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Report of the Working Group on Small Pelagic Fish, their Ecosystems and Climate Impact (WGSPEC)

30 March–3 April 2015

Thessaloniki, Greece



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International Council for the Exploration of the Sea Conseil International pour l'Exploration de la Mer

H. C. Andersens Boulevard 44–46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

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Executive summary

The Working Group on Small Pelagic Fishes, their Ecosystems and Climate Impact (WGSPEC) has met during its second reporting period (2013–2015) in Malaga (Spain), Santa Cruz de Tenerife (Spain) and Thessaloniki (Greece). Scientists from the General Mediterranean Fisheries Council (GFCM) from Greece, Italy, Spain and Turkey played a vital role in the WG. The meetings were attended by experts in climate variability, physical oceanography, zooplankton and fisheries biology.

The overarching theme of the WG was the impact of the Atlantic Multidecadal Oscillation (AMO) and related physical drivers such as the contraction of the subpolar gyre, the weakening of the North Atlantic Oscillation (NAO) and the eastward shift of the Icelandic Low on the dynamics of Eastern North and Central Atlantic ecosystems including North Sea and Mediterranean. The early focus of the WG was on small pelagic fishes. Dynamics of abundance and migrations of populations of small pelagic clupeoid fish such as anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*), sardinella (*Sardinella aurita*), sprat (*Sprattus sprattus*) and herring (*Clupea harengus*) in the eastern North and Central Atlantic between Senegal and Norway vary in synchrony with the warm and cool phases of the Atlantic Multidecadal Oscillation (AMO). This is shown by compiling retrospective data on fish catches and anecdotal observations, which in some cases date back to the mid-19th century. It is not primarily the temperature which drives the dynamics of the small pelagic fish populations. Instead, the AMO seems to be a proxy for complex processes in the coupled atmosphere–ocean system of the North Atlantic. This is manifested in large-scale changes in strength and direction of the current system that move water masses around the North Atlantic and likely involves the North Atlantic Oscillation (NAO), the Atlantic Meridional Overturning Circulation (AMOC), the Mediterranean Overflow Water (MOW) and the subpolar gyre (SPG). The contractions and expansions of the SPG apparently play a key role. This was particularly obvious in the mid-1990s, when the SPG abruptly contracted with the result that warm subtropical water masses moved to the north and east. Small pelagic fish populations in the eastern North and Central Atlantic, including those in the Mediterranean responded quickly by changing abundances and migrating northwards. It seems that the complex ocean–atmosphere changes in the mid-1990s caused a regime shift in the ecosystems of the eastern North and Central Atlantic and the small pelagic clupeoid fish populations are the sentinels of this shift. WGSPEC extended these studies to other components of NE Atlantic ecosystems, particularly plankton, larger pelagic and demersal fish species with a particular view to the regime shift in the mid-1990s. WGSPEC also started to assemble and analyse different data sets on early life stages of small pelagics, with the aim of investigating the effect of environmental change on their recruitment. The future work of WGSPEC will be a global comparison of climate variability impact on small pelagics.

Based, *inter alia*, on a recommendation by WGSPEC, ICES and PICES decided to organize a PICES/ICES Symposium on “Drivers of Pelagic Fish Resources” in early 2017 in Victoria, Canada. WGSPEC will prepare presentations for this meeting.

For the last six years, scientists of ICES and the General Fisheries Council of the Mediterranean (GFCM) have been cooperating successfully in WGSPEC.

1 Administrative details

Working Group name

Working Group on Small Pelagic Fishes, their Ecosystems and Climate Impact (WGSPEC)

Year of Appointment

2013

Reporting year concluding the current three-year cycle

2015

Chairs

Jürgen Alheit (Germany)

Priscilla Licandro (UK)

Meeting venue(s) and dates

2013 Fuengirola/ Malaga (Spain), 25 February–1 March 2013, 6 participants

2014 Santa Cruz de Tenerife (Spain), 10–14 March 2014, 11 participants

2015 Thessaloniki (Greece), 30 March–3 April, 8 participants

2 Terms of Reference and Summary of Work plan

- a) Specific analysis of climate impact of regime shift around the mid-1990s on ecosystems of NEAtlantic, incl. Mediterranean and NW African upwelling, with a focus on dynamics of AMO/AMV and N Atlantic gyres:
 - 1) understand respective physical mechanism;
 - 2) study reactions of plankton and small pelagic fish;
 - 3) compare with similar events in 1st half of 20th century.
- b) Study mechanisms that link the variability of the small pelagic fish populations in different ocean basins with the large scale climatic forcings.
- c) Global comparison of climate variability impact on small pelagics.
- d) Impact of climate variability on recruitment of small pelagics in different regions of the North eastern Atlantic and Mediterranean.
- e) Produce four short paragraphs for the ICES Ecosystem Overviews on the state of the pelagic habitat (oceanography and biology), one paragraph for each of the following ICES ecoregions: Greater North Sea, Celtic Seas, Bay of Biscay & the Iberian coast and Baltic Sea.

