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Low-cost monitoring buoys network tracking biogeochemical changes in lakes and marine environments – a regional case study

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Abstract: Lakes, rivers, estuaries and ocean waters control many important natural functions at the regional-global level. Hence, integrative and frequent long-term water monitoring is required globally. This paper describes the main features and innovations of a low-cost monitoring buoys network (MBN) deployed in a temperate region of Argentina. The MBN was designed to record extended time series at high-frequency, which is of great value for the scientific community, as well as for decision-makers. In addition, two innovative designs belonging to two versions of moored buoys (i.e. shallow waters and coastal marine waters) were presented. It was shown that the cost of either of two versions of the buoy is low, which can be considered as the main advantage.

Keywords: biogeochemical changes; buoy; Chemical Weapons Convention 2017; coastal marine areas; lakes; monitoring network.

Introduction

Lakes, rivers, estuaries and ocean waters control many important natural functions at the regional-global level. In order to respond to the challenge of water management due to increasing uncertainties caused by climate change and by fast changing socio-economic boundary conditions [1], it is essential to gather information. In this context, integrative and frequent long-term water monitoring is required globally [2].

The sampling frequency is critical for identifying and analyzing temporal patterns, processes or phenomena. Any process or phenomenon occurring at a temporal scale shorter than the sampling frequency leads

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to loss of valuable information; the latter is generally associated to traditional monitoring programs, which often are restricted to a specific time point. Marcé et al. [3] discussed the importance of adequate sampling in lakes where most biogeochemical processes, which are driven by microorganisms, often have generation times of hours to days. Thus, a high temporal resolution monitoring is relevant for understanding ecological dynamics in water environments. However, on the contrary, an inadequate sampling rate in which the sampling frequencies are higher than the Nyquist frequency, results in a loss and distortion of information.

Sensors and associated enabling technologies (e.g. physical and cyberinfrastructure) are becoming increasingly important tools for water monitoring [4]. In addition, there is a current trend worldwide to increase data collection frequency in time and space, gathered in monitoring networks. Several research projects are based on the idea of collecting data using low-cost sensor systems. Albaladejo et al. [5] gave a detailed description of a buoy sensor system for shallow marine environments in Spain using low-cost technology. Also, Raimondi et al. [6] presented a comprehensive description of an innovative monitoring underwater buoy system for marine and rivers environments. In another paper, Arle et al. [7] presented a review on the Water Framework Directive, which is the current basis for monitoring surface waters in Europe; a similar line of work is described in Marcé et al. [3].

The present paper describes the main features and innovations of a low-cost monitoring buoys network (MBN), including a description of a specific case study applied to a regional scale. The MBN was designed to record extended time series at high-frequency, which is of great value for the scientific community, as well as for decision-makers. In addition, two innovative designs belonging to two versions of moored buoys [i.e. shallow waters (SW) and coastal marine waters (CMW)] are presented.

A regional case study

The designed moored buoys, which are administered from different research funding, were deployed over a wide geographic coverage, aimed at studying shallow lakes on the one hand, and coastal marine waters, on the other (Fig. 1). The regional experience of the MBN is exposed below.

Regarding SW, a set of shallow lakes occurring in the Pampean region (Argentina) along the precipitation gradient ($300\text{--}1000\text{ mm year}^{-1}$) constitutes the core of the PAMPA² project (Argentinean Project for Monitoring and Prospecting Aquatic Environments, <http://www.pampa2.conicet.gov.ar/>) [8] (Fig. 1); this collaborating network project (one of the first long-term projects funded in Argentina) integrates research teams belonging to different scientific institutions to better understand the shallow lake functioning, in particular, its biological patterns associated with impact of human activity and climate change. In addition, other international research networks, such as Global Lake Ecological Observatory Network (GLEON, <http://gleon.org/>) and

Fig. 1: Location map of the MBN.

Sensing the Americas' Freshwater Ecosystem Risk from Climate Change (SAFER, <http://www.safer.conicet.gov.ar/>) supported the investigation in order to improve the state of knowledge about the lakes in this region and in other parts of the world. In addition to these continuous measurements, traditional sampling schemes continue to be carried out in these lakes as well as in other 15 shallow lakes.

