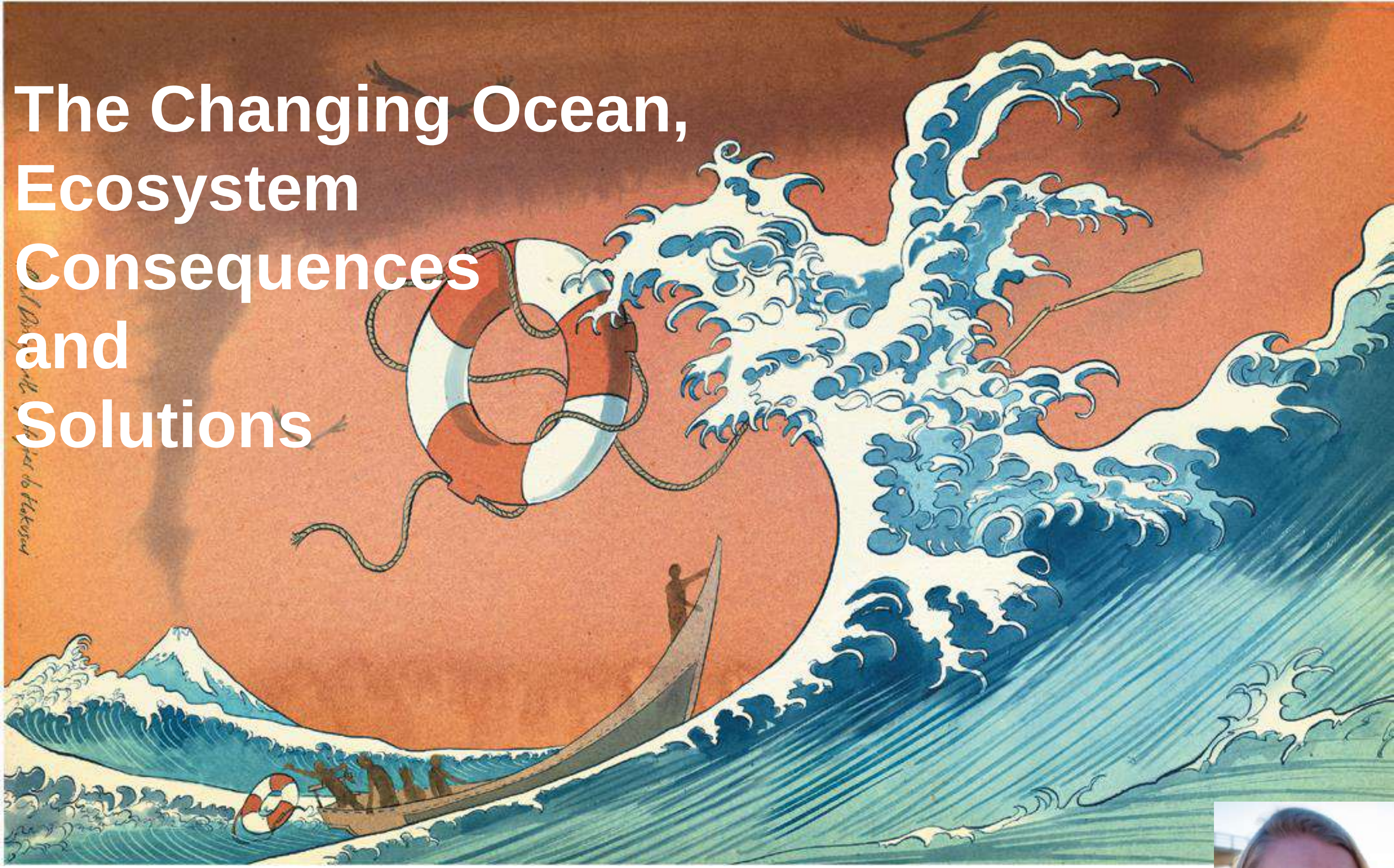
The Changing Ocean, Ecosystem Consequences and Solutions

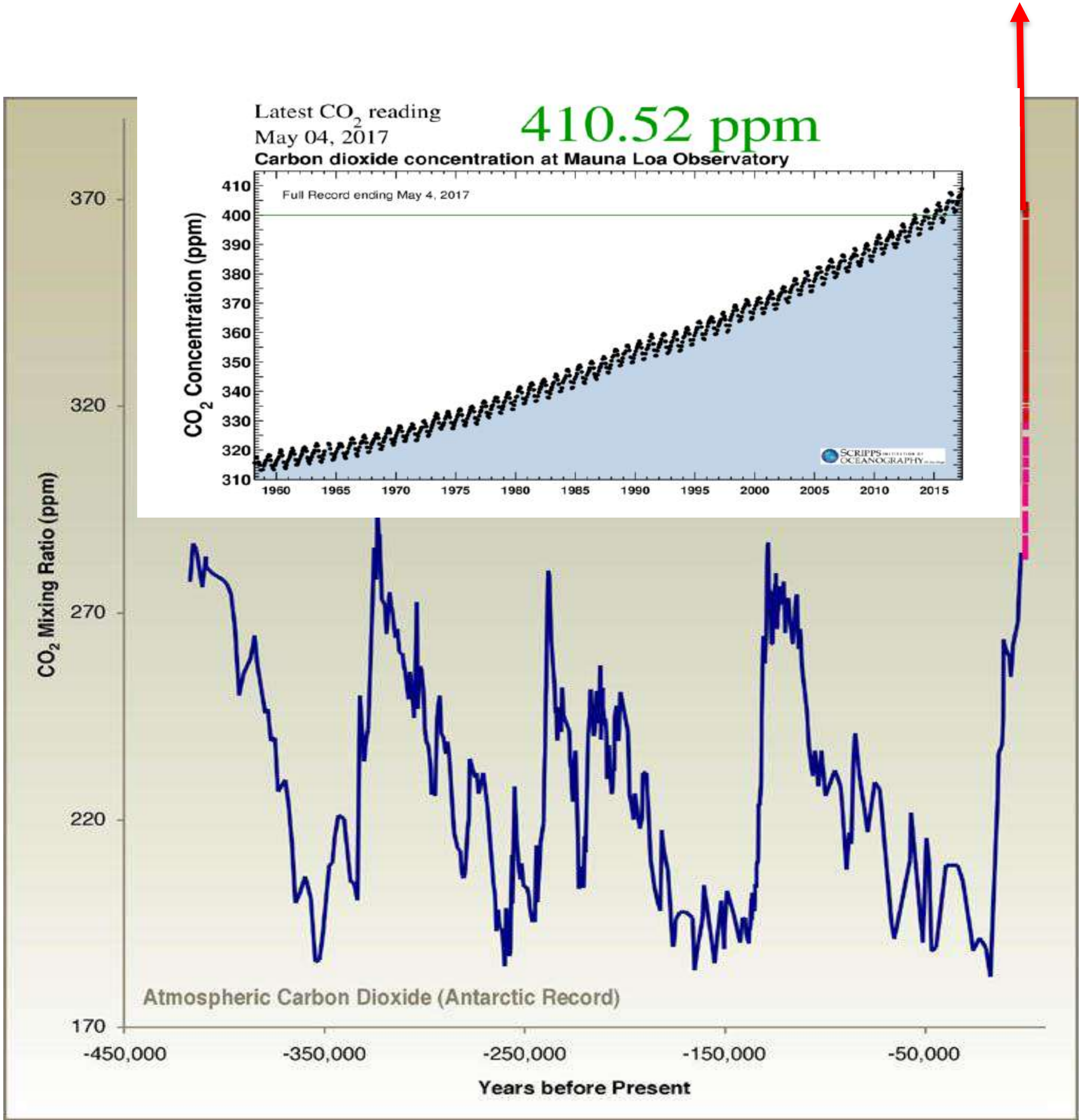


SCRIPPS INSTITUTION OF OCEANOGRAPHY

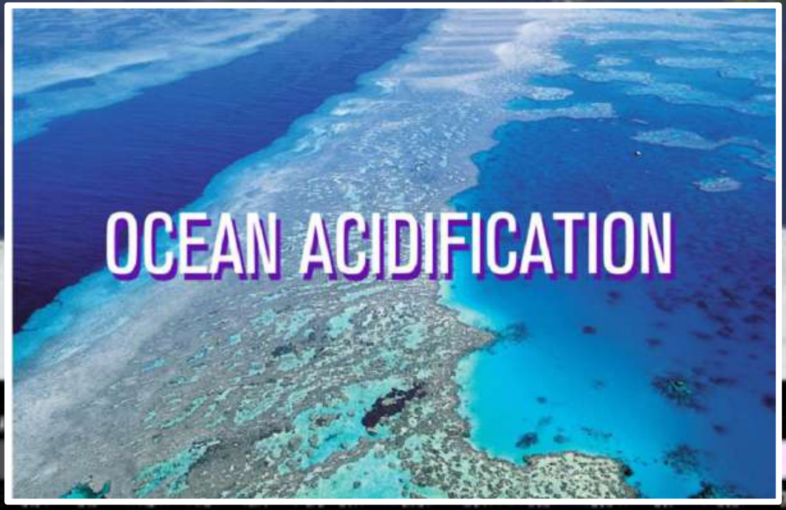
Lisa A. Levin and Natalya D. Gallo
Email: llevin@ucsd.edu

