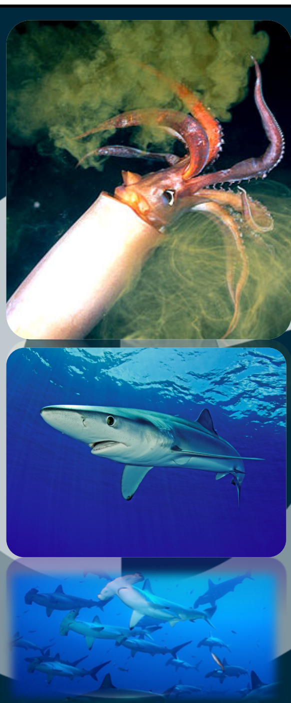
# Climate-driven oceanic deoxygenation, vertical habitat compression and overfishing of top predators

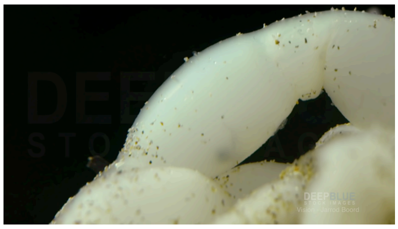


**Rui Rosa**
MARE-FCUL

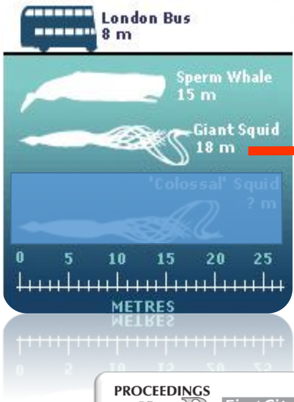
ROSA LAB
EXPLORING THE OCEANS OF TOMORROW

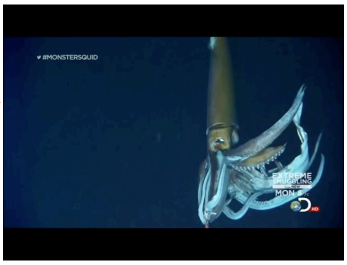
## Semelparidade

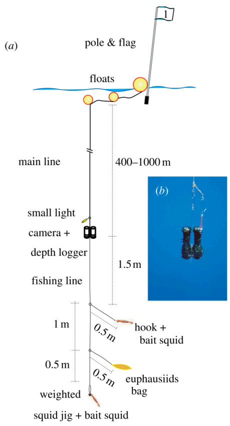
**("live fast die young"; ~12-18 meses)**

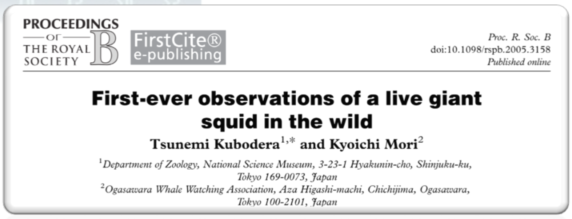



# Big oceanic (deep-sea) squids





PROCEEDINGS OF THE ROYAL SOCIETY B
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Proc. R. Soc. B
doi:10.1098/rspb.2005.3158
Published online

**First-ever observations of a live giant squid in the wild**

Tsunemi Kubodera[1,*] and Kyoichi Mori[2]
[1]Department of Zoology, National Science Museum, 3-23-1 Hyakunin-cho, Shinjuku-ku, Tokyo 169-0073, Japan
[2]Ogasawara Whale Watching Association, Aza Higashi-machi, Chichijima, Ogasawara, Tokyo 100-2101, Japan

# Big oceanic (deep-sea) squids

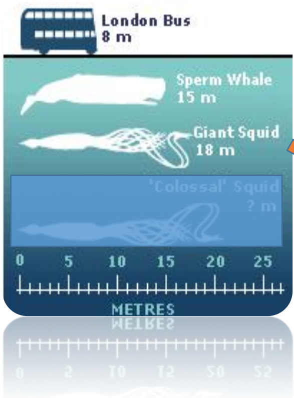


**Figure 1.** *Architeuthis* specimen collected at 38°11′N 08°48′W (south-west Portugal) on 24 August 2002.


J. Mar. Biol. Ass. U.K. (2005), **85**, 175–176
Printed in the United Kingdom

First recorded specimen of the giant squid *Architeuthis* sp. in Portugal

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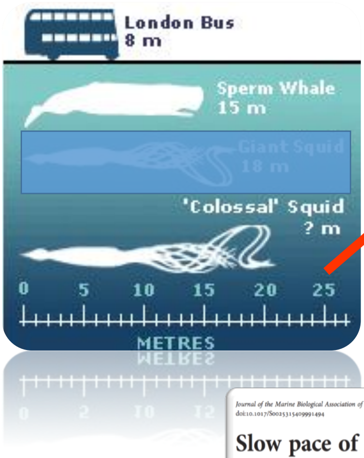
†Museu Oceanográfico, Parque Natural da Arrábida, Praça da República 2900-587 Setúbal, Portugal.
‡Centre of Marine Sciences (CCMAR), University of the Algarve, FCMA, Campus de Gambelas, 8000-117 Faro, Portugal.
∫Corresponding author, e-mail: rrosa@ipimar.pt

# Big oceanic (deep sea) squids




*Journal of the Marine Biological Association of the United Kingdom*, 2010, 90(7), 1375–1378. © Marine Biological Association of the United Kingdom, 2010
doi:10.1017/S0025315409991494

## Slow pace of life of the Antarctic colossal squid

RUI ROSA[1] AND BRAD A. SEIBEL[2]
[1]Laboratório Marítimo da Guia, Centro de Oceanografia, Faculdade de Ciências da Universidade de Lisboa, Avenida Nossa Senhora do Cabo, 939, 2750-374 Cascais, Portugal, [2]Department of Biological Sciences, University of Rhode Island, 100 Flagg Road, Kingston, RI 02881, USA

# "Destroying a myth"

*The colossal squid* (Mesonychoteuthis hamiltoni) *is the world's largest invertebrate and its large size and some unique morphological characters have fuelled speculation that it is an aggressive top predator in the circum-Antarctic Southern Ocean. Here, we present estimates on the metabolic and energetic demands of this cold-water deep-sea giant. The estimated mass-specific routine metabolic rate for the colossal squid at 1.5°C was 0.036 µmol $O_2$ $h^{-1}$ $g^{-1}$ and the projected daily energy consumption (45.1 kcal $day^{-1}$) was almost constant as a function of depth in the nearly isothermal Antarctic waters. Our findings also indicate the squid shows a slow pace of life linked with very low prey requirements (only 0.03 kg of prey per day). We argue that the colossal squid is not a voracious predator capable of high-speed predator–prey interactions. It is, rather, an ambush or sit-and-float predator that uses the hooks on its arms and tentacles to ensnare prey that unwittingly approach.*



