) (weather-france.fr, infoclimat.fr). In the Bay of Calvi, while 1981-2016 was characterized by an annual mean warming trend of 0.014°C/year, this trend has strengthened during the last decade (2006-2016) rising up to 0.066°C/year (Fontaine et al., 2016, Champenois and Borges, 2018). Regarding seasonal average seawater temperature, it showed a significant increase only for the winter season (January-March) and only since 2010 (2010-2016, 0.30 °/year, $r^2 = 0.82$, $p = 0.005$) (Fulgrabe, in prep).

Sea level: The exploitable series all confirm the same trend. The compilation of data from the "Global Sea-Level Observatory System" of 18 instruments placed *in situ* around Corsica shows an average increase of 2.35/year. For the period (1993-2017) and in satellite data, it is around 3.30 mm/year (Nerem et al., 2010). The increases of the sea level have implications for marine biodiversity. In Corsica, the climb is corroborated by the observations of *Lithophyllum byssoides* in the reserve of Scandola (Verlaque, 2010). This marine species colonizes the surf zone and is very sensitive to water level variations. Observations on the STARESO infrastructure show a rise in the water level, with seawater that currently covers practically permanently the loading dock of the station built in 1967.

Acidification: Gazeau et al. (2016) tested in mesocosms, the response of the planktonic ecosystem to increasing acidification. The results obtained were more mixed than expected but show that acidification is likely to lead to changes in planktonic populations, food chains and therefore associated material transfers.

Winds: Analysis of the long-term wind regime in Calvi Bay is ongoing, but preliminary results indicate that there are anomalies with a decline of winter wind intensity, particularly in the Northeast sector (Goffart et al., 2015; Fontaine et al., 2016).

A slight tendency towards the decrease of the annual precipitations was observed over the period 1959-2009: ClimatHD de Météo-France (Fullgrabe et al., 2019). In Calvi Bay, the cumulated precipitation from September to March over the 2006–2016 period, correspond to 82.0% of the annual total. The driest period was from June to August, over the 2006–2016 period, corresponding to 6.3% (Champenois and Borges, 2019).

The analyze of the seasonal variations of the physico-chemical and biological parameters show that the usual dynamics of Corsican coastal water masses are naturally governed by the alternation of the windy and cold winter season and the less turbulent and hot summer season. In late spring and summer, surface water bodies warm up and the water column stratifies with warm surface water (about 24°C) and deeper colder water (about 14°C). In winter, the agitation and cooling of surface water mixes and homogenizes the water column and allows deeper and more nutrient-rich water to rise to the surface. In early spring, if these nutrients are available in the area where light enters, phytoplankton blooms will occur. Thus, most of the annual surface phytoplankton production occurs over a relatively short period between February and March and is immediately followed by a peak in zooplankton development. The rest of the year, the system is oligotrophic, not very productive and the planktonic biodiversity is adapted to this situation. The study of phytoplankton biomass dynamics since the 1970s in Calvi Bay shows considerable interannual variations with years with a marked spring bloom and others with a reduced or sometimes non-existent bloom (Goffart et al., 2015). These phytoplankton production anomalies are often followed by abundance and zooplankton composition anomalies (Fullgrabe et al., 2016). Indeed, winters characterized by warmer than average water temperatures were systematically followed by weak or no spring mesozooplankton production (Fullgrabe et al., in prep).

On the Eastern coast, recent work (Garrido et al., 2014) shows that the dynamics of the planktonic ecosystem follows the rhythm of the seasons with a spring bloom under climate forcing. However, blooms may display a different configuration depending on the land inflows from rivers and lagoons, with, for instance, significant phytoplankton production outside the spring periods linked to the greater proportion of *Dinophyceae* in brackish environments.

Climatic causes of disturbance of the water column

Local causes

Research on CC impacts should not be performed in isolation but must be linked with research into impacts of other anthropogenic stressors (e.g. fishing, eutrophication, pollution, introduced species, etc.). All these anthropogenic stresses decrease the resilience of marine ecosystems to CC.

Corsican coastal water masses are naturally oligotrophic, particularly in summer, because of the small contributions of the terrestrial environment (no large rivers, limited rainfall of the Mediterranean climate, island territory far from the continental masses, etc.) and the absence of a large continental shelf that could limit the export of nutrients to deep water. Anthropogenic discharges to coastal environments, including nitrogen and phosphorus, are likely to alter this oligotrophy to which native planktonic species are adapted.

On the West coast, the STARECAPMED program (STAtion of Reference and rEsearch on Change of local and global Anthropogenic Pressures on Mediterranean Ecosystems Drifts), which follows the classical anthropogenic pressures (Fish farm, anchoring, sewage,…) of the Corsican coastline in Calvi Bay, tends to show that the impacts remain low and very localized around the discharge points. This is due in particular to the low population density, the short tourist season, the absence of industrialization and intensive agriculture (Richir et al., 2014).