Rising CO_2

An New Trajectory

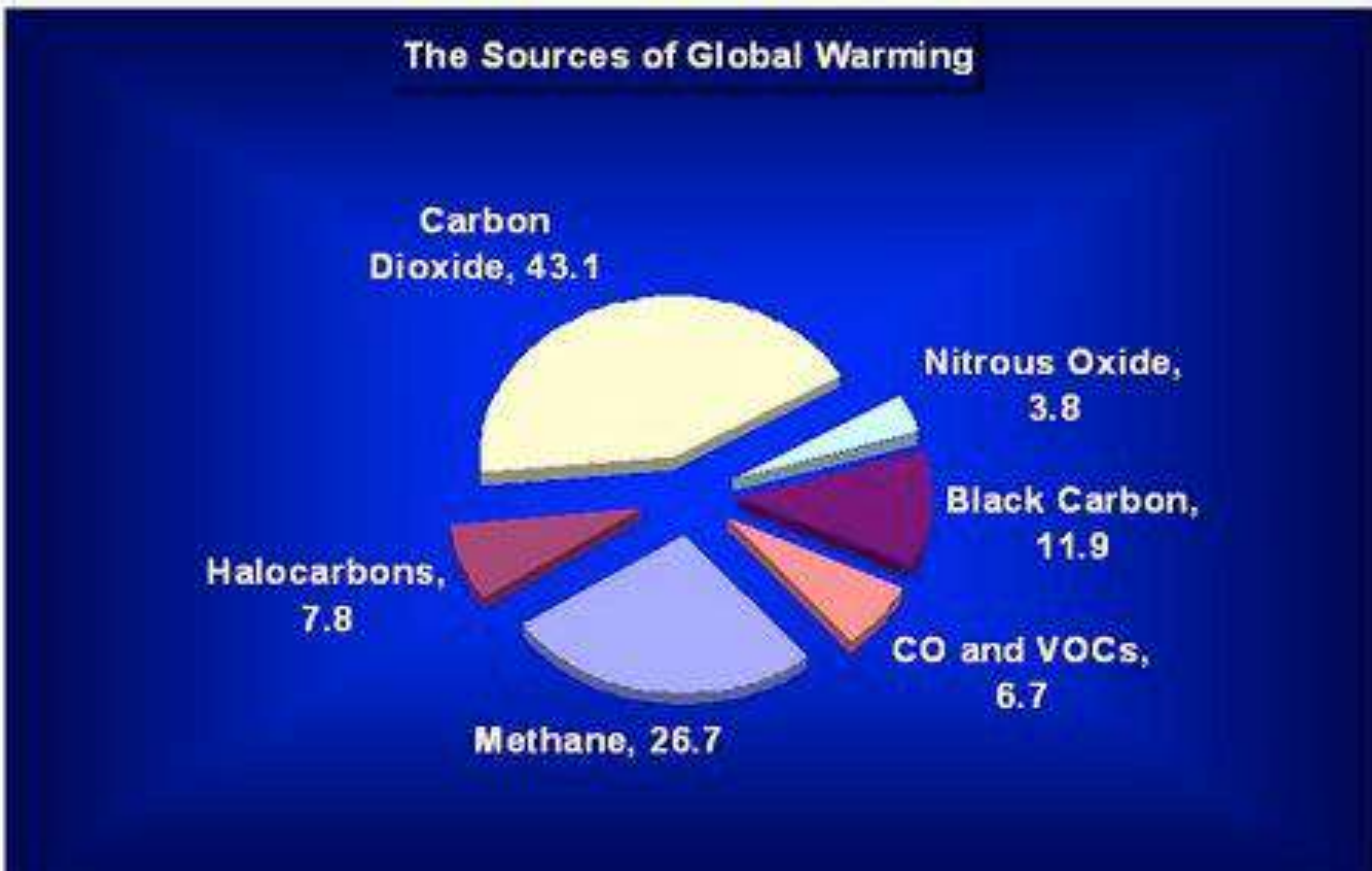


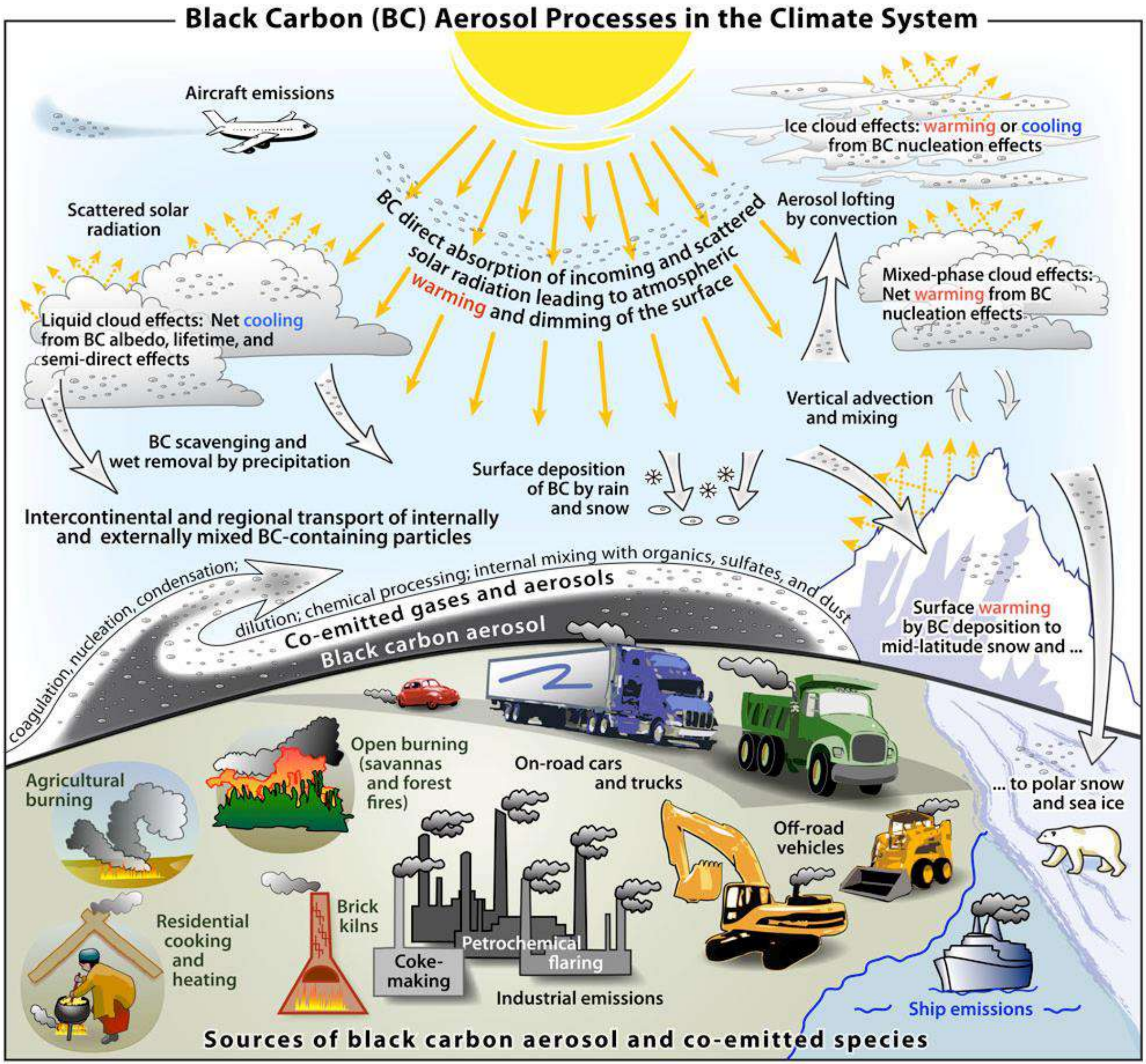
Carbon dioxide emissions are changing the climate – on land but also in the ocean



