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Assessing Vulnerability to Climate Variability and Change in Estuarine Waters and Coastal Fisheries of the Rio de la Plata[I]

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1. Introduction

1.1. Background

The Third Assessment Report of the Intergovernmental Panel on Climate Change (2001) identified two main environmental problems in South America: land use changes and El Niño Southern Oscillation (ENSO) variability. The Rio de la Plata basin (RPB) and estuary (RP) have been substantially influenced by human activities in recent decades and are highly sensitive to climate extremes and changing precipitation patterns.

Population of the RPB increased by 90% from 1961 to 1994 (Baethgen et al., 2001) leading to an increase in pressures on watersheds. For instance they are heavily used for agriculture, water storage, fertilizer application, and there is a heavy discharge of wastewater from point sources (wastewater treatment from domestic input is about 20%) and of nutrients from nonpoint sources. (Pizarro and Orlando, 1985; Tucci and Clarke, 1998; Nagy, 2000; Nagy et al., 2002*a*).

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The Uruguay River Basin (URB) has an area of 297,000 km^2 in Brazil, Argentina and Uruguay and a population density of 25/km^2. Some relevant land-use data are 4% wetlands, 2% protected areas, 44% cropland and 45% grassland areas. Main environmental deterioration data are 20% eroded area, 92% original forest lost a 12% rate of deforestation. There are two large dams on the River Uruguay (World Resources Institute, 1998).
Main climatic changes in the RPB are the increase in ENSO variability and precipitation (≥20%), southward displacement of the Atlantic subtropical high-pressure circulation (SAHP) and changes in frequencies of the prevailing winds increase in air and water temperatures (≥0.8 ºC), as well as changes in runoff, soil moisture and the Pantanal's extent (Díaz et al., 1998; Camilloni and Barros, 2000; Escobar et al., 2004; Bidegain and Camilloni, 2004; Liebmann et al., 2004).

1.2. Studied system

The studied system is the Rio de la Plata river estuary and the exposed unit is the estuarine frontal zone related to the salt intrusion limit (Figure 1). This productive environment sustains relevant ecological and biogeochemical processes (nutrient assimilation, denitrification, production of organic matter), goods (fisheries) and services (fish reproduction, CO_2 fixation and denitrification).

1.3. Goal

The overall goal of this paper is to better understand the current vulnerability, impacts and adaptive capacity to climate change and variability on estuarine waters of the Uruguayan coast of the Rio de la Plata**.** We focus on i) ENSO-related variability, river discharge fluctuationsand wind patterns change, and ii) the understanding of ecosystem response in order to obtain credible estimates of future impacts and vulnerability on trophic state changes (increase in symptoms of eutrophication), coastal fisheries, and associated livelihood quality.

The specific objectives addressed are to i) synthesize overall climatic background, ii) develop vulnerability scenarios, iii) develop impacts and vulnerability indicators, and iv) develop future climate scenarios and reference projections for a range of climate and nonclimate factors.

Time horizons considered are from the past 30 years and present through 2030-2050. Some climatic and environmental trends (i.e., precipitation and drivers of eutrophication) are analyzed since 1940 (see Figure 1).

The main overall questions addressed are

- How sensitive is the system to climate variability and change?
- Is eutrophication related to climate change and variability?
- Is the coastal fishery system sustainable under increased river flow variability?

2. Framework and Methods

Our general approach is based upon

i) a multi-level indicator of vulnerability to climate change and a driver-pressure-state-impact-response (d-PSIR) index for water resources, ecosystem and coastal fisheries and settlement adapted from Moss (1999) and Stockholm Environment Institute (SEI) (2001) as presented in Figure 2.

ii) vulnerability indicators, index and vulnerability matrices, regression models, and economic analysis of fishing activity. A combination of objective values (i.e. net income, education, wind speed, ENSO Sea Surface Temperature (SST) 3.4 index and expert judgment was used in order to assess social, economic, environmental and legal indicators of sensitivity of the fishermen's community as well as to assess harmful algal blooms (HABs) impact.

iii) Special Report on Emissions Scenarios (SRES) A2/B2 climatic scenarios and Hadley CM3/ECHAM-4 Global Climate Models (GCMs) (Bidegain and Camilloni, 2004).

3. Rio de la Plata Basin Climate Baseline (1961–1990)

3.1. Sea level pressure

Eastern zone of RPB is dominated by the influence of the SAHP (Figure 3*a*). Meanwhile the northern portion shows a typical low pressure system (Chaco low) more intense in summertime. Winds are northerly over most of the region with a maximum in the northeastern sector; westerlies are present throughout the year but are strongest during winter and in the south (Kalnay et al., 1996).

3.2. Temperature

The mean annual temperature ranges from around 15°C in the south to more than 25°C in the mid-western Chaco region (Figure 3*b*). In winter, monthly mean temperatures have a clear north-south gradient. In July, for example, the mean temperature over the northwest part of the basin is more than 20°C, while that in the province of Buenos Aires is around 10°C cooler. In summer the gradient is more zonal reacting to the land-ocean distribution. In January, maximum mean temperatures reach over 27.5°C in western Argentina, while they are less than 22.5°C along the coastlines of southern Brazil, Uruguay and Buenos Aires (Hoffmann, 1975).

3.3. Precipitation

The annual mean total precipitation in the region is about 1,100 mm (Figure 3*c*). Annual mean rainfall tends to decrease both from north to south and from east to west. Corresponding amounts range from 1,800 mm in the maritime uplands along the Brazilian/Paraguayan border to 400 mm along the western boundary of the region. Plentiful moisture supply from the Atlantic -and from Amazonia by prevailing northerly flux in around 60ºW in Subtropical South America- maintains the precipitation maximum over southern Brazil. The amplitude of the annual cycle in rainfall decreases from north to south. The northern part of the region has a well-defined annual cycle with maximum precipitation during summer (December to February). The central region (northeast Argentina /southern Brazil) has a more uniform seasonal distribution, with maximum precipitation occurring during spring and autumn. Around 20°–25°S, in the Planalto Meridional -near the Atlantic Ocean- the precipitation regime exhibits a maximum (Figure 4*c*), with a year-round regime.