Despite the efforts made in the South Atlantic Ocean, the current in situ observations are not able to monitor, for example, large-scale inter-basin flows, heat transfer, fresh water, mass and other quantities relevant to the climate [9]. As expected, Argentina is not alien to this weakness, even with the sea conditions and the richness of its resources. The Argentine Continental Shelf is among the most extensive (the area between 34 and 56°S is approximately 1 000 000 km²) and productive areas (commercial fisheries, hydrocarbon basins and mineral deposits of great economic importance) of the Southern Hemisphere. Very few autonomous monitoring systems were conducted in the Argentine sea, with the aim of providing short-term observations. For instance, an oceanographic buoy was deployed offshore of Las Grutas (Río Negro Province) for a brief period of 130 days in 2005 in order to collect oceanographic and meteorological measurements [10]. Currently, there are two offshore stations related to port functions that monitor only waves parameters in one case, and in the other case, waves, tides and wind parameters; however, data are often not available for reasons of privacy, except for collaboration members in response to a specific request.

Environmental monitoring buoy

Most electronic and mechanical parts of the designs were developed by a team of researchers from the Argentinean Institute of Oceanography (IADO-CONICET, Bahía Blanca, Argentina). The environmental monitoring buoy is a low-cost modular system that allows access by remote connection. In addition to the low-cost, the independence and standardization of the buoy designs lead to flexibility in functioning and configuration of the system. The key hardware and software elements of the designs are described below in greater detail.

Data logger

The data logger is a robust enough acquirer suitable for a wide range of configurations. Table 1 summarizes the description of the data logger. The device is compact in size and consists of a dual layer single board (Fig. 2a) involving the processing, communications, data storage, power management and the GPRS modem (Table 1). The data logger, with nine inputs (eight of these are analogical, Fig. 2a), uses a 10-bit analog-to-

Table 1: Description of the main characteristics of the data logger.

Parameters	Description
Operating temperature range	−40 to +70 °C
Analog inputs	Nine single ended (expandable to 27)
Pulse counters	One (expandable to three)
Communications ports	RS-232
Data storage	110 days @ 10 min sample
Input limits	+5 V
ADC	10 bits
Power range	12–25 V
Remote communication technology	GPRS/RADIO
Range remote communication	GPRS: dependent on service provider RADIO: 10 km
Idle current drain, Average	<2 mA (@12 Vdc)
Max. current supply	3 A
Capacity expansion	Until two loggers more (27 inputs; 9 A current supply)

Fig. 2: View of the assembled data logger (a). View of two data loggers interconnected working like one, mounted on a buoy (b).

digital microconverter, allowing the integration of existing commercial sensors with analogical outputs. An additional feature is the possibility of interconnection with other units, increasing the amount of inputs (Fig. 2b, Table 1). The associated configuration software is user-friendly and allows users to set a large variety of parameters.

The data storage capacity is equivalent to 110 days over a 10 min sample time; the data can be either downloaded locally or sent to a central server. The data logger is based on an 8 bit Ultra-Low-Power Microcontroller from Microchip. The device has an RS232 connection port and also can use a radio link to operate in remote environments. In addition, the data logger is equipped with a Telit GSM/GPRS modem. The above-mentioned characteristics lead to a significant impact on the design, both in terms of cost and practicality.

Control software

The software was developed by the first author in Delphi language. It runs both under Windows and Linux (window emulator: WineHQ). The software was designed to be operated by nonspecialists through an intuitive user interface (Fig. 3). The hardware requirements are minimal when it is compared with other of similar characteristics. As was mentioned previously, the tasks can be run in local or remote mode. By using this software, users can easily set each parameter (e.g. enable/disable input, select the sensor curve for each input, set the sample rate, set the server IP address, set the APN of the service provider, download the data, etc.) (Fig. 3a). Under local mode, the user can record and plot the data on real-time to allow a wide-range of laboratory/field works as, for example, to ensure a good performance of the sensor (Fig. 3a). The recorded data can be saved in a variety of file formats.

Under remote mode, in order to access the data, the software works in an environment where the communication is carried out according to a client/server communication style (Fig. 3b). The originality of the design lies in the fact that each node connects to the server in an autonomous mode and not as conventional systems where the server polls each node.