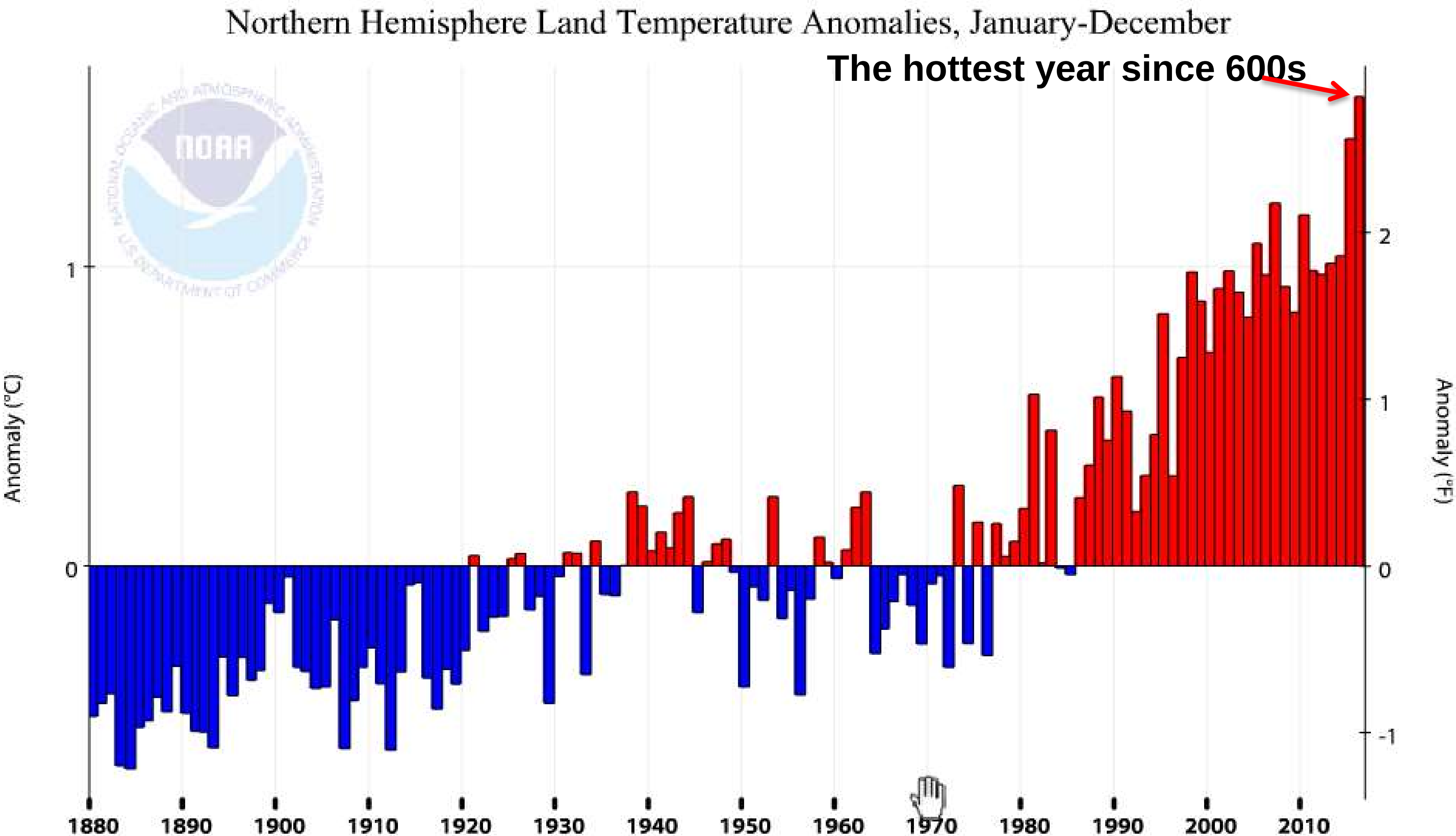
Global Modeling and Assimilation Office

CO_2 is not the only emission causing warming of the planet

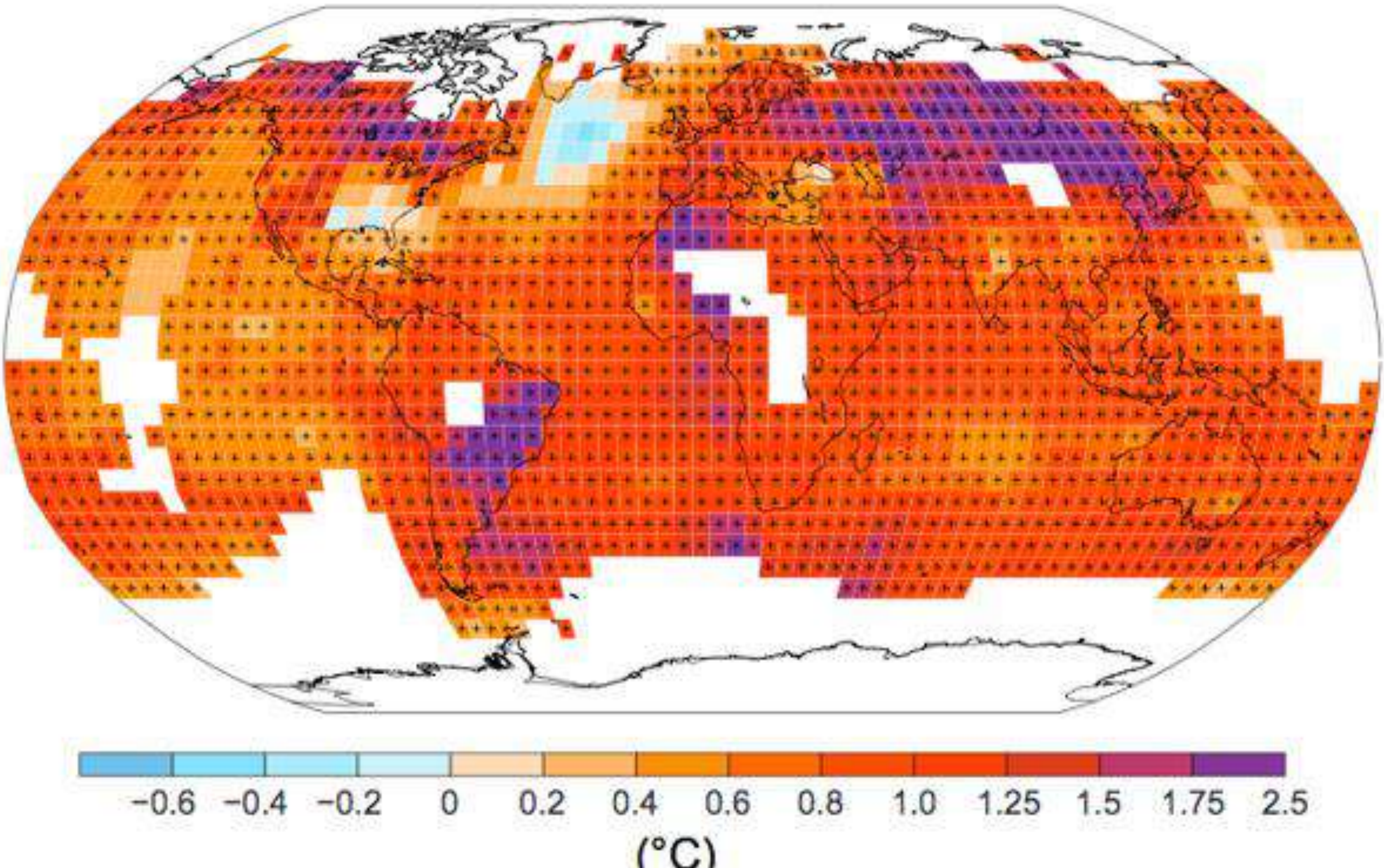



Black Carbon (BC) Aerosol Processes in the Climate System
Aircraft emissions
Ice cloud effects: warming or cooling from BC nucleation effects
Scattered solar radiation
BC direct absorption of incoming and scattered solar radiation leading to atmospheric warming and dimming of the surface
Aerosol lofting by convection
Mixed-phase cloud effects: Net warming from BC nucleation effects
Liquid cloud effects: Net cooling from BC albedo, lifetime, and semi-direct effects
Vertical advection and mixing
BC scavenging and wet removal by precipitation
Surface deposition of BC by rain and snow
Intercontinental and regional transport of internally and externally mixed BC-containing particles
coagulation, nucleation, condensation;
dilution; chemical processing; internal mixing with organics, sulfates, and dust
Co-emitted gases and aerosols
Black carbon aerosol
Surface warming by BC deposition to mid-latitude snow and ...
... to polar snow and sea ice
Agricultural burning
Open burning (savannas and forest fires)
On-road cars and trucks
Off-road vehicles
Residential cooking and heating
Brick kilns
Coke-making
Petrochemical flaring
Industrial emissions
Ship emissions
Sources of black carbon aerosol and co-emitted species