Summary of Work plan

Year 1	Specific analysis of climate impact and respective physical and biological processes around the mid-1990s
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Year 2	Specific analysis of climate variability impact on recruitment of small pelagic fishes and non-clupeid small pelagics
Year 3	Summing up of results of WGSPEC

3 Summary of Achievements of the WG during 3-year term

- WGSPEC successfully proposed to organize PICES/ICES Symposium 2017 on “Drivers of Small Pelagic Fish Resources” in Victoria, Canada, Mar 6-10
- Participation of and close collaboration with scientists of General Fisheries Council of Mediterranean (GFCM) from Greece, Italy, Spain, Turkey
- Special Issue on Atlantic Multidecadal Oscillation-mechanism and impact on marine ecosystems. 2014. J. mar. Syst. 133: 1-130. Ed. by Jürgen Alheit, Kenneth F. Drinkwater and Janet A. Nye
- Alheit, J., Licandro, P., Coombs, S., Garcia, A., Giraldez, A., Santamaria, M.T.G., Slotte, A., Tsikliras, A. 2014. Atlantic Multidecadal Oscillation (AMO) modulates dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic. J. mar. Syst. 131: 21-35
- Alheit, J., Drinkwater, K.F., Nye, J.A. 2014. Introduction to special issue: Atlantic multidecadal oscillation-mechanism and impact on marine ecosystems. J. mar. Syst. 133: 1-3
- Alheit, Groeger, Licandro, McQuinn, Tsikliras, *et al.* (in prep.) Changes in NE Atlantic and Mediterranean in mid-1990s (working title)
- Tsikliras, Licandro, McQuinn, Groeger, Alheit. (in prep). Synchronization of Mediterranean pelagic fish populations with Atlantic Multidecadal Oscillation.
- Licandro, Bonanno, Coombs, Jiménez, Petrillo, Somarakis, Tsikliras, Alheit. (in prep.). Impact of environmental changes on recruitment of small pelagics in the Mediterranean and North-East Atlantic.

4 Final report on ToRs, work plan and Science Implementation Plan

All work done by WGSPEC responds to the Science Priorities 1-4 of the ICES Science Plan.

Progress and fulfilment by ToR

ToR A) Specific analysis of climate impact of regime shift around the mid-1990s on ecosystems of NE Atlantic, incl. Mediterranean and NW African upwelling, with a focus on dynamics of AMO/AMV and N Atlantic gyres:

- 1) understand respective physical mechanism;
- 2) study reactions of plankton and small pelagic fish;
- 3) compare with similar events in 1st half of 20th century.

ToR was fulfilled. The results have been published in: Alheit, J., Licandro, P., Coombs, S., Garcia, A., Giráldez, A., Garcia Santamaría, M.T., Slotte, A., Tsikliras, A.C. 2014. Atlantic Multi-decadal Oscillation (AMO) modulates dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic. *J. mar. Syst.* 133: 88-102. (open access)

Abstract:

Dynamics of abundance and migrations of populations of small pelagic clupeoid fish such as anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*), sardinella (*Sardinella aurita*), sprat (*Sprattus sprattus*) and herring (*Clupea harengus*) in the eastern North and Central Atlantic between Senegal and Norway vary in synchrony with the warm and cool phases of the Atlantic Multidecadal Oscillation (AMO). This is shown by compiling retrospective data on fish catches and anecdotal observations, which in some cases date back to the mid-19th century. The AMO is defined as the de-trended mean of North Atlantic (0–60°N) sea surface temperature anomalies. However, it is not primarily the temperature which drives the dynamics of the small pelagic fish populations. Instead, the AMO seems to be a proxy for complex processes in the coupled atmosphere–ocean system of the North Atlantic. This is manifested in large-scale changes in strength and direction of the current system that move water masses around the North Atlantic and likely involves the North Atlantic Oscillation (NAO), the Atlantic Meridional Overturning Circulation (AMOC), the Mediterranean Overflow Water (MOW) and the subpolar gyre (SPG). The contractions and expansions of the SPG apparently play a key role. This was particularly obvious in the mid-1990s, when the SPG abruptly contracted with the result that warm subtropical water masses moved to the north and east. Small pelagic fish populations in the eastern North and Central Atlantic, including those in the Mediterranean responded quickly by changing abundances and migrating northwards. It seems that the complex ocean–atmosphere changes in the mid-1990s, which are described in the text in detail, caused a regime shift in the ecosystems of the eastern North and Central Atlantic and the small pelagic clupeoid fish populations are the sentinels of this shift.