*"Kraken lovers"*

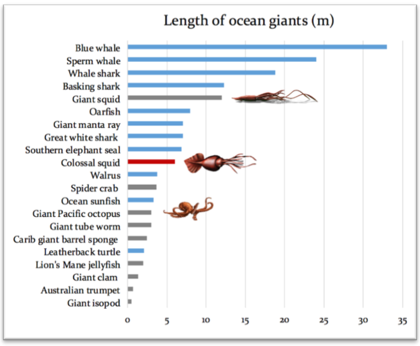

Polar Biol
DOI 10.1007/s00300-017-2104-5

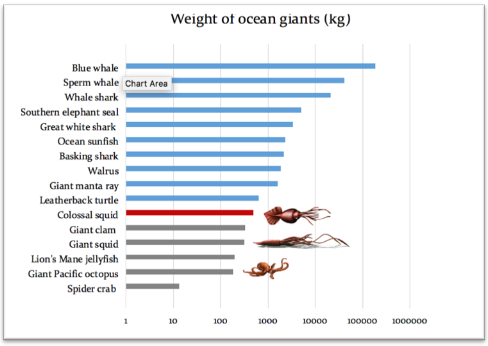
CrossMark

REVIEW

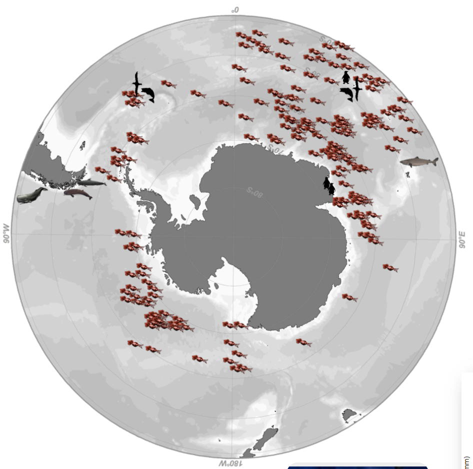
**Biology and ecology of the world's largest invertebrate, the colossal squid (*Mesonychoteuthis hamiltoni*): a short review**

Rui Rosa[1] · Vanessa M. Lopes[1] · Miguel Guerreiro[1] · Kathrin Bolstad[2] · José C. Xavier[3,4]

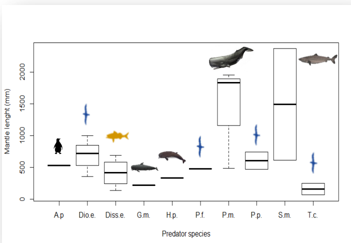



## Geographic distribution




stomach contents

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REVIEW

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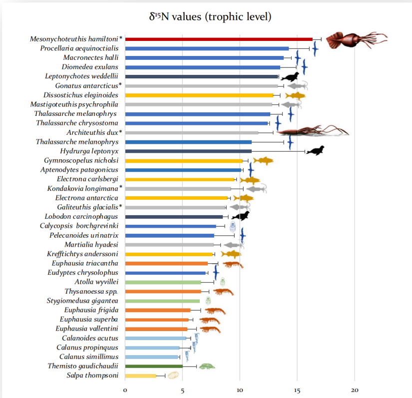
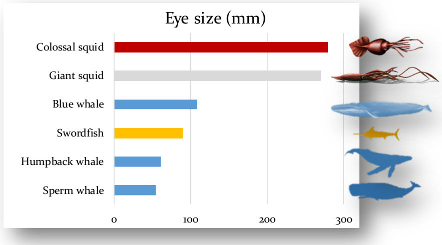
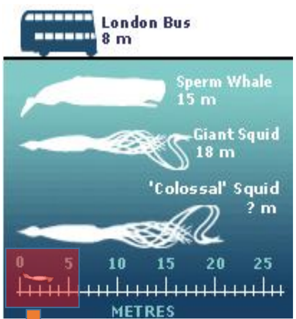



# Big oceanic squids




*Red devils* (US)
*Calamares gigantes* (Latin America)

**Moving from the Southern Ocean to the Eastern Pacific – jumbo (Humboldt) squids**

## Besides the size, why is *Dosidicus gigas* interesting?

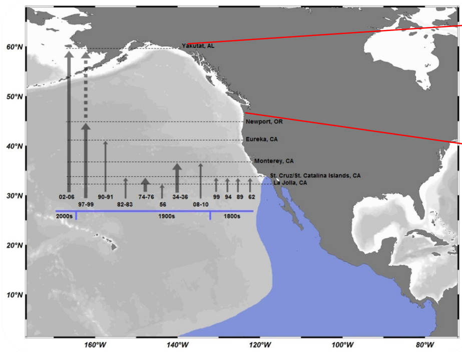
1. Expanding geographical range

2. Commercially important

3. Ecologically important

4. Physiologically perplexing (with unexpected vertical ecology)

## 1. Expanding range






- Over the last years it greatly extended the geographical range far north, where they are exerting a significant top-down forcing on commercial groundfish stocks

## 2. Commercial importance

FAO 2015: ~ 800.000 m tons

World´s largest cephalopod fishery

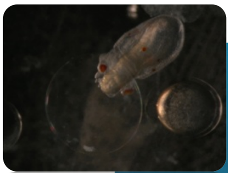
## 3. Ecological importance

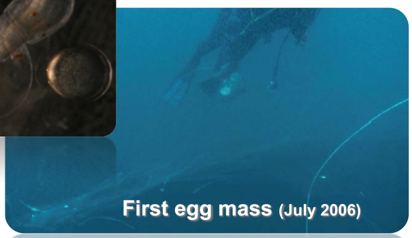
. As predator:

Rapid growth
(0.01 g to 50 kg in 12-18 months)

↓

demands high rate of food intake

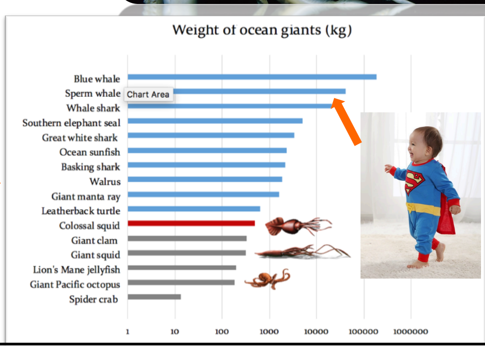





## 3. Ecological importance

Squid growth
(0.01 g to 50 kg in 12-18 months)

squid growth

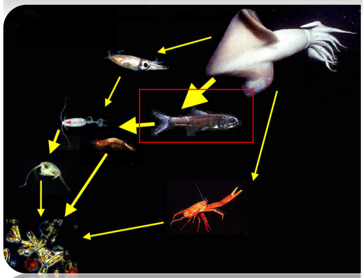



## 3. Ecological importance

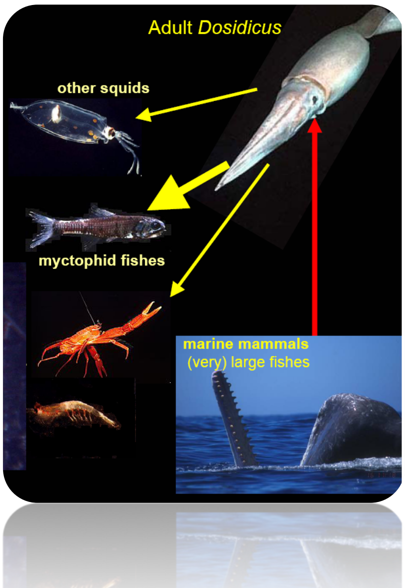
. As predator:

It is thought to follow the acoustic deep scattering layer to the surface at night for foraging.

Mostly small mesopelagic organisms, but larger fishes are also taken.