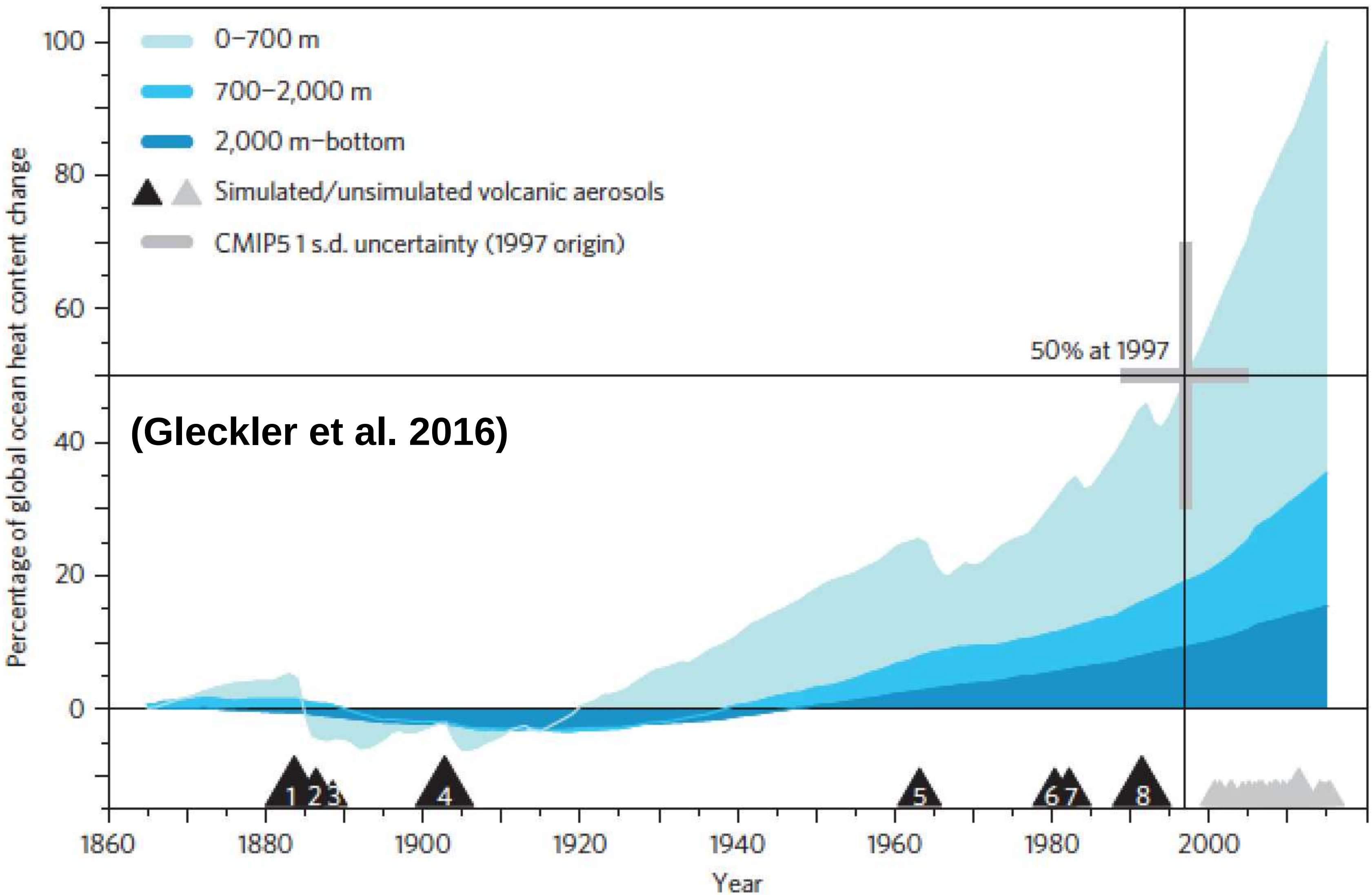
A Warming Atmosphere



Observed change in surface temperature 1901–2012

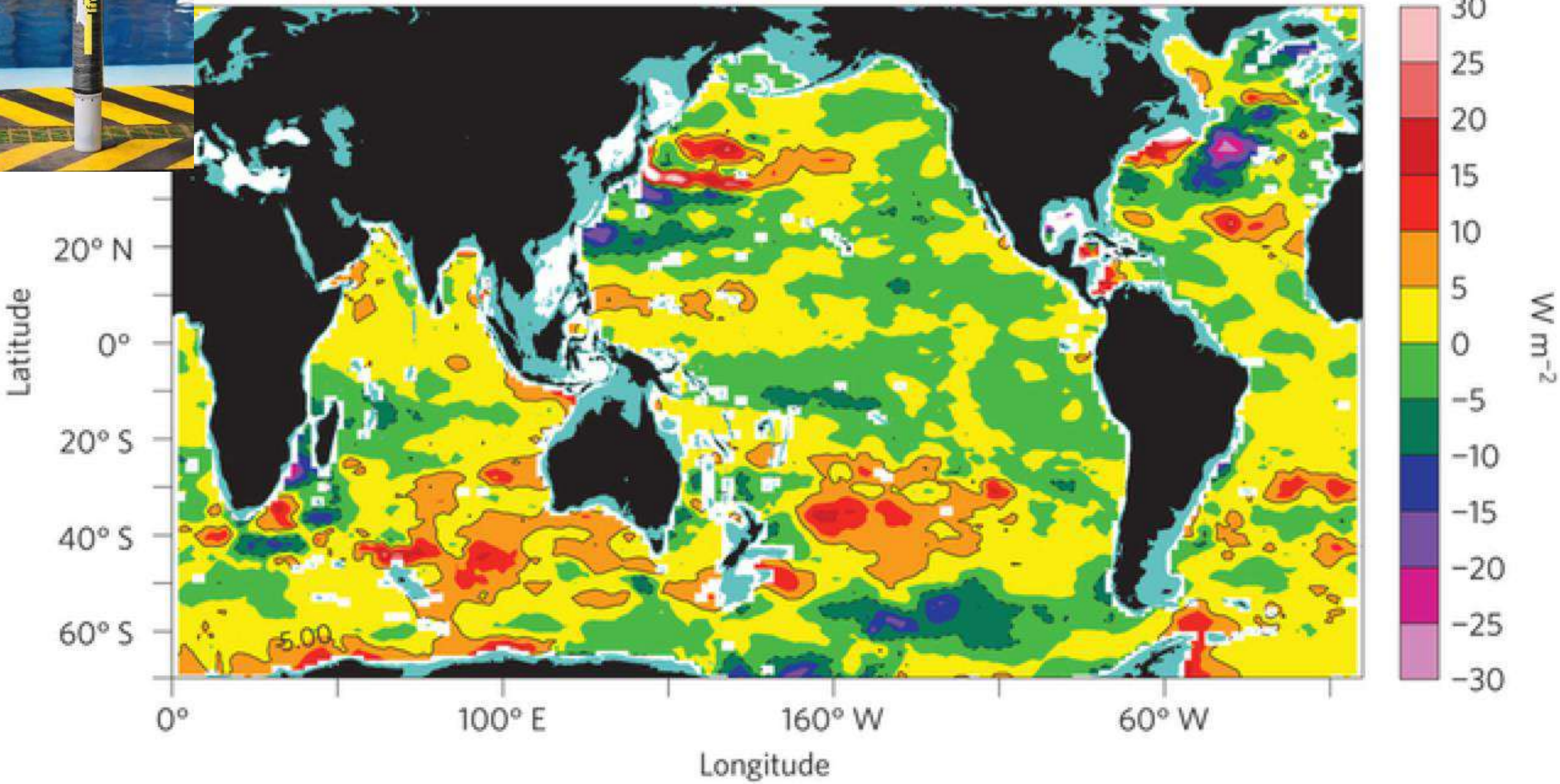


The ocean has absorbed >93% of the heat resulting from CO_2 emissions



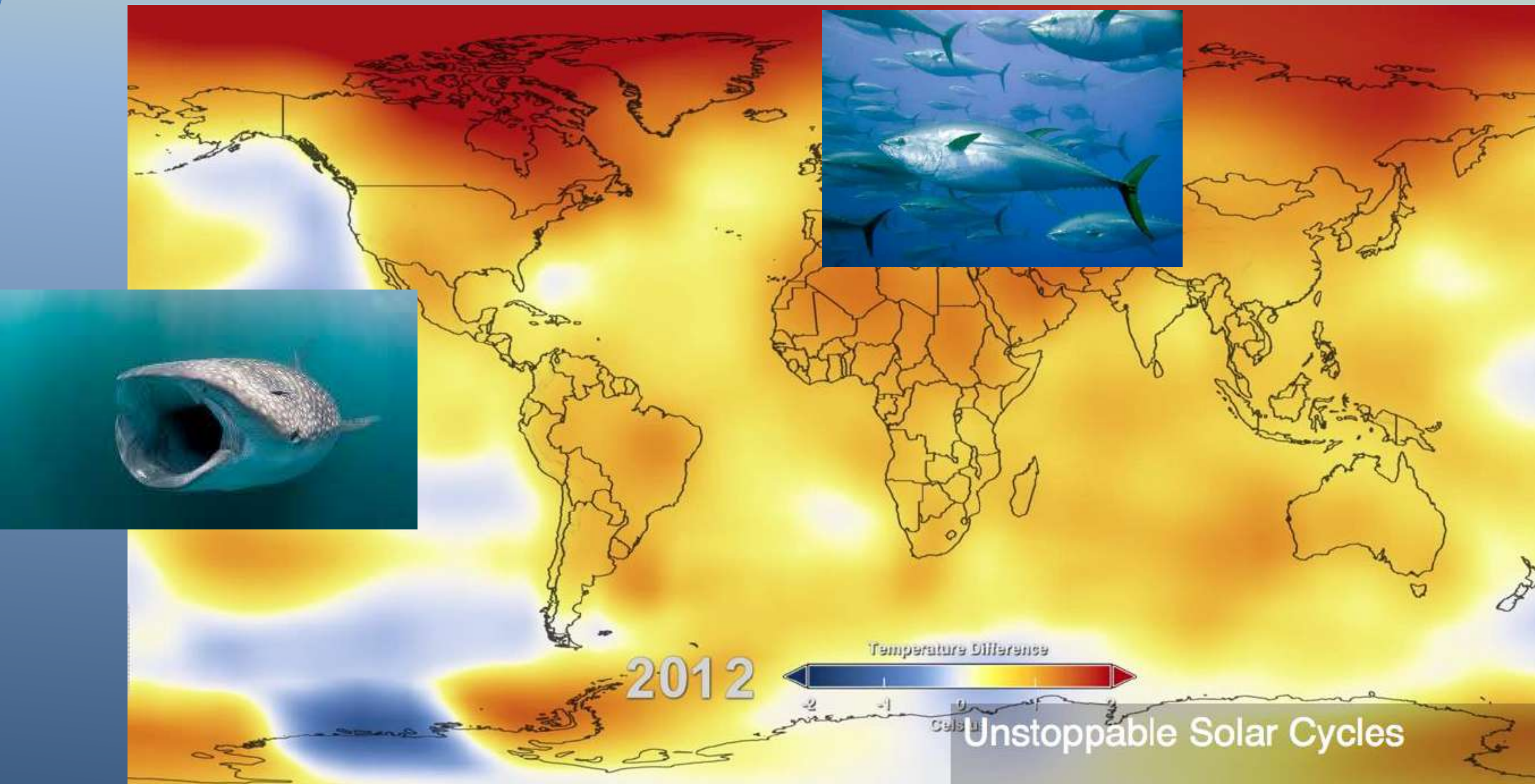
THE OCEAN as CLIMATE MITIGATOR

The spatial pattern of heat gain since 2006 (0 to 2000 m)



