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# LONG-TERM FLUCTUATIONS IN BLUEFIN TUNA TRAP CATCHES: ARE THEY ENVIRONMENTALLY DRIVEN?

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*SUMMARY*

*We tested whether synchronous long-term fluctuations in Atlantic bluefin tuna* (Thunnus thynnus) *trap catches, collected from the ancestral Mediterranean and Atlantic trap fishery, might be related to environmental changes in NAO and/or in temperature. Spectral analyses of trap catches and temperature displayed similar spectra with peak at low frequency whereas those of the NAO exhibited a broad band spectrum. Regression analyses and tests of correlation did not reveal any clear relationship between trap catches and NAO. In contrast, long-term fluctuations in trap catches appear to be negatively and significantly related to long-term trends in temperature. Underlying processes that could explain such a relationship are discussed, with special focus on changes in migration patterns of the Atlantic bluefin tuna.*

*RÉSUMÉ*

*Les séries historiques de captures de thon rouge* (Thunnus thynnus) *par les madragues présentent des fluctuations à long terme, synchrones à l'échelle du bassin méditerranéen occidental et du proche-Atlantique. L'objet de ce papier est de tester si ces fluctuations peuvent être liées à des changements à long terme du NAO et/ou de la température. Les analyses spectrales des séries de captures et de températures révèlent des spectres similaires, avec un pic sur les basses fréquences, alors que les analyses conduites sur les séries de NAO mettent en évidence une large bande spectrale. Les régressions et les tests de corrélations ne montrent aucune relation significative entre les captures par les madragues et le NAO. En revanche, les fluctuations à long terme des captures de thon rouge sont significativement et négativement corrélées avec les fluctuations à long terme de la température. Les processus sous-jacents susceptibles d'expliquer une telle relation, en particulier des changements migratoires, sont discutés.*

*RESUMEN*

*Las series históricas de capturas de atún rojo* (Thunus Thynnus) *realizadas por las almadrabas presentan fluctuaciones a largo plazo, sincrónicas a escala de la cuenca mediterránea occidental y del Atlántico vecino. La finalidad de este documento es comprobar si estas fluctuaciones pueden relacionarse con los cambios a largo plazo de la NAO y/o de la temperatura. Los análisis espectrales de las series de capturas y temperaturas revelan espectros similares, con un punto máximo en las frecuencias bajas, mientras que los análisis realizados para las series de la NAO evidencian una amplia gama de espectros. Las regresiones y las pruebas de correlación no muestran ninguna relación significativa entre las capturas realizadas por las almadrabas y la NAO. Por el contrario, las fluctuaciones a largo plazo de las capturas de atún rojo presentan correlaciones significativamente negativas con las fluctuaciones a largo plazo de la temperatura. Se debaten los procesos subyacentes que podrían explicar dicha relación, sobre todo los cambios en los patrones de migración del atún rojo atlántico.*

*KEY WORDS*

*Thunnus thynnus, NAO, temperature, trap fishery, migration.*

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## 1. INTRODUCTION

In a previous study, Ravier and Fromentin (2001) showed that bluefin tuna (BFT) trap catches displayed large pseudo-periodic fluctuations of 100-120 years and secondarily cycles of 20 years. Long-term fluctuations in catches were further synchronous between distant traps, so that they were likely to reflect fluctuations in BFT population migrating yearly in the Mediterranean. However, the causes of such fluctuations remained unclear. We here tested whether the BFT long-term fluctuations might be related to large-scale environmental changes.

We used two climate indices, the North Atlantic Oscillation index (NAO, Hurrell *et al.* 2001) and the temperature, that were likely to affect the spatial and temporal dynamics of Atlantic BFT:

- The NAO is known to influence the North Atlantic food web (Fromentin and Planque 1996) as well as reproduction, growth and spatial distribution of fish (such as herring, cod, temperate tunas, see Alheit and Hagen 1997, Bard 2001, Ottersen *et al.* 2001).