## 3. Ecological importance

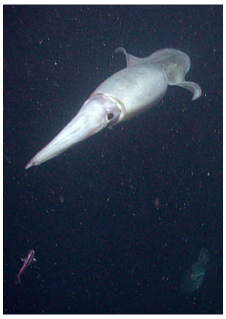



. As prey:

It provides direct trophic link from small mesopelagics to apex vertebrate predators (large fishes and marine mammals)

## 4. Physiologically perplexing

Squids as extreme animal models: "The edge of <u>oxygen</u> limitation"



1) High Oxygen Demand

2) Low carrying capacity of haemocyanin-containing blood

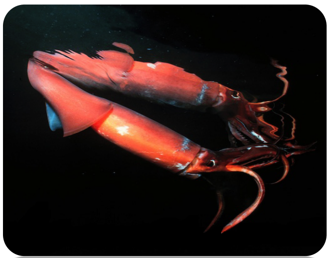
3) Blood-oxygen binding is highly pH sensitive (facilitates oxygen release to tissues)

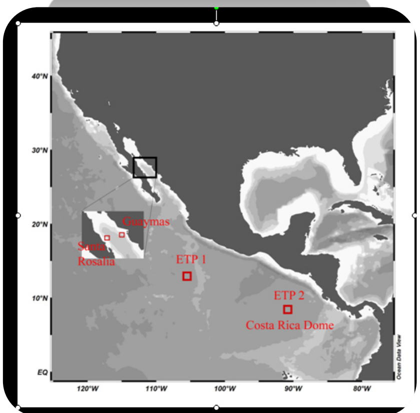
4) No venous reserve
(use all oxygen carried in the blood)

# Research locations

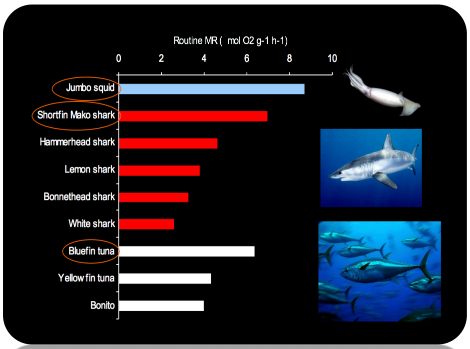
Sea of Cortez

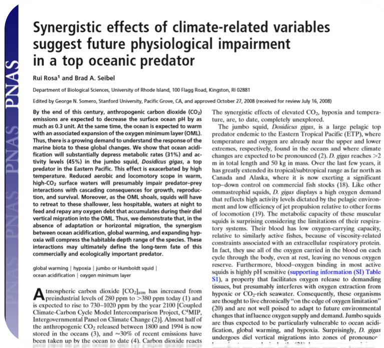
East Tropical Pacific - ETP






## Does *Dosidicus* have a high oxygen consumption rate?



PNAS

Synergistic effects of climate-related variables suggest future physiological impairment in a top oceanic predator

Rui Rosa[1] and Brad A. Seibel

Department of Biological Sciences, University of Rhode Island, 100 Flagg Road, Kingston, RI 02881

Edited by George N. Somero, Stanford University, Pacific Grove, CA, and approved October 27, 2008 (received for review July 16, 2008)

**By the end of this century, anthropogenic carbon dioxide ($CO_2$) emissions are expected to decrease the surface ocean pH by as much as 0.3 unit. At the same time, the ocean is expected to warm with an associated expansion of the oxygen minimum layer (OML). Thus, there is a growing demand to understand the response of the marine biota to these global changes. We show that ocean acidification will substantially depress metabolic rates (31%) and activity levels (45%) in the jumbo squid, *Dosidicus gigas*, a top predator in the Eastern Pacific. This effect is exacerbated by high temperature. Reduced aerobic and locomotory scope in warm, high-$CO_2$ surface waters will presumably impair predator–prey interactions with cascading consequences for growth, reproduction, and survival. Moreover, as the OML shoals, squids will have to retreat to these shallower, less hospitable, waters at night to feed and repay any oxygen debt that accumulates during their diel vertical migration into the OML. Thus, we demonstrate that, in the absence of adaptation or horizontal migration, the synergism between ocean acidification, global warming, and expanding hypoxia will compress the habitable depth range of the species. These interactions may ultimately define the long-term fate of this commercially and ecologically important predator.**

global warming | hypoxia | jumbo or Humboldt squid | ocean acidification | oxygen minimum layer

Atmospheric carbon dioxide $[CO_2]_{atm}$ has increased from preindustrial levels of 280 ppm to >380 ppm today (1) and is expected to rise to 730–1020 ppm by the year 2100 [Coupled Climate-Carbon Cycle Model Intercomparison Project, $C^4$MIP, Intergovernmental Panel on Climate Change (2)]. Almost half of the anthropogenic $CO_2$ released between 1800 and 1994 is now stored in the oceans (3), and ~30% of recent emissions have been taken up by the ocean to date (4). Carbon dioxide reacts

The synergistic effects of elevated $CO_2$, hypoxia and temperature, are, to date, completely unexplored.

The jumbo squid, *Dosidicus gigas*, is a large pelagic top predator endemic to the Eastern Tropical Pacific (ETP), where temperature and oxygen are already near the upper and lower extremes, respectively, found in the oceans and where climate changes are expected to be pronounced (2). *D. gigas* reaches >2 m in total length and 50 kg in mass. Over the last few years, it has greatly extended its tropical/subtropical range as far north as Canada and Alaska, where it is now exerting a significant top–down control on commercial fish stocks (18). Like other ommastrephid squids, *D. gigas* displays a high oxygen demand that reflects high activity levels dictated by the pelagic environment and low efficiency of jet propulsion relative to other forms of locomotion (19). The metabolic capacity of these muscular squids is surprising considering the limitations of their respiratory systems. Their blood has low oxygen-carrying capacity, relative to similarly active fishes, because of viscosity-related constraints associated with an extracellular respiratory protein. In fact, they use all of the oxygen carried in the blood on each cycle through the body, even at rest, leaving no venous oxygen reserve. Furthermore, blood–oxygen binding in most active squids is highly pH sensitive (supporting information (SI) Table S1), a property that facilitates oxygen release to demanding tissues, but presumably interferes with oxygen extraction from hypoxic or $CO_2$-rich seawater. Consequently, these organisms are thought to live chronically "on the edge of oxygen limitation" (20) and are not well poised to adapt to future environmental changes that influence oxygen supply and demand. Jumbo squids are thus expected to be particularly vulnerable to ocean acidification, global warming, and hypoxia. Surprisingly, *D. gigas* undergoes diel vertical migrations into zones of pronounce

MO2 rates unmatched by most aquatic ectotherms (at comparable °C and size). Due to the less efficient mode of swimming (jet propulsion).

Rosa & Seibel 2008 PNAS

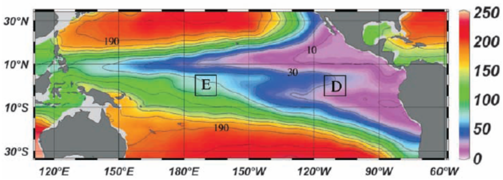
## 4. Physiologically perplexing

**Ommastrephid squids require stable high oxygen!**

. High Oxygen Demand ✓

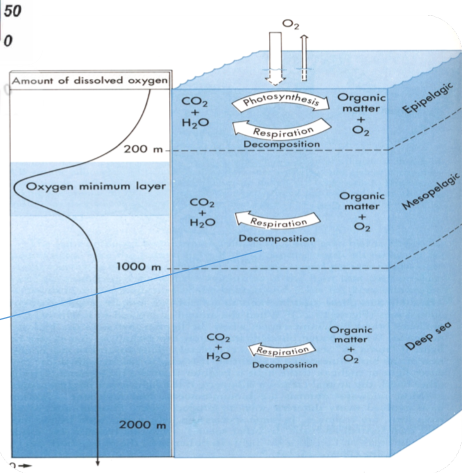
But,
Is *Dosidicus* a typical ommastrephid squid?
Is *Dosidicus* intolerant to hypoxia?