All the tasks are scheduled as shown Fig. 4. These tasks are performed simultaneously for each station and, therefore, the server can efficiently manage the whole MBN. Finally, once the server receives and saves the data, the instantaneous and accumulated data can be displayed in a web interface (Fig. 3c). The accumulated data are available for a period of up to a month, at different temporal resolutions (e.g. hourly, daily).

Sensors

Several low-cost sensors were developed for monitoring air/water interface. The buoy is equipped with a set of sensors (most of them are self-developed) to measure physico-chemical water parameters that, depending

Fig. 3: Data logger software operating in local mode (a). Data logger software operating in client-server mode belonging to a monitoring network (b). View of the web page showing instantaneous data (left) and stored data (right) (c). Available online at <http://emac.iado-conicet.gob.ar/>.

Fig. 4: Workflow showing the steps for acquisition, storage and transmission of data.

on the study type, can include temperature (two or more levels), conductivity, suspended solids, water level, dissolved oxygen, chlorophyll-*a* and wave height/period. The moored buoys are also significant in terms of getting meteorological data above the water surface (lakes, reservoirs, sea, etc.); the two buoy designs are equipped with sensors to measure temperature, solar radiation, wind speed/direction and other basic parameters, including also an internal compass to correct wind direction. The developed sensors were calibrated against standard instruments. Table 2 presents the main specifications of the monitored parameters in the MBN. In particular, the most innovative designs are described below.

Conductivity and temperature

The integrated sensor of conductivity and temperature is based on an inductive principle (Fig. 5a) and on an NTC thermistor, respectively; it is composed of three coils and two toroids. The sensor body is built in stainless steel and the head consists of a 3D printed piece (abs plastic). The sensor is fully filled with epoxy resin to make it highly waterproof. The sensor uses a Microchip PIC12F675 microcontroller to generate the 35 kHz signal to excite the electric current. For the analog output, the induced current is amplified and processed by a peak detection circuit (Fig. 6a).

Table 2: Technical specifications of the monitored parameters.

Monitoring parameters	Range	Accuracy	Power supply	Power drain	Unit	Transducer/principle	Manufacturer
Temperature	−20 to +60 °C	±0.2 °C	9–15 V	2 mA	°C	NTCLE203E3103SB0	EMAC team
Relative humidity	0–100 %	±2 %	9–15 V	2 mA	%	HH4001	EMAC team
Wind speed	0–50 m/s	±2 % FS	9–15 V	8 mA	m/s	TCRT1000	EMAC team
Wind direction	0–360°	±1 % FS	9–15 V	2 mA	°	6187R10KL1.0LF	EMAC team
Solar radiation	0–1250 W/m ²	±5 %	5–24 V	5 mA	W/m ²	SP-215	Apogee instruments
Solar radiation	0–1250 W/m ²	±7 %	9–15 V	5 mA	W/m ²	BPW20RF	EMAC team
Net radiation	−300 to 2000 W/m ²	±5 %	9–15 V	5 mA	W/m ²	NR Lite2	Kipp and Zonen
Water level	0–10 m	±0.01 m	9–15 V	7 mA	m	MPX5100DP	EMAC team
Conductivity (salinity)	0–25 mS	±2 % FS	9–15 V	60 mA	mS	TOROIDAL	EMAC team
	0–70 mS						
Suspended solids	0–1000 mg/L	±3 %	9–15 V	35 mA	mg/L	OPB730F	EMAC team
Chlorophyll- <i>a</i>	0–500 µg/L	±1 %	12 V	20 mA	µg/L	Cyclops-7F	Turner designs
Dissolved oxygen (DO)	0–200 %	±1 %	12–36 V	30 mA	%	DO6440	Sensorex
Wave height/period	0–5 m/50 s	±1 %	9–15 V	25 mA	m/s	ADXL345	EMAC team

Fig. 5: General view of the conductivity sensor (a), wind speed sensor (b, c), suspended solids sensor (d), water level sensor (e) and wave sensor (f).

Fig. 6: Schematic circuit of the conductivity sensor (a) and suspended solids sensor (b).

