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Carbon dynamics modelization and biological community sensitivity to temperature in an oligotrophic freshwater Antarctic lake

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ABSTRACT

Lake Limnopolar, located in one of the areas on Earth experiencing the strongest local warming, has been studied as a maritime Antarctic lake model by the Limnopolar Research Team during the last decade. Data collected during this period revealed the existence of an important meteorological interannual variability in the area of Byers Peninsula. With the aim of increasing the knowledge of this ecosystem and its sensibility to climate change as a model ecosystem, as well as to calibrate the extent of the interannual variability, a carbon flow model was developed partly describing its microbial food web. This preliminary model aims to describe part of the carbon dynamics, especially for bacterioplankton and associated factors, in this maritime Antarctic lake highly affected by temperature increase linked to regional warming. To describe the system, the effects of the variation of different forcing functions influencing the carbon flow within the microbial community, like temperature and irradiance, were studied. Among the studied factors, the sensitivity analysis showed the strongest response of the model to temperature changes. Consumption rates of organic matter by bacterioplankton, and therefore its abundance in lake water, greatly increased when temperature rise was higher. However, the highly variable meteorology over years in such an extreme environment causes that our model may fit well for some years, but fails to describe the system in years with contrasting meteorological conditions. Despite this assumption, the model reveals that maritime Antarctic lakes are very sensitive to temperature changes. This response can be monitored using eco-exergy, which allows a description of the system complexity. Due to this temperature sensitivity, the warming occurring in this area would lead to significant changes in the carbon flow, and consequently on the abundance of plankton in these systems.

1. Introduction

During the last decades, empirical evidences have led the scientific community to the search for clues and indicators of the nature of climate change (IPCC, 2007). Maritime Antarctica, which includes the west Antarctic Peninsula and surrounding islands, is probably one of the most affected areas by the rising temperatures (Clarke et al., 2007; Russell and McGregor, 2010). The climate in maritime Antarctica is less extreme than in continental Antarctica, with mean temperatures between 1 and 3 °C during summer (Toro et al., 2007; Bañón et al., 2013). The Maritime Antarctica is rich in water bodies that become ice-free during the Austral summer. Among them some representative lakes are good candidates as indicators of global change, particularly those located in Antarctic Special Protected Areas (ASPA) with almost no direct impact caused by human interference. Some of these protected areas, such as Byers Peninsula, located in Livingston Island (South Shetland Islands), have been the subject of extensive limnological studies since 2001 by the Limnopolar Research Team (Quesada et al., 2013). These studies have shown most ecological features and dynamics of the lakes therein, especially Lake Limnopolar that was selected as a model lake by our research team (e.g. Camacho, 2006; Fernández-Valiente et al., 2007; Toro et al., 2007; Quesada et al., 2009; Rochera et al., 2010, 2013; Villaescusa et al., 2010, 2013a, 2013b; Velázquez et al., 2011, 2013; Benayas et al., 2013). Antarctic freshwater lakes are characterized by the presence of short food webs dominated

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by microorganisms (Frenot et al., 2005). However, lakes situated in maritime Antarctica and nearby regions present slightly more complex food webs compared to those situated in continental Antarctica (Ellis-Evans, 1996). In this sense, they are somewhat similar to other lakes located at high mountain sites of lower latitudes (Carrillo et al., 2006; Catalan et al., 2006), though lacking fish. In spite of the existence of enough information about the ecology of Antarctic lakes, attempts to model aspects of the ecological functioning of these lakes have not been accomplished so far.

Many lake models have been developed during the last forty years, but as far as we know our study presents the first preliminary model of the biological functioning of an Antarctic lake. Based upon a few years' observations and the analysis of samples collected during the Antarctic summer, it has been possible to develop a model covering the carbon flow and the microbial components of the biological community of an Antarctic lake. However, the modeling process revealed some problems related to the system high sensitivity to within years differences in environmental conditions that impede the generalization of the model without taking into account of these conditions. The presumably strong effect of the rising temperatures and the simplicity of Antarctic aquatic systems (Quayle et al., 2002) when compared with those situated in temperate climates, make Antarctic lakes excellent candidates for the development of ecological models mainly based on temperature (Reid and Crout, 2008). Thus, the use of models can help us to forecast changes in the structure and dynamics of the biological communities of Antarctic lakes in response to the local warming affecting maritime Antarctica and nearby areas. Specifically, the development of a model based on temperature and carbon dynamics in the well-studied Lake Limnopolar, let us the opportunity to describe in more detail the response of the biological community of this type of systems to changes in temperature.

The calculation of system eco-exergy in Antarctic lakes during the austral summer can be used as a useful tool to describe the system complexity and the working capacity of the microbial community and its response against temperature changes. Eco-exergy, described in Jørgensen and Svirezhev (2004), developed by Jørgensen et al. (2010) and revised by Silow and Mokry (2010), is defined as the distance between the present system state and its state if it was in thermodynamic equilibrium with the environment, measured in energy units. Thus, eco-exergy provides a numeric value that measures the changes in complexity of the planktonic community as a response to temperature change.