## *ETP has a pronounced $O_2$ Minimum Zone*

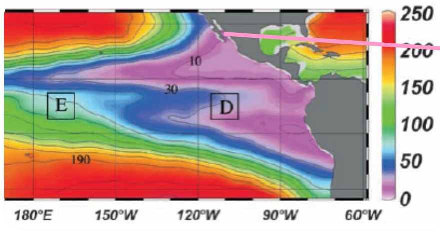


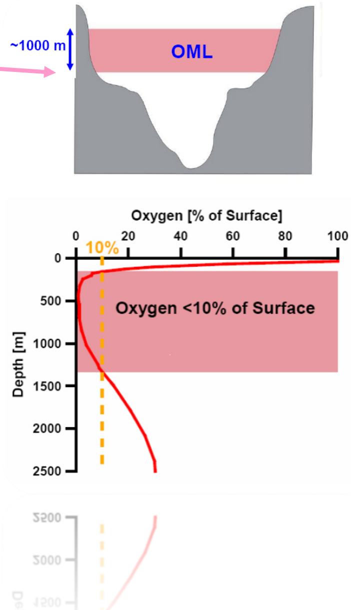

Low oxygen layer located at intermediate depths in the water column,

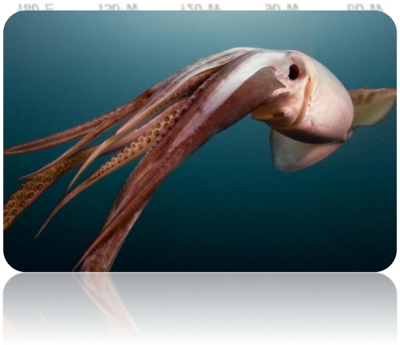
associated with the large primary production at the surface ocean and enhanced mesopelagic decomposition



## *ETP has a pronounced $O_2$ Minimum Zone*

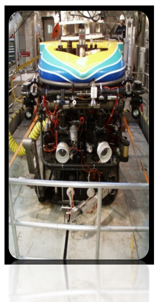


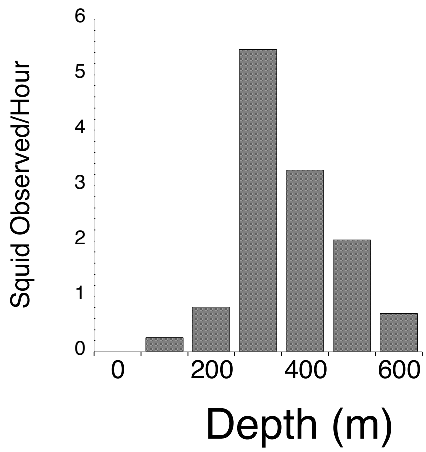
## Is *D. gigas* migrating into the OMZ?

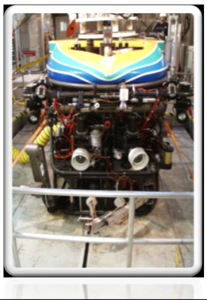
-Submersible Observations

-Archival Tagging

## Daytime Depth Distribution of *D. gigas* Observations using an ROV



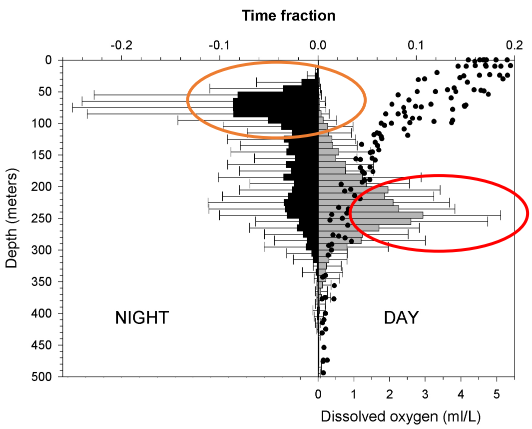
MBARI ROV

## Day and Night Depth Distribution as indicated by acoustic tagging

. Daytime in deep, cold and oxygen-depleted water

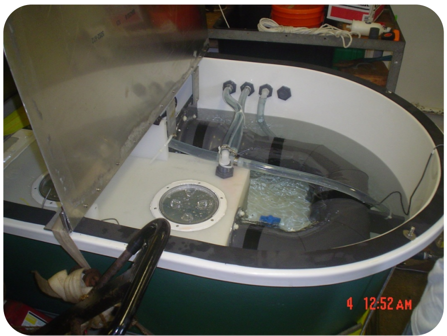
(OML; ~10 °C at 250 m)

. Night in shallow, warm (up to 25 °C) and aerated waters.

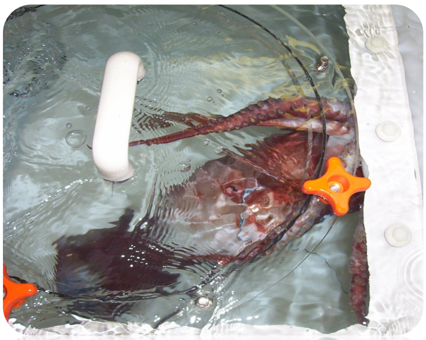


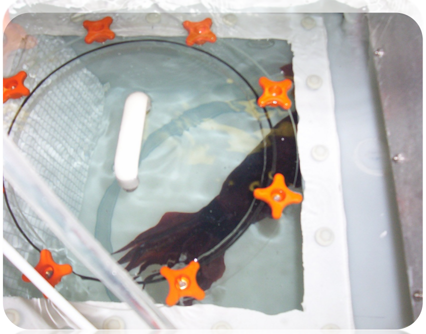
Here we've shown conclusively that *Dosidicus gigas* does live where it can't.

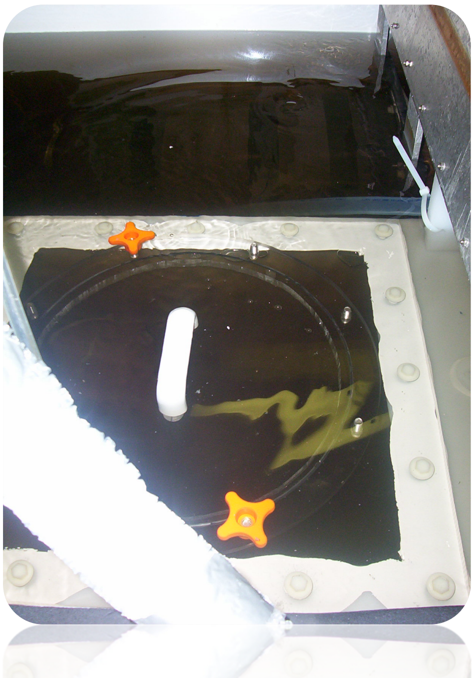
What determines hypoxia tolerance in *Dosidicus*?