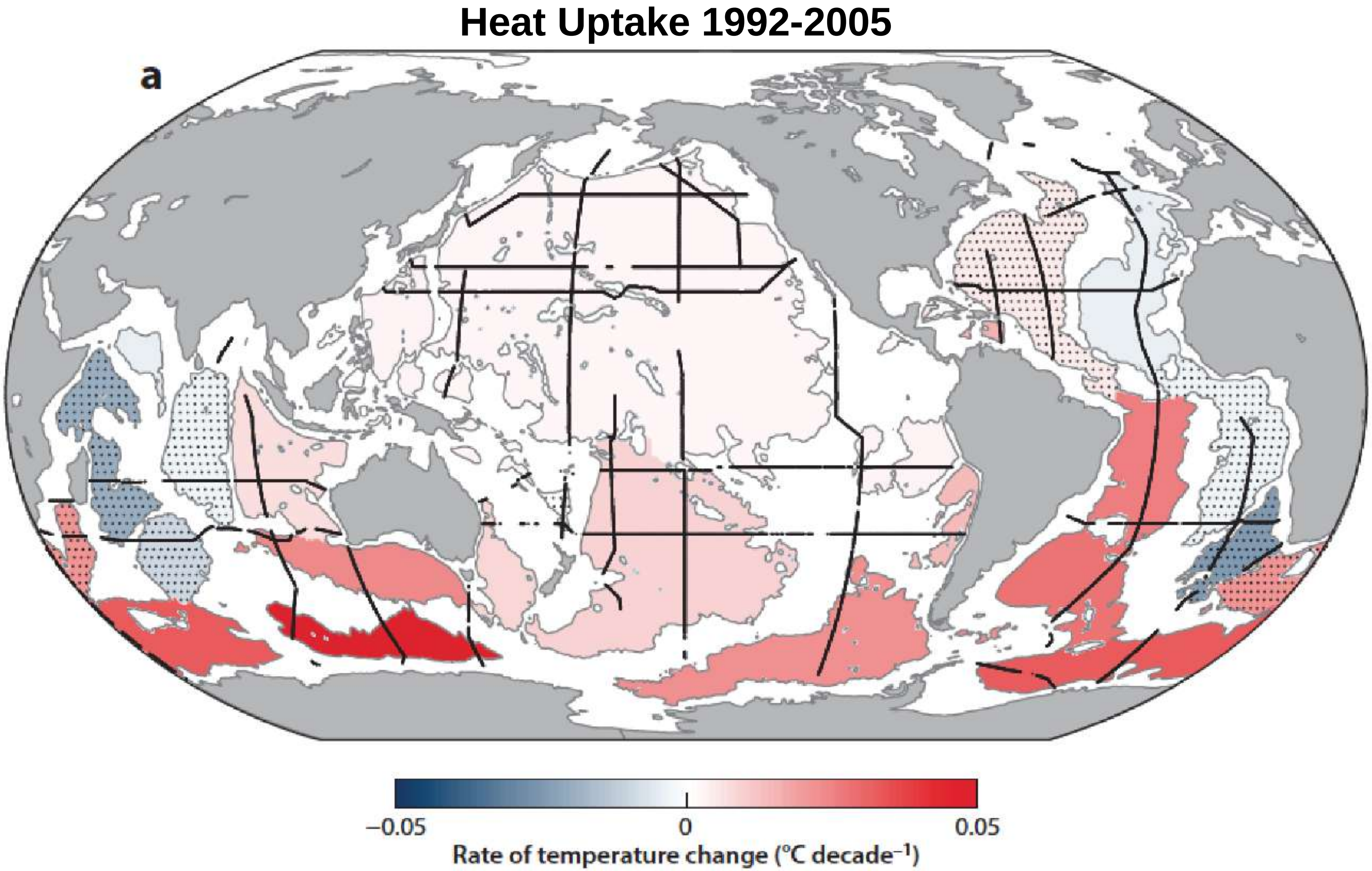
Roemmich et al. 2015

Warming



- **Species on the Move (towards the poles)**
- **Higher Metabolic Rates Exceeding Physiological Thresholds**

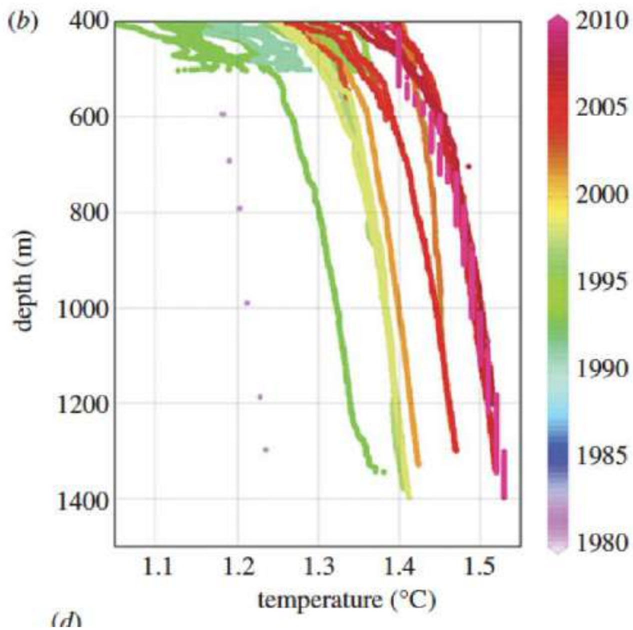
Even deep waters > 4000 m are warming



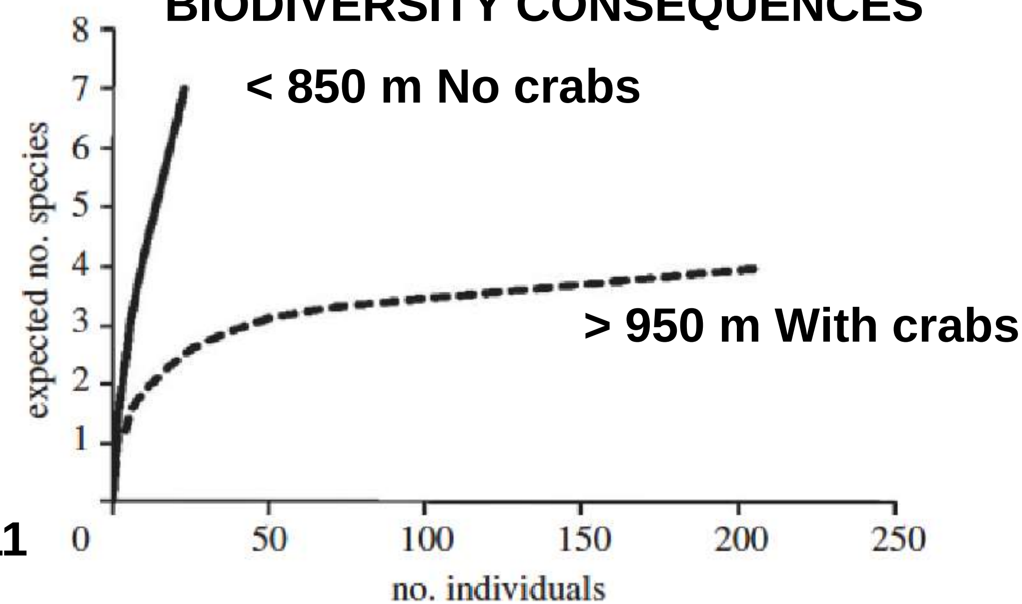
Talley et al. 2015 ARMS

- adapted from Rhein et al. (2013), based on Purkey & Johnson (2010)

Warming to > 1.4ºC has allowed a Lithodid crab invasion in the Palmer Deep, Antarctica

