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Joint European MSc Degree
Marine Environment and Resources
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Ref MO2006-00744

MASTER THESIS PROJECT

Spatial and temporal variability of phytoplankton biomass related to environmental conditions in the South West lagoon of New Caledonia (2008-2011).

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Plentzia (Bizkaia), September 2011

Universidad del País Vasco Euskal Herriko Unibertsitatea
UNIVERSITY OF Southampton
UNIVERSITE BORDEAUX 1 Sciences Technologies
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Dr ....
as teaching staff of the MER Master of the University of ……………………………

CERTIFIES:

That the research work entitled. **"Spatial and temporal variability of phytoplankton biomass related to environmental conditions in the South West lagoon of New Caledonia (2008 – 2011)**

has been carried out by **Anthony Gonzalez**
in **"Institut de Recherche pour le Développement" of Nouméa**

under the supervision of **Dr Cécile Dupouy**
in order to achieve 30 ECTS as a part of the MER Master program.

In Bordeaux, September 16th, 2011

Signed: .Tutor (………………………….)......

Supervisor (……………………….)......

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Abstract

Fluorometric method was performed in the framework of the ValHyBio monthly survey project (2008 – 2011) to measure total chlorophyll a (Tchl-a) concentrations at four monthly visited stations located in the South West lagoon of New Caledonia (SWL) and its adjacent oceanic area. The important question addressed in this study was how the phytoplankton dynamic is affected by environmental forcing. For that, the objectives were (1) to analyze the temporal variability of chlorophyll a in relation to environmental physical factors and meteorological conditions at a monthly, seasonal, and inter-annual scale; (2) to examine the spatial distribution of chlorophyll a in the SWL.

As a result of greater terrestrial influence, shallower depths, and longer water residence times, amplitude of the temporal variability appeared greater nearshore, particularly in bays. Monthly fluctuations of phytoplankton biomass were in the same range as annual variations. Inside the lagoon, these short term variations appeared mostly linked to meteorological events (wind in the lagoon, rainfall in the bays and close to the shore). At the oceanic station, output of lagoon waters through the pass explained most of the increase in surface Tchl-a, except during cooling and consecutive mixing of water in winter. Occasional upwelling along the barrier reef may also occur. Although we observed moderate annual variations compared to variations at shorter scale, phytoplankton production showed consistent seasonal patterns, with maximum noted in January and between April and June in the lagoon. Maximum in the ocean was noted in winter in relation with the disappearance of the summer thermocline. The inter-annual variability of Tchl-a concentration did not appear related to the Southern Oscillation Index (an equatorial index), stressing the need for a separate tropical index.

Concerning the spatial distribution, we found that phytoplankton productivity was clearly higher in the lagoon than in the ocean. And although the maximum is generally observed in the bays, we noted that productivity in a certain area was more dependent on hydrographic conditions prevailing in this area than in the distance of the site to the coast. Moreover, the significant increases of Tchl-a observed with depth in the lagoon informed us on the strong relationship existing between pelagic production and benthic recycling.

Résumé

La méthode fluorométrique a été utilisée dans le cadre du projet de suivi mensuelle ValHyBio (2008-2011) afin de mesurer la concentration en chlorophylle a totale (Tchl-a) à quatre stations échantillonnées chaque mois situées dans le lagon Sud-ouest de Nouvelle Calédonie (SWL) et dans la zone océanique adjacente. La question importante abordée dans cette étude fut de savoir comment la dynamique du phytoplancton est affectée par la contrainte environnementale. Pour cela, les objectifs ont été : (1) d'analyser la variabilité temporelle de la chlorophylle a, en relation avec les facteurs physiques environnementaux et les conditions météorologiques, à une échelle mensuelle, saisonnière, et interannuelle ; (2) d'examiner la distribution spatiale de la chlorophylle a dans le SWL.

Due à une plus grande influence terrestre, à de plus faible profondeurs, et à des temps de résidences de l'eau plus importants, l'amplitude de la variabilité temporelle est apparue plus grande près des côtes, et plus particulièrement dans les baies. Les fluctuations mensuelles de la biomasse du phytoplancton ont été équivalentes à celles observées à l'échelle annuelle. A l'intérieur du lagon, ces variations à court terme sont apparues principalement liée aux évènements météorologiques (vent dans le lagon, précipitation dans les baies et près de la côte). A la station océanique, les sorties par la passe des eaux du lagon ont expliqué la plupart des augmentations en Tchl-a de surface, à l'exception des épisodes de destratification de la colonne d'eau se produisant en hiver. Un upwelling peut également se former occasionnellement le long de la barrière de corail. Bien que nous ayons observé des variations annuelles modérées comparées aux variations à plus courte échelle, la biomasse du phytoplancton a présenté des tendances saisonnières claires, avec des maximums dans le lagon observés en Janvier et entre Avril et Juin. Le maximum dans l'océan a été noté en hiver, en relation avec la disparition de la thermocline d'été. La variation interannuelle en Tchl-a n'est pas apparue liée au « Southern Oscillation Index » (un indice équatorial), soulignant la nécessité d'un indice tropical distinct.

En ce qui concerne la distribution spatiale, nous avons constaté que la productivité du phytoplancton était clairement plus importante dans le lagon que dans l'océan. Et bien que le maximum soit généralement observé dans les baies, nous avons noté que la productivité dans un certain secteur était plus dépendante des conditions hydrographiques de ce secteur que de la distance du site à la côte. De plus, les augmentations significatives de Tchl-a observé avec la profondeur dans le lagon nous ont informés sur la relation forte existante entre la production pélagique et le recyclage benthique.

List of contents

List of illustrations

Figures

Tables

Foreword

An institute at the service of Southern countries

The “Institut de Recherche pour le Développement” is a French public research institute that has been working in Southern countries for over sixty years. It operates under the joint authority of the French ministries responsible for research and overseas development.

All its work – in research, consultancy and capacity-building activities – is designed to assist the economic, social and cultural development of Southern countries. The work hinges around six priorities:

- poverty reduction,
- migration,
- emerging diseases,
- climate change and natural hazards,
- access to water,
- ecosystems.

Partnerships in France and in the world

In close collaboration with their colleagues in partner institutions, 858 researchers, 973 engineers and technicians and 341 local staff were at work in some fifty countries in 2008. They took part in numerous national, European and international programs.

In September 2008 the IRD moved its head office to Marseille. It has 30 other establishments including two in Metropolitan France (Bondy and Montpellier), five in the French overseas territories (la Réunion, French Guiana, Martinique, New Caledonia and French Polynesia) and 23 in countries of the intertropical zone in Africa, the Mediterranean, Asia and Latin America.

The IRD in New-Caledonia

The Pacific is a region of contrasts enjoying an exceptional marine and terrestrial biodiversity and a big cultural diversity.

The Pacific region is constituted of numerous micro-island states, particularly exposed to natural risks (erosion, cyclones), climate change (increase of the temperature, rise of seal level, acidification) and certain risks related to human activities (mines, overfishing).

The region has specific needs in development and constitutes at the same time a real opportunity for the scientific research: the researches on the global change can be approached here at the local level (management of the water, protection of the biodiversity, governance).

The IRD of New Caledonia, based in Nouméa, includes numerous scientific disciplines: oceanography, marine ecology, geology, etc. Approximately 200 persons work within the center in the various departments of research. The evolution of the center is marked by the implementation of 13 Units of Research (UR) and 5 Units of Service (US) in New Caledonia which are connected with the various departments. The first ones aim to increase the scientific knowledge on the intertropical zone, whereas the others units have for mission to value the results of the research by answering the requests of expertise of the local partners.

The Mixed Unit of Research 6535: Laboratory of Physical and Biogeochemical Oceanography (LOPB)

The UMR 6535 is a common Research Unit composed by the CNRS (Centre National de la Recherche Scientifique), the University of the Mediterranean, and the IRD. The IRD 1M213 Unit, a member of the LOPB since 2008 (previously the CAMELIA team) is interested in the mechanisms of transport and transformation of the particles responsible for eutrophication and of potentially toxic metals in coastal areas (Mexico, New Caledonia, Tahiti, Mediterranean coast, Tunisia). The island states of the Pacific are subjected to profound economic changes which have strong implications on the balance of coastal environment. The CAMELIA team was the leader of the National Program of Coastal Environment (PNEC) as New Caledonia was one of the 5 National Workshops of this program (www.ird.nc/PNEC). The CAMELIA team was composed of about 20 scientists and Students. LOPB joins in the continuation of the dynamics of research implemented since 1996 by CAMELIA (IRD) on the general theme of the influence of human activities on the coastal and tropical ecosystems. The marine chemistry laboratory of the UMR at IRD Nouméa allows all the chemical and biological analyses essential for the knowledge of the lagoonal environment.

The ValHyBio/ValHySat projects

The works realized during my MSc thesis join the projects ValHyBio (Validation Hyperspectral of a Biogeochemical model) and ValHySat (Validation Hyperspectral of Satellital data at medium and high resolution).

The VALHYBIO project, supported by the IRD, the CNRS (Centre National de la Recherche Scientifique) and the PNTS (Programme National de Télédétédection Spatiale) with the collaboration of the GKSS (Hambourg), combines the numerical modeling, the calibration of satellite data and the biogeochemical study of the lagoon of New Caledonia.

It has for main objective to follow the spatio-temporal variation of surface chlorophyll in the lagoon of New Caledonia. Indeed the chlorophyll is an indicator of the production of phytoplankton, base of the food chain. This spatio-temporal study would be made thanks to the satellite pictures of water color. The knowledge of the distribution and the spatio-temporal variations of the chlorophyll is crucial to understand the marine ecosystems and the oceanic carbon cycle. This survey would allow a better observation and comprehension of the pressures which are applied to the lagoon (urbanization, mining activities).

The researchers of the LOPB within the IRD Nouméa developed biogeochemical and physical models of the functioning of the ecosystem in the southwest lagoon of New Caledonia. The model used presently takes into account the wind, the tide, the bathymetry, the temperature and calculates the rise of the sea, the diffusion coefficients and the currents. It considers the river and anthropological contributions, the ocean-atmosphere exchanges and the evolution of inorganic matter.

The final aim is thus the surveillance of the lagoon ecosystems thanks to satellite observations. It would also allow to validate and to improve the modeling of the biogeochemical functioning of the lagoon.

For that, we use surface chlorophyll data from MODIS and SeaWiFS satellites. Those data are based on absorption and reflection of the solar spectrum by chlorophyll. Now, the effect of solar reflection on seabed is actually difficult to quantify. The bottom color perturbs not only the estimation of the chlorophyll but also that of suspended materials. Moreover, colored dissolved organic matter (CDOM) and suspended particulate matter (SPM) in the water masses also falsifies the chlorophyll estimation by satellites.

To estimate using satellites the in situ chlorophyll concentrations, it is so necessary to use new algorithms of calculation. Knowledge about optical properties of the water column is thus necessary to calibrate satellite data. Optical and pigment data are used to elaborate an algorithm more adapted to lagoon waters than classic algorithm (OC4) elaborated from oceanic waters data.

Currently, estimations of chlorophyll are reasonably precise in open waters. However, in coastal zone, the satellite estimation seems more complex and imprecise and thus requires specific algorithms.

Several hypotheses are advanced to explain the model limits:

- in coastal zone, optical properties of waters are strongly influenced by the bottom and the presence of particles of terrigenous and/or anthropological origin. The bottom effect is not taken into account in the model. For a correct measure of the surface chlorophyll by satellites in a shallow lagoon with relatively low turbidity, it is necessary to clearly assess the seabed reflection which perturbs the measures (Dupouy and al., 2008; Dupouy et al., 2010).

- using in situ measures, it was deducted that chlorophyll is not homogeneous in the lagoon. This spatial variability is also not considered by the model.

The ValHySat project is the complement of the ValHyBio project. It has for objective to compare in situ data stemming from ValHyBio project as well as from previous research survey with the satellite data water color acquired SeaWIFS and MODIS satellites since 1997. The aim is to validate the algorithms used to estimate the chlorophyll concentration in the lagoon.

The longer-term purpose is to build a database grouping together the corrected satellite chlorophyll data of the lagoon of New Caledonia, in association with the Espace research unit in the framework of the future GOPS project (Grand Observatoire du Pacifique Sud).

1.Introduction

Chlorophyll is a green pigment found in almost all plants, algae, and cyanobacteria. It is an extremely important biomolecule, critical in photosynthesis, which is a chemical process that converts carbon dioxide and water into organic compounds, especially sugars, using the energy from sunlight.

Chlorophyll a is the most common specific form of chlorophyll, and is present in all oxygenic photosynthetic organisms. In phytoplankton, it constitutes generally about 1 to 2 % of the dry weight. Other accessory pigments like chlorophyll b and c may occur in phytoplankton. The presence or absence of such various pigments is used, among other features, to separate the major algal groups.