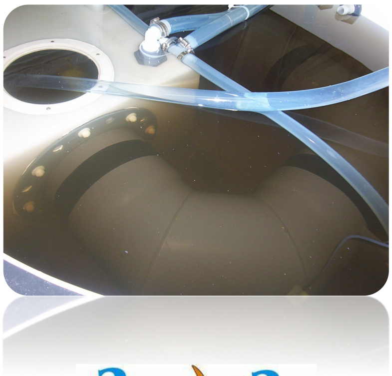



Swimming tunnel
(> 2000g)



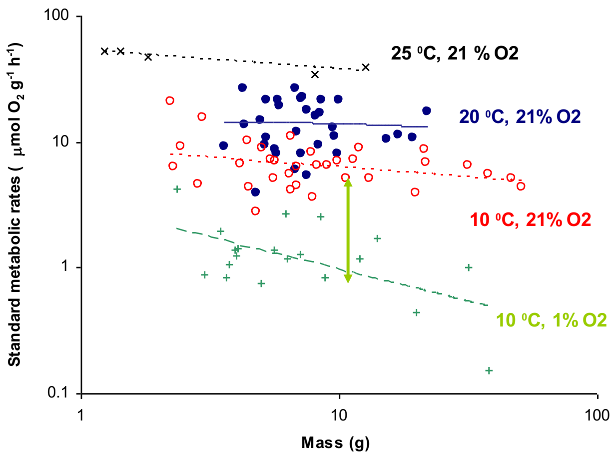






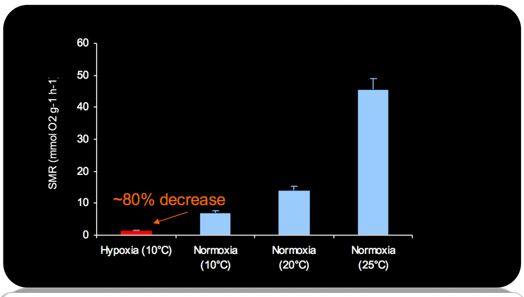
Flow-through chambers
(juveniles, up to 50g)

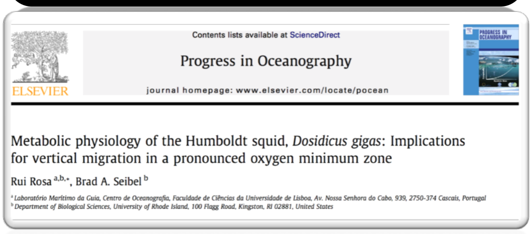
# Temperature dependence and hypoxia-induced hipometabolism




Squid decreases standard metabolism up to 75%

# Temperature dependence and hypoxia-induced hipometabolism





Contents lists available at ScienceDirect

Progress in Oceanography

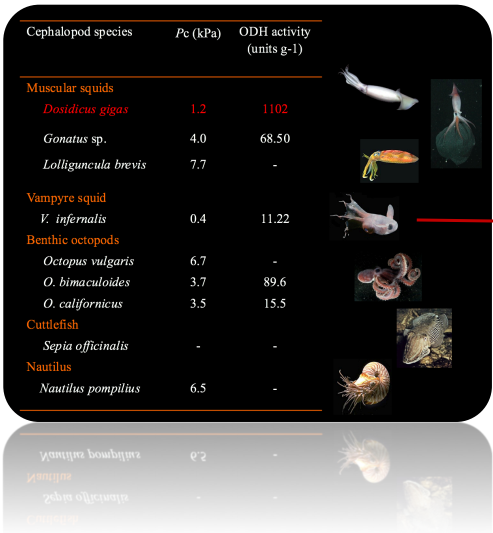
journal homepage: www.elsevier.com/locate/pocean

Metabolic physiology of the Humboldt squid, *Dosidicus gigas*: Implications for vertical migration in a pronounced oxygen minimum zone

Rui Rosa [a,b,*], Brad A. Seibel [b]

## Critical oxygen partial pressure (*Pc*) and anaerobic potential

(octopine dehydrogenase activity, ODH)

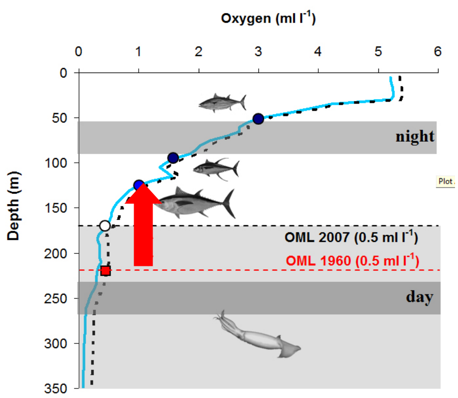


| Cephalopod species | *Pc* (kPa) | ODH activity (units g-1) |
|---|---|---|
| Muscular squids | | |
| *Dosidicus gigas* | 1.2 | 1102 |
| *Gonatus* sp. | 4.0 | 68.50 |
| *Lolliguncula brevis* | 7.7 | - |
| Vampyre squid | | |
| *V. infernalis* | 0.4 | 11.22 |
| Benthic octopods | | |
| *Octopus vulgaris* | 6.7 | - |
| *O. bimaculoides* | 3.7 | 89.6 |
| *O. californicus* | 3.5 | 15.5 |
| Cuttlefish | | |
| *Sepia officinalis* | - | - |
| Nautilus | | |
| *Nautilus pompilius* | 6.5 | - |

Vampire squid (OMZ resident)

## *Ocean warming and expanding hypoxia in ETP*

. Expanding hypoxia - -0.13 mmol kg-1 year-1, from 1960 to 2003 (Stramma et al. 2008)




- If the OML continues to expand vertically in the ETP, it will drives the hypoxic threshold to shallower depths causing a more compressed epipelagic habitat
- *D. gigas* will have to retreat to even shallower waters at night to hunt and to repay any accumulated oxygen debt.

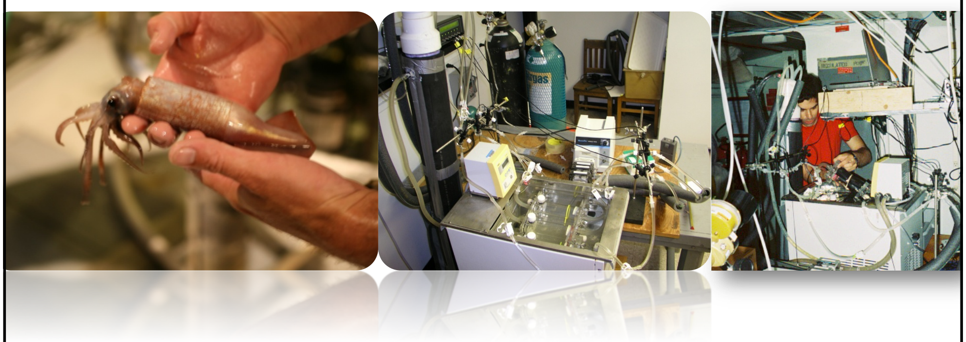
Rosa & Seibel 2008 PNAS

# What determines hypoxia tolerance in *D. gigas*?

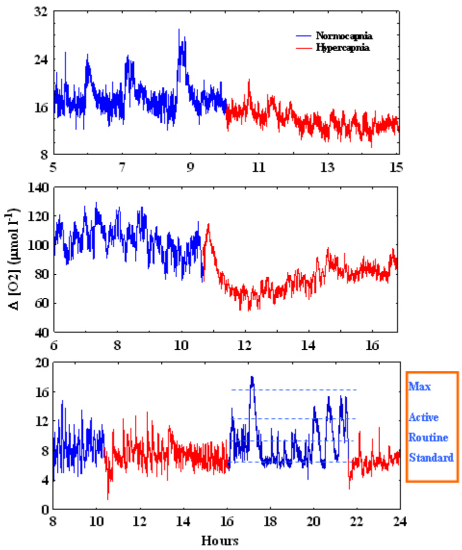
Ability to suppress metabolism and high capacity for anaerobic metabolism

# OMZ as natural lab for Ocean Acidification studies

Seawater was acidified, at 10℃, 20℃ and 25℃ by bubbling an air certified mix with 0.1% $CO_2$ (conc. within OMZ and also expected to be attained in 2100)