ToR B) Study mechanisms that link the variability of the small pelagic fish populations in different ocean basins with the large scale climatic forcings.

ToR has been fulfilled. Two manuscripts are in preparation. However, one (Alheit *et al.*) is somewhat delayed by health problems of key authors, but will be finished in 2015.

These manuscript are a follow-up of the previous one above. It extends the results gained on small pelagics and includes other ecosystem compartments such as zooplankton and non-pelagic fishes. It demonstrates very clearly that there was a regime shift in the mid-1990s in all ecosystems of the eastern North and Central Atlantic investigated in synchrony with the contraction of the subpolar gyre, strong weakening of NAO, eastward shift of Icelandic Low and increase of AMO.

ToR C) Global comparison of climate variability impact on small pelagics.

This ToR had to be moved to the WGSPEC meeting in 2016 because of health problems of key authors.

ToR D) Impact of climate variability on recruitment of small pelagics in different regions of the North eastern Atlantic and Mediterranean.

In a climate change scenario, the identification and conservation of suitable habitats for pelagic fish species represents a main challenge. Evaluating the impact of climate variability on small pelagic fish in southern European seas is considered a high priority by researchers and stakeholders at present, as for many years studies have focused on larger predatory fish (e.g. cod) and more northern marine ecosystems (e.g. North Sea).

European anchovy (*Engraulis encrasicolus*), which together with sardine (*Sardina pilchardus*) sustain about 50% of the Fisheries in the Mediterranean, has significantly decreased in the last decade in the Mediterranean as well as in other regions of the North Eastern Atlantic. A link between environmental change and recent poor recruitment of anchovy has been hypothesized, but the environmental factors mainly responsible for such failure in recruitment are yet to be clarified. Within WGSPEC we investigate the influence of different environmental factors on spatio-temporal variability of anchovy stocks (from larvae to adults) in different Mediterranean regions (i.e. Ligurian Sea, Strait of Sicily Channel, North Aegean Sea), which have been identified as key areas for the spawning and recruitment of European anchovy. The results of this study will contribute to identify environmental preferences associated with a successful recruitment of European anchovy. Comparison with similar studies conducted in the North eastern Atlantic (e.g. Western English Channel, Gulf of Cadiz) will help clarifying the mechanisms that link the variability of small pelagic fish populations in different ocean basins to the large scale climatic forcing.

ToR E) Produce four short paragraphs for the ICES Ecosystem Overviews on the state of the pelagic habitat (oceanography and biology), one paragraph for each of the following ICES ecoregions: Greater North Sea, Celtic Seas, Bay of Biscay & the Iberian coast and Baltic Sea.

WGSPEC did not have a possibility to work on this additional ToR. Whereas experts on these regions participated in WGSPEC meetings during the first 3-year period, they did not join from 2013–2015. Consequently, the respective expertise has to be sought outside of WGSPEC.

Science highlights

- Abundance fluctuations of fish populations correspond to alternating AMO phases.
- Regime shifts in eastern North Atlantic ecosystems are associated with AMO dynamics.
- AMO affects Mediterranean fish populations.
- European clupeoid populations exhibit synchronous multi-decadal changes in abundance.
- Contraction of sub-polar gyre assumed to trigger synchronicity in fish populations.

5 Cooperation

- Cooperation with other WG
Instead of a formal cooperation with WGOH and WGZE, WGSPEC chose to respective experts to integrate directly in its work.
- Cooperation with Advisory structures: no
- Cooperation with other IGOs: no

6 Summary of Working Group evaluation and conclusions

WGSPEC has adopted the Science Plan Objectives:

- Describe and quantify the state of North Atlantic Ocean regional systems.
- Understand and forecast the impacts of climate variability and change of marine ecosystems.

Main achievements:

- WGSPEC successfully proposed to organize PICES/ICES Symposium 2017 on “Drivers of Small Pelagic Fish Resources” in Victoria, Canada, Mar 6-10
- Participation of and close collaboration with scientists of General Fisheries Council of Mediterranean (GFCM) from Greece, Italy, Spain, Turkey
- Six publications and manuscripts

ToRs:

ToR C) had to be moved to the WGSPEC meeting in 2016 because of health problems of key authors.

ToR E) was suggested by SCICOM. It was not done, as WGSPEC did not have the respective expertise.

Continuation of WG is required.

Conclusions

The work of the WGSPEC highlighted consistent changes in the stocks of small pelagics of the North-eastern Atlantic and Mediterranean, that appeared to be related with large scale climatic variability. This result outlines the need of developing a large-scale Ecosystem-Based Fishery Management approach in support to regional management, to exploit small pelagics stocks in a sustainable way.