4. The Rio de la Plata River Estuary: Setting, Subsystems and Sectors

4.1. Physical setting

The Rio de la Plata is a large (38 _ 10^3 km^2) and wide funnel-shaped (30–240 km width) coastal plain microtidal estuary with a river paleovalley (called Canal Oriental) at the Northern coast (López Laborde and Nagy, 1999) which behaves as an advective mass conduit channel to the coastal ocean (Nagy et al., 2002*b*). Microtidal systems, like the RP, have a low mixing capacity, which depends mainly on the wind thus river inflow is the "master variable" that controls stability (vertical difference in salinity as a function of depth: dS/dZ), nutrient excess, flushing time (ft) of water and particles, stratification and gravitational circulation, salinity and bottom-water hypoxia (EPA, 2001; Nagy et al., 2002*b*; Nagy, 2003, 2005).

4.2. Freshwater inflow to the Rio de la Plata

Total freshwater inflow (Q_V) to the Rio de la Plata, estimated as the sum of the discharges of Rivers Paraná (Q_P) and Uruguay (Q_U), typically varies from ~1.5 to >3 x 10^3 m^3 s^{-1} for strong La Niña and El Niño years respectively. A strong relationship has been reported between ENSO SST 3.4 Index (temperature anomaly at regions 3 and 4 in the Pacific Ocean) with Q_V, especially with Q_U during 1998–2002. Both the location and structure of the estuarine front and salinity off Montevideo closely follow river flow on monthly to interannual timescales (Severov et al., 2004; Nagy et al., "Rio de la Plata estuarine system I: Relatonship between river flow and frontal variability, submitted manuscript) and have important effects on most ecological and biogeochemical processes in the estuarine waters and resources (Nagy et al., 2002*a*, *b*; 2003). However Q_V extremes also depend on other climatic and human-driven factors which are not considered in this paper.

Q_V has increased by ~35% over the past 50 years because of increased precipitation, runoff and land-use changes (García and Vargas, 1998; Tucci and Clarke, 1998; Kane, 2002; Nagy et al., 2002*a*; Menéndez and Re, 2005) and closely follows interannual fluctuations of ENSO events (Figure 4) as shown for the long-term series of River Uruguay (Nagy et al., 2002*a*,*b*).

Small changes in precipitation are doubled in the streamflow signal. This amplification of signal takes places at different time scales, from interannual to decadal (Berbery and Barros, 2002), revealing a high vulnerability of the region to increased precipitation (see Figure 4).

5. Eutrophication: Susceptibility and Climatic Forcings

5.1. Trophic state change

Eutrophication is the process by which a body of water is enriched with organic material (CH_2O) (Nixon, 1995). It is a cumulative global environmental change called trophic state change (TSC) associated with nutrient excess, the drivers of which are the increase in population and economic activities (e.g. the use of synthetic fertilizers; Seitzinger et al., 2002). The balance between production (P) and respiration (R) of organic matter (CH_2O) dictates the magnitude and direction of air-sea flux of bioactive elements (Gordon et al., 1996).

The occurrence of eutrophication effects or symptoms (i.e., excess algal biomass, hypoxia and harmful algal blooms or HABs) indicates when the system cannot cope with the available nutrient inputs (NCR, 2000; De Jonge et al., 2002). The main factors in the expression of symptoms of eutrophication are i) flushing time (ft), ii) turbidity, iii) nutrient inputs (N_I) and iv) mixing state (stratification-destratification cycle) (De Jonge et al., 2002; Nagy et al., 2002*b*). The susceptibility of conditions to express these symptoms depend on both N_I (NCR, 2000; De Jonge et al., 2002) and the balance between river flow (Q_V) and wind stress (W), which determine mixing and transport processes (EPA, 2001; Nagy, 2003, 2004).

The export scenario of Nitrogen (Ni) for South America for the year 2050 would increase nearly three times. Generically, the temperate regions export less than half Ni from total anthropogenic sources than tropical regions do, which is partially explained by lower precipitation (Seitzinger et al., 2002). Thus, ENSO variability and other hydroclimatic drivers play a major role as a control factor of drivers, control and state variables of TSC in the RP (Nagy et al., 2003b, 2004; 2005).

5.2. Trophic state changes of the Rio de la Plata

The RP shows an increasing trend of pressure indicators of TSC since the mid 1940s and a shift of state indicators during the 1980s (Nagy et al., 2003*b*; López and Nagy, 2005; Calliari, Gomez, and Gomez, 2005). For example, eutrophic concentrations of nitrate and chlorophyll were found during extreme floods (e.g., during El Niño of 1983 and La Niña of 1999 respectively; Nagy et al. 2002*a*, *b*). Human and climatic drivers have indirectly altered trophic state (TS) by modifying the physical environment and stimulated the development of new symptoms. These drivers of vulnerability and impacts are expected to increase in the next few decades.

HABs have occurred since at least 1980, becoming more frequent during the last decade and they have a great economic impact because they affect the commercialization of mollusks and fish, tourism and public health in Uruguay (Mendez et al., 1996; Méndez et al., 1997; Ferrari and Nagy, 2003). Freshwater cyanobacterial blooms (cyano-HABs) have also multiplied in recent years becoming persistent during the summer (López and Nagy, 2005). The occurrence of HABs is closely connected to Q_V (Méndez et al., 1996; Nagy et al., 2002*b*; López and Nagy, 2005).

The mouth of Santa Lucia River estuary (SLRE) is located a few miles to the West of Pajas Blancas, within the estuarine frontal zone and close to the studied fishing area. This system is eutrophic because of nutrient excess mostly from fertilizer application. The interannual variability of water height and river flow (Q_{SL} <0.02 to >1.8 10^3 m^3 s^{-1}, average ~0.10 _ 10^3 m^3 s^1) is related to ENSO from August to February. Yearly means of Q_{SL} and persistence of floods has increased by about 25% since 1979 because of the increase in precipitation in the basin (Caffera et al., 2005) Thus, river discharge fluctuations play an important role on the local variability of salinity, sea level, turbidity, nutrient content and trophic state during the peak of primary productivity and fishing activity.