Wind speed

The wind speed sensor uses a reflective optical sensor to account the revolutions (4 pulses per revolution; Fig. 5b and c). The frequency to voltage conversion was made using integrated circuit technology (LM2907N) (Fig. 5b). The sensor body is built in stainless steel and Delrin. The designed rotor (Savonius-type) consists of a robust and simple 3D printed piece (Fig. 5c).

Suspended solids

Suspended solids are measured using an optical backscatter sensor (Fig. 5d). The parts of the sensor (body and head) are similar to the conductivity sensor. The sensor uses a Microchip PIC12F675 microcontroller to generate 1 KHz infrared pulse through OPB730F (reflective object sensor). For the analog output, the backscatter signal is amplified and processed by means of a precision rectifier circuit, using integrated circuit technology (TL082) (Fig. 6b).

Water level

A dual sensor for simultaneous sensing of water level and temperature was developed. The former sensor uses an integrated silicon pressure sensor (Fig. 5e). Freescale family of MPX5XXXDP devices provides a flexible and low-cost solution for several applications in water level measurements. The sensor body is built in stainless steel and the head consists of Delrin. A polypropylene tube, to which the cable is attached, is used for air ventilation (Fig. 5e).

Waves

The wave sensor is based on a combination of an accelerometer (ADXL345) and a real time processing on an Arduino Nano board (Fig. 5f). The vertical displacement of the buoy carrying the sensor is obtained from the double integration of the vertical acceleration in combination with the use of low/high-pass filters. Amplitude and period parameters of the signal were determined using the zero-down-crossing. For the analog output, PWM Arduino pin was used. The electronics are encapsulated in a plastic housing (3D printing) which is filled with epoxy resin to make it highly waterproof.

Buoy architecture

Two versions of moored buoys (i.e. SW and CMW) were designed to meet requirements to support multiple aspects, such as cost, buoyancy, stability, durability and operability. Both versions were administered under different funding projects. Table 3 summarizes the main features of the two designs. The buoys characteristics are described in detail below.

The SW version consists of a vertical structure based on a stainless steel tube of 3 m length and 38 mm diameter (Fig. 7a–d) and of a float of 1.2 m diameter and 0.5 m height that is placed in the bottom of the tube (Fig. 7b and c). The float is composed of fiberglass filled with polyurethane foam. All the structure and fixing elements are made of stainless steel to protect against corrosion. The buoy has 70 kg of iron plates to stabilize it and keep it upright (Fig. 7b and c). Usually, the SW is anchored using three 40 kg concrete blocks attached to their three mooring accessories (Fig. 7d).

The upper part of the buoy contains several elements: meteorological sensors (e.g. wind speed and direction, temperature, relative humidity, solar radiation, etc.), boxes, a vertically polarized omnidirectional

Table 3: Comparative characteristics of buoy designs.

Characteristics	Version	
	SW	CMW
Max. draft	0.5 m	1 m
Material	Fiberglass/stainless steel	Rotomolded plastic/stainless steel
Dimension	1.2 × 2.5 m	0.5 × 3 m
Weight (fully load)	140 kg	70 kg
Reserve buoyancy	200 kg	80 kg
Max. power	four solar panels, 10 watts	one solar panel, 40 watts
Battery bank	14 amp-h	48 amp-h
Mooring attachment	Single or three point	Single point
Max. number of data loggers	2	3
Max. number of sensors	14	22
Designed for	Stability	Waves measurement
Beacon	LED light	LED light

Fig. 7: Different views of the SW version.

antenna and a light-emitting beacon to provide night-time visibility. The sensors are mounted at a height approximately of 2 m above the water level. The water sensors are placed in the rear part of the buoy and are supported in a stainless steel tube of 1 m length and 25 mm diameter (Fig. 7c); thus, the depth of the sensors can be adjustable from 0.25 to 1 m. The front box was designed to contain the data loggers and the compass (if needed; Fig. 7a, c, d); the rear box contains the batteries storage and the solar charge regulator (Fig. 7c). In addition, the design can also support a vertical chain of sensors for profiling; a measurement study of water temperature at seven depth levels was made in Paso Piedras reservoir.