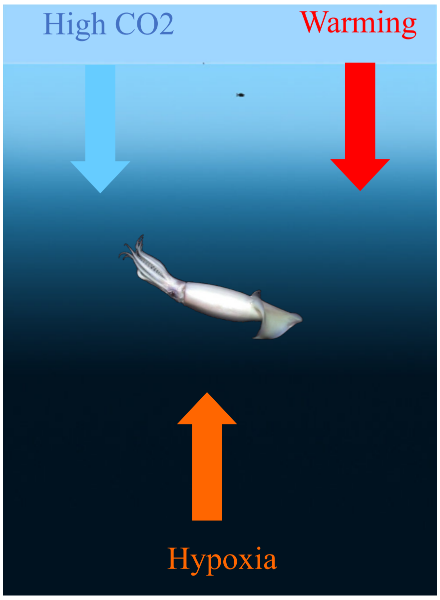
## Normocapnia vs. Hypercapnia in D. gigas




Control pH = 7.93 ± 0.05

Treatment pH = 7.62 ± 0.08

## Combined effects

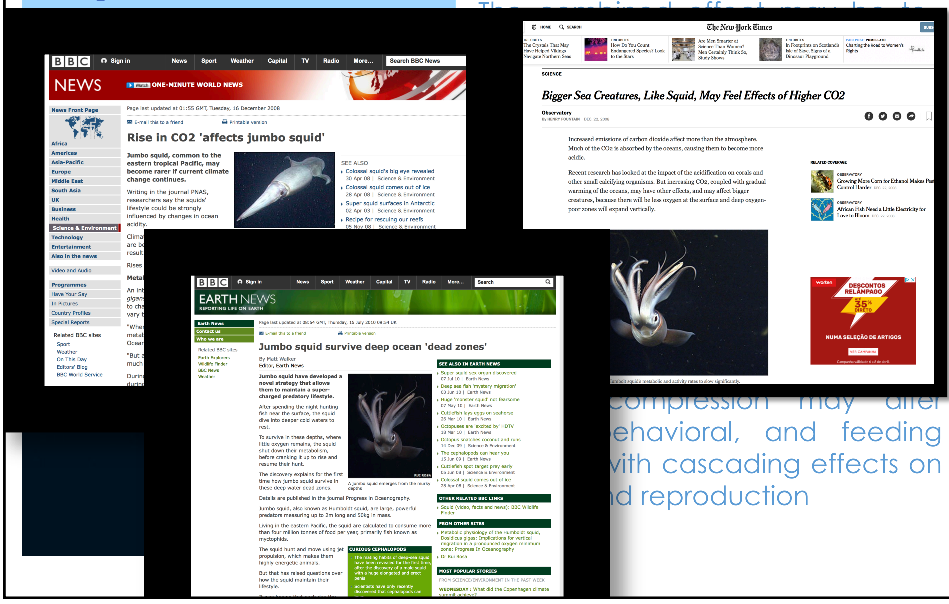



The combined effect may be to vertically-compress the habitable night-time depth range of the species.

Habitat compression may alter squid's behavioral, and feeding ecology with cascading effects on growth and reproduction

## Combined effects

High CO2 Warming




## Repercussions

. Habitat compression may alter squid's behavioral and feeding ecology with cascading effects on growth and reproduction.

. Cascading impacts to the top of the food-web will be expected (ranging from sharks and bony fishes to marine mammals)

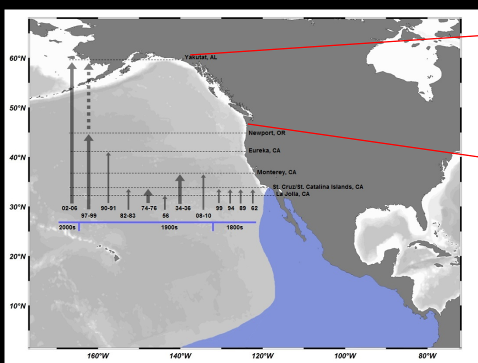
## Final remarks

So, in the absence of adaptation…

**Horizontal migration** - squids may eventually migrate to more northern climes where lower temperatures would reduce oxygen demand and relieve them from CO2 and oxygen stress

## Final remarks

1. Expanding range

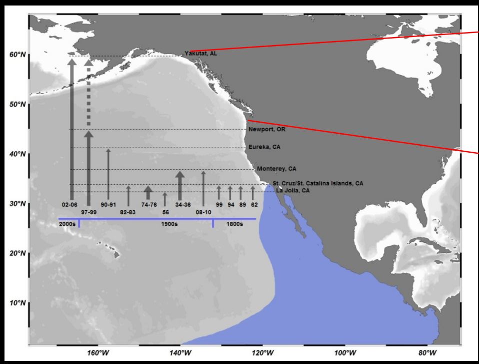





Yet, they are already doing it for poorly understood reasons!

# Final remarks

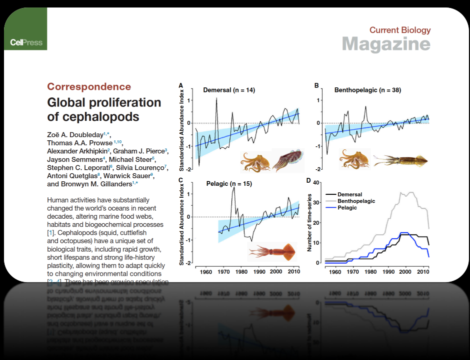
1. Expanding range






Yet, they are already doing it for poorly understood reasons!

# Mandatory reading – cephalopods "as winners"



CellPress

Current Biology
Magazine

Correspondence

Global proliferation of cephalopods

Zoë A. Doubleday[1,*], Thomas A.A. Prowse[1,10], Alexander Arkhipkin[2], Graham J. Pierce[3], Jayson Semmens[4], Michael Steer[5], Stephen C. Leporati[6], Sílvia Lourenço[7], Antoni Quetglas[8], Warwick Sauer[9], and Bronwyn M. Gillanders[1,*]

Human activities have substantially changed the world's oceans in recent decades, altering marine food webs, habitats and biogeochemical processes [1]. Cephalopods (squid, cuttlefish and octopuses) have a unique set of biological traits, including rapid growth, short lifespans and strong life-history plasticity, allowing them to adapt quickly to changing environmental conditions



moves quickly
Culture
Opinion

This article is more than 3 years old

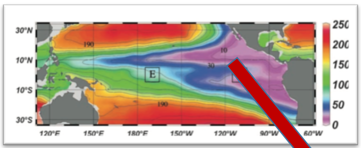
Squids and octopuses thrive as 'weeds of the sea' warm to hotter oceans

Squid, cuttlefish and their relatives appear to benefit from 'live fast, die young' mentality as study shows cephalopods have thrived over past 60 years

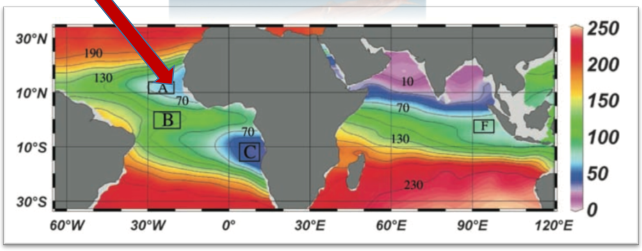
263 110

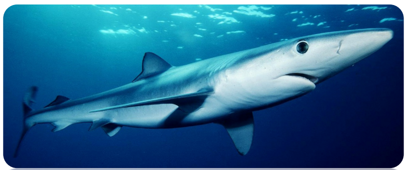
## Moving from the Pacific to the Atlantic Ocean

(and from oceanic squids to oceanic sharks)



**But still in OMZ environments**



ROSA LAB

## Sharks

Sharks are known to fundamentally shape the structure and function of marine communities

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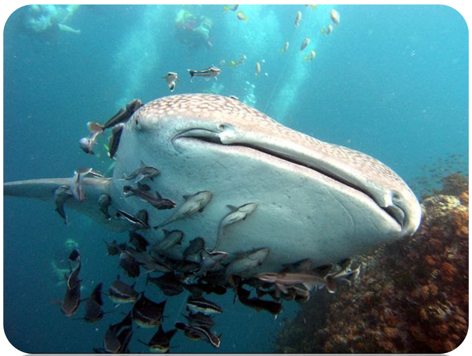
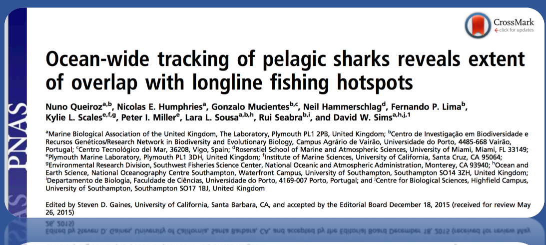
## Sharks

. Low fecundity
. Low growth rates
. High life span

Limited capability to rapidly evolve to human-induced changes in their environments.