The evolution of the TS in the SLRE was related to both Q_U and Q_{SL} during the studied period (October 2002 to May 2004). We selected one state / impact variable of TS (chlorophyll-a) to show the response and coping capacity of the ecosystem to ENSO events. The increase in both Q_U and Q_{SL} decreased salinity from about 5 to 1 blocking the expression of TS symptoms (i.e. chlorophyll-a < 5 _g/l). Once river flows were within the coping range, salinity increased to about 10 and chlorophyll-a increased to eutrophic levels > 20 _g/l (Nagy et al., 2004; Caffera et al., 2005). To conclude:

i) within normal river flow and salinity ranges the system expresses symptoms of TSC,

ii) when river flow is high (e.g., El Niño years 2002-2003) the river does not develop symptoms of TSC because both water and nutrients are exported to the RP; and

iii) hydrological fluctuations associated with ENSO events seem to exert some control on the coping capacity of the ecosystem.

These results are in close agreement with previous observations for the adjacent waters of the RP (Nagy et al., 2002*a*, *b*), which showed that during La Niña years and low river flow (i.e., 1999-2000) the system should be prone to increase TSC.

5.3. Indicators of susceptibility, impact and vulnerability

We must develop indicators of susceptibility of TS for both cross-system and long-term comparisons as well as for the assessment of the impact of nutrient excess in estuaries (NCR, 2000; De Jonge, Elliott, and Orive, 2002; Environmental Protection Agency (EPA), 2003). Nagy et al., (2002*b*, 2004), Nagy (2003) and Ferrari and Nagy (2003) developed such indicators for fresh and estuarine waters of the Uruguayan coastal zone. Some expected impacts and responses under current and future scenarios should be an increase in hypoxia, HABs events, P-R balance and changes in biodiversity. The main variables considered are

i) susceptibility (e.g. flushing and residence times of water, buoyancy and mixing state);

ii) drivers (population density, fertilizer use, point sources and Q_V)

iii) pressure (N, P, and Si load)

iv) state variables [N, P] and

v) response/impacts "symptoms"; monthly (chlorophyll-a); [O_2],, , HABsoccurrence, nutrient ratios (N/P and N/Si) and dominant species.

Some variables are both state or impact (i.e., O_2) (Figure 5).

Table 1 shows an example of impact matrix of an important symptom of TSC -HAB occurrence - developed by Ferrari and Nagy (2003) for the Uruguayan coastal zone of RP for the decade 1991–2000. Four indicators were estimated and aggregated: i) intensity of HABs (cells/l), ii) persistence (months), iii) extension along the coast (% of coverage) and iv) toxicity (toxin concentration from low to very high). Both freshwater (cyanobacteria HABs, i.e., *Mycrocystis aeruginosa*) and estuarine/marine species as well as toxic and noxious species were considered. Impact HAB Index = Toxic Species Index + Noxious Species Index (see Table 1).

A second aggregated impact matrix was then built in order to take into account the occurrence of the four main HAB species weighted from absence (0) to very high (4) according to the criteria defined in Table 1, Weights of the HAB species were summed and ranked from 0 to 100 or very low to very high, respectively. Weighting criteria were based on both the literature (EPA, 2001) and local occurrence range according to expert judgment of the authors (Table 2). The SST 3.4 index, which is well correlated with Q_U, is reported on an annual basis (from March to February) (see Table 2).

Finally, these indicators were weighted taking into account their impacts on three sectors: i) human health (-H), ii) economic activity (-Ec) specifically mollusks consumption and iii) environmental health (-Ev) according to the expert judgment of the authors. Coefficient weights were 0.75, 0.50 and 0.25 for H, Ec and Ev respectively, which were multiplied by the values reported in Table 2. Thus, a weighted aggregated impact index of persistence/extension/toxicity (IPET) was built (Table 3). An impact coefficient was assigned for each of the four species. Relative impact of each indicator (IPET from 0 to 1) is shown for each species and sector. Extreme values are toxicity of *Gymnodinium* for H and intensity of *Dinophysis* for Ev (Table 3).

The overall impact of HAB occurrence was moderate, with only one high-impact year (1992) and two low-impact years (1998 and 2000), which coincide with strong ENSO events (1997–1998 and 1999–2000, respectively). However, the only one species that reached high values in 1991 and 1993 (*Alexandrium tamarense*) was related to both the northward displacement of Malvinas current, where *Alexandium* is present, and low Q_V (Méndez et al., 1996), especially because of low Q_U (Nagy et al., 2002*b*). Usually, both drivers are associated with El Niño and La Niña years respectively, which reduces the vulnerability of RP to suffer the presence of these blooms. To date they have occurred during spring time, but they could be potentially dangerous to H- if they were to occur during summer time.

Some examples such as the blooms of *Alexandrium*, the relatively high index of El Niño multiyear event (1991–1994), and extreme events of the years 1998 and 2000 suggest some hydroclimatic control on HABs occurrence. Recent years (2001 and 2003, not shown here) have shown a marked increase in Cyano-HABs (López and Nagy, 2005) at intensities higher (>3) than those found during the past decade. El Niño and La Niña events could stimulate cyano-blooms, the former by advecting freshwater and the latter by decreasing ft.

6. Coastal Fishery System Vulnerability: Fishing Activity and Sustainable Livelihood

6.1. Pajas Blancas community fishing activity

An artisanal fleet exploit fisheries within 5-7 miles off the Uruguayan coast in the estuarine zone of the Rio de la Plata close to the Santa Lucia river mouth. The main community is based at Pajas Blancas (see Figure 1) within the estuarine front (EF). The peak of the fishing period October to December (Figure 6) is controlled by Q_V (especially by Q_U) and wind rotation (Norbis, 1995; Nagy et al., 2003a; Norbis et al., 2004; G. J. Nagy et al., submitted manuscript).

The location of the EF displaces as a function of

i) Q_V (which in turn is strongly associated with both seasonal and ENSO-related interannual variability of precipitations) and

ii) Offshore and onshore winds on weather development timescale (1 -10 days; Norbis et al, 2004; G. J. Nagy et al., submitted manuscript).