Concentration of chlorophyll a in seawater, expressed in $mg.m^{-3}$ or in $\mu g.L^{-1}$, is commonly used as an indicator of phytoplankton biomass. Phytoplankton, which are the main marine primary producer, are essential for marine ecosystems. They are the foundation of the marine food chain, feeding everything from microscopic, animal-like zooplankton to multi-ton whales. Via their role on the carbon cycle, phytoplankton productivity is also one of the main forces regulating our planetary climate. Indeed, through photosynthesis, phytoplankton consume carbon dioxide on a scale equivalent to forests and other land plants. They thus decrease the oceanic carbon dioxide concentration which will in turn regulates the atmospheric carbon dioxide level. Finally, still through the reaction of photosynthesis, phytoplankton release high quantity of oxygen, essential for the life in the water. Through ocean-atmosphere exchanges, they are also the source of most oxygen in Earth’s atmosphere. All those actions make phytoplankton of incalculable importance for all organisms living on Earth, either from marine or terrestrial ecosystems.

As chlorophyll a concentration is an indicator of phytoplankton abundance and biomass, it is an excellent indicator of trophic status of any water body and helps to prevent from eutrophication risks. It is also commonly used to measure water quality and thus to determine the level of pollution of water. High levels often indicate poor water quality and low levels often suggest good conditions. However, elevated chlorophyll a concentrations are not necessarily a bad thing. It is the long-term persistence of elevated levels that is a problem.

Chlorophyll is popular because it is relatively easy to measure compared to algal biomass and does not suffer from the interferences (detritus and non-algal particulates) found in the other variables.

Compared to most coastal zones, coral reef lagoons are isolated to a variable extent from the surrounding open ocean waters. These open waters flow in and out through passes and over the barrier reef making their transit time within lagoons a key factor of the lagoon environment. This transit time reflects the main differences of the physical, chemical and biological characteristics between the lagoon and open ocean waters. Besides, because of their shallowness, lagoons are more reactive to atmospheric conditions, such as solar radiation and wind stress, than the deep sea and are influenced by benthos and sediments. The difference between lagoonal and oceanic water characteristics is therefore a function of the combined effects of land and atmosphere which originate from the basin morphology and meteorological regime (Dandonneau et al., 1981; Rougerie, 1986).

Fluctuation of phytoplankton biomass (expressed as chlorophyll a concentration) is under the influence of several biotic and abiotic factors, including light and temperature regime, natural and anthropogenic nutrient sources, predation, and water residence time. All of these features undertake temporal variations, which occur on the short (from 1 day to 1 week), mid (seasonal) and long term (inter-annual), inducing temporal variations of phytoplankton abundance and activity and implying that any description of those variations should be placed in a temporal context, for both their interpretation and validity of their conclusions.

Diel to seasonal changes in abundance and growth of plankton have been studied extensively in various marine environments in temperate waters. While the pattern and range of diel variations may change with trophic status (Gasol et al., 1998), seasonal variations are usually high compared to short term fluctuations.

In contrast, in low latitude coastal ecosystems, like in coral reef lagoons, the respective importance of diel and seasonal variations may change considerably. Seasonal variations of phytoplankton biomass and production are usually low in coral reef lagoons (Burford et al., 1995; Furnas and Mitchell, 1986; Torréton and Dufour, 1996). Moreover, any seasonality found is often variable and is superimposed by short term variations induced by meteorological forcing such as sediment resuspension (Muslim and Jones, 2003; Walker and O'Donnell, 1981) or marine intrusion (Furnas and Mitchell, 1986; Gast et al., 1999). The relative importance of temporal variations at different scales in tropical ecosystems may differ from those observed in temperate systems (Longhurst and Pauly, 1987). Therefore, evaluating the range of temporal variations over a period of hourly, daily and annual time scales is of critical importance to assess the representativeness of observed planktonic processes (Tsai et al., 2005).

Planktonic functioning in the South-West lagoon of New Caledonia has received increasing attention in the recent years (Jacquet et al., 2006; Torréton et al., 2007; Conan et al., 2008; Rochelle-Newall et al., 2008; Pringault et al., 2009; Faure et al., 2010), however, most of these process studies were performed during short campaigns. Several recent studies have described temporal variations of phytoplankton standing stocks in this system (Rodier and Le Borgne, 2008; Le Borgne et al., 2010; Fichez et al., 2010; Torréton et al., 2010) and all suggested moderate seasonal fluctuations compared to variations at shorter time frames.

The objective of this study is to assess spatio-temporal variations of phytoplankton biomass in relation to environmental forcing in a tropical coastal ecosystem, the South-West lagoon of New Caledonia. We compare the variability of chlorophyll a concentration, as well as temperature and salinity at four sites: one "coastal" station, two "lagoon" stations subject to different hydrographic conditions, and one "oceanic" station.

At first, we will assess temporal variability at different time frames of these parameters over the May 2008 - April 2011 period, in relation to meteorological conditions (precipitation and wind). The short-term scale will be considered first, in order to describe the different factors taking place. This will allow a better interpretation of seasonal and long-term variations, which occur with a certain periodicity and within possible trends. Thus, knowledge of such long-term variations is important for environmental management and climate change projections.

Then, we will examine the spatial distribution of phytoplankton biomass in relation to meteorological and hydrographic conditions.

2.Material and methods

2.1. Study site

New Caledonia (Figure 1) is a island included in the French territories, which is located in the Southwest Pacific Ocean (Coral Sea) between latitudes 19° and 23° south and longitudes 163° and 168° east, just to the north of the Tropic of Capricorn. The main island, Grande Terre, is surrounded by a 1500km long and 100-1000m wide coral barrier reef (David et al., 2010) delimiting the largest lagoon worldwide, representing approximately 22,200 km² (Andréfouët et al., 2009). It is also known for its high level of biodiversity.

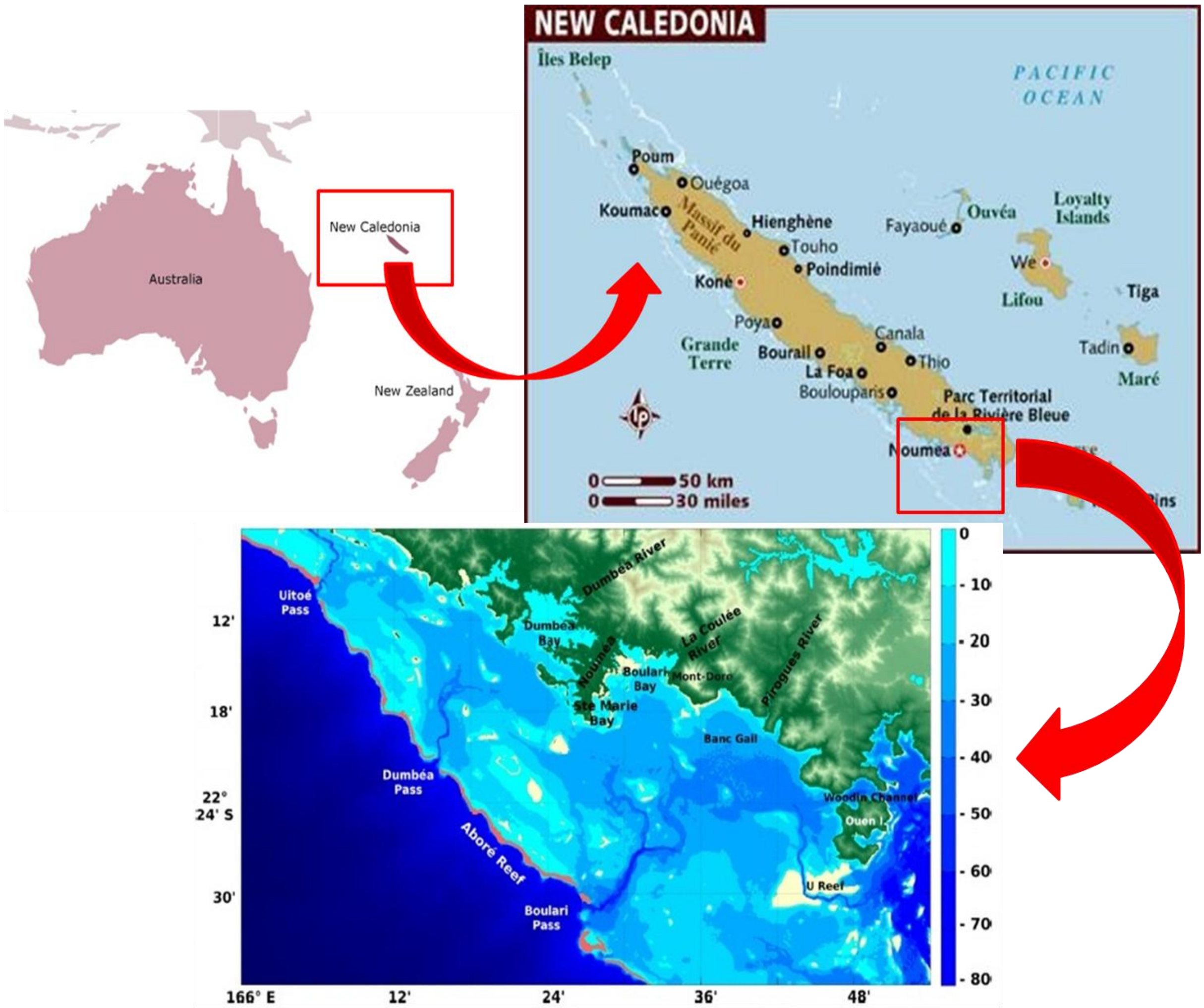

Figure 1: Location and map of New Caledonia and bathymetric map of the South West lagoon.

More than 60 percents of the inhabitants of New Caledonia live in the city of Nouméa, located in the southwest coast of the Grande Terre. The lagoon area surrounding Nouméa (Figure 1), referred as the South-West lagoon of New Caledonia (SWL), is separated from the ocean by an emerging barrier reef interrupted by 3 narrow passes. Its width varies from 5km (northern limit) to 40km (southern limit), and its mean depth is 17.5m, with maximum depths of 60-70m observed in the narrow canyons located in front of the passes. The SWL is connected to the Southern lagoon at its southeastern end, from which it receives the main input of oceanic waters. Freshwater inputs are mainly provided by the Dumbéa, Boulari, and Pirogues Rivers. Rivers outflows and runoff water carry mineral and organic particulate matter as well as dissolved nutrients that can stimulate phytoplankton growth and productivity in the lagoon (Neveux et al., 2009). The anthropogenic influence is very important in the SWL in relation with waste water and industrial effluents originating from Nouméa and its suburbs. Also, as nickel mining is the major economic resource of New Caledonia, open-cast mining have facilitated land erosion over the last century, and have increased the load of terrigenous inputs into the lagoon (Fernandez et al., 2006). Lagoon water quality hence is considered as chiefly determined by ocean water inflow, land originating inputs and anthropogenic inputs mainly originating from industrial and waste water discharges and mining activities (Labrosse et al., 2000).

2.2. New Caledonia’s meteorological context

2.2.1. Seasonal variations

New-Caledonia’s climate is mainly constrained by the position of the Inter-tropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) (Caudmont and Maitrepierre, 2007). From January to March (warm season), the ITCZ is in its southernmost position, rainfall is heavy and tropical storms or cyclones can affect New Caledonia. When the ITCZ moves to the northern hemisphere (mid-May to mid-September), cold fronts carrying polar air from the Tasman Sea can occasionally bring heavy rainfall. The intermediate periods (April– May and September–December) are characterized by sunny and dry weather (Ouillon et al., 2005).

Concerning the seasonal variations of wind regime, they are characterized by two major seasons (Caudmont and Maitrepierre, 2007). From October to May, strong southeasterly (∼110◦) trade winds dominate while wind velocity is weaker and direction more variable from June to September (Ouillon et al., 2005).

2.2.2. Inter-annual variations

Rainfall may vary significantly from one year to another. Nicet and Delcroix (2000) analyzed the correlation between anomalies in precipitation in New Caledonia with the Southern Oscillation Index (SOI), which is a good indicator of ENSO variations. They showed that ENSO modulates rainfall regime in New Caledonia with a 20-50% decrease (increase) during El Niño (La Niña) events.

The Southern Oscillation Index (SOI) is calculated from the monthly fluctuations in the air pressure difference between Tahiti and Darwin. When this index is negative (respectively positive) the Pacific is in phase popularly known as an El Niño episode (respectively La Niña). These negative values are usually accompanied by sustained cooling of the western tropical Pacific Ocean, an increase in the strength of the Pacific Trade Winds, and a reduction in rainfall over the region. Positive values of the SOI are associated with lower Pacific trade winds and warmer sea temperatures in the western tropical Pacific Ocean, as well as at a higher precipitation rate.

2.3. Sampling

Sampling was done on the IRD ship the “Coris” in the framework of the ValHyBio (Validation Hyperspectral of a Biogeochemical model) monthly survey project. Different types of measurements were carried out in four stations of the SWL (Figure 2) every month over a period of three years (May 2008 – July 2011), in order to observe the evolution of different parameters in function of spatial and temporal variations.