Taking into account the above mentioned statements, the model developed for Lake Limnopolar was focused on a detailed description of the carbon and energy sources driving lake's functioning, as well as on an accurate selection of the main state variables likely controlling the system, paying especial attention to the bacterioplankton community. Unlike temperate lakes where phytoplankton play a prominent role, nutrient fluxes in Lake Limnopolar flow mainly through the bacterioplankton community, and its abundance and activity is linked to the availability of dissolved organic carbon (DOC) in the water column. However, prognoses of our model should be taken with care due to their characteristic properties and the problems caused by the high interannual meteorological variability in the area, especially linked to how climate warming could affect the performance of each component of the biological community and the interactions among them, which is quite variable from year to year, and thus should be considered as a preliminary model that could be further improved when data from more field seasons are available. In any case, as demonstrated by our model, the strong warming in the area of the maritime Antarctica and the observed lake community response makes temperature a key sensitive forcing function to monitor and detect changes on several components of the microbial community and lacustrine processes driven by climate change.

2. Material and methods

2.1. Study area

Lake Limnopolar is located on Byers Peninsula (Livingston Island, South Shetland Islands, Antarctica; 62°34′35″–62°40′35″ S and 60°54′14″–61°13′07″ W) (Fig. 1). The lake is a small (2.2 ha) and shallow (4.5 m maximum depth during the summer) water body located in the central plateau of the peninsula. It has a scarcely vegetated drainage watershed of 0.582 km^2 mainly covered by microbial mats and moss carpets. Byers Peninsula is one of the largest ice-free areas on the Maritime Antarctica (SCAR, 2003). It is characterized by the presence of a great amount of water bodies, where the melting of their ice caps during the austral summer allows for a great development of microbial communities, both planktonic and benthic (Toro et al., 2007; Villaescusa et al., 2010). Lake Limnopolar was selected to develop an ecological model due to its highly representativeness of inland maritime Antarctic lakes, and also to higher knowledge on their ecological features.

2.2. Ecosystem features

Lake Limnopolar is completely covered by ice during most of the year (Rochera et al., 2010). During the austral summer, however, the ice cover melts keeping the lake without ice for a variable period. For the studied years 2001–2012, the summer ice-free period in Lake Limnopolar ranged from a minimum of 41 for up to 116 days, depending on the year (Rochera et al., 2010; Villaescusa et al., 2013b). Temperature and solar radiation during the spring and early summer are the main physical factors, together with the amount of snowfall accumulated in the catchment, forcing the length of the ice-free period. Light extinction in ice-covered lakes is higher when the ice cover is present (Hawes and Schwarz, 2001), but when the ice layer melts light penetration increases and activity of primary producers rises, and even more when the ice cap disappears. A wide range of trophic status can be seen in different lakes of Byers Peninsula (Villaescusa et al., 2010). Among them, Lake Limnopolar, as a representative example of non-coastal maritime Antarctic lakes, shows an ultraoligotrophic status with low concentrations of inorganic nutrients (dissolved inorganic nitrogen below 2 μM and soluble reactive phosphorus mostly below 0.03 μM). As typical for non-coastal maritime Antarctic lakes, supply of inorganic nutrients and organic carbon to the lake is influenced by the microbial mats growing within the lake's catchment, being even more important during the first days of summer by the intense run-off processes produced when the snow melts.

Planktonic food webs of temperate lakes show greater complexity than those found in Antarctic lakes, showing the classic food web, including bacterioplankton, phytoplankton, zooplankton, macroinvertebrates/planktivorous fish and piscivorous fish (Fig. 2A). In these systems, inputs of inorganic nutrients, mainly nitrogen and phosphorus, allow an important phytoplankton development, which mostly supports the rest of the plankton community. Contrastingly, the planktonic food web of maritime Antarctic lakes shows a lower complexity (Fig. 2B), and is mainly composed of microorganisms (Ellis-Evans, 1996; Hansson et al., 1996; Wynn-Williams, 1996; Laybourn-Parry et al., 2001; Sommer and Sommer, 2006). Due to these particular characteristics, energy transfer between planktonic organisms, mostly circulates through the microbial loop (Azam et al., 1983; Laybourn-Parry, 1997; Camacho, 2006). In addition to other components, the phytoplankton community in the lake is mainly composed by Prasinophytes, Chrysophytes, and nektobenthonic diatoms (Camacho, 2006; Toro et al., 2007; Quesada et al., 2009), as well as a small fraction of unicellular picocyanobacteria (Toro et al., 2007; Rochera et al., 2010). The influence of subsidized supplies of allochthonous carbon