- Temperature influences fish life history at various stages, i.e. larval growth and mortality (Pepin 1991), timing of food availability for early ages (Ellersten *et al.* 1989), growth (Brander 1995), maturity (Tyler 1995), timing of spawning (Hutchings and Myers 1994) and egg viability (Flett *et al.* 1996). Temperature has been also shown to play a key role in spawning activity of both tropical and temperate tunas (which spawn in warm water generally > 24°C, Schaefer 2001). Finally, temperature is known to influence the planktonic production (McGowan et al. 1998) and subsequently, the food resource for juvenile and adults BFT (Mather *et al.* 1995).

To test these possible relationships, we investigated and compared the patterns of variability of BFT, NAO and temperature in both the time and frequency domains.

## 2. MATERIALS AND METHOD

An intensive investigation through archives and historical literature allowed to collect 9 long-term time-series (TS, >80 contiguous years) of catches from the ancestral Mediterranean and Atlantic trap fishery (for more details, see Ravier and Fromentin 2001). Environmental data (NAO indexes, Northern Hemisphere temperature proxies, regional and actual temperatures) were collected from scientific literature, online database or communicated by climatologists **(Table 1)**.

The total annual trap catches are given in number of tuna and were log-transformed (natural logarithm) to stabilize the variance. To test for relationships between BFT and environmental data, we first computed spectral analyses to compare patterns of variability in the frequency domain. Then, we investigated relationships in time domain, through regression and correlation, to gain statistical inference of the relationship between the series. As we focussed on long-term trends, pairwise comparisons were computed between each pair of BFT/environmental TS that overlapped on a sufficiently long period (i.e., 80 years minimum). To deal with serial correlation due to long-term fluctuations, we also fitted linear models using the generalized least squares (GLS), in which errors were specified to follow an autoregressive process (Box and Jenkins 1976). Performing linear models on each pair of BFT/environmental TS induces multiple testing (e.g. Legendre and Legendre 1998), so we applied the Holm's procedure for non-independent tests to compute adjusted probabilities values (which may be larger than 1, see Holm 1979). Since few TS were not normally distributed, we used the non-parametric Spearman correlation coefficient. Correlation was tested using a Monte Carlo procedure (1000 simulations).

## 3. RESULTS

### *3.1 BFT and NAO*

Similarly to the spectrum of trap catches TS from Favignana **(Figure 1)**, spectra of BFT TS were all strongly dominated by low frequency signal (<0.1 $yr^{-1}$, i.e. periods >10 yrs); short- to medium-term variations being weak or negligible. In contrast, the NAO indexes presented a broad band spectrum with medium- to short-term variability that also appeared **(Figure1)**. Pairwise regression analyses between NAO indexes and BFT TS led generally to non-significant relationships (in 22 among the 25 cases, **Table 2**). The slopes were weak and either positive or negative ($a \in [-0.32; 0.08]$, **Figure 2**, **Table 2**). The results of the GLS models (that took into account for the autocorrelation) were similar to the linear regressions and always non-significant at 5% **(Table 2)**. Correlation analysis confirmed the previous findings: 72% of the correlation coefficients were non-significant; this proportion rose to 88% when correction for multiple testing was applied. The results of all the above analyses clearly indicated that long-term fluctuations in BFT TS were statistically not related to the NAO.

### *3.2 BFT TS and temperature*

Spectra of the two Northern Hemisphere temperature proxies were both dominated by low frequencies and presented red-shifted spectra, similar to those of the BFT TS **(Figure 1)**. All the regressions between trap catches and NH temperature displayed strong negative slopes ($a \in [-2.90 ; -0.17]$, **Table 2**). Moreover, 13 of the 15 analyses were significant at the 5% level **(Table 2)**. Most of the fits of the GLS model led to lower slope coefficients ($a \in [-2.75 ; 0.44]$) and to a significant drop in the strength of the relationship (only 1 of the 15 regressions remained significant, Table 2). This shows that long-term trends were the most common feature to BFT, Jones' and D'Arrigo's TS. These findings were confirmed by the highly negative correlation coefficients, among which 100% (for Jones' proxy) and 66% (for D'Arrigo's proxy) were significant at the 5% level on corrected correlation analyses **(Table 2)**.