Stations were chosen to represent a panel of the variety of sites which can be found in the lagoon. The four stations (Figure 2) have the following characteristics:

-GD10: in the inner lagoon, just outside the Bumbéa bay, the bottom is composed of muddy sand and algae, and the depth is about 20m.

-M33: in a channel of the outer lagoon near the Maître Island, with a bottom composed of grey sand, and a depth of 23m.

-G003: in the inner reef, near the Crouy Island, where the sand is white, with a depth of 11m.

-OC1: outside the lagoon, in the open ocean near the Dumbéa pass, with a depth > 500m.

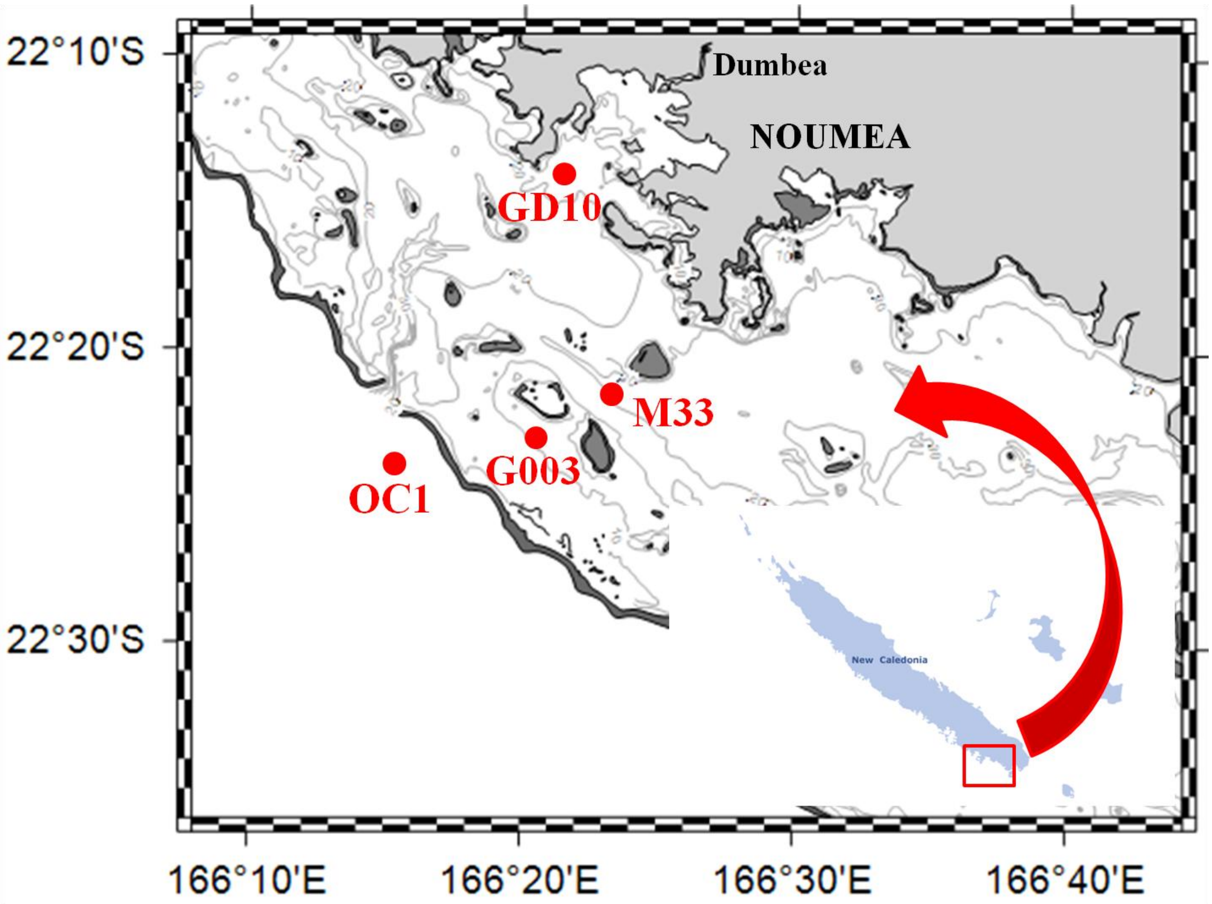

Figure 2: Map of the South West lagoon of New Caledonia showing station locations.

2.4. Field works

Measures of temperature, salinity, and fluorescence were made on the water column thanks to a SEABIRD CTD (Conductivity-Temperature-Density) probe of type SBE 19 equipped with additional in-situ fluorescence (Wet Lab Wetstar) sensor. The Wetstar fluorometer allows to measure chlorophyll a fluorescence which is light that has been re-emitted after being absorbed by chlorophyll molecules of phytoplankton. In our case, light is emitted at 470nm and the signal is recovered at 695nm. The results are given in mg.m^{-3} and correspond to chlorophyll a concentration. The spatial and temporal variability of chlorophyll a concentration can be rapidly estimated by fluorescence as sensors are relatively cheap, easy to use and can rapidly provide depth-profiles.

Discrete water samples were collected with a 5L Niskin bottle at around 2.5m depth at each station and shielded from the light in two 5L bottles per station made of polyethylene (NALGENE), while waiting for the filtrations in laboratory.

2.5. Laboratory works

Filtrations were carried out in the laboratory of marine chemistry directly after the field work to prevent water samples from degradation linked to temperature and light.

Chlorophyll a measurements were made by filtering 500mL of seawater on 0.7µm Whatman GF/F filters. Filters were placed in cryotubes and frozen at -80°C before being analyzed fluorometrically following Holm-Hansen et al. (1965) on methanol extracts. The main interest of the fluorometric method (Yentsch and Menzel, 1963; Holm-Hansen and al., 1965; Lorenzen, 1966) with regard to the spectrophotometric one is its highest sensibility. It also allows handling samples of more reduced volume (0.1 to 1L against 5 to 10L for the spectrophotometric method), what represents a considerable saving of time. Furthermore, the measure is made by direct reading at a single wavelength. After the extraction of pigments on methanol, samples are excited by a beam of light at 450nm and the emitted fluorescence is measured at 670nm. Each extract’s fluorescence is measured twice, one time before and one time after acidification. The decrease of fluorescence observed between these two readings is in connection with the relative percentage of chlorophyll a with regard to the sum chlorophyll a + pheophytin a.

At the marine chemistry laboratory, we use a Turner Designs TD700 fluorometer equipped with an optical kit n°7000-961 including:

- blue light lamp F4T5 with a emission spectrum varying between 360 and 600nm,

- excitation filter λ_{ex} = 340-500 nm,

- emission filter λ_{em} > 665 nm,

To have a reliable reading, it is advised to switch on the device at least one hour before its use. As long as filters and lamp were not manipulated, the calibration does not need to be systematically redone every time the device is switched off. The last calibration is automatically kept in memory.

The Holm-Hansen et al. (1965) method is simple and fast and allows to determine selectively weak concentrations of chlorophyll a (chl-a) and pheophytin a (pheo-a).

We define in this study the total chlorophyll a (Tchl-a) as the sum of chlorophyll a + phaeophytin a. Indeed, we assume that the sum of chlorophyll a + divinyl chlorophyll a measured by spectrofluorometry and the sum of chl-a + phae-a measured by fluorometry give comparable results, as observed by Neveux and Lantoine (1993).

2.6. In-vivo fluorescence validation

To validate in-vivo fluorescence data, we first calculated surface chlorophyll a fluorescence as the mean of the 2.5-3.5m depth Wetstar values collected with the SeaBird CTD at the 4 monthly visited stations from July 2009 to July 2011. Then, we compared these surface values with correspondent values of extracted Tchl-a measured by fluorometry. The simple linear regression obtained between both parameters is presented in the Figure 3.

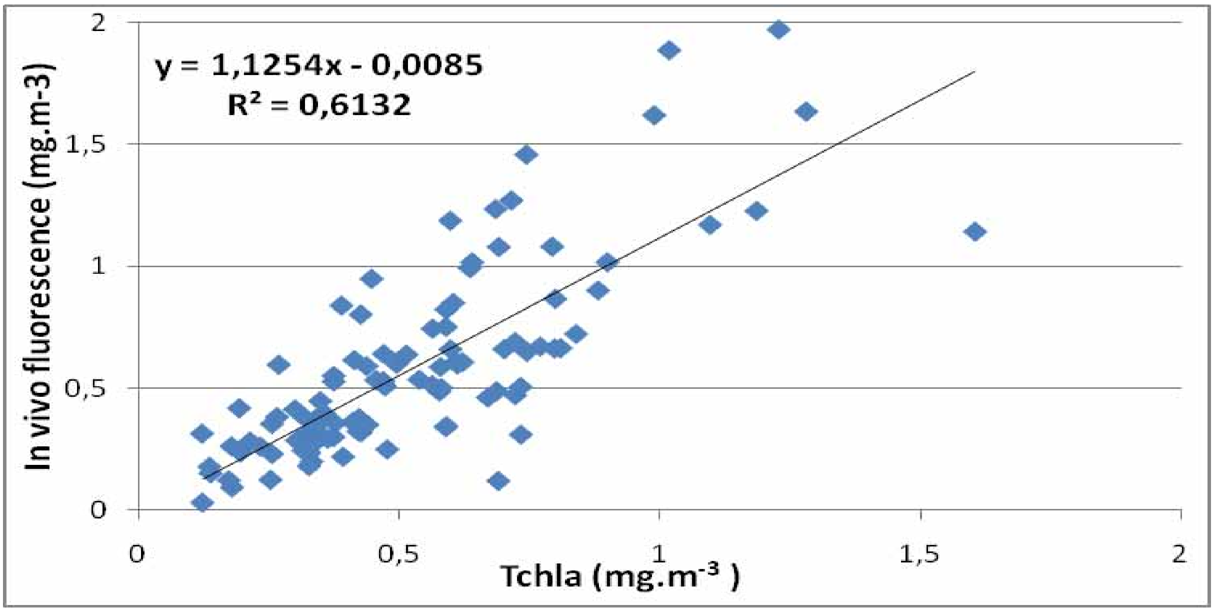

Figure 3: Relationship between surface in vivo fluorescence calculated as the mean of the 2.5-3.5m depth values and extracted total chlorophyll a measured by fluorometry for the July 2009-May 2011 period.

We observe a significant linear relationship ($R^2 = 0.61$; n = 103) between both parameters and the value of the slope (1.13) is close to one which signifies that fluorescence values can be used without being modified to be comparable to Tchl-a values.

2.7. CTD data processing and Surfer

Data collected by the CTD were extracted using SeaTerm software as terminal program. Then, the raw data obtained were converted using SBE Data Processing software. The modules "Data Conversion", "Filter", "Align CTD", "Loop Edit", "Derive", and "ASCII Out" were successively performed to obtain usable data.

Graphics representing the variability of the CTD's data (temperature, salinity, and fluorescence) in the water column as a function of time were performed using Surfer 8 software. The kringing method was used to grid the data. It is a geostatistical interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown areas.

2.8. Meteorological variables

Wind and rainfall were recorded at the Meteo France station at Faubourg Blanchot in Nouméa. Southern Oscillation Index (SOI) data were taken on the website: www.cpc.noaa.gov/data/indices/soi.

Additional field and laboratory works realized during the master thesis project are presented in appendix A.

3.Results

3.1. Temperature

The maximum sea surface temperature (SST) observed is 28.24°C at GD10 the January 04th 2011 and the minimum is 21.72°C at G003 the September 03rd 2008 (Figure 4). Figure 4 shows us a clear seasonal trend in SST at all the stations, with temperature increasing from September to February, and decreasing from March to August. We also remark that the seasonal variability is higher than inter-annual one.