## Sharks' major threats



PNAS

Ocean-wide tracking of pelagic sharks reveals extent of overlap with longline fishing hotspots

Nuno Queiroz[a,b], Nicolas E. Humphries[a], Gonzalo Mucientes[b,c], Neil Hammerschlag[d], Fernando P. Lima[b], Kylie L. Scales[e,f,g], Peter I. Miller[e], Lara L. Sousa[a,b,h], Rui Seabra[b,i], and David W. Sims[a,h,j,1]

[a]Marine Biological Association of the United Kingdom, The Laboratory, Plymouth PL1 2PB, United Kingdom; [b]Centro de Investigação em Biodiversidade e Recursos Genéticos/Research Network in Biodiversity and Evolutionary Biology, Campus Agrário de Vairão, Universidade do Porto, 4485-668 Vairão, Portugal; [c]Centro Tecnológico del Mar, 36208, Vigo, Spain; [d]Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL 33149; [e]Plymouth Marine Laboratory, Plymouth PL1 3DH, United Kingdom; [f]Institute of Marine Sciences, University of California, Santa Cruz, CA 95064; [g]Environmental Research Division, Southwest Fisheries Science Center, National Oceanic and Atmospheric Administration, Monterey, CA 93940; [h]Ocean and Earth Science, National Oceanography Centre Southampton, Waterfront Campus, University of Southampton, Southampton SO14 3ZH, United Kingdom; [i]Departamento de Biologia, Faculdade de Ciências, Universidade do Porto, 4169-007 Porto, Portugal; and [j]Centre for Biological Sciences, Highfield Campus, University of Southampton, Southampton SO17 1BJ, United Kingdom

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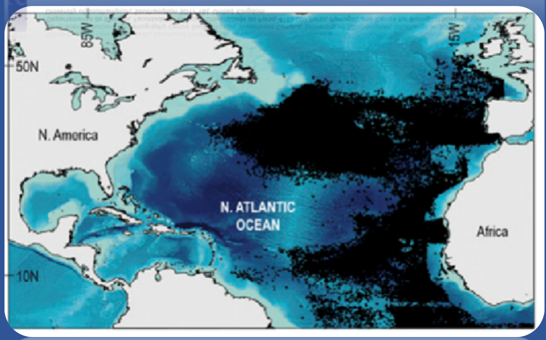
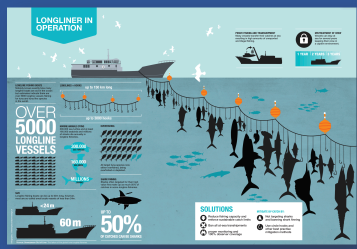


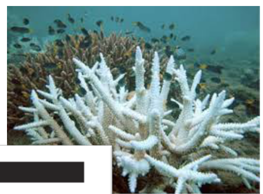



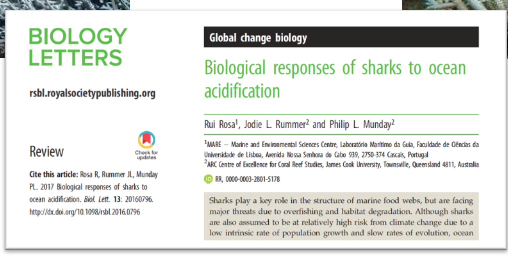

Distribution of longline deployment locations by 186 Spanish and Portuguese vessels, 2003–2011.

80% overlap!

Queiroz et al PNAS (2016)

## Sharks' major threats



BIOLOGY LETTERS

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Review

Cite this article: Rosa R, Rummer JL, Munday PL. 2017 Biological responses of sharks to ocean acidification. *Biol. Lett.* **13**: 20160796. http://dx.doi.org/10.1098/rsbl.2016.0796

Global change biology

Biological responses of sharks to ocean acidification

Rui Rosa[1], Jodie L. Rummer[2] and Philip L. Munday[2]

[1]MARE – Marine and Environmental Sciences Centre, Laboratório Marítimo da Guia, Faculdade de Ciências da Universidade de Lisboa, Avenida Nossa Senhora do Cabo 939, 2750-374 Cascais, Portugal
[2]ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia

RR, 0000-0003-2801-5178

Sharks play a key role in the structure of marine food webs, but are facing major threats due to overfishing and habitat degradation. Although sharks are also assumed to be at relatively high risk from climate change due to a low intrinsic rate of population growth and slow rates of evolution, ocean

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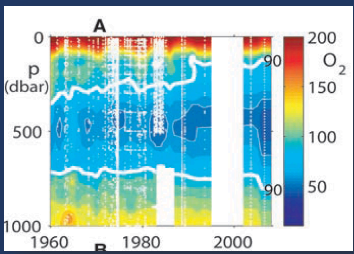
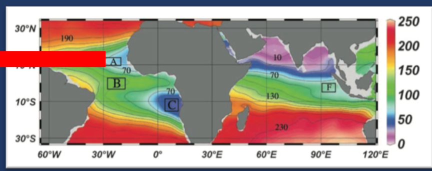
## *Vertically-expanding hypoxia and sharks*




(Stramma et al. Science 2008)

Models predict climate-driven **ocean warming** and **reduced ventilation** of the deep ocean

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## Oxygen minimum zones and Mako sharks