Annex 1: List of participants

NAME	AFFILIATION	PHONE	EMAIL
Jürgen Alheit (Co-Chair)	Leibniz Institute for Baltic Sea Research Seestr. 15 18119 Warnemünde Germany	+49 3815197208	juergen.alheit@io-warnemuende.de
Santiago Alvarez Fernandez	WUR-IMARES Landsdiop-1797 't Honte Netherlands	+31 623379524	santiago.alvarezfernandez@wur.nl
Angelo Bonanno	Institute for the Marine Coastal Environment of the Italian National Research Council (IAMC-CNR) Via del Faro, 3 – Capo Granitola 91021, Campobello di Mazara (TP) Italy	+39 09244061146	angelo.bonanno@iamc.cnr.it
Marta Carballo	Centro Oceanográfico de Canarias c/Acorán nº33 38111 Santa Cruz de Tenerife Spain	+34 661078943	martagcarballo@gmail.com
Alberto Garcia	Instituto Español de Oceanografía Centro Oceanográfico de Málaga Puerto Pesquero s/n 29640 Fuengirola, Spain	+34 952197123	agarcia@ma.ieo.es
M ^a Teresa García Santamaria	Instituto Español de Oceanografía Centro Oceanográfico de Canarias Vía Espaldón , dársena pesquera, Parcela 8 38180 Santa Cruz de Tenerife Spain	+34 922549400	teresa.garcia@ca.ieo.es
Ana Giráldez	Instituto Español de Oceanografía Centro Oceanográfico de Málaga Puerto Pesquero s/n 29640 Fuengirola, Spain	+34 952198073	agiraldez@ma.ieo.es
Joachim Gröger	Thünen-Institute for Sea Fisheries Palmaille 9 22767 Hamburg Germany	+49 4038905266	joachim.groeger@ti.bund.de
Hjalmar Hátún	Faroe Marine Research Institute Gerdisbreyt 6 176 Velbastadur Faroe Islands	+298 229092	hjalmarh@hav.fo

Priscilla Licandro (Co-Chair)	Sir Alister Hardy Foundation for Ocean Science (SAHFOS) The Laboratory Citadel Hill PL1 2PB Plymouth UK	+44 1752633133	prli@sahfos.ac.uk
Ian H. McQuinn	DFO – Maurice Lamontagne Institute C.P. 1000 850, Route de la Mer Mont-Joli, Quebec Canada, G5H 3Z4	+1 4187750627	ian.mcquinn@dfo-mpo.gc.ca
Ana Sabatés	Institut de Ciències del Mar (CSIC) P. Maritim 37-49 08003 Barcelona Spain	+34 932309500	anas@icm.csic.es
Konstantinos I. Stergiou	Laboratory of Ichthyology School of Biology Aristotle University of Thessaloniki UP Box 134, University Campus 541 25 Thessaloniki Greece		kstergiou@bio.auth.gr
Athanassios Tsikliras	Laboratory of Ichthyology School of Biology Aristotle University of Thessaloniki UP Box 134, University Campus 541 25 Thessaloniki Greece	+30 2310998391	atsik@bio.auth.gr
Pedro Vélez	Instituto Español de Oceanografía Centro Oceanográfico de Canarias Vía Espaldón , dársena pesquera, Parcela 8 38180 Santa Cruz de Tenerife Spain	+34 922549400	pedro.velez@ca.ieo.es
Christina Zikidou	Aristotle University of Thessaloniki Dimitsanas 43 K. Toumpa 54454 Thessaloniki Greece	+30 6978168592	christina_zikidou2@hotmail.com
Participants by correspondence			
Ceren Guraslan	Institute of Marine Sciences Middle East Technical University P.O.Box 28, 33731 Erdemli Turkey	+90 3245212406	ceren@ims.metu.edu.tr
Maria Paz Jiménez	Instituto Español de Oceanografía, Puerto Pesquero, Muelle de Levante s/n 11006 Cádiz, Andalucía Spain	+34 956294189	paz.jimenez@cd.ieo.es

Mario Petrillo	Dipartimento di Scienze della Terra dell'Ambiente e della Vita University of Genoa Corso Europa 26 16132 Genoa Italy	+39 0185 283415	petrillo@dipteris.unige.it
Stylianos (Stelios) Somarakis	Hellenic Centre for Marine Research P.O.Box 2214 71003 Heraklion, Crete Greece	+30 2810 337832	somarak@hcmr.gr

Annex 2: Draft multi-annual resolution 2016–2018

The **Working Group on Small Pelagic Fishes, their Ecosystems and Climate Impact** (WGSPEC), chaired by Priscilla Licandro, UK, and Athanassios Tsikliras*, Greece, will work on ToRs and generate deliverables as listed in the Table below.