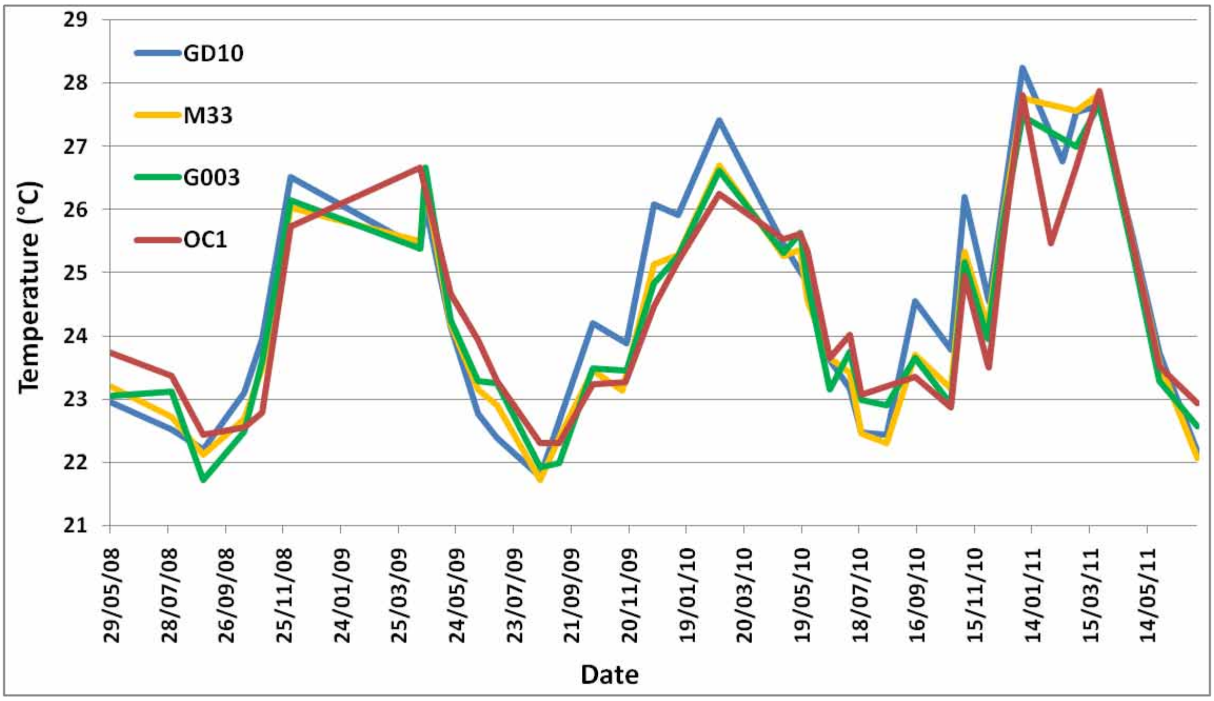

Figure 4: Temporal variations of sea surface temperature (in °C) calculated as the mean of the 2.5-3.5m depth values obtained with a SeaBird CTD at the 4 monthly sampled stations over the May 2008-July 2011 period.

If we consider the distance to the coast of the 4 stations, we observe a temperature gradient from the coast to the barrier reef and the ocean that inverse seasonally (Figure 4). During austral summer, temperature is maximal in the bays and near the coast and decrease going to the reef, to be minimal in the ocean. In winter, the gradient is reversed, with surface water temperature maximal in the ocean and minimal close to the shore.

If we examine now the vertical profiles of temperature at each station (Figure 5), we observe that the water column is generally well mixed inside the lagoon (Figure 5 a, b and c). However, a weak thermal stratification can sets up during summer, as between January and April 2011 when temperatures were the highest of the series. It is more pronounced in the ocean bordering the lagoon (OC1 station) where we note a strong thermal stratification of the 0-100m layer during the warm season whereas the water column is homogeneous the rest of the year (Figure 5 d).

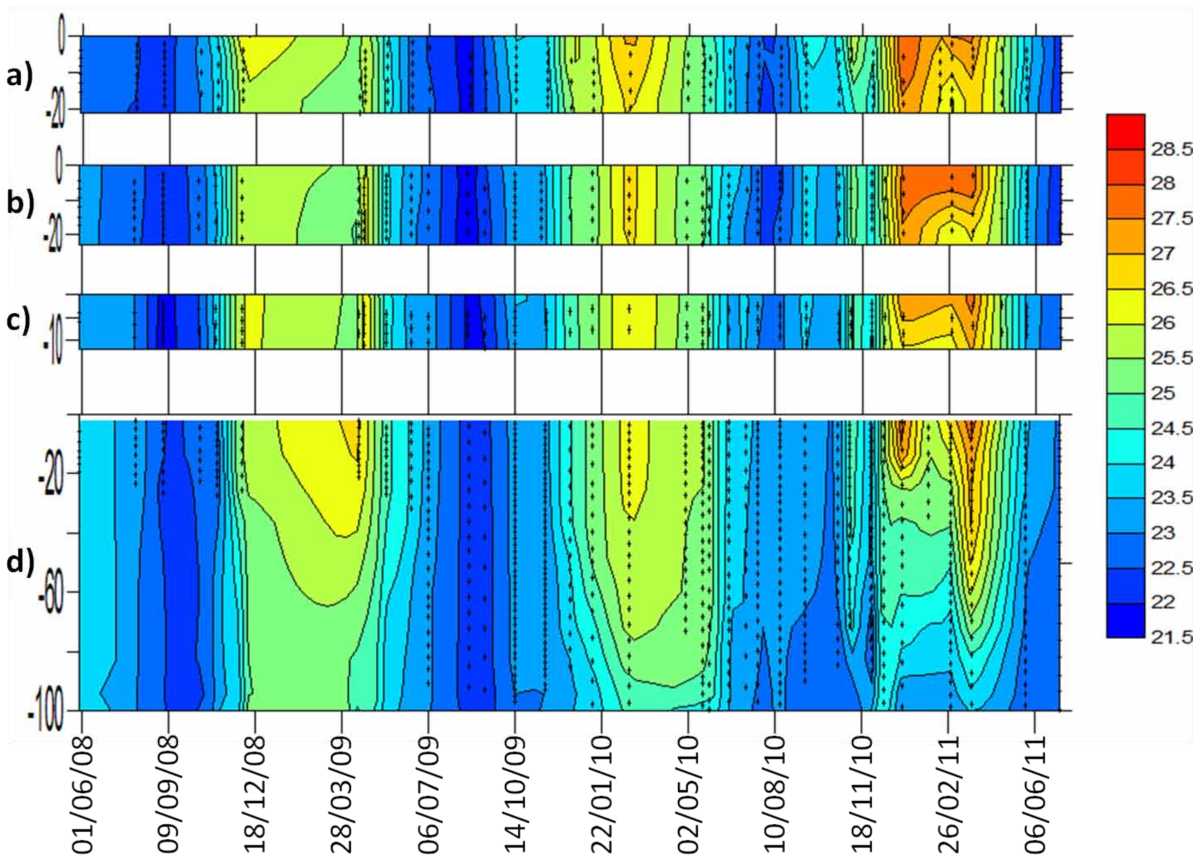

Figure 5: Interpolated temporal variation (May 2008-July 2011) of temperature (in °C) along depth at GD10 (a), M33 (b), G003 (c), and OC1 (d), collecting during the ValHyBio monthly survey in the SWL of New Caledonia.

3.2. Salinity

The maximum sea surface salinity (SSS) observed in our data is 35.79 the December 14th 2010 at I12 and the minimum is 34.33 the April 22nd 2009 at GD10 (Figure 6). Unlike what we observed with temperature, figure 6 does not show clear trend in SSS. We remark that salinity tends to decrease at the 4 stations for summers 2009 and 2011 while it increases for summer 2010, except an important diminution between December and January. We have to note that summer 2009 cannot be clearly studied due to the lack of data for almost the entire period (no data between December 03rd 2008 and April 17th 2009). However, the strong decline in salinity observed between the two dates let us think that SSS tended to decrease during this period. Then for every year, we observe a general increases in SSS from April to December approximately.

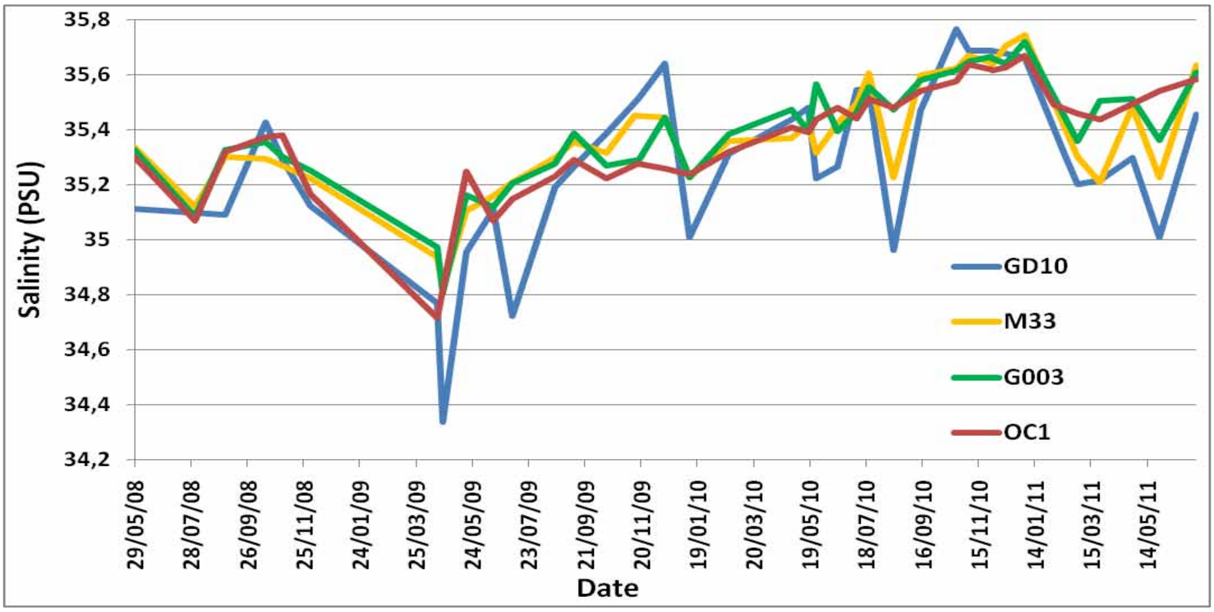

Figure 6: Temporal variations of sea surface salinity (in PSU) calculated as the mean of the 2.5-3.5m depth values obtained with a SeaBird CTD at the 4 monthly sampled stations over the May 2008-July 2011 period.

Another important point has to be noted as regards to the variability between the stations (Figure 6). For summer 2011, salinity usually exhibit a decreasing gradient from the ocean to the shore whereas it is the reverse for summer 2010 with minimum value generally found at the oceanic station (the lack of data for summer 2009 prevent us from analyzing this period). During the rest of the year, salinity is almost systematically higher in the ocean than in the lagoon.

Concerning the vertical profiles of salinity at each station (Figure 7), we observe that the column water is generally well mixed, wether in the lagoon or at OC1. However, temporary haline stratification can occasionally occur in the lagoon, especially between January and May. We remark as well that this stratification is mostly visible at GD10 (Figure 7 a), becoming weaker as we move offshore. Finally, haline stratification is very rare at OC1 (Figure 7 d).

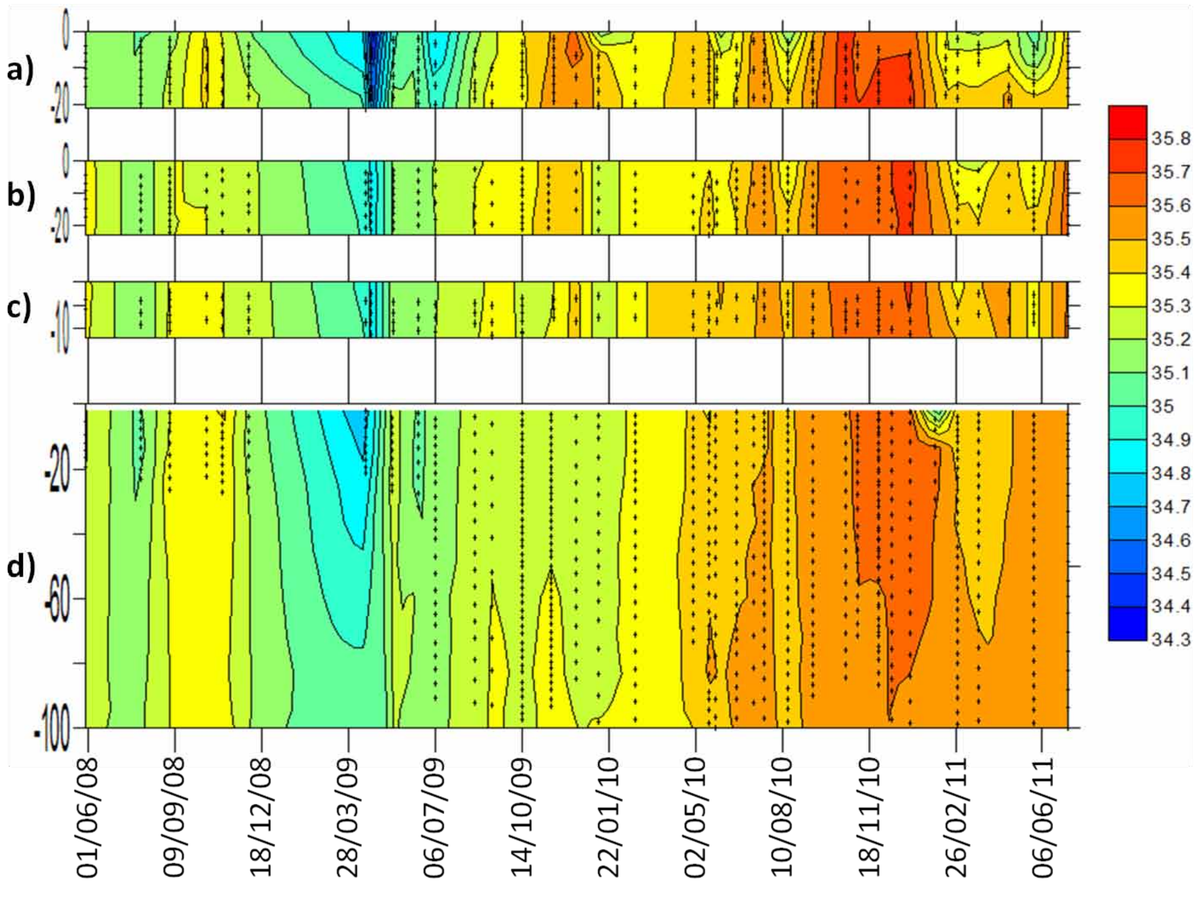

Figure 7: Interpolated temporal variation (May 2008-July 2011) of salinity (in PSU) along depth at GD10 (a), M33 (b), G003 (c), and OC1 (d), collecting during the ValHyBio monthly survey in the SWL of New Caledonia.