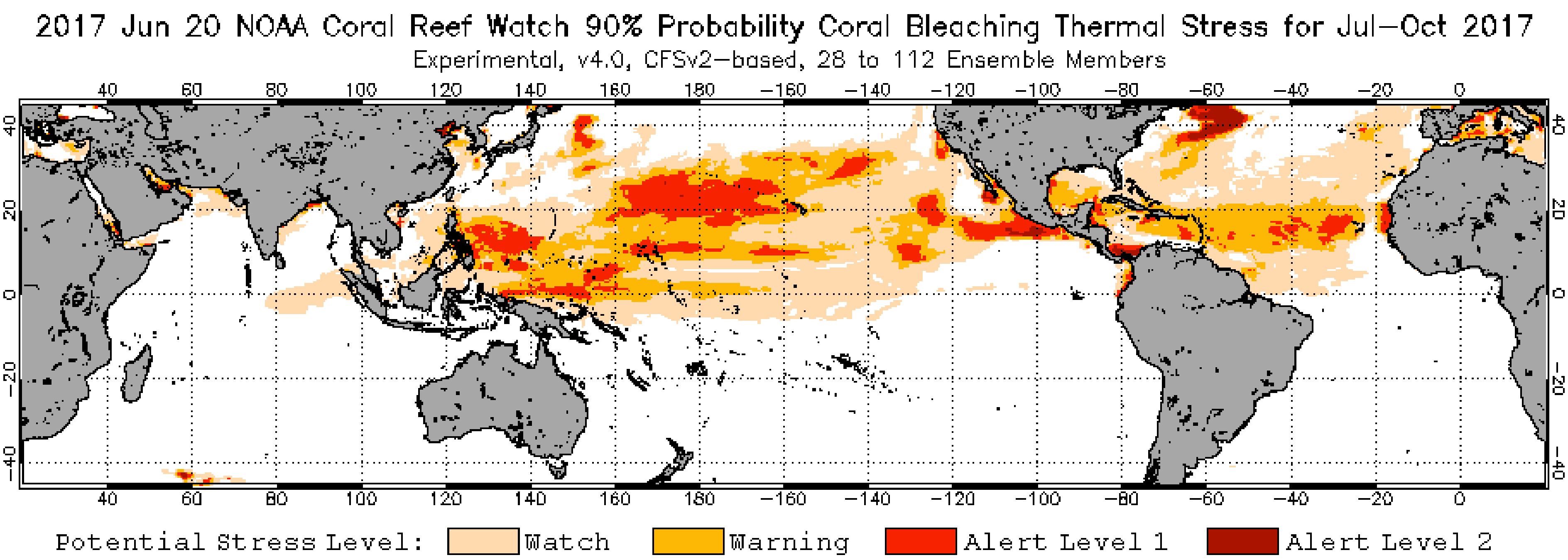


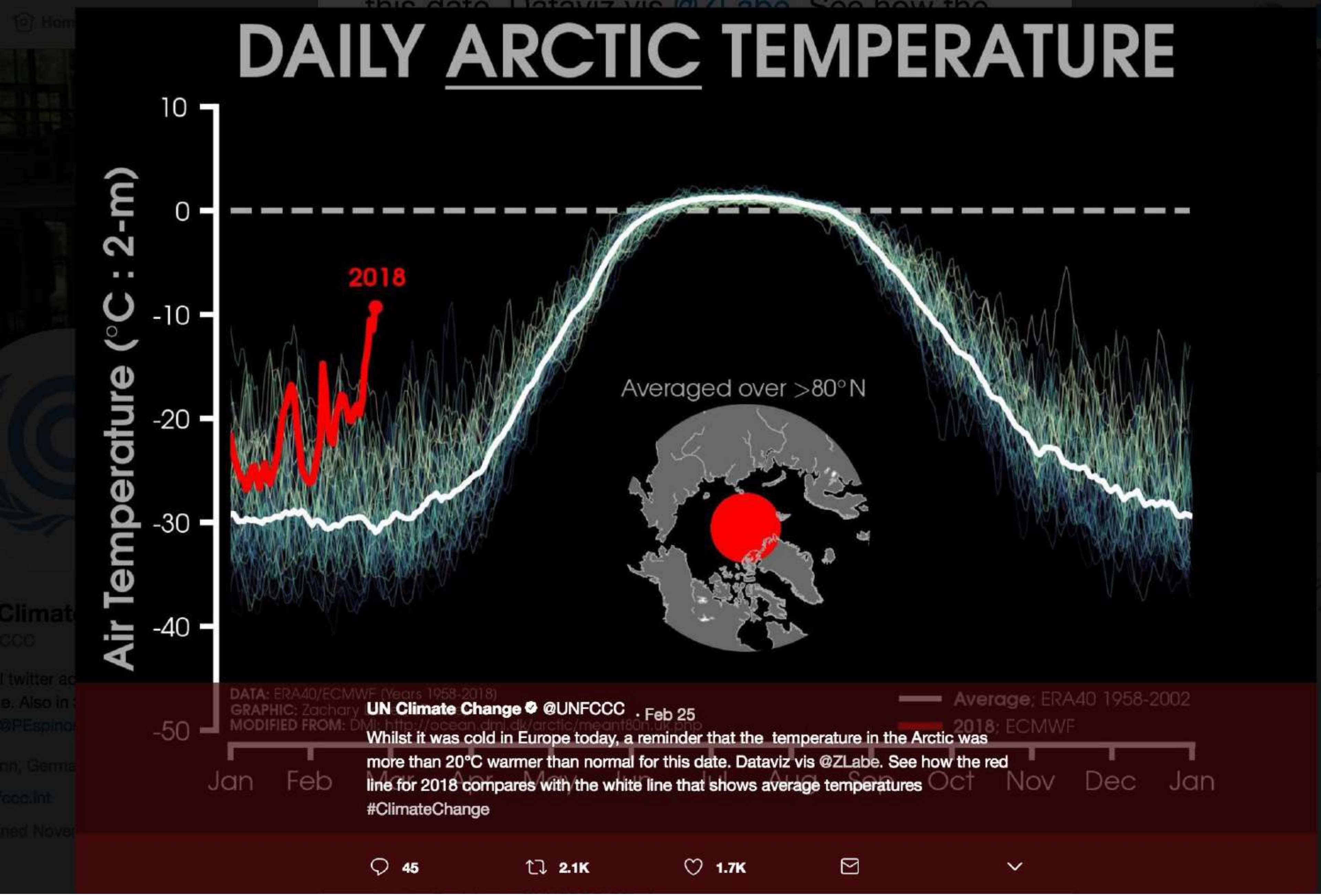
BIODIVERSITY CONSEQUENCES



Smith et al. Proc. R. Soc. B 2011

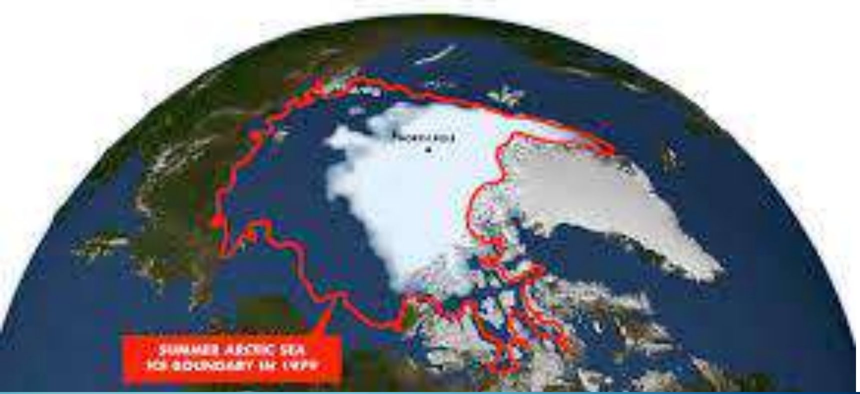
Warming-Induced Coral Bleaching

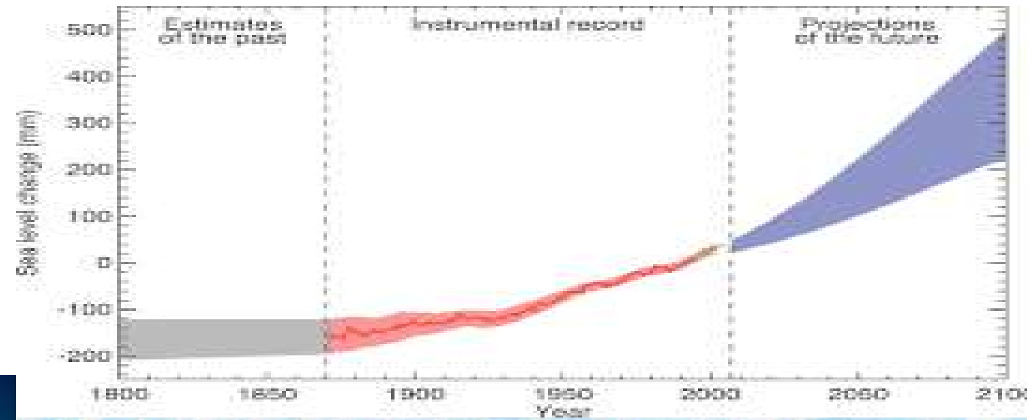




In Feb 2018 – 20^{o}C warmer than normal!

Warming causes:
Melting glaciers and ice sheets
Expansion of seawater
=Sea Level Rise



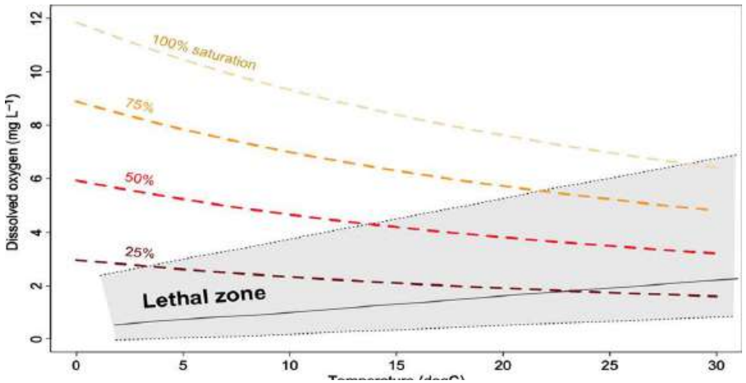


Storm Surge, Flooding

Ocean Deoxygenation

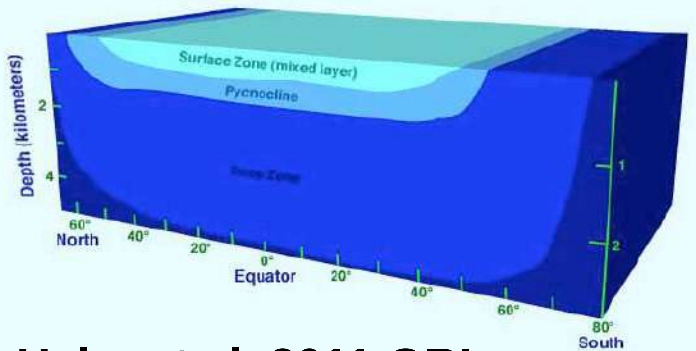
A warming ocean holds less oxygen

Warming raises oxygen thresholds for living organisms



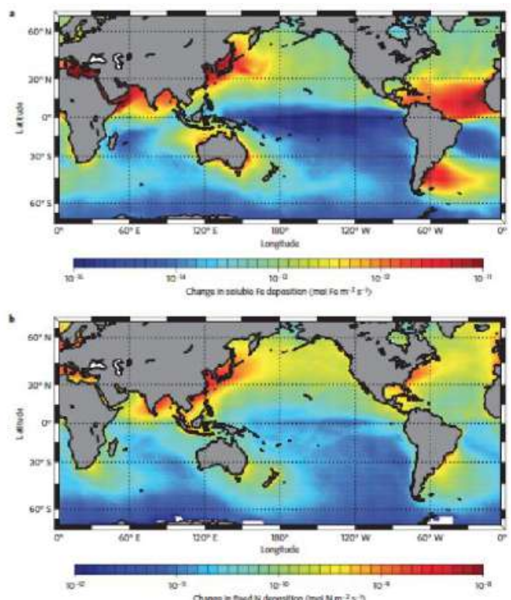
Altieri and Gedan 2015 GCB
(data from Vaquer Sunyer and Duarte 2011)