	MEETING DATES	VENUE	REPORTING DETAILS	COMMENTS (CHANGE IN CHAIR, ETC.)
Year 2016	TBA	TBA	Interim report by 15 May to SSGEPD	
Year 2017			Interim report by	
Year 2018			Final report by	

ToR descriptors

ToR	DESCRIPTION	BACKGROUND	SCIENCE PLAN TOPICS ADDRESSED	DURATION	EXPECTED DELIVERABLES
A	Global comparison of climate variability impact on small pelagics	Support action for SICCME	1, 2, 3, 4	1 year	Review paper
B	Impact of climate variability on recruitment of small pelagics in different regions of the North eastern Atlantic and Mediterranean	Support action for SICCME	1, 2, 3, 4	1.5 Years	Review paper
C	Preparation of joint presentations for PICES/ICES Symposium in 2017 on Drivers of Pelagic Fish Resources		1, 2, 3, 4	1.5 years	2-3 presentations

Summary of the Work Plan

Year 1	Global comparison (A), Impact on recruitment (B), preparation of presentations
Year 2	Preparation of presentations
Year 3	Summing up of results of WGSPEC

Supporting information

Priority	<p>This Working Group has a high priority because the impact of climate variability on small pelagic fishes and their ecosystems has been largely ignored, as, in the past, ICES had put its focus on climate studies of larger predatory fish (cod) and more northern ecosystems.</p> <p>This working group contributes to the preparation of the PICES/ICES Symposium on 'Drivers of Pelagic Fish resources' in Victoria, Canada, 2017.</p> <p>This Working Group is a support action for the Strategic Initiative on Effects of Climate Change on Marine Ecosystems (SICCME) of ICES.</p> <p>This Working Group is an ideal vehicle to continue and strengthen collaboration with PICES which was successfully started some years ago in the field of small pelagics and climate by joint workshops and theme sessions.</p> <p>This Working Group cooperates with scientists of the General Fisheries Council of the Mediterranean (GFCM).</p>
Resource requirements	None
Participants	<p>The participants of this Working Group should represent different disciplines such as fisheries science, planktology, physical oceanography, climatology.</p> <p>Scientists from the General Fisheries Council of the Mediterranean (GFCM)</p>
Secretariat facilities	None.
Financial	No financial implications.
Linkages to ACOM and groups under ACOM	There are no obvious direct linkages.
Linkages to other committees or groups	The Working Group will link up with other ICES groups such as SICCME, WGOH, WGZE.
Linkages to other organizations	The Working Group will seek close cooperation with other international organisations, particularly from the North Pacific (PICES) and the Mediterranean (GFCM).

Annex 3: Copy of Working Group self-evaluation

- 1) Working Group name
Working Group on Small Pelagic Fishes, their Ecosystems and Climate Impact (WGSPEC)
- 2) Year of appointment: 2010
- 3) Current Chairs
Jürgen Alheit (Germany)
Priscilla Licandro (UK)
- 4) Venues, dates and number of participants per meeting
2013 Fuengirola (Spain), 25 Feb-1 Mar 2013, 6 participants
2014 Santa Cruz de Tenerife (Spain), 10-14 Mar 2014, 11 participants
2015 Thessaloniki (Greece), 30 Mar-3 Apr, 8 participants

WG Evaluation

- 5) Research priorities of the Science Plan to which the WG makes a significant contribution

WGSPEC has adopted the Science Plan Objectives:

- Describe and quantify the state of North Atlantic Ocean regional systems.
- Understand and forecast the impacts of climate variability and change of marine ecosystems.

It contributes to the Science Priority areas:

1. Assess the physical, chemical and biological states of regional seas, and investigate the predominant climatic, hydrological, and biological features and processes that characterize regional ecosystems.
2. Quantify the nature and degree of connectivity and separation between regional ecosystems.
3. Quantify the differential effects of climate change on regional ecosystems, and develop species and habitat vulnerability assessments for key species.
4. Understand the influence of climate impacts across a range of spatial and temporal scales, from local to global and from seasonal to multidecadal, and identify indicators of climate-driven biotic responses and forecast trajectories of change.

Note: the focus of WGSPEC is on **climate variability**.