3.3. Chlorophyll a

3.3.1. Surface Tchl-a variability

We will interest first on surface extracted total chlorophyll a measured from April 2008 to May 2011. Maximum and minimum values at each station, as well as the mean ± standard deviation are reported on table 1.

Table 1 : Minimum, maximum, and mean (± standard deviation) of surface extracted total chlorophyll a (in $mg.m^{-3}$) measured by fluorometry at the 4 stations monthly visited from April 2008 to May 2011.

	OC1	G003	M33	GD10
Min	0.12	0.14	0.12	0.26
Max	0.8	1.60	0.99	1.37
Mean	0.41 ± 0.2	0.61 ± 0.30	0.45 ± 0.18	0.58 ± 0.26

This table shows us that within the lagoon (for the 3 stations inside the barrier reef, see Figure 2), chlorophyll values vary between 0.12 $mg.m^{-3}$ (at M33 the December 16^{th} 2009) and 1.6 $mg.m^{-3}$ (at G003 the May 26^{th} 2010). Outside of the barrier reef, values are sensibly lower. They vary between 0.12 (December 16^{th} 2009) and 0.80 $mg.m^{-3}$ (July 21^{st} 2010).

To interpret the means, Kruskal-Wallis test was done first to verify that means are not all considered as statistically similar. The result (p-value = 6.10^{-4}) prove us that at least one mean can be considered as different from the others. Then, Wilcoxon-Mann-Whitney test was performed. Results (see Appendix 2) teach us that surface Tchl-a means at GD10 and G003 cannot be considered as significantly different. The same conclusion is done between G003 and OC1. As regards to the comparison of means between GD10 and M33, we see that they are also not statistically different. However, the weak value of the result, hardly upper to the threshold value, as well as the low size of the sample, lets us think that it can be considered as little significant compared with the previous results. Results show as well that OC1 station values are remarkably different from those of GD10 and G003.

GD10 and G003 present thus global surface chlorophyll values sensibly similar, whereas M33 appear quite aside in the lagoon, with values closer to those of OC1. Those conclusions are confirmed by the means values presented in the Table 1.

Figure 8 presents the surface Tchl-a time series at the 4 stations station over the 3 years study period (2008-2011).

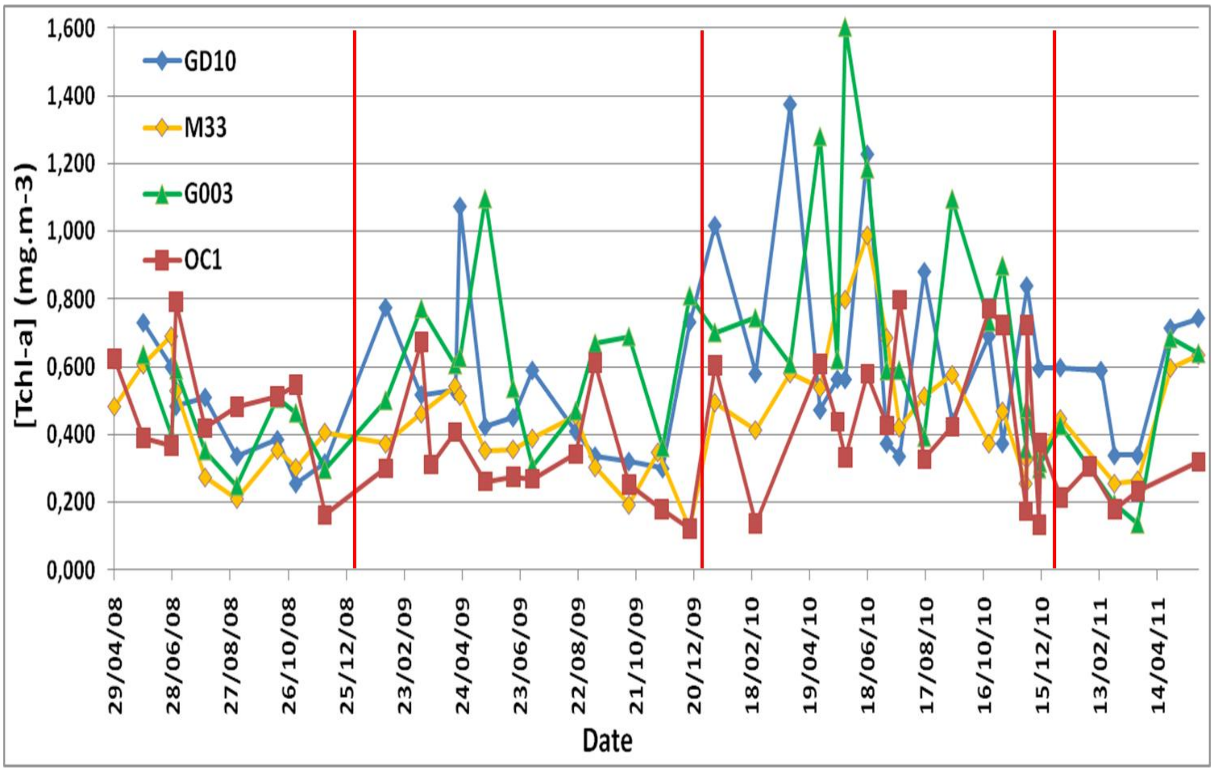

Figure 8: Temporal variations of surface Tchl-a (in mg.m^{-3}) measured by fluorometry at the 4 monthly sampled stations over the April 2008-May 2011 period.

Important points have to be noted as regards to the whole data.

Firstly, it appears that variations between two consecutive sampling are in the same range than annual variations.

Secondly, concentrations in the lagoon appear higher between January and June compared to the rest of the year, with maximum concentrations observed between April and June. We remark as well that following a first increase generally noted in January, Tchl-a concentration tend to decrease in February-March (up to a very low level in some case as in 2011), before increasing again in April.

Finally, concentrations in 2010 were higher than for the other years. We recorded a mean of 0.61 mg.m^{-3} in 2010 when it was of 0.45 mg.m^{-3} during the rest of the study period.

If we observe now each station profile individually (Figure 8) we remark that highest Tchl-a concentrations are reached at GD10 and G003 whereas values at M33 and OC1 are lower (see also Table 1). Concerning the Tchl-a peaks, we observe that they generally do not appear at the same moment in all the stations.

Figure 8 show us that during austral spring (September to December), very low values are generally noted at GD10 and M33 while values at G003 are high (September to November). Low Tchl-a concentration is usually observed at G003 in summer (July-August) and in December.

Clear seasonality is less visible at OC1 (Figure 8). We observe several peaks at periods corresponding to those in the lagoon (January, April-June). The two highest values are reached in July 2008 and 2010 (0.793 and 0.798 mg.m^{-3} respectively). Whereas we note that surface concentrations are generally significantly lower at this station compared to the lagoon, we remark that during those periods surface Tchl-a is higher at OC1 than at the 3 lagoon stations. Similar episodes are visible in austral spring (September-November 2008, September 2009, and October-November 2010), but they are usually accompanied by almost similar surface Tchl-a values at G003. Concerning the lowest OC1 surface Tchl-a concentration, they generally occur in December.

3.3.2. Vertical profiles description

We will now analyze the vertical distribution of in situ chlorophyll a related fluorescence in the water column from July 2009 to July 2011 (Figure 9). It is used here to assess the representativity of discrete water sampling. It will also allow us to determine if surface enrichments remain superficial or are linked to the whole water column.

Figure 9 shows that in the lagoon (a, b, c), despite occasional sub-surface maxima, the most common trend observed correspond to an increase with depth of chlorophyll a, with maximum values reached at the bottom.

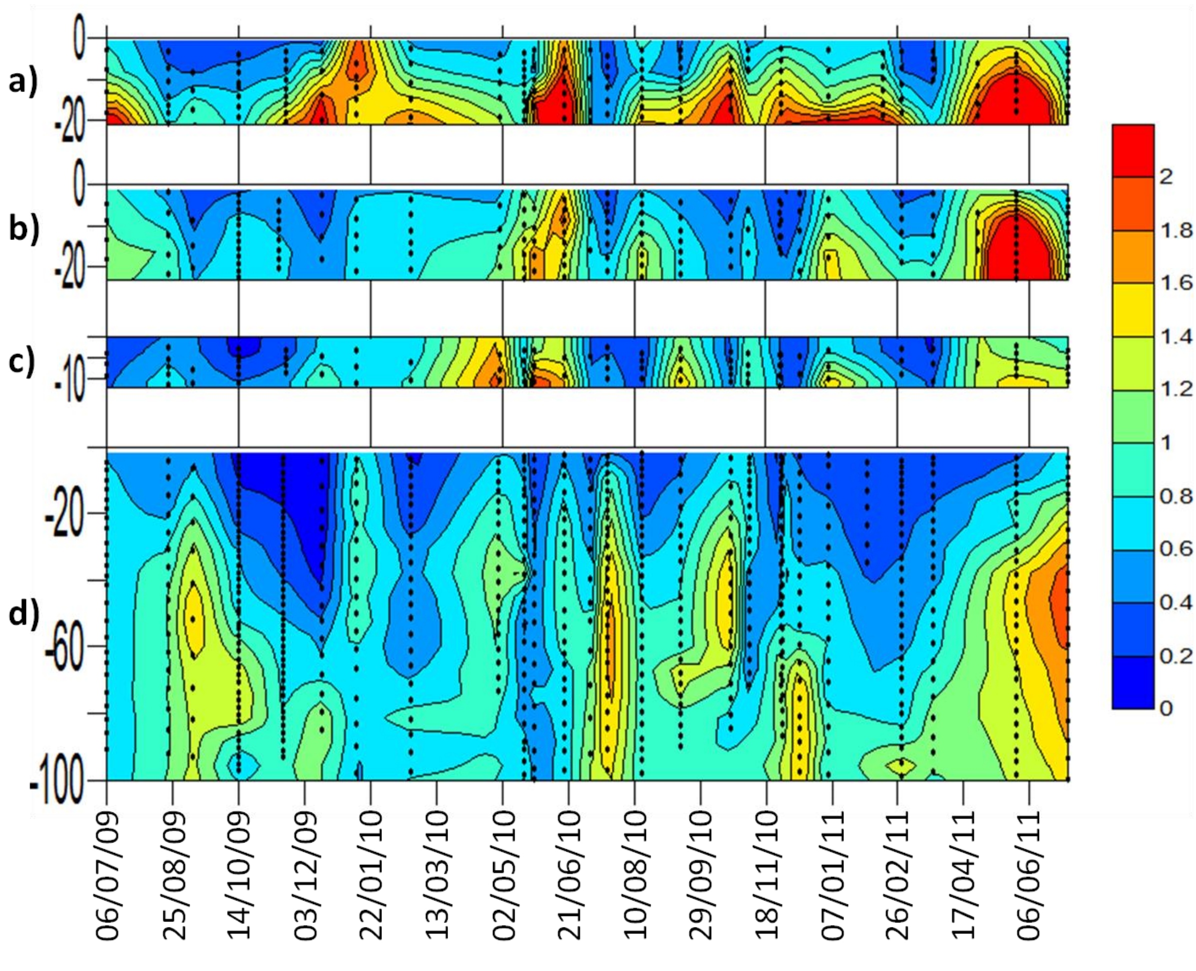

Figure 9: Interpolated temporal variation (July 2009-July 2011) of in vivo chlorophyll a fluorescence (in mg.m^{-3}) along depth at GD10 (a), M33 (b), G003 (c), and OC1 (d), collecting during the ValHyBio monthly survey in the SWL of New Caledonia.

At oceanic OC1 station (Figure 9 d), fluorescence shows a deep maximum (typical in oligotrophic zones), generally included between 50 and 80m during major fluorescence increase episodes. We remark that during the two strongest episodes, visible on July 2010 and

July 2011 (which corresponds to the same maximum concentration period than the one noted for Figure 8), chl-a is well distributed along the 0-100m column water and spread deeper than most of other weaker episodes that appear more superficial. We can also see, like noted previously with surface Tchl-a values, that these strong July episodes appear as chlorophyll concentration in the lagoon is particularly weak.