The spectra of the 4 local temperature TS were also dominated by long-term variability, being highly similar to those of the BFT TS **(Figure 1)**. The 24 regressions between BFT and local temperature were significant at the 5% level **(Table 2)** and all regressions exhibited downward slopes. The GLS regressions led to lower and non-significant relationships in 84% of the cases and weak slopes coefficients ($a \in [-0.30 ; 0.26]$, **Table 2**). This again indicated that long-term signal were the common feature to BFT and local temperature TS. Finally, correlation analyses confirmed the strong and negative relationships between BFT and local temperature. All the correlation coefficients were significant, even when correction for multiple testing was applied.

Thus, analyses with local temperature TS corroborated those with large-scale temperature proxies: (1) both BFT and the various temperature TS were largely dominated by low-frequency signals and (2) there was an unambiguous and significant negative relationship between the long-term fluctuations of BFT and those of temperature.

## 4. DISCUSSION

Recent studies put forward that the NAO could affect Atlantic BFT, through its impact on recruitment (Santiago 1998, Marsac 1999). However, Fromentin (2002) and the recent ICCAT workshop on environment and tuna recruitment (ICCAT 2002) further analyzed the NAO/recruitment relationship and showed no clear connection between BFT recruitment and NAO. Our results, based on long-term comparisons, would support these last findings. A potential long-term forcing of the temperature was also investigated. The analyses both in time and frequency domain between BFT and temperature TS led to consistent and trustworthy results. Significant analyses do not imply causal relationship, but we can neither deny the possibility that BFT long-term fluctuations were induced by changes in temperature. To check for it, further modeling and experimental studies are needed.

However, we can already discussed, on the basis of our current knowledge, the most probable underlying processes of such relationship.

Climate-induced fluctuations in fish catches have been demonstrated for several commercial fish stocks (e.g. Cushing 1995). Fluctuations in temperature have been shown to influence: (1) the catchability of gears, (2) the recruitment of fish, and (3) the spatial dynamics of migrating fish populations (e.g. Southward et al. 1988, Corten 2001). In the case of long-term fluctuations of BFT, these two last hypotheses appeared more likely (see Ravier and Fromentin 2001).

Temperature mainly affects directly fish recruitment through the daily development and mortality of the fish larvae as well as juvenile growth (Pepin 1991). Our results highlighted a significant, but negative relationship between temperature and trap catches. In other words, warmer was the weather, less BFT were caught in the Mediterranean. However, high temperature are expecting to enhance recruitment, since the maturation and reproductive activities of tuna species (among which BFT) require high temperature (Mather *et al.* 1995, Schaefer 2001). Consequently, the relationship between temperature and BFT recruitment is expected to be positive and not negative. Therefore, we tend to dismiss the hypothesis of changes in BFT recruitment in relation to temperature.

The negative relationship between long-term fluctuations in temperature and BFT catches could be more easily explained by changes in migration patterns. Changes in environmental conditions are also known to influence spatial and temporal distribution and/or migration patterns of fish (e.g. Southward *et al.* 1988, Brill and Lutcavage 2001). BFT is a large pelagic fish, which carry out large migration over the North Atlantic for feeding and spawning purposes. It is caught by the trap fishery when it finally joins the Mediterranean Sea to reproduce (Mather *et al.* 1995). Fluctuations in trap catches could, therefore, result from changes in spawning migrations attributable to modifications in oceanographic conditions. When temperature raises, some additional locations in the North Atlantic could be suitable for spawning, so that a part of the eastern Atlantic BFT population could reproduce elsewhere from its traditional Mediterranean grounds. This hypothesis is in agreement with some pop-up tag records (Lutcavage *et al.*, 1999) and several past works which have mentioned the occurrence of other hypothetical spawning areas, such as the Ibero-Moroccan bay and the Bay of Biscay (Mather *et al.* 1995). At the opposite, when temperature cools down, the Mediterranean Sea would be the main suitable place for BFT spawning, which would lead to higher catches by traps. This hypothesis of an "opportunistic homing", which combines the "natal homing" hypothesis with the opportunistic reproductive strategy of tuna, allows to give a coherent explanation in agreement with our results and current knowledge on tuna (for more details, see Ravier-Mailly and Fromentin submitted).