Displacement of the EF induce changes of the spatial distribution of fish and their recruitment. Frequency patterns of winds have changed over the past few decades (Pshennikov et al., 2003) with an increase in onshore E-SE winds (Escobar et al., 2004). In spite of the increase in river flow variability (Q_P and Q_U) and related extreme locations of

EF, as well as the increase in onshore winds, fishermen have shown good adaptive capacity since 1988. Many of them have migrated seasonally or definitively away from the EF along the coast following resources (Hernández and Rossi, 2003; Norbis and Verocai, 2003) in order to reduce their long-term vulnerability to the fluctuations of Q_V and avoid bad years (Norbis et al., 2004). Climatic stimuli (Q and W) displace EF upward and downward (Framiñán and Brown, 1996; Severov et al., 2003, 2004; G. J. Nagy et al., submitted manuscript) out of the fishing area. During strong ENSO events, EF was located far from Pajas Blancas fishermen community (see Figure 6).

6.2. Sensitivity and vulnerability of coastal fisheries

We estimated proxy variables, classified and valued respectively as low (1), moderate (2) and high (3), in order to assess social, economic, environmental and legal indicators of sensitivity of the fishermen's community. The sum of all indicators (nonweighted index of vulnerability) suggests that the community is subject to moderate to high vulnerabilities (Table 4) but it seems to be resilient. Only those strong ENSO events which effects are noticeable during the peak of the fishing period (i.e., El Niño 1992, 1997 and 2002 and La Niña 1989 and 1999), seem to impact fishing activity and net income. Therefore, less than one-third of the peak fishing periods are very bad in economic terms, when the net income of fishermen is estimated to be reduced by ~60% with regard to normal years as shown in Figure 6 (Nagy et al., 2003a; Norbis et al. 2004).

The question addressed about the sustainability of coastal fisheries was thus empirically answered because the fishing activity remains sustainable regardless of their (estimated) high vulnerability.

We suggest that their resiliency is (or was) due to

i) the combination of planned and reactive adaptation measures to hydroclimatic variability (i.e. migration to escape from the high variability of the estuarine front),
ii) good to high fishing performance of most fishermen. Many fishermen have acquired skills to be good sailors, fishers and developed a high capacity to understand weather and environmental conditions. For instance, they usually conduct exploratory samplings of bottom waters with hand-made domestic instruments (Hernández and Rossi, 2003), and
iii) their (dominant) cautious behavior (to avoid weather-related risks in spite of economic losses), all of which reduced their vulnerability to remaining sustainable. Fishermen do not risk fishing for at least one day after nonfavorable wind conditions occur, even if fish are often available the day after (Norbis, 1995). Even if this behavior should be considered a bad practice in terms of cost-benefit analysis, it has not significant affected their long-term income. However, real-time weather forecasting applied to fisheries would be a good adaptation practice, provided fishermen can trust the information, which is not always current.

Thus, the following question arises: Will fishermen have the adaptive capacity to be performant under increasing climatic and economic pressures such as those that occurred in 2002?:

i) severe economic crisis,
ii) increase in fuel prices,

iii) a moderate El Niño year that decreased surface salinity at Pajas Blancas to close to zero because of the seaward displacement of the EF, and

iv) increase in the occurrence of nonfavorable wind conditions for fishing activity (> 8 m/s; Nagy et al., 2003a; Norbis et al., 2004).

According to Norbis (1995) and Norbis et al. (2003) southern winds (SW to SE) > 8m/s are nonfavorable for fishing and most fishermen prefer not to risk fishing on the first day of favorable conditions, usually losing one favorable day. In fact, fishing activity for the 1998–1999 period shows that the number of fishing boats and capture increase during the favorable days suggesting that there is no resource limitation and that the community follows performative (leaders) fishermen (Norbis et al., 2004, 2005).

The average wind speed in the region is 5-6 m/s but it increases to > 6 m/s during spring and summer time because of the prevailing SE winds (Nagy et al., 1997; Escobar et al., 2004). It means that fishermen are both highly exposed and resilient to developing their activity within a narrow wind range close to the limit of 8 m/s. However, the overall conditions during 2002 forced fishermen to change their no-risk behavior (Nagy et al., 2003a; Norbis et al., 2004, 2005).

For this scenario, the assessment of vulnerabilities shown in Table 4 seems to be more realistic, suggesting the methodological need to put more weight on climatic indicators because fishermen cannot cope with them (see Table 4).

6.3. Scenarios of coastal fisheries activity

Norbis et al. (2005) developed an empirical scenario of fishing activity and productivity based on both the long-term yearly fishing activity gross income (see Figure 4) and the fishing period 1998-1999. This economic scenario was built for

i) 30 boats

ii) fishing period (2, 3 and 4 months),

iii) monthly fishing days (8, 14 and 17 days), and

iv) efficiency of fishing units (26, 38 and 46 boxes)

Thus, nine different combinations of i), ii) and iii) empirical scenarios were built that represent maximum (1) and minimum (9) fishing activity within the range of observed conditions since 1988 especially during 1998/1999 for each variable.

Six scenarios give captures greater than the maximum observed in 1998–1999 and the most performant are those based upon four and three months performant fishing activity: maximum fishing days and boxes. It must be noted that these scenarios do not include captures during the low fishing activity period (from February to September, see Figure 4) when many fishermen migrate seaward of the estuarine front to San Luis (see Figure 1).

Both the observations and the economic scenario suggest that

i) the longer the peak of the fishing period the greater the capture, which depends mainly on hydro climatic conditions (i.e. ENSO-induced EF location)

ii) the number of fishing days per month is crucial and this is highly dependent on the occurrence of southern winds (i.e. wind induced EF location and mixing state)

iii) the sustainability of the fishing activity depends on several factors or the combination of them, for which thresholds have been estimated: Fishing activity must be ≥15 days/month, and fishing period must be >2 months;

iv) in case of an increase in climatic constraints only the most performant fishermen should be able to maintain present net income and

v) it will be necessary to continue this analysis for at least two more years (from the past and/or future) with different climatic, environmental and socio-economic conditions, as well as to incorporate anthropological research.