Comparing the fluorescence values at the 4 stations, we note differences with observations made previously. Indeed, we reported from surface extracted Tchl-a data (Table 1 and Figure 8) that values at G003 and GD10 are almost similar and clearly higher than in the 2 other stations. Vertical profiles presented in Figure 9 do not show the same trend. We remark that values at GD10 (Figure 9 a) are obviously higher than at the 3 other stations. Furthermore, values at G003 (Figure 9 b) appear fairly comparable to those observed at M33 and OC1.

3.4. Principal component analysis

Principal component analyses were performed to determine parameters influencing most the surface chlorophyll a variation at each station. We used, as a supplement to the data of surface Tchl-a concentration, data of precipitation and wind (obtained from the Faubourg Blanchot meteorological station) averaged over the 5 days preceding sampling date, as well as data of sea surface temperature and salinity from the Seabird CTD (calculated as the mean of the 2.5-3.5m depth values).

Results of the PCA at GD10 (Figure 10 a) show that surface Tchl-a concentration at this station is positively correlated with precipitation along the first axis, and to a smaller extent positively with wind and negatively with salinity.

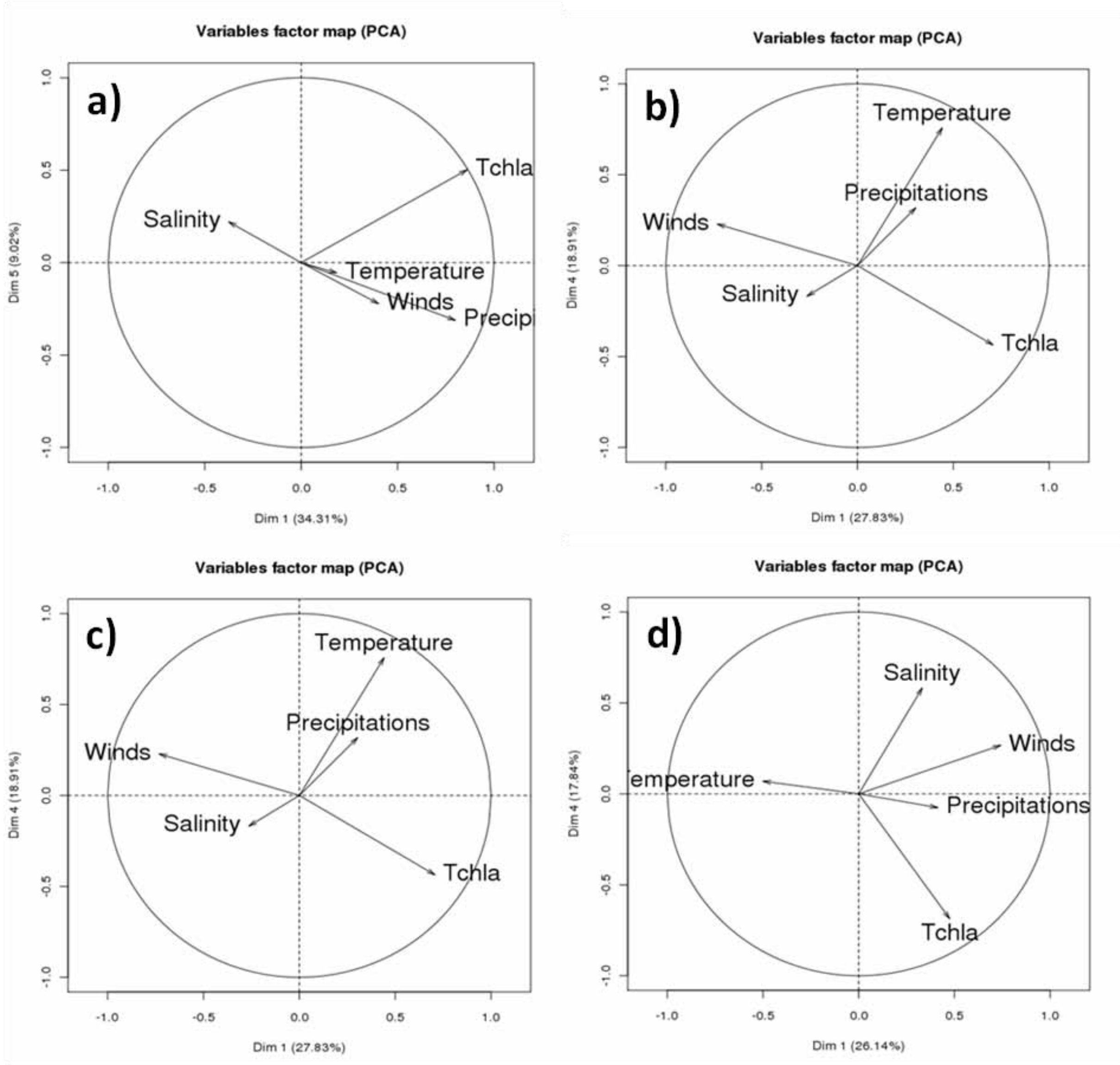

Figure 10: Variables factor map for GD10 (a), M33 (b), G003 (c), and OC1 (d).

At M33 (Figure 10 b), we find that Tchl-a is negatively correlated with wind along the first axis.

Results at G003 are vague (Figure 10 c), but seem exhibit negative correlation between Tchl-a and salinity along the fourth axis and weaker positive one between Tchl-a and wind along the first axis.

Finally, results of the PCA at OC1 (Figure 10 d) show that surface Tchl-a concentration is positively correlated with wind and negatively with temperature, both along the first axis.

4.Discussion

4.1. Short-term variability

Here, we describe variations which take place during periods of about one month. We remarked that short-term variations are in the same range than annual variations, as noted by Torréton et al. (2010) at shorter variability scale (2 weeks). From previous studies, it appears clearly that short-term variations are linked to local meteorological events, precipitation and wind essentially (Neveux et al., 2009; Torréton et al., 2010). To determine the main factors influencing Tchl-a variability, we made a principal component analyze (PCA) at each station.

4.1.1. In the lagoon

We found a direct impact of precipitation on Tchl-a only at GD10, located at the mouth of the Dumbea bay which is under the influence of the Dumbea river. At this station, Tchl-a is positively correlated with precipitation and negatively with salinity, which means that an increase in rainfall, and thus a decrease in water salinity, results in a higher chlorophyll concentration. Ouillon et al. (2010) observed that average freshwater inputs to the SWL are weak since the catchment areas are small and, when freshwater inputs occur, they are generally reduced to a period of a few days at most. It was also determined that effect of short heavy rain period provoke only a local increase of Tchl-a and do not seem to strongly impact the community of central lagoon (Neveux et al., 2009). We can so deduced from our results and from literature that only exceptionally strong or long rainfall events are able to affect the lagoon at a regional scale, usual precipitation only impacting bays and adjacent area at a local scale.

Concerning wind, we found a relationship between this factor and Tchl-a at the three lagoon stations. However, the nature of the effect appears different depending on the station. We observe a positive correlation at GD10 and G003, meaning that wind at those station induce higher Tchl-a, whereas correlation is negative at M33, showing that productivity is higher in absence of wind.

At GD10, the positive correlation found can be explained by the fact that trade winds promote surface water transport from the Dumbea bay to the station so favoring the productivity in this place, as observed by Neveux et al. (2009) at the scale of the whole SWL.

This phenomenon can also explain the similar correlation observed at G003. It is partially confirmed by the inverse correlation observed between Tchl-a and salinity, which can be linked to the influence of two different water sources. The first water type is the slightly desalted coastal water, transported by trade wind and tide, with relatively high nutrient concentration enhancing productivity; the second one is the oceanic saltier water with low nutrient content, which penetrates the lagoon through passes and over the barrier reef. Productivity at this station is thus dependant of the contribution of each water type which is in turn partially wind induced. However, wind may also act on the productivity in a different way in that case. Indeed, the shallow depth of this station let us think that wind is able to stimulate phytoplankton growth through resuspension of nutrient rich sediment, as observed in the shallow waters of the Great Barrier Reef (Ullman and Sandstrom, 1987; Gabric et al., 1990; Muslim and Jones, 2003).

Finally, we observed at M33 a negative correlation between wind and Tchl-a which can be explained by the position of the station in a channel. Wind forcing is, with tide, the major mechanism driving the lagoon circulation (Ouillon et al., 2005). As trade wind increases, the water circulation in the channel will also increase, reducing the local residence time of water and thus resulting in a decrease of the productivity (Torréton et al., 2007).

As expected, we can conclude that the short term variability in the SWL is closely linked to wind and precipitation. However, as noted by Le Borgne et al. (2010), causes of these temporal variations are quite complex: some causes may originate locally, when other are regional. Interpretation of observed Tchl-a concentration should thus not be restricted to only terrigeneous inputs or sediment composition at a local scale. Changing from a local to regional scale will depends on the duration and geographical extension of the meteorological event.

Effects of nutrients inputs induced by precipitation are more pronounced in semi-closed areas (bays) than in the rest of the lagoon, where productivity is mostly wind dependant.

4.1.2. At the oceanic station OC1

The clear positive correlation observed between Tchl-a and wind at this station can be explained by two mechanisms. Firstly, due to its position near the Dumbea pass, we can consider that most Tchl-a increases are related to nutrient outputs from the lagoon (Le Borgne et al., 1985; Neveux et al., 2009), which are widely controlled by trade winds. Indeed, stronger the trade winds are, higher the lagoon nutrient-rich water outputs will be, leading to an increase of productivity in the area surrounding the pass. Secondly, during strong trade wind events, a temporary upwelling could occasionally occur along the barrier reef (Ganachaud et al., 2010; Marchesiello et al., 2010), enhancing phytoplankton production in the region (Henin and Cresswell, 2005).

Concerning the negative correlation observed with temperature, it is probably related to a regional phenomenon. Dandonneau and Gohin (1984) observed an increase in surface water chlorophyll of Coral Sea until 20°S during winter water cooling and consecutive water column mixing. This phenomenon has been observed at the OC1 station by Neveux et al. (2009). As temperature increases, the thermal stratification of the water column will also increase and stop the exchange between the euphotic zone and the nutrient rich deep water. The productivity of the surface water will thus be very low. In winter, the disappearance of the thermocline will increase the vertical mixing and thus the nutrient supply of surface water. The phytoplankton productivity will so be enhanced.

4.2. Seasonal variation

4.2.1. Temperature

Our study shows clear seasonal variations of sea surface temperature compared to other physical and biological parameters, as previously observed by Jacquet et al. (2006). And as noted by Ouillon et al. (2005) these seasonal changes are higher than inter-annual variations. Water temperature is maximal during the warm season (austral summer) between December and May and minimal during the cool season (austral winter) between July and September. Furthermore, whereas the water column in generally well mixed during the whole year in the lagoon, we observe a strong stratification of the 0-100m layer in the surrounding ocean during austral summer, as previously observed by Neveux et al. (2009).

Regarding to the ocean-shore gradient reversing seasonally that we evidenced previously, we can maintain that temperature is varying in the same way in the lagoon as at a regional scale (due to the connection between the lagoon and the ocean through passes) with seasonal variations amplified in shallower and island-influenced lagoons, as remarked by Ouillon et al.(2005).

4.2.2. Salinity

A relatively clear seasonal signal in salinity has been evidenced through a 35 years (December 1974 - January 2010) time series data (Magnen, 2010). It was established that salinity tends to decrease from December to April (wet season) and to increase from April to December (dry season) due to rainfall in summer. This trend was observed as well by Neveux et al. (2009) and Le Borgne et al. (2010) on shorter time scale studies.

The minimum and maximum salinity noted (respectively in April and December) correspond well to the cycle previously described, as well as the observations made for summers 2009 and 2011. However, summer 2010 do not agree since salinity clearly tended to increase during this period. It could be explained by the fact that salinity of oceanic waters entering the lagoon knows more important variations due to ENSO (inter-annual variability) rather than to the seasonal cycle, as reported by Delcroix and Lenormand (1997) and Gouriou and Delcroix (2002).

4.2.3. Chlorophyll a

Seasonal variations of phytoplankton biomass and production are generally low in coral reef lagoons (Burford et al., 1995; Furnas and Mitchell, 1986; Torréton and Dufour, 1996). Moreover, any seasonality found is often variable and is superimposed by short term variations due to meteorological forcing such as sediment resuspension (Muslim and Jones, 2003; Walker and O'Donnell, 1981) or marine intrusion (Furnas and Mitchell, 1986; Gast et al., 1999).

New Caledonia is subject to clear seasonal variations of solar radiation, temperature, rainfall, and to a smaller extent, wind velocity and direction in its southern part (Caudmont and Maitrepierre, 2007). These variations have an effect on the lagoon environment.