A warmer ocean is more stratified Enabling less ventilation



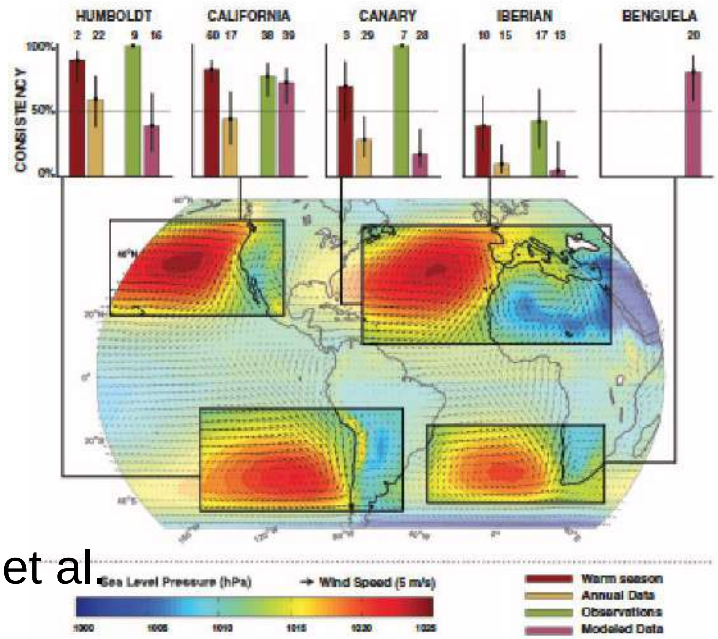
Helm et al. 2011 GRL

Rising Fe and N deposition in the N. Pacific



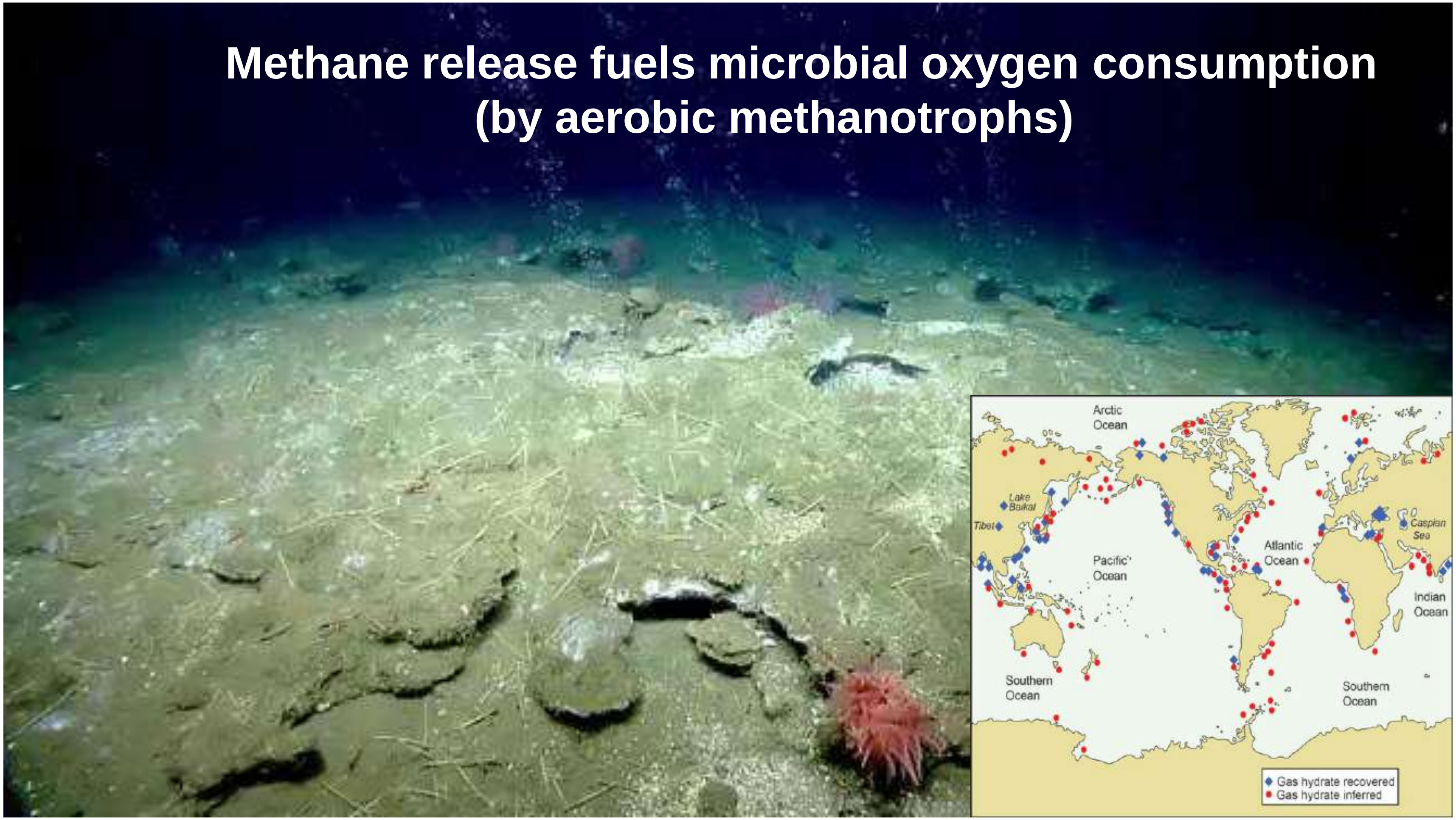
Ito et al. 2016

Enhanced Upwelling in Eastern Boundary currents



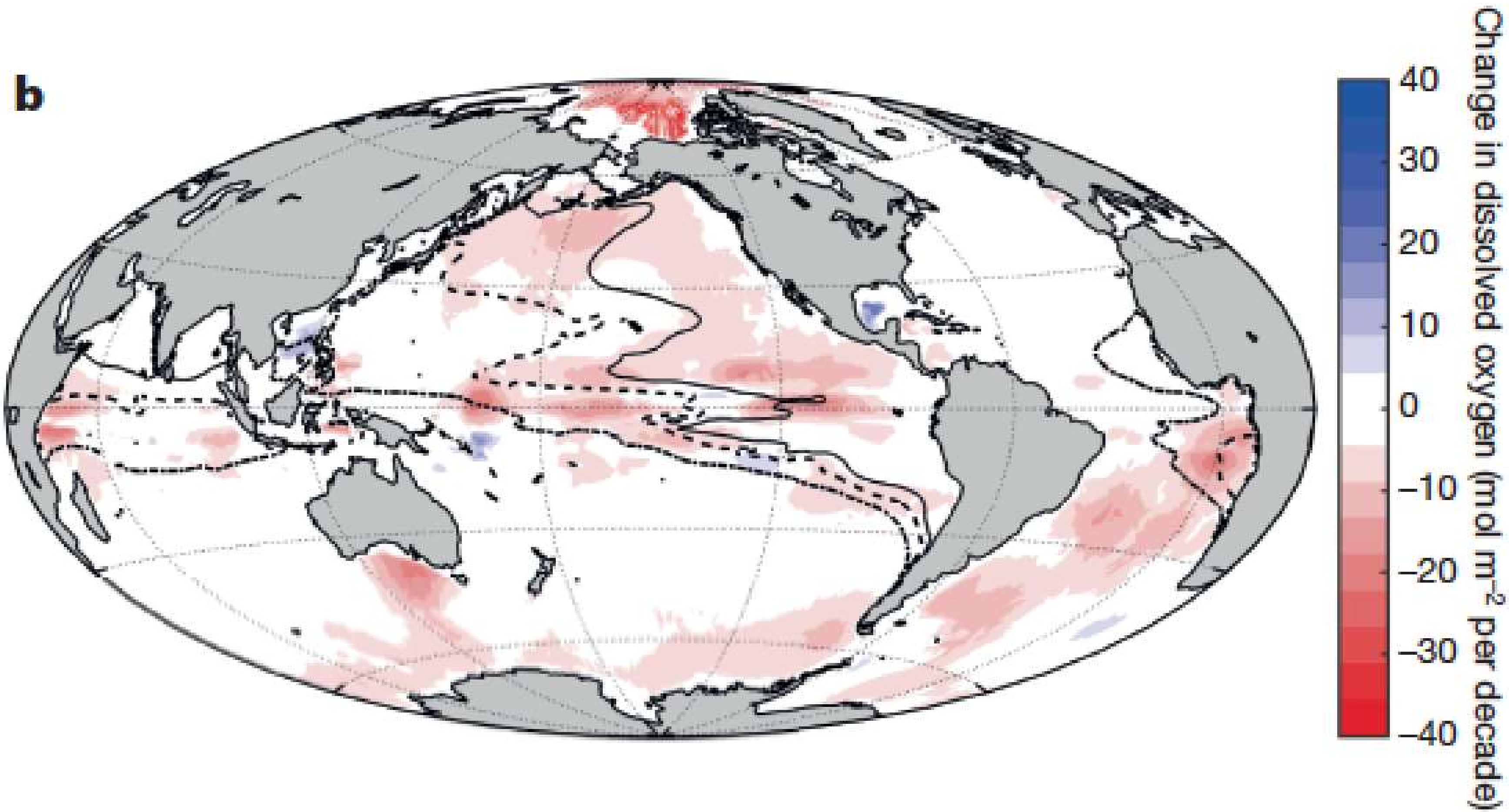
Sydeman et al. 2014

A warmer ocean may release more methane via dissociation of gas hydrates on margins



Warming Causes Ocean Deoxygenation

The ocean has loss 2% of its oxygen since 1960s, but not uniformly
Much loss has occurred in the North Pacific at 150-700 m