## 5. ACKNOWLEDGEMENTS

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## REFERENCES

ALHEIT, J. and E. Hagen. 1997. Long-term climate forcing of European herring and sardine populations. Fish. Oceanogr. 6:1054-6006.

BARD, F. X. 2001. Extension of the geographical and vertical habitat of albacore (*Thunnus alalunga*) in the North Atlantic. Possible consequences on true rate of exploitation of this stock. Col. Vol. Sci. Pap. ICCAT 52:1447-1456.

BOX, G. E. P. and G. M. Jenkins. 1976. Time series analysis forecasting and control. Holden-Day, San Francisco.

BRANDER, K. M. 1995. The effect of temperature on growth of Atlantic cod (*Gadus morhua*, L.). ICES J. Mar. Sci. 52:1-10.

BRILL, R. W. and M. E. Lutcavage. 2001. Understanding environmental influences on movements and depth distributions of tunas and billfishes can significantly improve population assessments. American Fisheries Society Symposium 25:179-198.

CORTEN, A. 2001. Northern distribution of the North Sea herring as a response to high water temperatures and/or low food abundance. Fish. Res. 50:189-204.

CUSHING, D. H. 1995. Population production and regulation in the sea. A fishery perspective. Cambridge University Press, Cambridge.

ELLERSTEN, B., P. Fossum, P. Solemdal and S. Sundby. 1989. Relation between temperature and survival of eggs and firstfeeding larvae of northeast Arctic cod (*Gadus morhua* L.). Rapp. P.-v. Réun. Cons. int. Explor. Mer 191:209-219.

FLETT, P. A., K. R. Munkittrick, G. Van Der Kraar and J. F. Leatherland. 1996. Overripening as the cause of low survival to hatch in Lake Erie coho salmon (*Oncorhyncus kisutch*) embryos. Can. J. Zool. 74:851-857.

FROMENTIN, J.-M. 2002. Is the recruitment a key biological process in the hypothetical NAO-Atlantic tunas relationships? Col. Vol. Sci. Pap. ICCAT 54:1008-1016.

FROMENTIN, J.-M. and B. Planque. 1996. *Calanus* and environment in the eastern North Atlantic. 2) Role of the North Atlantic Oscillation on *Calanus finmarchicus* and *C. helgolandicus*. Mar. Ecol. Prog. Ser. 134:111-118.

HOLM, S. 1979. A simple sequentially rejective multiple test procedure. Scand. J. Stat. 6:65-70.

HURRELL, J. W., Y. Kushnir and M. Visbeck. 2001. The North Atlantic Oscillation. Science 291:603-604.

HUTCHINGS, J. A. and R. A. Myers. 1994. What can be learned from the collapse of a renewable resource? Atlantic cod, *Gadus morhua*, of Newfoundland and Labrador. Can. J. Fish. Aquat. Sci. 51:2126-2146.

ICCAT. 2002. Report of the workshop on environment and tuna recruitment. Col. Vol. Sci. Pap. ICCAT in press.

LEGENDRE, P. and L. Legendre. 1998. Numerical Ecology. Elsevier, Amsterdam.

MARSAC, F. 1999. Changements hydroclimatiques observés dans l'Atlantique depuis les années 50 et impacts possibles sur quelques stocks de thons et leur exploitation. Col. Vol. Sci. Pap. ICCAT 49:346-370.

MATHER, F. J., J. M. Mason and A. C. Jones. 1995. Historical Document: Life History and Fisheries of Atlantic Bluefin Tuna. NOAA Technical Memorandum, NMFS-SEFSC - 370.

MCGOWAN, J. A., D. R. Cayan and L. M. Dorman. 1998. Climate-ocean variability and ecosystem response in the Northeast Pacific. Science 281:210-217.