7. Future Climate Scenarios and Some Environmental Impacts

7.1. Future climate scenarios

Future climate changes for the RPB were extracted from GCM runs (Bidegain and Camilloni, 2004). Estimates of future changes in mean temperature and precipitation over the region are based upon two recent GCMs: HADCM3 model from Hadley Centre (U.K.) and ECHAM4 model from the Max Planck Institute (Germany) run with the IPCC A2 and B2 SRES socioeconomic scenarios. We selected these two medium scenarios: A2 (medium high) and B2 (medium low). We used the original spatial resolution of both models: HADCM3 has horizontal resolution of 2.5° of latitude by 3.75° of longitude. The model ECHAM4 has horizontal resolution of 2.8° of latitude by 2.8° of longitude. Changes in annual precipitation across the RPB are expected to vary between +0.1 and +0.2 mm/day by the 2050s according to HADCM3 model, and between +0.0 and +0.6 mm/day by 2050s according to ECHAM4 for the high emissions scenario (A2). In the case of the low emissions scenario (B2) it should vary between +0.0 and +0.3 mm/day by the 2050s according to HADCM3 model and +0.0 to +0.5 mm/day by 2050s according to ECHAM4.

Annual temperature across the region would rise between +1.5°C and +3.0°C by the 2050s according to HADCM3 model, and +0.5°C to +2.0°C by 2050s according to ECHAM4 for the high emissions scenario (A2). For the low emissions scenario (B2) it should rise +1.3°C to +2.5°C by the 2050s according to HADCM3 model, and +0.4°C to +2.0°C by 2050s according to ECHAM4. Annual sea level pressure across the RPB by the 2050s indicates, according to ECHAM4 model, a southern displacement of the Atlantic subtropical high pressure. Under this scenario and projecting the trends observed over the past three decades (changes in SAHP and Sea Level Pressure) and the increase in east and southeast winds reported by Escobar et al. (2004), we can assume an increase in the frequency of onshore winds.

7.2 Some conjectures about climate scenarios, environmental vulnerability, and impacts

Current environmental scenarios (1971–2003) in the RPB and estuary discussed in this paper are dominated by the following main stresses:

i) increase in temperature, precipitation, streamflow, sea level and onshore winds
ii) increase in population, use of natural resources and export of nutrients;
iii) increase in economic activities, land use changes, soil erosion and runoff/infiltration ratio; and
iv) increase in symptoms of eutrophication.

Current climate and future scenarios (time horizon 2020–2050) presented in sections 1, 3 and 7.1 for the RPB and estuary suggest a change in precipitation within the range +5% to +20% and in temperature from +1 to +2°C, whereas during the last few decades these changes have been + 20 to 25% for precipitation and +0.5 to +0.8°C for temperature, as well as + 25 to 40% for river flows (Q_V).

Trends for Q_{Vs} are very difficult to estimate because of both the uncertainty of regional human drivers (i.e., landuse change) and the varied regional scenarios from different GCMs. For precipitation, all the scenarios have systematically underestimated the precipitation over the region, but not necessarily the increase of it. Indeed, during the past few decades the observed increase in precipitation (Liebmann, 2004) was associated with the observed increase in riverflow. Moreover, small changes in precipitation are doubled in the streamflow signal (Berbery and Barros, 2002). Tucci and Clarke (1998) suggested that one-third of observed increases in streamflows were attributable to land use changes.

From an environmental point of view, under one future scenario (2020–2050) in which streamflow remains similar or slightly lower (i.e. 0% to –10%) with regard to present values, we do not expect a significant increase in present environmental stresses on the estuarine system (which are already moderately high).

Our concern is about a future scenario where Q_V increases within the range around 10-25%, together with projected temperature increases, for which significant impacts are expected in the estuarine and coastal systems (i.e., increase in the vulnerability to TSC and air-water and sediment-water gases and nutrient exchanges) besides changes in the shelf and contour current circulation (i.e., water temperature changes; ocean-driven HABs).

Thus, the following question arises: is this scenario (increase in temperature and Q_V) plausible under projected changes in temperature (i.e., +1-2° C) and precipitation (~5-20%), taking into account the consequent increase in evapotranspiration?

Some assumptions are i) about one-third of Q_V changes may be due to land use changes (Tucci and Clarke, 1998), ii) observed vs. projected changes are of the same sign in all variables, iii) the expected value for temperature change is 2 to 4 times greater than that formerly observed. A key question relates to the relative amounts of potential and actual evapotranspiration rates in the future. This uncertainty makes it very difficult to establish any coherent scenario about future streamflow, especially if current landuse changes continue increasing the runoff / infiltration ratio (which could reduce the impact of temperature rise on evapotranspiration).

Considering the fact that seasonal temperature, precipitation and streamflow cycles are not superposed, any changes should modify seasonal circulation, stratification and mixing patterns, inducing further environmental shifts (i.e. _ gas and nutrient exchanges, Δ P-R), with a probable increase in both the degree and occurrence of hypoxic events (estimated to be about 20%) in deep bottom waters and denitrification (emission of N_2 to the atmosphere; Nagy et al., 2002*a*,*b*; 2003b), as well as an increase in the vulnerability of fishermen and low-lying areas.

The long-term evolution of salinity off Montevideo (Nagy et al., 2002*a*; Bidegain et al., 2005) and the monthly evolution during the period 1998-2002 (Severov et al, 2004; G.J. Nagy et al., submitted mansucript;), as well as the evolution of the estuarine fronts location within the RP and adjacent shelf since 1998 (Severov et al., 2003, 2004; G. J. Nagy et al, submitted manuscript) allows to develop a conceptual model (not detailed here) on both yearly and monthly basis: when Q_U was/is 4,000 m^3/s, typical yearly salinities were/are

>10-12, when Q_U was/is >5,500 m^3/s they are ~7-9 (present average: ~8) and when Q_U was/is >7,000 m^3/s salinity is <5 on timescales greater than weather development, whereas when Q_U is > 10,000 m^3/s freshwater prevails in most of the Uruguayan coast and the EF is displaced tens of miles to the mouth.

Under a hypothetical environmental scenario for 2020–2050, based upon climate models outputs, past trends, reference projections and expert judgment, some predictions can be made.

Both long-term and monthly analysis of recent years suggests that a hypothetical increase in Q_U of ~ 20% should reduce average salinity at Montevideo by 2-3 (reaching 5 or 6) and displace riverward the EF. If these changes were coupled with a plausible increase in onshore winds, especially during spring months, when ENSO is active and biological processes and goods are in their activity peak period, significant changes in both the structure and location of the several fronts of the RP, as well as of the biological and biogeochemical functions associated, including fish reproduction, fishing activity and gas dynamics, are expected to shift (Severov et al., 2004; Nagy et al. 2004; López and Nagy, 2005; Lappo et al., 2005; G. J. Nagy et al., submitted manuscript).