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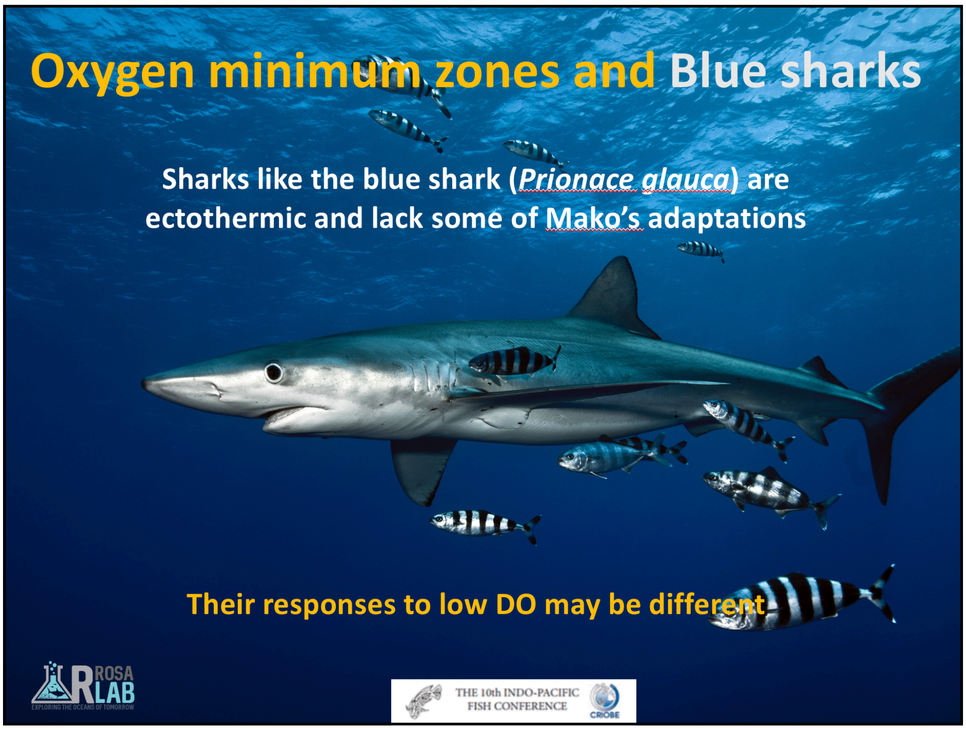
Oxygen minimum zones and Blue sharks
Sharks like the blue shark (Prionace glauca) are ectothermic and lack some of Mako's adaptations
Their responses to low DO may be different
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Oxygen minimum zones and Blue sharks
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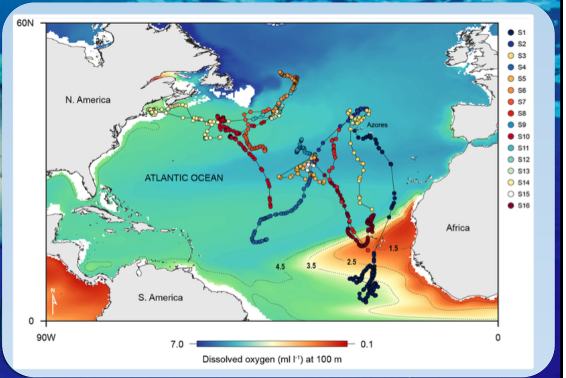
# Oxygen minimum zones and Blue Sharks

Of the 23 tagged sharks
with pop- off satellite-linked
archival transmitter tags (PSATs)

- three individuals (S1, S8 and S16) entered the eastern tropical Atlantic OMZ

Shark 1 spent 19 days inside the OMZ (8.6% of tracking time),
while shark 8 and shark 16 spent eight (8.9% of tracking time) and 24 (25.5% of tracking time) days in the OMZ, respectively.

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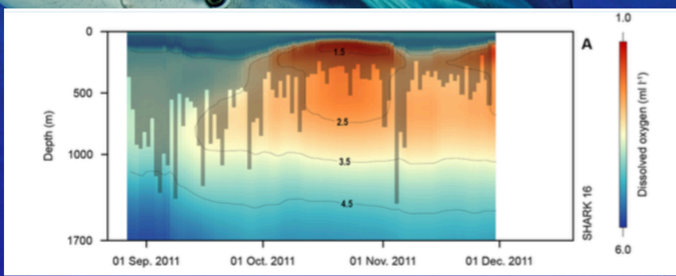
# Oxygen minimum zones and Blue Sharks




**Daily maximum dive depth for blue shark #16 overlaid on DO concentration**

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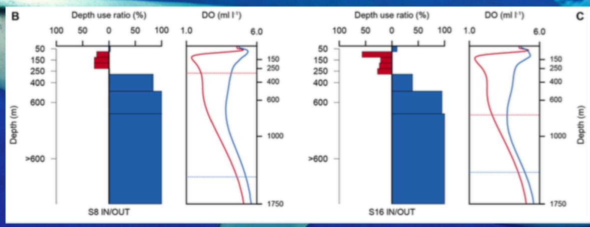
# Oxygen minimum zones and Blue Sharks




**Depth use ratio and vertical oxygen profiles for S8 (B) and S16 (C) when inside the OMZ (red) and outside (blue).**

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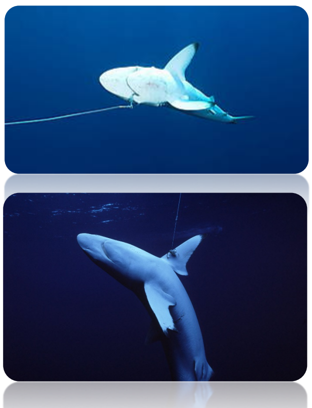
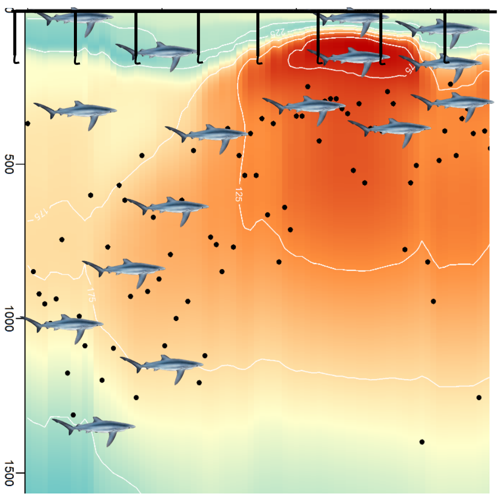


## Longline Fisheries




OMZ shoaling will further concentrate blue sharks in near-surface waters

where greater gear presence may increase capture risks.

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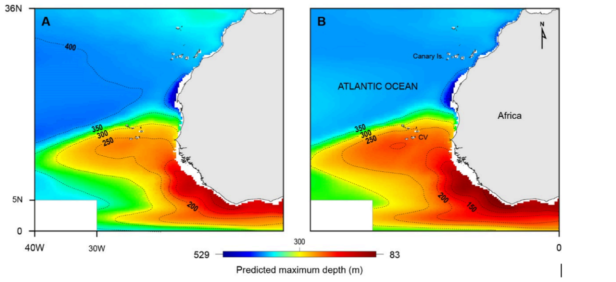
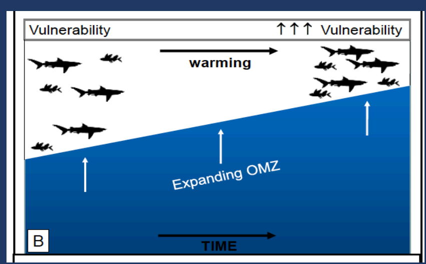



**Figure 3.** Daily maximum dive depth (MDD) predictions from the GAMM model for present (A) and future (B) oxygen concentration-at-depth and sea surface temperature scenarios. Note the broader expanse of shallow MDD in (B).

## Habitat trap hypothesis




Avoidance of those areas in the near future? Not likely.

Sharks will benefit first from increased habitat "compression" acting on prey species (small fish, cephalopods) that will become also more aggregated in surface water by shoaling hypoxic waters

## Mandatory Reading - sharks

PNAS

# Ocean-wide tracking of pelagic sharks reveals extent of overlap with longline fishing hotspots

Nuno Queiroz[a,b], Nicolas E. Humphries[a], Gonzalo Mucientes[b,c], Neil Hammerschlag[d], Fernando P. Lima[b], Kylie L. Scales[e,f,g], Peter I. Miller[e], Lara L. Sousa[a,b,h], Rui Seabra[b,i], and David W. Sims[a,h,j,1]

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## Mandatory reading – Sharks

MENU
nature
International journal of science

Article | Published: 24 July 2019

# Global spatial risk assessment of sharks under the footprint of fisheries

Nuno Queiroz, Nicolas E. Humphries, […] David W. Sims

*Nature* 572, 461–466 (2019) | Download Citation