OTTERSEN, G., B. Planque, A. Belgrano, E. Post, P. C. Reid and N. C. Stenseth. 2001. Ecological effects of the North Atlantic Oscillation. Oecologia 128:1-14.

PEPIN, P. 1991. Effect of temperature and size on development, mortality and survival rates of the pelagic early life history stages of marine fish. Can. J. Fish. Aquat. Sci. 48:503-518.

RAVIER, C. and J.-M. Fromentin. 2001. Long-term fluctuations in the Eastern Atlantic and Mediterranean bluefin tuna population. ICES J. mar. Sci. 58:1299-1317.

RAVIER-MAILLY, C. and J.-M. Fromentin. submitted. Are the long-term fluctuations in Atlantic bluefin tuna population related to environmental changes? Fish. Oceanogr.

SANTIAGO, J. 1998. The North Atlantic Oscillation and recruitment of temperate tunas. Col. Vol. Sci. Pap. ICCAT 48(3):240-249.

SCHAEFER, K. M. 2001. Reproductive biology of tunas. Pages 225-270 *in* B. A. Block and E. D. Stevens, editors. Tuna: physiology, ecology and evolution. Academic press, New York.

SOUTHWARD, A. J., G. T. Boalch and L. Maddock. 1988. Fluctuations in the herring and pilchard fisheries of Devon and Cornwall linked to change in climate since the 16th century. J. Mar. Biol. Ass. U.K. 68:423-445.

TYLER, A. V. 1995. Warm-water and cool-water stocks of Pacific cod (*Gadus macrocephalus*): a comparative study of reproductive biology and stock dynamics. Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121:537-545.

**Table 1.** Main characteristics of the environmental and trap catches time-series: type of variable, source (instrumental or reconstructed, location), period and bibliographic references.

| Variable | Source | Period | References |
|---|---|---|---|
| NAO | Field measure | 1865-2000 | Method from Rogers (1984)<br>Data from the World Monthly Surface Station Climatology<br>http://www.cgd.ucar.edu/~jhurrell/nao.htm |
| | Reconstruction (ice cores) | 1648-1991 | Appenzeller (1998) |
| | Reconstruction (tree ring) | 1701-1980 | Cook (1998) |
| Temperature HN | Reconstruction (field measures) | 1856-2001 | Jones (1997, 1999, 2001)<br>Data from the Climatic Research Unit<br>http://www.cru.uea.ac.uk/ |
| | Reconstruction (tree ring) | 1671-1973 | D'Arrigo (1999) |
| Temperature | Cadix (Gibraltar), instrumental | 1870-1994 | Wheeler (pers.com.) |
| | Dar-El-Beida (Algeria), instrumental | 1878-1995 | Global Historical Climatology Network data base<br>http://cdiac.esd.ornl.gov/ghcn/ghcn.html |
| | Cagliari (Sardinia), instrumental | 1866-1996 | Brunetti (2000); Maugeri (pers.com.) |
| | Palerme (Sicily), instrumental | 1866-1996 | Brunetti (2000); Maugeri (pers.com.) |
| Trap catches | Medo das Casas (Portugal) | 1852-1933 | Ravier et Fromentin (2001) |
| | Sidi Daoud (Tunisia) | 1863-1960 | Ravier et Fromentin (2001) |
| | Formica (Sicily) | 1634-1813<br>1878-1960 | Ravier et Fromentin (2001) |
| | Favignana (Sicily) | 1634-1813<br>1878-1960 | Ravier et Fromentin (2001) |
| | Bonagia (Sicily) | 1657-1809 | Ravier et Fromentin (2001) |
| | Saline (Sardinia) | 1868-1960 | Ravier et Fromentin (2001) |
| | Porto Paglia (Sardinia) | 1825-1960 | Ravier et Fromentin (2001) |
| | Porto Scuso (Sardinia) | 1825-1960 | Ravier et Fromentin (2001) |
| | Isola Piana (Sardinia) | 1825-1960 | Ravier et Fromentin (2001) |