The remaining version (CMW) was designed specifically to provide an even lower cost solution, with more payload capability (Fig. 8a). At the same time, CMW seeks to sample wave parameters, such as height and period by using an acceleration sensor. The CMW consists of a rotomolded tank (0.50 m diameter) and a steel structure (Fig. 8a–c). All elements are made of stainless steel to protect against corrosion. In order to stabilize

Fig. 8: Different views of the CMW version.

the buoy and keep it upright, the inside of the body is filled with concrete (50 kg) and polyurethane foam. Usually, the CMW is anchored using only one 150 kg concrete block attached to its central mooring point.

The upper part of CMW version is the same as in the SW version. The water sensors are placed all around the buoy over a specially designed structure (Fig. 8c). The depth of the sensors is fixed at 0.5 m. The data loggers, the compass (if needed), the wave sensor and the batteries are located inside the buoy. This version can also support a vertical chain of sensors for profiling.

The proposed buoy version for marine environments was firstly tested in the Paso Piedras reservoir (Buenos Aires Province) since October 2017 (Fig. 1). The design, which was funded by the Ministry of Education of Argentina under the project called “Universidad Agregando Valor”, was deployed in the coastal zone of Monte Hermoso (Buenos Aires Province) (Fig. 1). The reservoir (33 500 m²) has a maximum depth of approximately 30 m, with waves generated by local winds ranging from 0.30 to 2 m of height and a mean period of 2 s. It should be mentioned that the wave period in the reservoir implies a major structural requirement than in the coastal zone, which has typical periods of 5–8 s.

Results and discussion

Operability of the MBN

At present, the total sum of the operating time of the MBN equals 20 years. However, the MBN exhibits high-performance variability (Table 4). The data indicate that the expected useful life of the buoy should exceed 5 years useful, as can be seen in the case of the buoy installed in La Salada Lake, which accumulates a useful life of more than 5 years and it continues to work effectively.

The goal of any measurement system is to provide reliable data without costly frequent maintenance. Table 5 summarizes the performance of the sampled parameters after QA/QC procedures for all buoys network. Usually, water sensors require more maintenance than meteorological ones, as is expected. Among the former, optical sensors (i.e. suspended solids, chlorophyll-*a*) showed the most highest levels of maintenance requirement; here, the decrease in the water level of these shallow lakes is usually accompanied by an

Table 4: Summary of the MBN activity.

	Sauce Grande Lake*	La Salada Lake*	Otamendi Lake	Chascomus Lake	La Barrancosa Lake	La Helvecia Lake	Rocha Lake (Uruguay)	Paso Piedras Reservoir*	Monte Hermoso Coast*
First deployment	Jul-10/ Ago-16	May-12	Sep-12	Nov-12	Feb-13	Mar-13	Dic-15	Abr-16	Apr-18
Operative time (months)	20	69	31	24	32	45	13	21	2
Number of sensors	8	13	8	8	8	7	10	9	7

Asterisk indicates the buoys currently in use.

Table 5: Summary of the data collection after QA/QC procedures for each measured parameter (in months), the performance and the maintenance requirement for all buoys network.

Parameter	Data amount under QA/QC (months)	Performance (%)	Maintenance requirement
Air temperature	234	95	Low
Water temperature	217	88	Low
Relative humidity	181	74	Medium
Wind Velocity/direction	217	88	Low
Solar radiation	52	95	Low
Suspended solids	110	56	Very high
Conductivity	176	72	Medium
Dissolved oxygen	51	61	High
Chlorophyll- <i>a</i>	62	78	Very high
Water level	176	77	Medium

Maintenance requirement: very high: <3 months; high: 3–6 months; medium: 6–12 months; low: >12 months.

increase in suspended solids affecting the sensitivity of optical sensors. The dissolved oxygen sensor (electrochemical in nature) also showed a high maintenance. This sensor and the above mentioned underwater sensors experience biofouling effects, which disturb the continuity of the measurements (Fig. 9); sometimes, the disturbance is manifested in a few days. As can be appreciated in the Fig. 9a, the dissolved oxygen sensor loses its sensitivity as a result of the biofouling cover, which increases in early summer in accordance with the algae bloom in the Sauce Grande Lake. The use of automatic cleaning systems may be unnecessary and expensive since they are not adaptable for use on several shapes and sizes of sensors and their cost may be

Fig. 9: Example of biofouling effect in the Sauce Grande Lake. Dissolved oxygen (a) and water/air temperature (b) time series for approximately a year; (c) buoy (SW version) and its sensors under biofouling effect.

substantial. Therefore, the local maintenance of this kind of sensors is required; however, this is also valid even for the most expensive commercial sensors.