While early work did not provide any evidence of Tchl-a periodicity (Rougerie, 1986), more recent ones highlighted the occurrence of seasonal trends (Neveux et al., 2009; Torréton et al., 2010; Fichez et al., 2010; Le Borgne et al., 2010). However in these works as in our study, observed seasonal fluctuations appear moderate compared to variations at shorter scales.

4.2.3.1. In the lagoon

If we consider the Tchl-a maximum observed from our data between April and June in the 3 lagoon stations, it corresponds well with temporal trends generally observed in previous works conducted in the SWL. Indeed, Neveux et al. (2009) and Torréton et al. (2010) found from their respective study a maximum included between April and June as well, while investigations of Le Borgne et al. (2010) and Fichez et al. (2010) showed it respectively between mid-May and June and at the end of May.

Most of them (Torréton et al., 2010; Le Borgne et al., 2010; Fichez et al., 2010) also reported important peaks in January like in the present study.

Hence, our data set is in agreement with the few studies so far investigating Tchl-a seasonality in the SWL of New Caledonia.

Those two periods of relative surface Tchl-a maximum are thus observed at the beginning and at the end of the austral summer warm season (January-March) during which water temperatures, solar radiations, and precipitations are maximum (Caudmont and Maitrepierre, 2007). Several hypotheses can be emitted to explain this.

A first one concern the light intensity, quite lower in January and between April and June than during summer, what could lead, as noted by Le Borgne et al. (2010), to a higher chlorophyll a concentration independently of the phytoplankton biomass. Those noted Tchl-a maximum could thus be a consequence of phytoplankton's photoadaptation rather than phytoplankton biomass increase.

We can also consider that this variability is imposed by nutrients cycle. Nutrient surveys in the SWL are relatively recent, and were not conducted over a long enough period to evidence seasonality. Most nutrients appear to have a terrigeneous origin in the SWL, their concentration being several orders of magnitude greater in estuarine systems than in the middle lagoon, as shown by Fichez et al. (2010). However, no relationship between nutrient concentration and precipitation has been found in their study, as initially expected. They noted NO_3^- maximum values at the end of May corresponding to maximum Tchl-a concentration, and NH_4^+ maximum values in January corresponding to Tchl-a peaks. Torréton et al. (2010) also observed maximum of NO_{3+2} between April and June and Jacquet (2005) found peaks of NO_3^- in June. Surface Tchl-a maximum in January and between April and June could thus be linked respectively to maximum in NH_4^+ and in NO_{3+2}. However, the relationship between seasonal signals of chlorophyll a and nutrients is still being debated due to the lack of sufficient data.

The maximum surface Tchl-a concentration found systematically at the end of the austral summer can also be related to a change in the wind regime controlling the flushing rates of the lagoon by surrounding oceanic water, as relieved by Le Borgne et al. (2010). At this period, winds velocity is weaker, and the presence of westerly winds increase. As the SWL face west, the water residence time in the lagoon thus increases, resulting in aging of water masses and therefore to higher phytoplankton biomass. This hypothesis is supported by previous works (Bujan et al., 2000; Pinazo et al., 2004; Torréton et al., 2007) showing that the distributions of some nutrients and planktonic variables were linked to the residence times of water masses.

The lowest Tchl-a concentration are observed in austral spring at GD10 and M33, as precipitations are weak (dry season), while values at G003 are rather high. It could be due to the fact that the strong trade winds season begins at this period. Indeed, G003 which is the shallowest station (11m) is more subject to sediment resuspension following strong wind events than the 2 other stations. Low values at G003 are observed in summer compared to the rest of the lagoon. During this period, occasional heavy rainfall events are often visible, but their short duration is suspected to provoke only local increases which prevent the G003 station to be impacted, as shown by Neveux et al. (2009).

4.2.3.2. At the oceanic station OC1

Due to its position close to the Dumbea pass, we can consider that OC1 station is subject to both seasonal signals affecting the ocean and the lagoon. We can define 3 distinct periods in the seasonal variation of this station.

From January to June, the strong stratification of the water column separates the euphotic zone from the nutrient-rich deep waters. Most of Tchl-a increase episodes seem thus related to output of lagoon water rich in nutrients induced by trade winds (Le Borgne et al., 1985; Neveux et al., 2009), as they concern a small thickness of surface water and exhibit chlorophyll concentration lower than in the lagoon. During strong trade wind events, upwelling along the barrier reef could also enhance phytoplankton production (Henin and Cresswell, 2005). Such episodes are accompanied by a reduced stratification and a cooling of surface water. They are recognizable as Tchl-a is distributed in the whole surface water column and shows values generally higher than in the lagoon.

Then in winter (July to September), the disappearance of the summer thermocline due to water cooling increases the vertical mixing and thus enriched the euphotic zone in nutrients (Neveux et al., 2009). This phenomenon has been noted at a larger scale in the Coral Sea until 20°S by Dandonneau and Gohin (1984). As for upwelling events, Tchl-a exhibit values widely higher than in the lagoon and is distributed all along the euphotic zone.

Finally, during the dry season (October to December), Tchl-a concentration tends to decrease to very low level with increasing stratification (Neveux et al., 2009). As the nutrient supply to the lagoon is low at this moment, lagoon water outputs induced by trade winds are generally not accompanied by surface Tchl-a increase. However, some strong trade winds events can provoke sediments resuspension in some part of the lagoon or upwelling along the barrier reef, both phenomenon leading to an enrichment of the surface water at OC1 and therefore to Tchl-a increases.

4.3. Inter-annual variability

The long-term variability scale is important in the inter-tropical Pacific with regards to the El Niño – Southern Oscillation (ENSO) phenomenon (Le Borgne et al., 2010). As previously described, from a meteorological viewpoint, El Niño periods in the western Pacific are dry, with stronger winds and cooler temperatures. Such periods feature a negative Southern Oscillation Index (SOI), while the opposite climatic regime, called La Niña, has a positive SOI. Neutral or intermediate situations are observed between the two periods (Caudmont and Maitrepierre, 2007). The SWL characteristics are affected by ENSO, due to the variation of solar radiation, wind and precipitation. As regards to our period of study, summer 2009 and 2011 presented positive SOI values (La Niña) while summer 2010 was characterized by negative ones (El Niño) (see appendix C for monthly SOI values).

4.3.1. Temperature

Inter-annual variations related to El Niño/La Niña events are not clearly emerging from temperature temporal variations because of the strong annual signal, as mentioned by Le Borgne et al. (2010) when studying the 1979-1989 period. We however remark in our data that temperatures for summer 2010 (El Niño) were slightly lower than for other years (we note a lack of data for the summer 2009, but looking at the values before and after summer, temperatures are expected to be higher during this summer than during the next one).

4.3.2. Salinity

To understand the inter-annual variability of sea surface salinity, it is essential at first to establish factors responsible for its variations in and outside the lagoon. Salinity in the lagoon is first induced by oceanic waters entering the lagoon. As mentioned previously, salinity of such waters is subject to inter-annual variability (linked to ENSO) higher than their seasonal variations (Delcroix and Lenormand, 1997; Gouriou and Delcroix, 2002).

During El Niño event, the oceanic waters bordering the New Caledonia lagoon are more salted, as a result of the weak regional precipitations. During La Niña event, regional precipitations increase, inducing less salted oceanic waters. These inter-annual variations thus regulate the salinity in the SWL through oceanic waters penetrating mainly at its southeastern end.

Once in the lagoon, waters are also subject to local meteorological and hydrological ENSO consequences which will act on salinity, particularly in coastal areas (Ouillon et al., 2005). Indeed, during El Niño, low freshwater inputs resulting from weak local rainfall, as well as enhanced evaporation due to stronger winds and reduced cloud cover will reduce the salinity of water. It creates inverse salt gradients in summer, with saltier waters found in the bay, and salinity decreasing as we go offshore to be minimal in the ocean, as remarked by Ouillon et al. (2005) on a 1997-2001 time series data. This is what we observe for summer 2010 (El Niño event), and it could explain why salinity does not decrease as expected. On the contrary, during La Niña, freshwater inputs increase and evaporation decrease leading to much lower salinity in the bays than in the lagoon, with maximal values in the ocean, as seen during summer 2011.

To summarize, salinity in the SWL appears to be the result of the combined effects of local and regional precipitation and wind induced evaporation (Le Borgne et al., 2010). Salinity is seen varying in the same way nearshore than at a regional scale, with variations amplified due to the meteorological and hydrological ENSO influences (Ouillon et al., 2005).

4.3.3. Chlorophyll a

The highest Tchl-a concentrations are observed in 2010, during a El Niño episode, as precipitations are supposed to be low. This observation is the opposite of what we expected to obtain, and can be explained by various things.

Firstly, as we saw that short-term variations of Tchl-a are strong, meteorological conditions during the short period prior to the sampling date are important and may give results that are not representative of the general trend. Indeed, although it is supposed as regards to the SOI that year 2010 was the driest of the period, we remark that in opposition to other years, samplings for year 2010 were often performed following period of heavy rainfall (see appendix D). The high values of surface chlorophyll observed in 2010 may be explained by this situation; it however does not explain why lowest values noted during this year remain widely stronger than for the other years.

Another explanation can be emitted in relation to the importance of wind on the productivity of the SWL. We know that El Niño episodes are characterized by low precipitation, but also by strong trade winds. And as seen previously wind may act on phytoplankton richness through several mechanisms, particularly the sediment resupension which will release nutrients on the water column and thus enhance primary production. The importance of such action is maybe underestimated compared with that of precipitations.

Finally, the lack of correlation between the SOI and the chlorophyll concentration, as well as the poor relation observed with temperature and salinity, may be simply related, as remarked by Le Borgne et al. (2010), to the choice of the SOI value. The SOI is an equatorial climatic index and there is no reason why a direct effect of ENSO-associated variations should be expected in the inter-tropical zone. Indeed, equator and tropic are separated in the western Pacific by the South Pacific Convergence Zone (SPCZ), and its location will affect wind and rain regimes. And although Vincent et al. (2009) has shown that the SPCZ location is correlated to the SOI, its consequences will depend on the geographical position of the region considered. It has been proved for example that the drought periods in New Caledonia corresponds to moderate rather than strong El Niño events (Vincent et al., 2009).

4.4. Spatial distribution

Considering first the vertical trend of Tchl-a concentration observed in the lagoon stations, namely an increase with depth with maximum reached at the bottom, it correspond well to the observations made during previous works (Fichez et al., 2010; Le Borgne et al., 2010). Considering the weak density stratification and the prevailing euphotic conditions, this phenomenon could be explained by photo-inhibition in the upper layer and/or nutrient inputs from the benthic system (Fichez et al., 2010). Very little is known about photo-inhibition but that process would not be of significance beyond a few meter depths. Furthermore, the second hypothesis is strongly supported by recent work on benthic metabolism and biogeochemical modeling in the New-Caledonia lagoon that concluded that pelagic primary production was strongly controlled by benthic recycling and nutrient release in the water column (Bujan et al., 2000; Grenz et al., 2003; Pinazo et al., 2004).

If we focus now on the differences evidenced between the stations, our results are consistent with literature revealing that Tchl-a concentrations in the SWL of New Caledonia are higher than in the surrounding ocean and are not uniformly distributed (Bourguet et al., 2003; Briand et al., 2004; Jacquet et al., 2006).

Rougerie (1986) evidenced studying the SWL an increasing Tchl-a gradient from the ocean through the coastal lagoon to the bays and urban effluent areas. Pinazo et al. (2004) found that eutrophication is limited to coastal bays near Noumea and that oligotrophic conditions are prevalent in most part of the lagoon. It was also shown that the southern part of the SWL, which is closer to oceanic inputs flushing the lagoon, has usually lower nutrient concentrations and plankton biomass and activity than the northern part (Jacquet et al., 2006).

From our results, we found that Tchl-a concentrations are relatively high and similar at GD10 and G003, respectively located at the mouth of the Dumbea bay and between the barrier reef and the Crouy Island, compared to values at M33 which is in a channel in the middle lagoon. Those results are thus not coherent with the barrier reef-coast increasing gradient expected to be found according to the previous studies. Two parameters may explain this difference.

It has been showed from several works that precipitations, winds, anthropogenic activities, and hydrodynamics are the main environmental factors that can explain the Tchl-a variations in the SWL (Bujan et al., 2000; Torréton et al., 2007; Neveux et al., 2009; Torréton et al., 2010; Fichez et al., 2010). Precipitations and anthropogenic activities enrich mainly bays through river and waste water discharge, while winds promote surface water transport that favor productivity in the lagoon, which explain the decreasing gradient generally found from the coastal area to the barrier reef.

However, strong winds are also responsible for sediment resuspension leading to nutrients release in the water column, and thus to enhanced primary production. This phenomenon has more impact in shallow water area, like in coastal zone or around lagoon islands. It could explain the high Tchl-a concentration observed at G003 (11m depth), in contrast to M33 (23m) which is yet closer to the shore.