If projected scenarios of human drivers (i.e., +70–100% population, > ~150% N input: Nagy et al., 2003b) as well as landuse changes for the URB are to be accounted, significant changes in symptoms of eutrophication and coastal fisheries livelihood are expected. The former should be noxious for both the environmental and human health, as well as for fisheries. The latter should modify the timing and quantities of ecological processes and services and could make unsustainable coastal fisheries by reducing the number of days/month and the months favorable for fishing activity.

We need to assume a plausible pessimistic point of view. Taking into account the evolution, variability and extremes of temperature, precipitations, river flow and trophic state variables change during the past 10 to 30 years, and projecting them through the next 10-30 years, together with a plausible extreme future scenario for temperature and streamflow, significant environmental impacts and changes can be expected soon.

8. Overall Concluding Remarks

- The overall vulnerability and associated impacts in the fresh and estuarine waters, coastal zone, ecosystem goods, processes and services in the Uruguayan coast of the Rio de la Plata is primarily associated with ENSO-related climate variability.
- In addition, human and climatic shifts are drivers of environmental pressure and state variables within the RP basin and sub-basins at different spatial scales and timescales, which produce, stimulate or trigger impacts, ecosystem responses and shifts within the estuarine waters of the Rio de la Plata and its coastal zone.
- Increase in precipitation plays a major role in controlling buoyancy, eutrophication and P-R processes**,** since sensitivity to trophic state changes depends on the balance between river flow and winds.
- Projected scenarios for 2050: [+1-2º C, +5 to +20% precipitations,+ ~70% inhabitants, + ~200% Nitrogen, +0.3-0.5 m SLR, + ~15-25% river flow, –2 in surface salinity, + ~100% nutrients, ~-20 % oxygen saturation in bottom waters, and ~25% net income of coastal fisheries], will increase vulnerabilities of the exposed sectors and some of them

will be heavily impacted and/or will be unsustainable (coastal fisheries, low-lying wetlands and beaches, tourism, and supply of drinking water.

- Climatic changes (Q_V and W) should modify the circulation, stratification and mixing patterns inducing further environmental impacts (i.e., Δ P-R, oxygen status, increase in the vulnerability of fishermen).

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Table 1. *Aggregated Impact Matrix of HABs in the Uruguayan Coastal Zone of the Rio de la Plata for the Period 1991–2000*

	Prevailing				Extreme
Indicators	**0**	**1**	**2**	**3**	**4**
Intensity (cells/l)	0	10^2	10^3	10^4	10^5
Persistance (months)	0	0.25	0.75	1-6	>6
Extension (% of coverage)	0	10	25	50–75	>75
Toxicity (concentration)	0	low	moderate	high	very high

Table 2. *Aggregated Impact Index of HABs for the Rio de la Plata (1991–2000)*

Year	**SST 3.4**	***1 Alexandrum tamarense***	***2 Gymnodium catenatum***	***3 Dinophysis acuminata***	***4 Mycrocistis aeruginosa***	**–**	**Index 0-100**	**Impact**
1990–1991	0.3	3	0	0	0	3	21	low
1991–1992	1.0	2	3	2	2	9	64	high
1992–1993	0.4	2.75	2.75	0	0	5.5	39	low
1993–1994	0.4	1.25	2.25	1.5	2.75	7.75	55	medium
1994–1995	0.6	2	2.25	0	0	4.25	30	low
1995–1996	–0.4	3	2.25	1.5	0	7	50	medium
1996–1997	–0.3	1.25	1.5	0	3	6	43	medium
1997–1998	1.8	0	2	0	0	2	14	very low
1998–1999	–0.7	1.25	1.25	0	2	4.5	32	Low
1999–2000	–1.3	1.0	1	0	0	2	14	Very low
Average	**0.2**	**1.75**	**1.83**	**0.5**	**0.98**	**4.7**	**36**	**Low to medium**

Table 3. *Weighted Aggregated Impact Index of HABs (Index of Persistence/Extension/Toxicity, or IPET) for Each Species and Sector in the Northern Coast of the Rio de la Plata (1991–2000)*

Weighted Index for each sector (0-1)			
Species	**Health: 0.75**	**Economic activity: 0.50**	**Environment: 0.25**
Gymnodinium 0.50	T: 0.37	T: 0.25	P: 0.13
Alexandrum 0.42	E: 0.32	P: 0.21	E: 0.11
Microcystis 0.33	P: 0.25	E: 0.17	T: 0.08
Dinophysis 0.22	I: 0.19	I: 0.13	I: 0.06

Table 4. *Assessment of the Vulnerability of the Coastal Fishermen Community.* Modified from Nagy et al. (2003a) and Norbis et al. (2004). Unweighted total index of vulnerability (IV) = 2.2 (scale 1–3).

Proxy variable		**Vulnerability**	
Social	**High (3)**	**Moderate (2)**	**Low (1)**
Family		X	
Education		X	
Housing		X	
Employment		X	
Health		X	
Social organization	X		
Sub-total: 2.2/3			
Economic			
Boats		X	
Engines		X	
Fishing gears			X
Communications		X	
Refrigeration	X		
Catch		X	
Prices		X	
Net income		X	
Sub-total: 2.0/3			
Environmental			
Climate - ENSO	X		
Winds	X		
Storm surges/Flooding		X	
Eutrophication		X	
Habitat loss			X
Subtotal: 2.2/3			
Legal/Institutional			
Laws		X	
Territorial planning		X	
Coast Guard controls	X		
Conflicts with industrial fleet	X		
Conflicts with neighbours		X	
Legal organization	X		
Subtotal: 2.5/3			
Grand-total: 2.2/3			