**Table 2.** Results from the analyses between environmental and BFT time-series: number of pairwise analyses (N), slope (minimum, median, maximum) and number of significant p-values of the linear regressions, number of significant p-values of the fitted generalised least squares models, % of significant Holm's corrected probabilities of the Spearman correlation (bold values indicate significant probabilities > 50%).

| Environmental time-series | N | Linear regression | | Generalised Least Squares model | Correlation Holm's |
|---|---|---|---|---|---|
| | | Slope [min, median,max] | significant p-values | significant p-values | % significant p-values |
| NAO Hurrell | 7 | [-0.01; 0.05; 0.08] | 0 | 0 | 0 |
| NAO Cook | 9 | [-0.05;-0.02; 0.00] | 2 | 1 | 22 |
| NAO Appenzeler | 9 | [-0.32;-0.00-;0.07] | 1 | 0 | 11 |
| Temperature HN Jones | 6 | [-2.20;-1.88;-1.41] | 6 | 0 | **100** |
| Temperature HN D'Arrigo | 9 | [-2.90;-0.96;-0.17] | 7 | 1 | **66** |
| Temperature Palerme | 6 | [-0.55;-0.49;-0.34] | 6 | 1 | **100** |
| Temperature Cagliari | 6 | [-0.60;-0.49;-0.34] | 6 | 1 | **100** |
| Temperature Cadix | 6 | [-0.94;-0.67;-0.48] | 6 | 2 | **100** |
| Temperature Dar-El-Beida | 6 | [-0.71;-0.52;-0.44] | 6 | 0 | **100** |

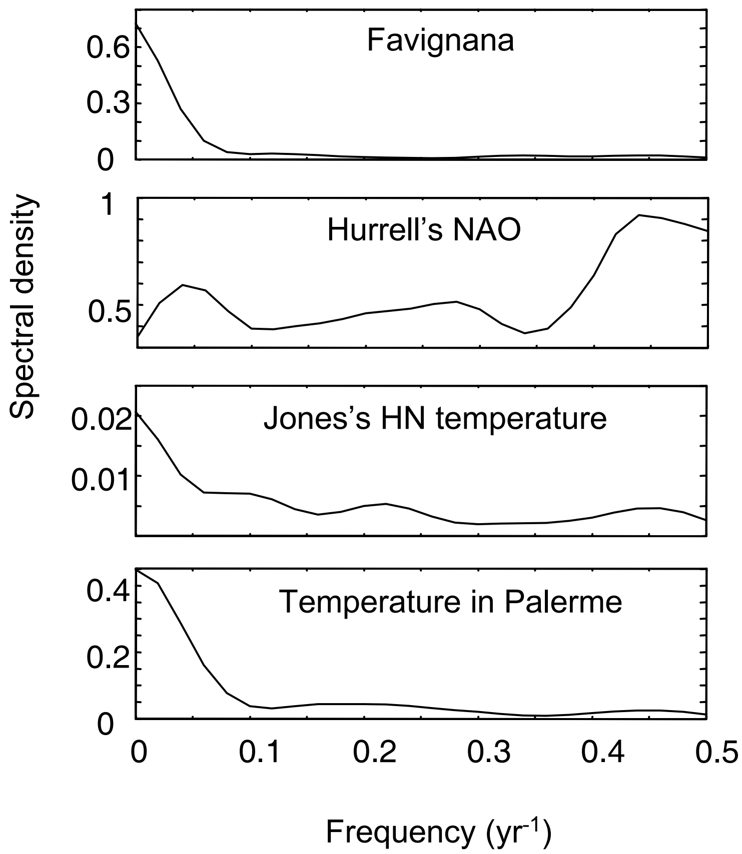


**Figure 1.** Spectral densities of the Favignana trap catches time series,Hurrell's NAO index, Jones's Northern Hemisphere temperature and instrumental temperature recorded at Palerme.