The other important parameter acting on the distribution of phytoplankton blooms is the local residence time of water. Indeed, Torréton et al. (2007) evidenced significant correlations between Tchl-a concentrations and local e-flushing times in several lagoon stations. Considering our stations, it appear clearly that water residence time at M33 located in the middle of the channel and so subject to stronger water circulation is lower than at GD10 or G003 which are more sheltered. It may be responsible for the lower Tchl-a concentration observed at this station compared to G003.

5. Conclusion

The South West lagoon of New Caledonia is under the influence of both oceanic oligotrophic waters and land inputs. Each of these influences occurs within a meteorological context which, in turn, has seasonal and inter-annual variations. In addition to meteorology, the water mass turnover time is affected by geomorphology, bathymetry and hydrodynamics.

Amplitude of the temporal variability, whatever the timescale chosen, is greater nearshore and, particularly, in semi-closed basins (bays).

Short-term variations are in the same range as annual variations. In the lagoon, monthly variability is closely linked to wind and precipitation, from local or remote origin. The lagoon surface area involved will depend on the magnitude of the meteorological event. In the ocean near the barrier reef, trade winds explain most of the increase of surface Tchl-a. Indeed, most increase at OC1 appeared related to output of lagoon waters except during cooling and mixing of water in winter. Some enrichment could have an upwelled origin. Since upwelling waters drift offshore, their effect on the lagoon is questionable and needs to be proved. Moreover, to what extent this upwelling can enrich the euphotic zone in nutrients and stimulate the biological activity around New Caledonia remains an important question for environmental as well as economic point of view.

The seasonal variability is clear both in the lagoon and in the ocean for all parameters considered in this study and results from the latitudinal position of the lagoon near the tropic of Capricorn.

The inter-annual variability appears to be less marked than seasonal variability for all parameters considered. Its relation with the SOI (an ‘‘equatorial” index of the ENSO situation) is weakly significant in terms of water temperature and salinity, and does not appear significant for chlorophyll a concentration. This stresses the need for a ‘‘tropical” index which could be the location and extension of the SPCZ.

Water in the lagoon is generally well mixed with moderate to no thermal or haline stratification. Thermal stratification may occur in summer and strong haline stratification can set up in coastal areas during the wet season. Chlorophyll a concentration often significantly increases with depth, certainly as a consequence of nutrient release at the water–sediment interface. That indicates a strong relationship between pelagic production and benthic recycling.

Phytoplankton productivity is clearly higher in the lagoon than in the ocean. The maximum phytoplankton biomass is generally observed in bays and coastal area. However, the increasing Tchl-a gradient from the ocean to the coast evidenced in previous works is not emerging from our study. We find that the productivity in a certain area is more dependent on hydrographic conditions prevailing in this area, depth and local water residence time mainly, than in the distant of the site to the coast, as shown by the almost similar Tchl-a concentration observed at GD10 and G003.

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Appendix

Appendix A: Additional field and laboratory works.

As a supplement to the variables approached on this report, several other parameters were measured during my master thesis project in the framework of the ValHyBio monthly survey. Furthermore, another station was monthly visited in the plan of a different research project. It is the station I12, located close to the coast at 5m depth, in the marine protected area of the Canard Island, above an alternation of living coral and white sand. The same measurements were realized for this station than for the four stations described in the report.

Measure of turbidity was made on the water column thanks to the SEABIRD CTD probes previously described (type SBE19) equipped with an additional turbidity (Seapoint optical backscatter) sensor. Turbidity is often considered as a proxy for suspended matter concentration. The Seapoint turbidimeter detects light scattered by particles and uses a 880nm light source wavelength. The sensor was factory adjusted to a Formazin Turbidity Standard measured in Formazin Turbidity Units (FTU). The spatial and temporal variability of SPM and chlorophyll a concentration can be rapidly estimated by turbidity and fluorescence as sensors are relatively cheap, easy to use and can rapidly provide depth-profiles. The attenuation coefficient c_p was also measured with a transmissometer (10 cm path-length) coupled to the SeaBird CTD.

Various optical properties of water were also measured during field trip. The vertical profiles of the backscattering coefficient (*bb*) were realized with a Hydroscat-6 profiler (HobiLabs) at wavelengths corresponding to those of the SeaWIFS satellite (wavebands centered at 442, 488, 510, 550, 620 and 670 nm). The in-situ downwelling irradiance *Ed* and upwelling radiance *Lu* (without inclination measurement) were collected with two hyperspectral TriOS-RAMSES radiometers. The two devices have a spectral range of 320 nm to 950 nm and measure approximately every 3.3 nm. To minimize impacts of the ship shadow and reflection, the sensor measuring *Lu* was mounted in a home-made PVC frame and positioned into the water as far of the ship as possible, at exactly 5mm under the air-sea interface. The sensor measuring *Ed* was positioned pointing the sky, as horizontally as possible. From these two parameters, the in-situ water leaving reflectance was then calculated using the formula:

$Rrs = 0.98 * Lu/Ed$ (sr^{-1})

Moreover, the transparency of the water related to water turbidity was measured thanks to a Secchi disk. The Secchi depth obtained is used to calculate the light attenuation coefficient of water, noted k_w.

In complement to chlorophyll a, several other parameters were in the Marine Chemical laboratory.

For phycoerythrin estimation, filtration of 2L seawater samples was done onto 0.4µm polycarbonate membranes (NUCLEPORE). As for the chlorophyll, filters were placed in cryotubes and frozen at -80°C. They are sent later in liquid nitrogen to the “Observatoire Océanologique de Banyuls” (Jacques Neveux) where the concentrations in pigments are analyzed by spectrofluorometry.

The colored dissolved organic matter (CDOM) was measured by spectrophotometry with a Perkin Elmer lambda 20 UV/visible spectrophotometer. Each sample was first of all filtered onto 0.2µm polycarbonate filters and the filtrate was placed in 10 cm long (optical length) precision quartz cell. The reference water used in the protocol is Milli-Q water.

Suspended particulate matter (SPM) was obtained by measurements of total particle dry weight for which 1L water sample was filtered onto pre-combusted (450°C, 5h) in order to remove any trace of organic matter and pre-weighted 0.4µm Nuclepore polycarbonate filters and then rinsed with 20mL ammonium formiate (1.08mM) to eliminate salt. After that, filters were dried at 60°C in oven (24h) and placed on the desiccators before to be weighted using a Perkin Elmer AD 4 microbalance with a precision of ±0.001 mg (Jouon et al., 2008).

The concentration of particulate nitrogen (PN) and particulate organic carbon (POC) was determined using a Perkin Elmer elemental analyzer after decarbonation with HCl. 1L of water samples were filtered onto pre-combusted (450°C, 4h) 0.7µm Whatman GF/F filters. Filters were then dried at 60°C in oven (24h) and placed on the desiccators until to be analyzed.

For the determination of the absorption by particles (a_p), 1L sample was filtered onto a 0.7µm Whatmann GF/F filters. Then, a_p coefficient was measured by the filter pad technique on a Beckman spectrophotometer.

Nitrate + nitrite and phosphate concentration were analyzed from the three polypropylene flasks containing $HgCl_2$ preserved samples. Nitrates were reduced to nitrites according to Wood et al. (1967) and NO_3 + NO_2 concentrations were determined according to the "high sensitivity" procedure of Raimbault et al. (1990) on a Bran + Luebbe Autoanalyzer III. Phosphate concentrations (Soluble Reactive Phosphorus, SRP) were determined using the same autoanalyzer according to Grasshoff et al. (1983).

Appendix B: Wicoxon-Mann-Whitney test results (comparison of means).

The table 2 presents results of the comparison of means (WMW test). It was done to determine if the difference of mean at two stations is considered as statistically significant. If the result of the test is > 0.05 (threshold value), it indicates that the two means cannot be considered as significantly different. Inversely, results < 0.05 signify that the two means considered are statistically different.

Table 2: Results of the Wilcoxon-Mann-Whitney test.

	G003	GD10	M33
GD10	0.6195	-	0.0642
M33	0.0285	0.0642	-
OC1	0.0062	0.0085	0.4670

Appendix C: Southern Oscillation Index values.

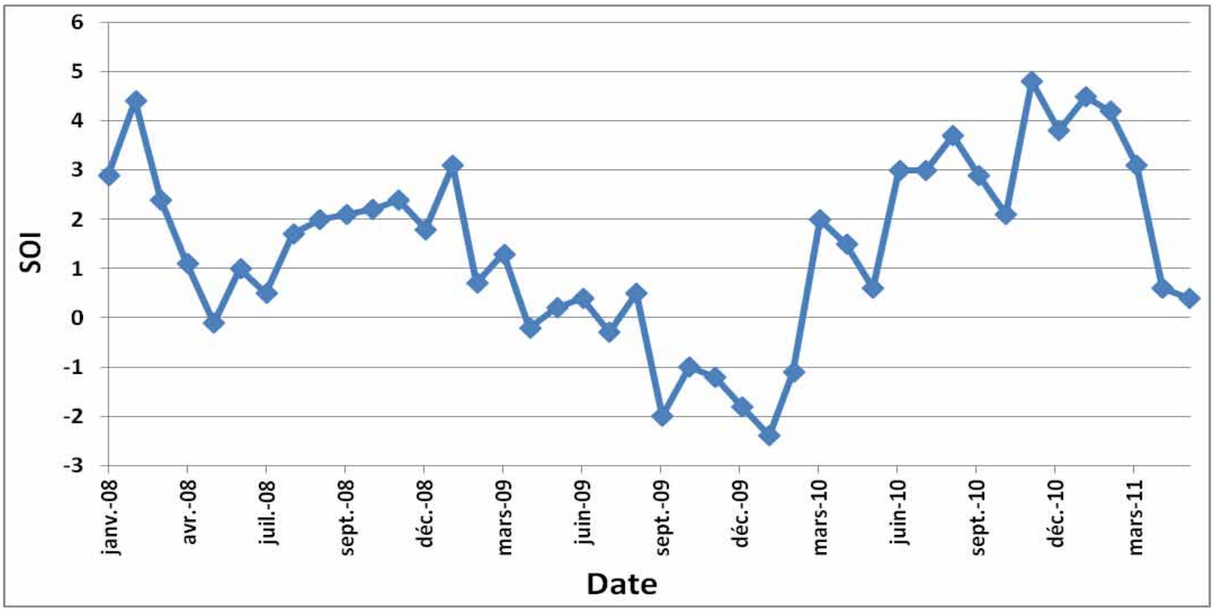

Figure 11: Monthly SOI values for the January 2008 – June 2011 period.

Appendix D: Average daily precipitation for sampling dates.

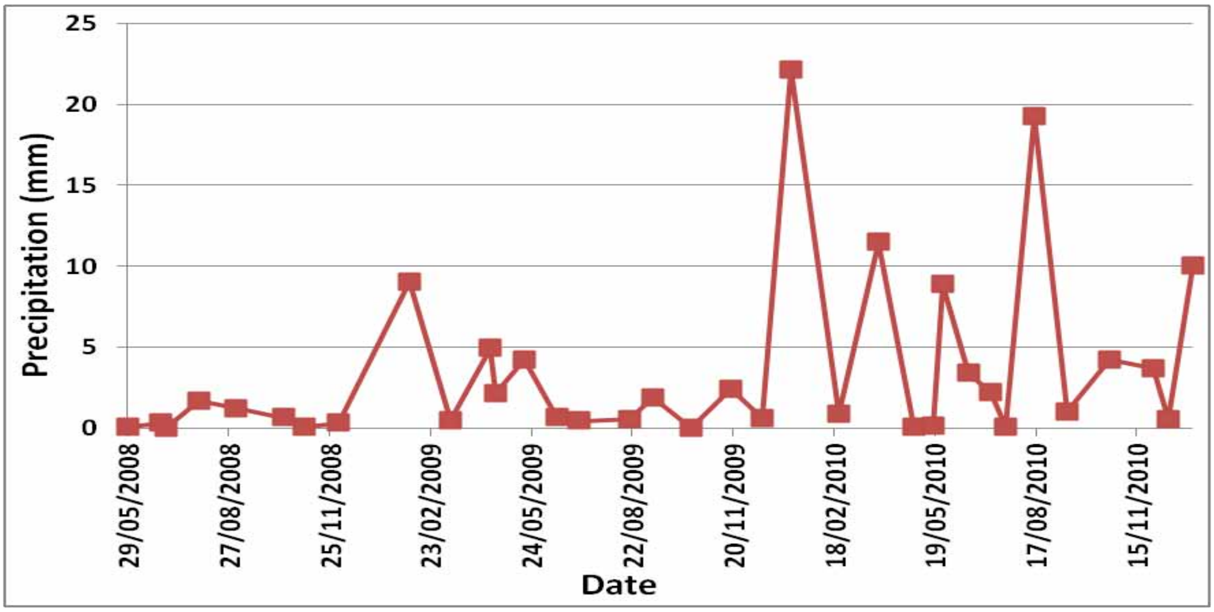

Figure 12: Average daily rainfall for sampling dates taken as the mean of the 5 days preceding sampling.