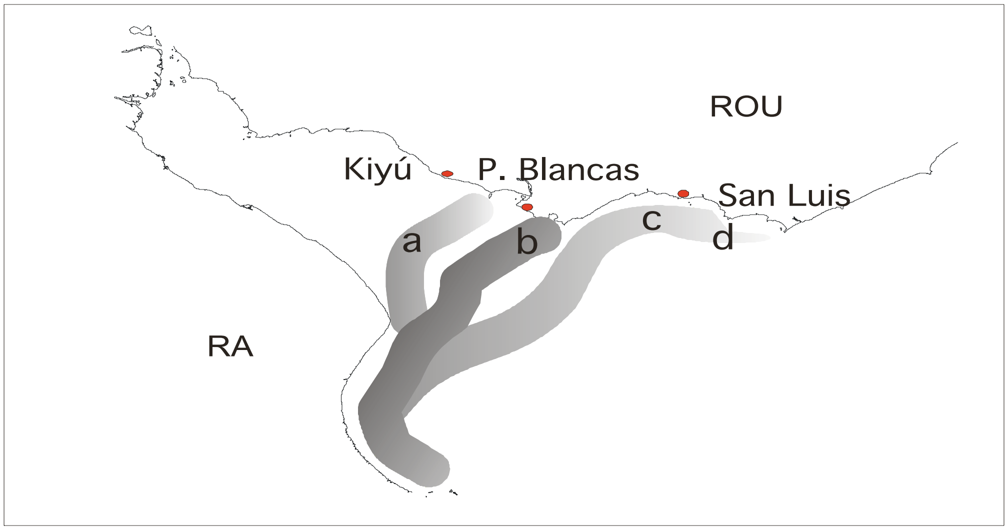

Figure 1. Estuarine front location under different ENSO conditions: a) strong La Niña event (1999–2000), b) typical c) moderate El Niño (winter 1987) d) strong El Niño 1997–1998/2002–2003 (modified from Nagy et al., 2002b). RA (República Argentina) and ROU (República Oriental del Uruguay).

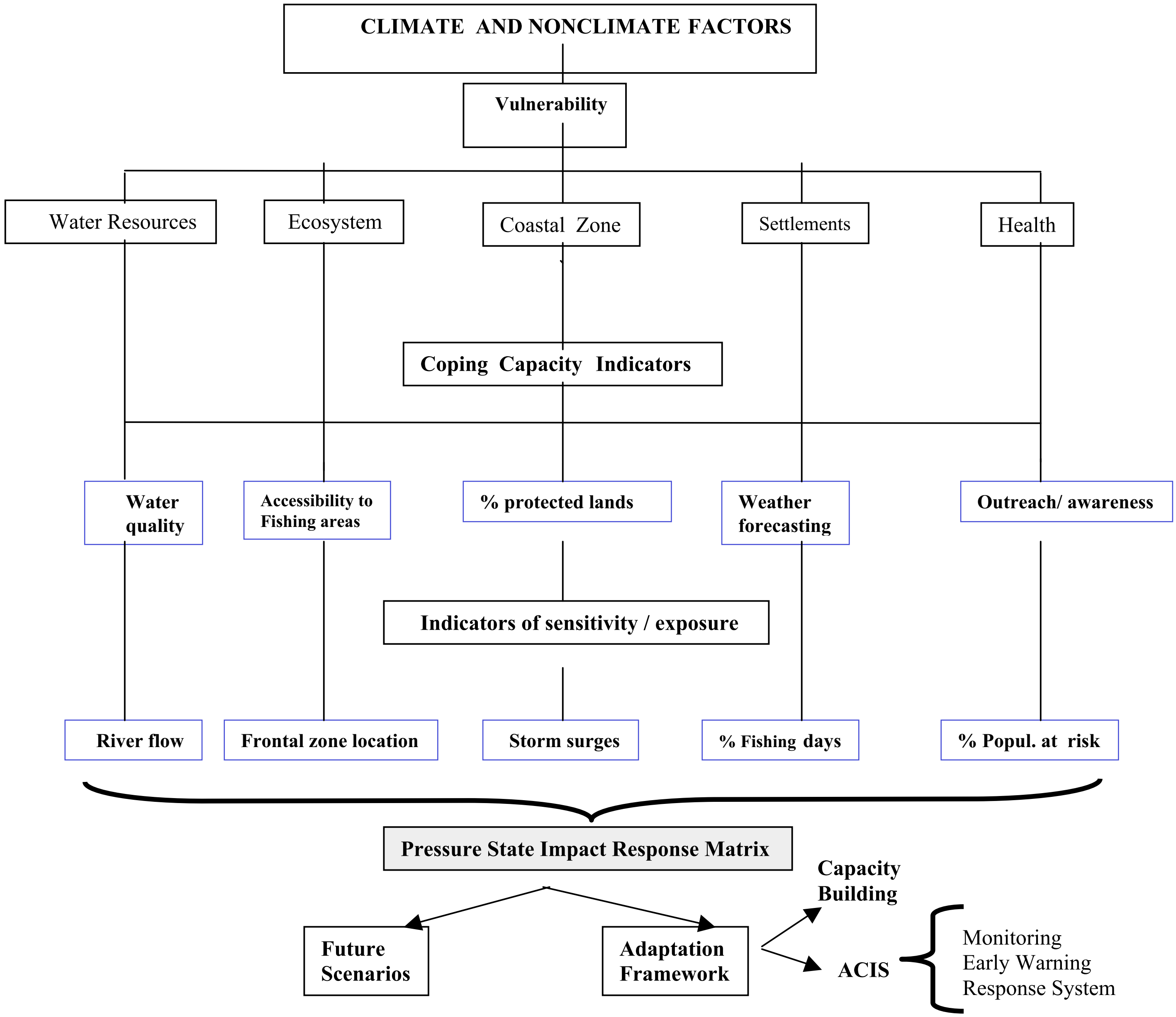

Figure 2. Multilevel indicator of vulnerability and adaptation to climate change and variability for estuarine waters, goods, services and coastal settlements in the Rio de la Plata. Adapted from Moss (1999).