- 6) Main outcomes and achievements of the WG since their last evaluation
 - WGSPEC successfully proposed to organize PICES/ICES Symposium 2017 on “Drivers of Small Pelagic Fish Resources” in Victoria, Canada, Mar 6-10
 - Participation of and close collaboration with scientists of General Fisheries Council of Mediterranean (GFCM) from Greece, Italy, Spain, Turkey
 - Special Issue on **Atlantic Multidecadal Oscillation-mechanism and impact on marine ecosystems**. 2014. J. mar. Syst. 133: 1-130. Ed. by Jürgen Alheit, Kenneth F. Drinkwater and Janet A. Nye
 - Alheit, J., Licandro, P., Coombs, S., Garcia, A., Giraldez, A., Santamaria, M.T.G., Slotte, A., Tsikliras, A. 2014. Atlantic Multidecadal Oscillation (AMO) modulates dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic. J. mar. Syst. 131: 21-35
 - Alheit, J., Drinkwater, K.F., Nye, J.A. 2014. Introduction to special issue: Atlantic multidecadal oscillation-mechanism and impact on marine ecosystems. J. mar. Syst. 133: 1-3
 - Alheit, Groeger, Licandro, McQuinn, Tsikliras, *et al.* (in prep.) Changes in NE Atlantic and Mediterranean in mid-1990s (working title)
 - Tsikliras, Licandro, McQuinn, Groeger, Alheit (in prep) Synchronization of Mediterranean pelagic fish populations with Atlantic Multidecadal Oscillation.
 - Licandro, Bonanno, Coombs, Jiménez, Petrillo, Somarakis, Tsikliras, Alheit. Impact of environmental changes on recruitment of small pelagics in the Mediterranean and North-East Atlantic.

- 7) Has the WG contributed to Advisory needs?
No

- 8) Outreach activities of the WG outside the ICES network
See 6)

- 9) Please indicate what difficulties, if any, have been encountered in achieving the workplan
 ToR C) had to be moved to the WGSPEC meeting in 2016 because of health problems of key authors.
 ToR E) was suggested by SCICOM. It was not done, as WGSPEC did not have the respective expertise. (See report)

Future plans

- 10) Does the group think that a continuation of the WG beyond its current term is required?
 - WGSPEC will in 2016 prepare presentations for the PICES/ICES Symposium on ‘Drivers of Pelagic Fish resources, meet during the symposium in 2017, and wrap up the results in 2018.

- The studies on mechanisms that link variability of small pelagic fish populations in different ocean basins with large-scale climatic forcing have to be continued.
- A global comparison of climate variability impact on small pelagics will be carried out.

- 11) If you are not requesting an extension, does the group consider that a new WG is required to further develop the science previously addressed by the existing WG.

Not applicable.

- 12) What additional expertise would improve the ability of the WG to fulfil its ToR?

Although WGSPEC had physical oceanographers actively and successfully participating in meetings, additional collaboration from the fields of atmospheric sciences and physical oceanography would strengthen the output.

- 13) Which conclusions/or knowledge acquired of the WG do you think should be used in the Advisory process?

The work of the WGSPEC highlighted consistent changes in the stocks of small pelagics of the North-eastern Atlantic and Mediterranean that appeared to be related with large scale climatic variability. This result outlines the need of developing a large-scale Ecosystem-Based Fishery Management approach in support to regional management, to exploit small pelagics stocks in a sustainable way.

Annex 4: Presentations from the 2015 meeting

Presentation by K. Stergiou

Trends in productivity and biomass yields in the Mediterranean Sea Large Marine Ecosystem during climate change

Stergiou K.I.^{1,2}, Somarakis S.¹, Triantafyllou G.³, Tsiaras K.P.³, Giannoulaki M.¹, Petihakis G.³, Machias A.¹, Tsikliras A.C.²

¹ Institute of Marine Biological Resources & Inland Waters, Hellenic Centre for Marine Research, Athens, Greece

² Department of Zoology, School of Biology, Aristotle University of Thessaloniki, Thessaloniki, Greece

³ Institute of Oceanography, Hellenic Centre for Marine Research, Athens, Greece

In this essay we describe the effects of climate change and variability in the Mediterranean using different indices. We also describe the evolution of yearly catches and species composition of the catches in the western (W), central (C) and eastern (E) Mediterranean during 1970–2010 and the exploitation status of the fisheries resources. In addition, we explore the mean temperature of the catch in the W, C and E Mediterranean under a scenario considering the catches of species migrating through the Suez Canal (Figure 1) and we review various signals of climate variability on Mediterranean fisheries. We further review the existing habitat modelling studies at the Mediterranean scale of various species and discuss their response to climate change. Finally, we present the development of a 3-D full life cycle population model and the respective model forecasts of European anchovy *Engraulis encrasicolus* biomass at the Mediterranean scale.

In a simulation undertaken here in which hypothetical catches of species migrating through the Suez Canal were included in the analysis, the MTC rate of increase was higher for all areas, especially so for the E Mediterranean (i.e. 0.58°C, 1.07°C and 0.32°C per decade for W, C and E Mediterranean, respectively: Fig. 1) when compared to those of Tsikliras and Stergiou (2014) mentioned above. The rate of MTC increase when Lessepsian migrants were included is also higher than that previously reported for the entire Mediterranean Sea (Cheung *et al.* 2013) and the NE Aegean Sea (Keskin and Pauly, 2014).