Collecting data

Collecting in situ data from moored buoys at high sampling rates and at mesoscale resolution means an important approach for the analysis of the regional climate with emphasis on the air-water coupling. Examples of measurements after quality control from buoys moored in different water bodies of the Pampean region are shown in Fig. 10. The first group of time series (Fig. 10a–c) refers to basic parameters in La Salada Lake for the whole period (from 2013 to the present); here, there is a trend towards an inverse relationship between the temperature (air/water) and the chlorophyll-*a* levels during a good part of the time. The following group of time series (Fig. 10d and e) refers to hydrodynamic parameters of the Paso Piedras reservoir; as it can be seen, the waves respond strongly to wind duration and wind speed, which is typical for small-medium enclosed basins. Finally, the third group of time series (Fig. 10f–i) exhibits a heat wave event that was significant in terms of intensity and geographic extent; it is interesting to note that the water temperature was lower in Paso Piedras reservoir than in the remaining shallow lakes because of its greater depth.

Advantages and limitations of the MBN

The buoy concept proposed in this work (i.e. the two versions) is based on low unit costs and robust design. This concept gained increased interest within the technological and scientific community. The buoy, including materials and manufacturing processes (without electronic components) can be made from \$400 (steel) to \$800 (stainless steel) for the CMW version, and \$1000 for the SW version; therefore, it is viable for monitoring projects and researches with budgetary constraints. Researchers who are responsible for designing the buoy received an award from the Ministry of Science, Technology and Productive Innovation of Argentina (MINCYT) for their low-cost innovation efforts within the category of applied research (*Innovar Award 2011*; <https://issuu.com/innovar/docs/catalogo-innovar-2011>).

The importance of studying continental water bodies and oceans demands a regional-global framework in collaborative data collection. Long-term and spatially widespread monitoring programs, such as (in this case) GLEON, SAFER and PAMPA², need to have access to reliable and low-cost equipment. The latter is essential since water sensors have a more limited lifespan, requiring replacement (or repair) at a certain time point during the monitoring period. In many developing countries like Argentina, the importation of equipment is often expensive for local researchers because of their low budget; in this regard, taxes (e.g. customs, excise duties, etc.), fees and others costs play an important role in determining the price level. On the other hand, in Argentina, bureaucratic time-consuming procedures constitute a problem because they can take up to 60 days before it is possible to make the purchase. Another fact of importance is that even when researchers receive funds to purchase equipment, it is also certain that they rarely or never receive support to purchase spare parts or repair. With all these considerations, one of the main purposes of continuous monitoring becomes difficult to achieve.

As a result of many of the points stated above, it was decided to build our own sensors and support systems, which are significantly cheaper than existing commercial options. Every piece is largely known and well understood; so, instead of acting as “black box”, the system can act as “white box”. Therefore, repair or build a new piece is cheap and simple. Because of real-time monitoring, it is known when a sensor is failing and thus one can quickly either go to the site and make the replacement, or send it to the local user to do so.

The MBN offers an open access data portal of each monitored parameter for anyone to use, at different temporal resolutions, but with a storage period restricted to 1 month. Large time series data sets must be requested. National database systems given by the MINCYT with the mission to guarantee the accessibility to data, are gaining strength in Argentina. Among them, the National Sea Data System, the National Biologic

Fig. 10: Results of some measured parameters in LS, PP and SG sites. (a–c) Water (WT) and air (AT) temperature (°C) (a), chlorophyll-*a* (CL) (mg L⁻¹) (b) and water level (WL) (m) (c), in LS from May 2012 to December 2017. (d, e) Wind speed (WS) (m s⁻¹) (d) and wave height (H) (m) and wave period (P) (s) (e), in PP from 01 December to 31 December 2017. (f–i) AT (f) and WT (g) in LS, PP and SG; dissolved oxygen (O2) (%) (h) and WS (i) in SG during a heat wave in the region. Note: It must be mentioned that the time series corresponding to other research groups are still not available for publication.