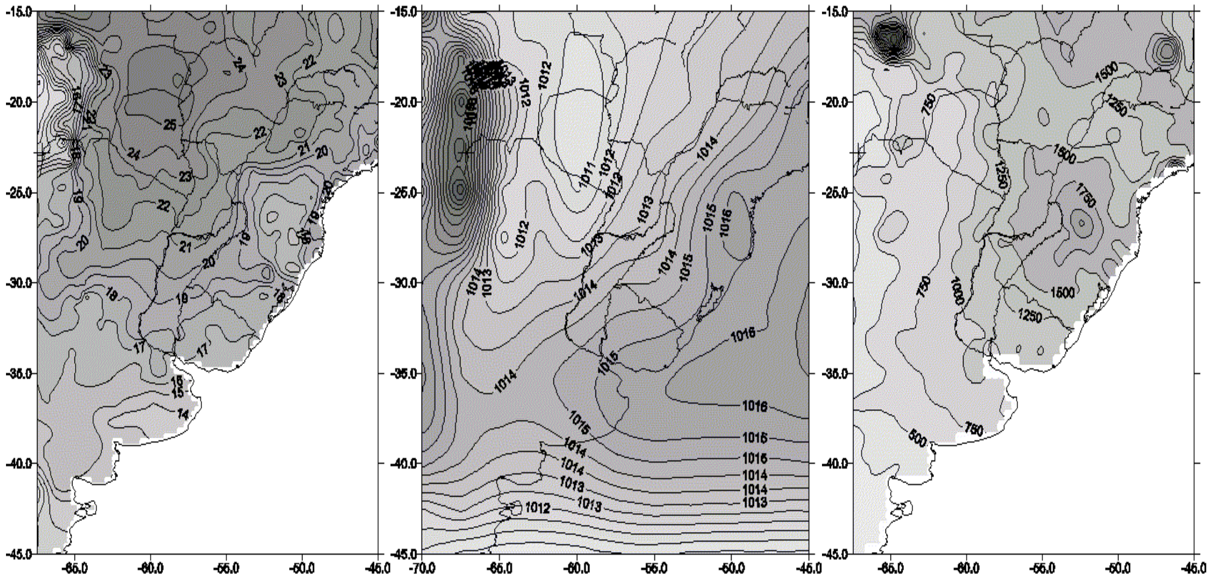

Figure 3. Climate baseline scenarios for RPB for the period 1961−1990. Sea level pressure in hPa (left), temperature in degrees celsius (center) and precipitation per year in mm (right).

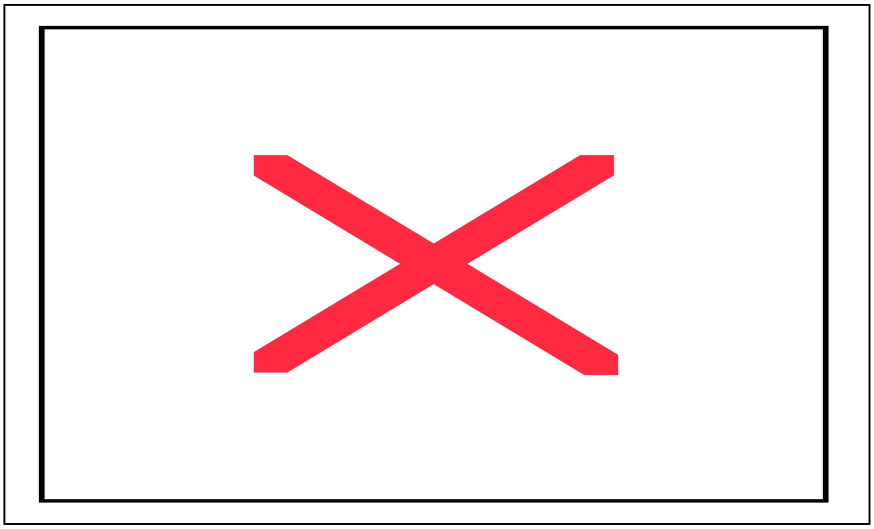

Figure 4. River Uruguay flow at Salto from 1921 to 2003 (from Bidegain et al., 2005).

DRIVERS PRESSURE STATE / IMPACT and / or RESPONSE

Changes in:

Socioeconomic __ > Nutrient Load > N,P > HABs Trophic State, P-R,
__ >Chl a < O_2 __ > N/P and > N/Si
Climatic __> Water load > Stratification Dominant species

Figure 5. d-PSIR Framework of trophic state and symptoms of eutrophication for the Rio de la Plata. N, nitrogen; P, phosphorus; HABs, harmful algal blooms; Chl a, chlorophyll-a, Si, silicon.

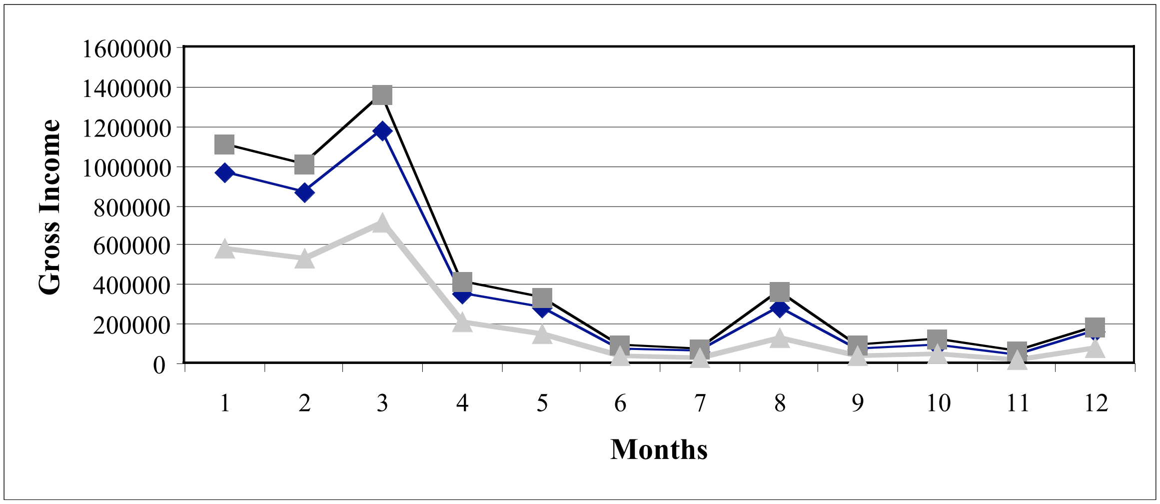

Figure 6. Long-term fishermen gross income (local currency-1999). Average: black; Strong ENSO years: light gray, and maximum: dark gray. 1: October - 12 September (from Nagy et al., 2003a).