In Corsica, there are no strong phytoplankton developments linked to anthropogenic discharges and there is no red tide bloom (potentially toxic). There are simply some changes in the summer phytoplankton composition near certain pressures such as aquaculture or mooring areas that do not seem to lead to serious consequences (Goffart et al., 2015; Richir et al., 2014).

Climate causes

The normal temporal dynamics of Corsican coastal waters are naturally punctuated by the alternation of the winter season, windy and cold and the summer season, less agitated and warm. In winter, the agitation and cooling of surface water mixes and homogenizes the water column, allowing the return to the surface of deeper and more nutrient-rich waters. In early spring, these nutrients are available in the area where light enters and the phytoplankton blooms can occur, eventually followed by zooplankton. In late spring and summer, surface water bodies warm up and the water column laminates warm surface waters from colder deeper waters. All surface water nutrients have been widely consumed and the water column can only sustain very low phytoplankton production.

On the West coast, the large gulfs open onto underwater canyons that extend deep into the narrow continental shelf to reach depths of more than 1,000 m. Northeasterly winds, naturally frequent in winters but rare in summer, would generate a transport of surface waters to the sea compensated by deep and rich upwelling along these canyons to the bottom of the gulfs. Wind regime (intensity, frequency, direction) and air and water temperatures are determining climatic factors in the mixing of oligotrophic surface water with deeper and more nutrient-rich water bodies. Thus, the state of the Corsican coastal planktonic ecosystem is extremely dependent on climatic forcings. Work in Calvi Bay shows that the spring phytoplankton bloom is highly dependent on the climatic situation that prevailed in the previous fall and winter (Goffart et al., 2015; Gazeau et al., 2016). No significant correlation was found between cumulated precipitation and the intensity of the spring phytoplankton bloom indicated by Chl *a* concentration (Champenois and Borges, 2019).

On the East coast, the presence of rivers and lagoons in the watersheds influences the phytoplankton community. A change in coastal rainfall regime and watersheds could affect the planktonic ecosystem of the eastern coast during bloom periods (Garrido et al., 2014).

The expected consequences of climate change on the water column

Any CC that modifies the wind regime and seawater temperatures is likely to profoundly alter the dynamics of coastal water masses and thus the state of the planktonic ecosystem. If current winter climatic trends are confirmed and strengthened (increase in winter temperature, decrease in winter wind regime), spring planktonic blooms are expected to decrease with significant impacts on coastal ecosystems. Indeed, most benthic species with larval planktonic phase synchronize their reproduction with spring in order to benefit from the "fodder" produced by the bloom. CC can therefore potentially degrade the state of the planktonic ecosystem and hinder the reproduction of benthic and pelagic species.

From an economic point of view, this could, for example, have consequences on fisheries resources. The decrease in the intensity of the winter winds and in particular the northeasterly winds could significantly affect the upwelling of the nutrient-rich deep waters, spring blooms that are crucial for the reproduction of native species. This differential response of phytoplankton and zooplankton may lead to a mismatch between successive trophic levels and a change in the synchrony between primary, secondary, and tertiary production (Winder and Sommer, 2012). Asynchronization between peak food availability and requirements could result in predator–prey mismatches that can affect energy transfer to higher trophic levels (e.g., such as those occupied by commercial fish species (Cushing, 1974). Furthermore, successful fish recruitment is highly dependent on synchronization with pulsed planktonic production. An increase in surface temperatures in winter with the maintenance, even very partial, of stratification, would have a negative influence (stop of nutrient supply) going in the same direction.

If climatic conditions (mainly wind regimes) seem to favor summer planktonic production, we can expect exogenous and/or native but invasive species, which have summer reproductive capacities, to appear and ultimately replace the species normally present in that season. The increasing occurrence of species of warm waters affinity may, for some planktivorous species, ultimately affect the planktonic ecosystem. An increase in summer wind intensity, particularly from the northeast, could at least partially and punctually break down the thermal stratification of coastal water bodies. This could change the strictly oligotrophic nature of summer surface waters and allow for the installation of planktonic species or non-native larvae that would not have survived without these changes.

The increase in CO_2 concentration in the atmosphere induces acidification of water in every ocean. It is recognized that this acidification can induce conditions under which benthic or planktonic organisms, producers of calcified structures (shells, skeletons, etc.) can be affected in their development.

Conclusion

Any CC that changes the wind regime and atmospheric temperatures is likely to profoundly alter the dynamics of coastal water masses and thus the state of the planktonic ecosystem. In Corsica, the decrease in winter wind intensity, and in particular northeasterly winds, significantly affect the upwelling of nutrient-rich deep waters that allow phytoplankton spring production blooms that are very important for native breeding. There are no strong phytoplankton developments linked to anthropogenic discharges and there is no red tide bloom (potentially toxic). There are simply some mild changes in phytoplankton composition near certain pressures such as aquaculture or mooring areas. Focusing on the water column, our team produced a document analyzing current available information on the temporal evolution of physical and biological characterization of the marine coastal water masses. In view of the results presented, is required to apply integrated research that assesses management options for addressing synergistic effects of climate change, together with other human stressors.

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Key words

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