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Presentation by C. Guraslan

Modeling the impact of Climate Variability on Black Sea anchovy (*Engraulis encrasicolus ponticus*) recruitment and production

Ceren Guraslan*, Bettina Fach, Temel Oguz

Institute of Marine Sciences, Middle East Technical University, Erdemli, Turkey –
*ceren@ims.metu.edu.tr

Abstract

The influence of climate variability on anchovy population dynamics and trophic interactions in the Black Sea ecosystem was studied with a 1D coupled lower trophic level and anchovy bioenergetics model. Stochastic climate variability in the form of fifty-year inter-annual temperature and total mixing rate time-series served as input to the model. Model results show a high correlation of anchovy egg production and recruitment success in response to changes in temperature, indicating it to be the main factor influencing anchovy population dynamics. Simulations show that water temperatures in the spawning season have greater control over the intensity of egg production than the number of available spawning females. Moreover, recruitment is found to be the most sensitive adult class to temperature variations and the overall effect of temperature on the entire stock is observable in each different age class. Variation in mixing has no effect on egg production, however the effect of temperature on the other stages of anchovy is slightly counteracted by vertical mixing.

Keywords: anchovy bioenergetics model, anchovy recruitment, climate impact, stochastic temperature variability

Introduction

The Black Sea anchovy is known to experience high-frequency stock fluctuations within the last five-decades due to the synchronous effects of heavy fishing activity, over-enrichment, introduction of alien species, i.e., *Mnemiopsis leidyi*, and climate-induced variability (Oguz, 2005). There is strong correlation between variability in the regional climate indices, i.e., North Atlantic Oscillation (NAO) and Black Sea anchovy stock fluctuations (Niermann *et al.*, 1999; Oguz and Gilbert, 2007). In the present study the influence of climatic variability of total vertical mixing and water temperature on anchovy production and recruitment is investigated using a 1D model.

Methods

A one-dimensional, online coupled anchovy life-cycle and ecosystem model for the Black Sea (Oguz *et al.*, 2008a,b) is used in this study. Model vertical structure extends from the surface mixed layer down to the bottom of sub-thermocline which together represents the euphotic zone. A nutrient source layer is located beneath the euphotic zone supplying nutrients to euphotic zone via mixing processes. The ecosystem model includes three stage-based phytoplankton groups, two size-based zooplankton groups and parameterizations for the gelatinous carnivore. The anchovy bioenergetics model tracks each individ-

ual spawner's progeny through developmental and adult stages (age 0+, 1+, 2+, 3+). Female adults are assumed to start spawning at June 1st when the water temperature exceeds 20°C and spawning lasts until the end of August. Model forcing files of total mixing rates (day⁻¹) and daily mixed layer temperatures (°C) are derived from observations representing the mean climatology of the Black Sea. The model is run for 50-years with stochastic variations of the forcing.

Results

Egg production is found to be very sensitive to temperature variations ($r^2=0.98$) whereas mixing is found to have no such effect since spawning takes place in summer when mixing is already very low. Adding to that, spawning intensity in a given year is seen to be dependent on the prevailing temperature conditions during that spawning season of that particular year, rather than the available stock of spawners. This is in contrast to an earlier theory by Cushing (1996) that relates recruitment success directly to the number of available spawners. Variability in annual recruitment numbers is in-line with variability in temperature. However, addition of mixing effects counteracts the effect of temperature slightly and hence decreases recruitment. The same situation also applies to the spawners but not so pronounced as in the case of recruits. This is due to the fact that spawner stock include adults of 1+, 2+, 3+ year classes that carry the temperature signal of earlier years. Recruits (age 0+ class)(▼) variability directly follows the temperature signal of the same year (Fig.1). However, in older age classes the temperature signal can still be tracked in the individual age class but with a delay in timing. For instance, age 1+ year class (◆) matches the temperature signal of the previous (n-1)th year and the same applies for the older age classes. At the end, each age class matches the temperature signal they are subjected to when they were recruits. Therefore, overall effect of temperature variability on the entire stock is hard to resolve considering the current and traditional management based approaches. For future yield estimations, it is of importance that individual anchovy age groups and the time it requires for the environmental effect to propagate to this age are considered.