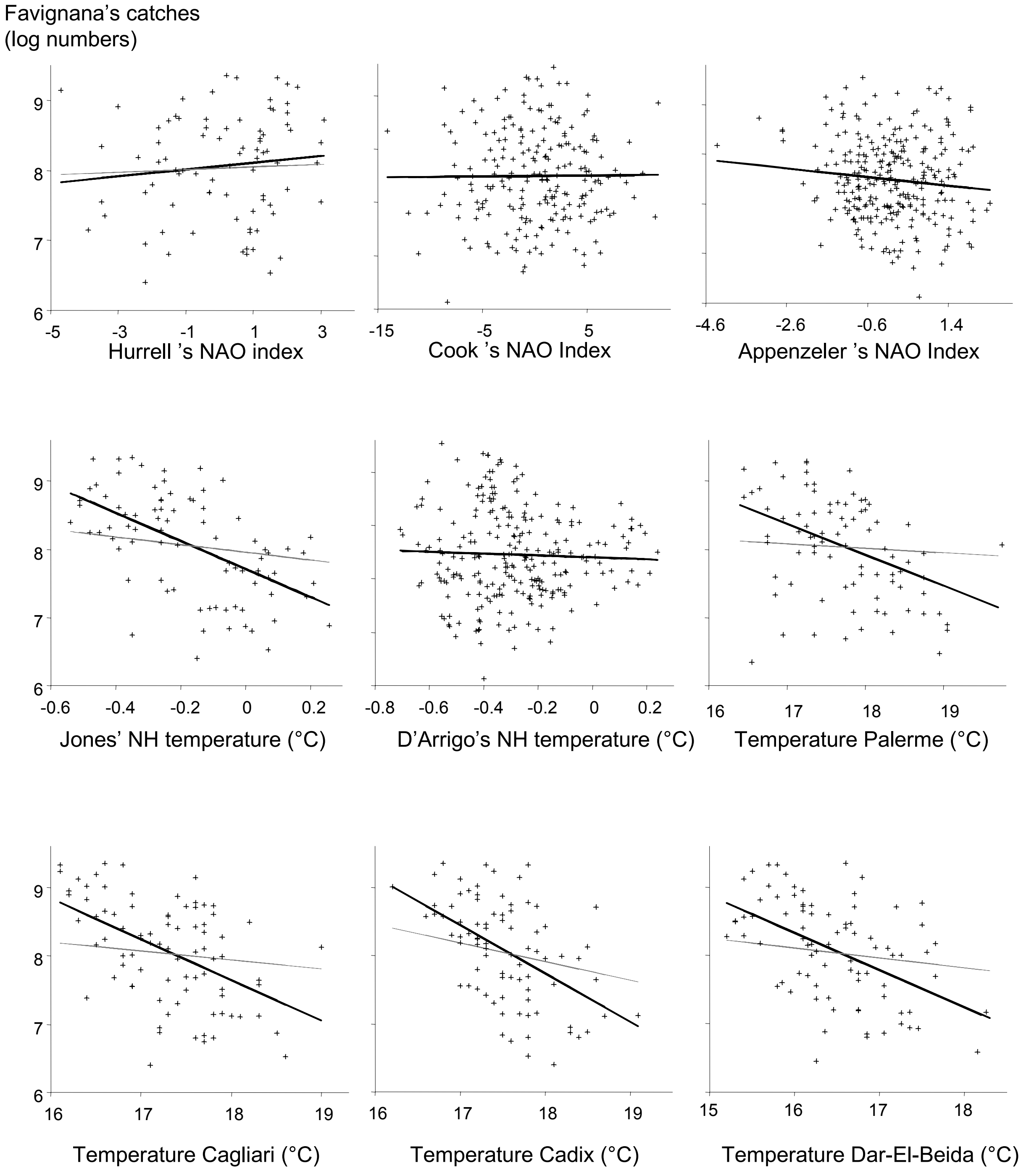


**Figure 2.** Relationships between the Favignana's trap catches and the different environmental time-series. Straight lines correspond to the linear regressions, dotted lines to generalised least squares models with errors specified to follow an appropriate autoregressive process (i.e. models that take into account for the autocorrelation).