Data System and the National Climatic Data System will provide an important means of storing metadata or eventually time series data of the MBN.

Buoys data cover satisfactorily most aspects of interest to the scientific exploration in the continental waters and the oceans. Thus, errors from satellite-derived products as well as model uncertainties can be validated by comparing them with in situ data. From the late 90s, several studies reported the usage of buoy data to validate remote sensing products mainly for climatology and oceanic wave modeling research. In situ observations from buoys networks during a long-term period will provide a more complete dataset for optimizing satellite products as well as numerical models. At present, for the purposes of rigorous validation process from buoy data, collaborative practices are being carried out. For example, data from MBN and from Coastal Environmental Monitoring Station (EMAC) network (<http://emac.iado-conicet.gob.ar/>) are used to evaluate forecasting models performance for the region in question by local researchers in atmospheric science (<http://meteobahia.com.ar>).

The MBN supplies a data resource for a variety of scientific studies. Many research scientists who are integrated within the MBN made significant contributions about water bodies in multiple fields of science that can be found in different scientific documents such as papers (e.g. [11–14]), postgraduate studies (numerous unpublished doctoral thesis), conference papers, etc.

According to Teng et al. [15], any interference (unlawful) with data buoys (willful or malicious destruction, defacement or theft) is considered to be vandalism. A number of vandalism incidents occurred in the MBN, some of which were reported in the regional daily newspaper (e.g. <http://www.lanueva.com/nota/2011-9-23-11-47-0-destrozan-una-boya-de-monitoreo-ambiental-en-la-laguna-sauce-grande>). Typical damages were mostly observed in the vertical structure, the electrical system components or cables, as well as in the mooring rope. There were cases where the buoy was severely damaged and the whole equipment was all gone. In the last years, the widespread increase in activities that are linked to water use (fishing, bathing, recreation and navigation), poses a major risk for the maintenance of the MBN. These facts highlight the need to raise awareness among the local community, tourists and visitors about the protection of the monitoring buoys. In this regard, education and outreach efforts over a long-term period seem to produce positive results [15]. Here, it is important to mention the efforts of education programs with primary and secondary school students and teachers in La Salada Lake by using high-frequent lake data [13]. In many cases, the buoys also experienced damages from natural factors such as storms (e.g. the hydro-meteorological phenomenon known as “sudestada”), hydrologic alterations (e.g. sudden decrease of water level in a shallow lake) and animal actions (e.g. birds nesting and landing on the solar panels). Here, the mentioned biofouling effects could be well added to this kind of damages.

The operational maintenance to ensure the continuity of the monitoring requires a laboratory with relatively complex equipment and specialized technicians. The lack of available specialized technical personnel covering all measurement sites can usually be an obstacle to the continuity of the monitoring. Because of this, there is a need for sensors (or parts of the system) that can be managed by all research members (researchers, students, technicians, etc.), even with minimum technical training; this is precisely the philosophy of the design, which is also based on the idea of “developed by researchers, for researchers”. This links research needs with the field of measurement technology.

The continuity of the monitoring, as well as the expansion of any monitoring network, are mainly subject to the available budget. The budget depends basically upon the public preferences about policy direction, which may not be congruent with certain scientific objectives. In this context, for example, the emergence of public initiatives, such as Pampa Azul (Law 27,267, year 2015) represents an active preference for knowledge support of the Argentine Sea.

Conclusions

This paper is focused on the characterization of a low-cost monitoring buoys network, that is, its main features and innovations. The paper also includes a description of a specific case study applied to a regional

scale in a temperate region of Argentina. Two innovative designs belonging to two versions of moored buoys (i.e. SW and CMW) were presented.

The MBN was designed to record extended time series at high-frequency. This research revealed a number of advantages and limitations of the MBN that should be considered for the scientific community, as well as for decision-makers. It was shown that the cost of either of two versions of the buoy is low, which can be considered as the main advantage. The unfolding of the MBN will induce further cooperation between national and international institutions aimed at the advancement of knowledge of lakes and marine environments. The development of equipment for monitoring and tracking of biogeochemical changes in water bodies continues to be a challenge, in part because different requirements need specific design solutions.

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