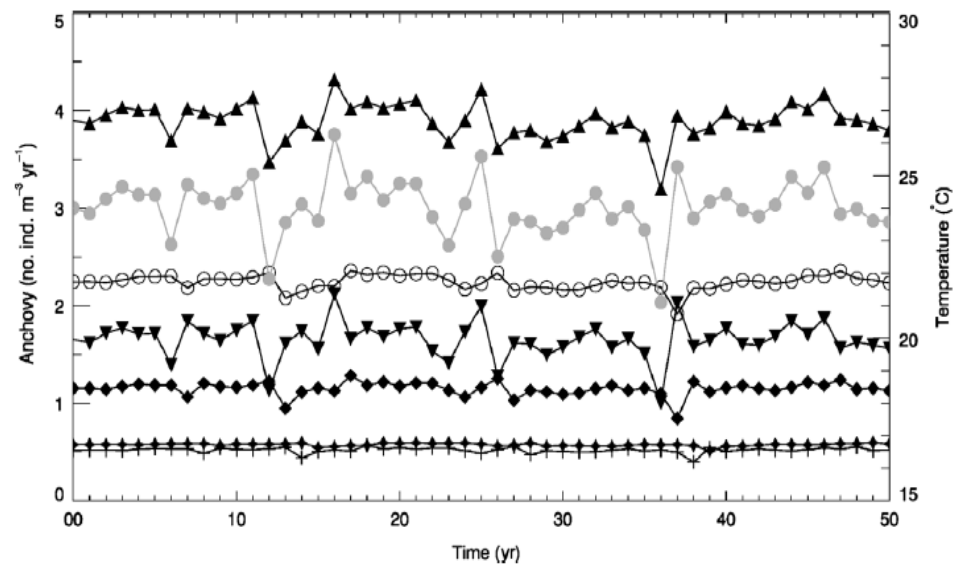


Figure 1. Time series of summer temperature maxima ($^{\circ}\text{C}$) at the end of August (\bullet) and total number of the whole anchovy population (\blacktriangle), total number of adult anchovies (\circ), as well as total numbers of anchovies in age classes 0+ (\blacktriangledown), 1+ (\blacklozenge), 2+ ($+$), and 3+ (\ast) (ind. $\text{m}^3 \text{yr}^{-1}$).

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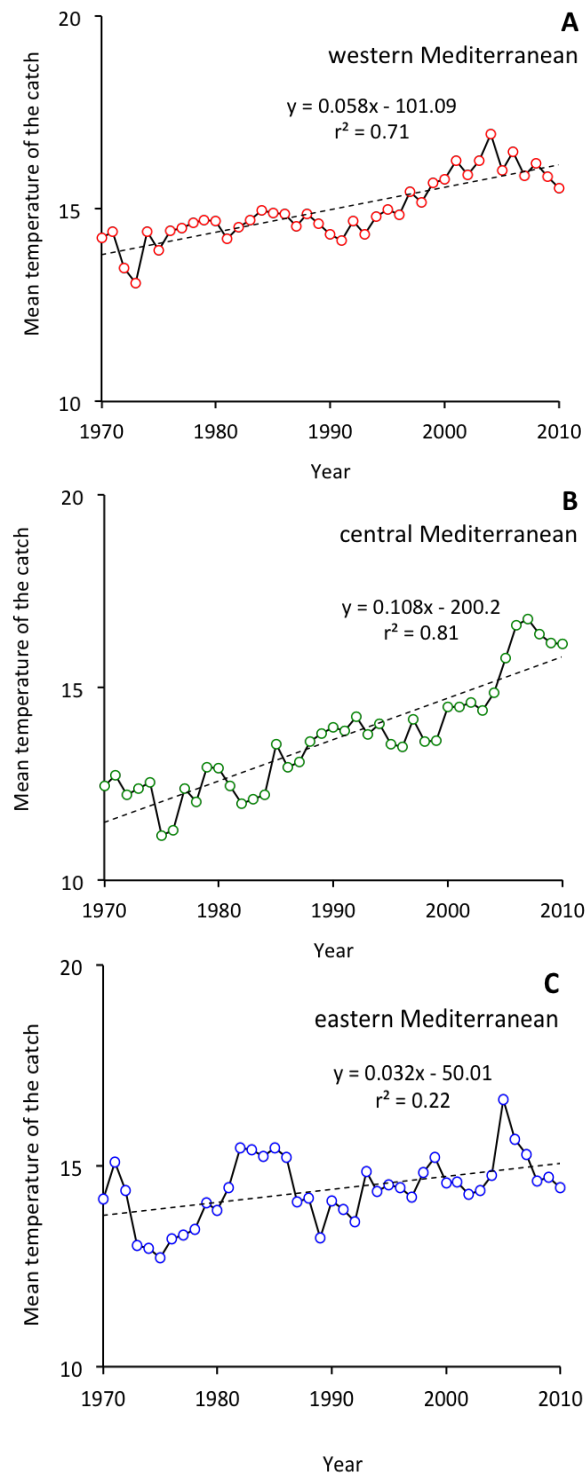


Figure 2. The mean temperature of the catch (MTC, °C) for the W (red bars), C (green bars) and E (blue bars) Mediterranean Sea during 1970–2010. MTC calculated annually based on the median temperature preference of each species weighted by its catch (Cheung *et al.*, 2013) taking here, however, into account a hypothetical scenario in which we considered a catch of 1500 t for a hypothetical species (or group of species) with a median temperature preference of 25 °C (i.e. approximating Lessepsian migrants) starting in 2003 and increasing by 500 t for each of the following years, thus reaching 5000 t in 2010.