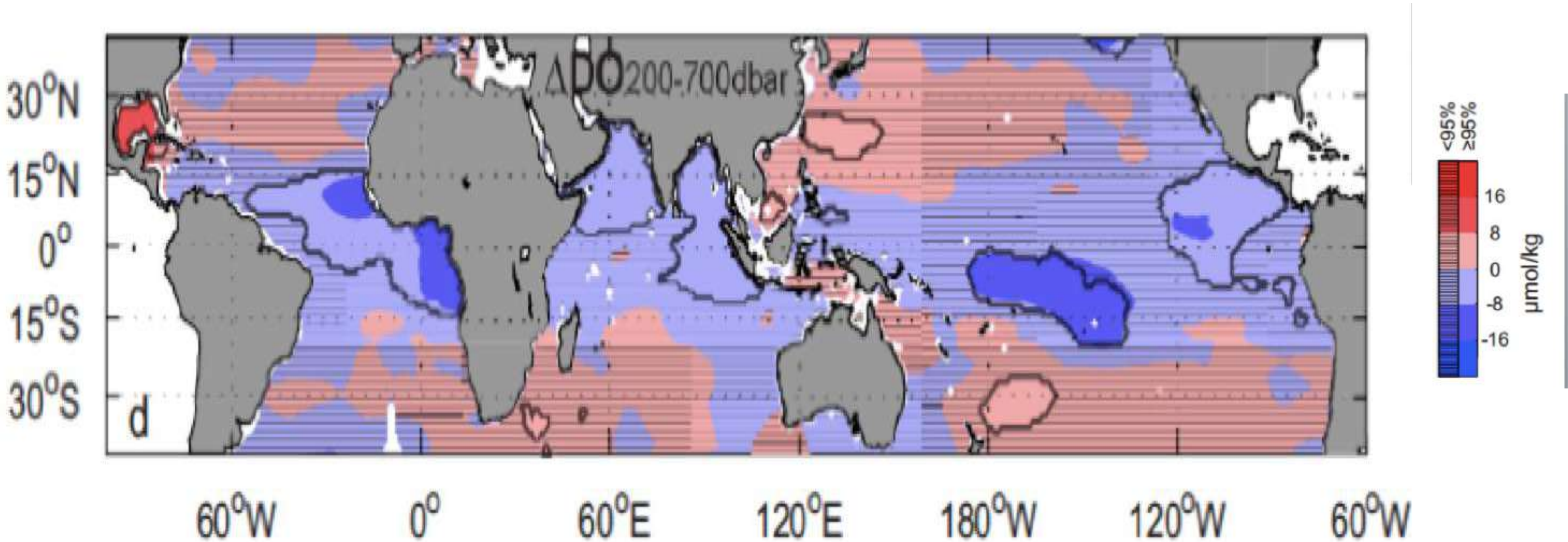


Schmidtko et al. 2017 Nature

As a result….low oxygen areas are expanding

In the last 50 y there has been massive oxygen loss in the tropical and subtropical ocean

At 200 m the hypoxic area (with < 70 μM O_2) has increased by 4.5 million km^2 area

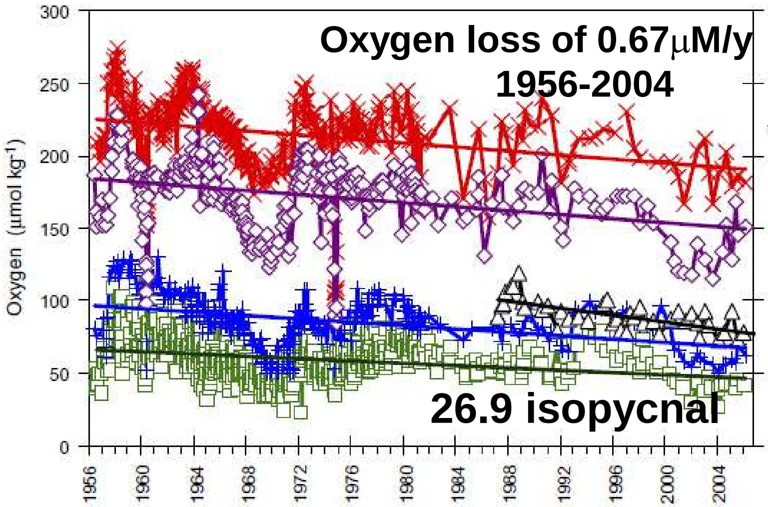


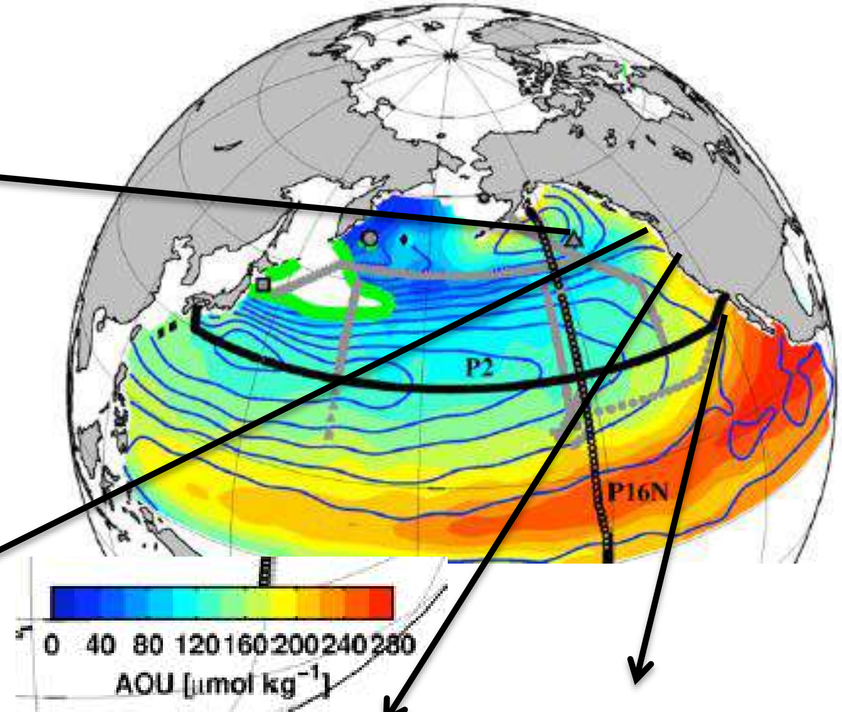
Dissolved oxygen in 1964-70 vs 1990-2008

Stramma et al. 2010
Deep-sea Research I

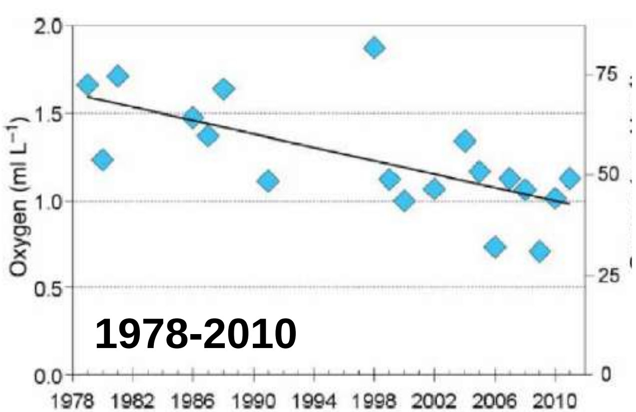
Oxygen has declined in the NE Pacific Ocean over the last 60y

Station P - Whitney et al. 2007



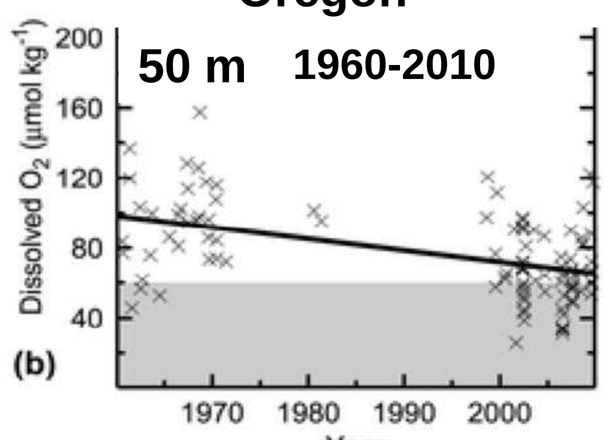


British Columbia



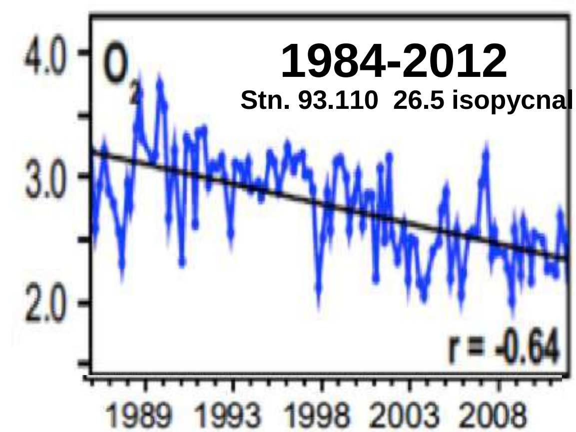
Crawford and Pena 2013

Oregon



Pierce et al. 2012

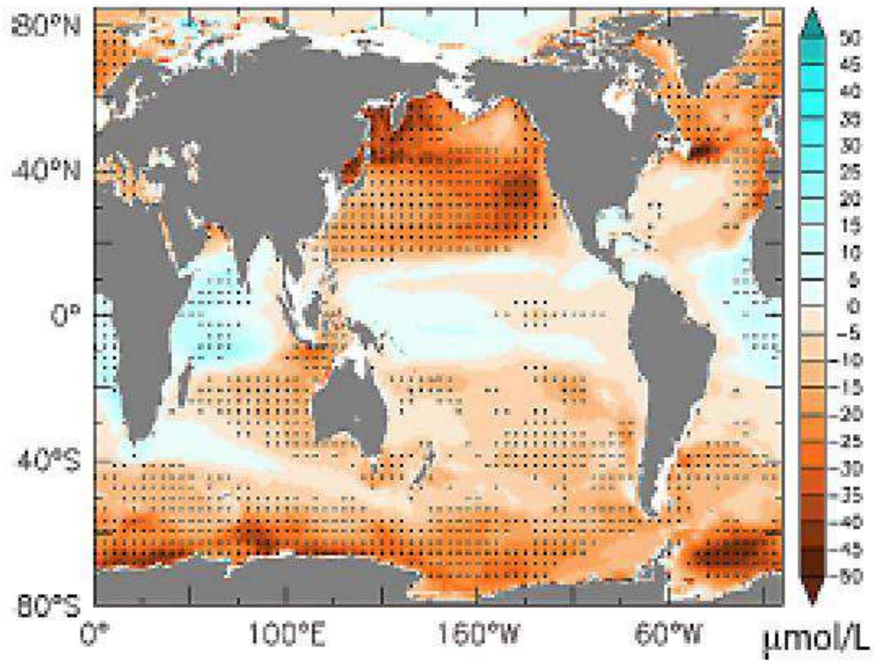
So. Califoarnia Bight

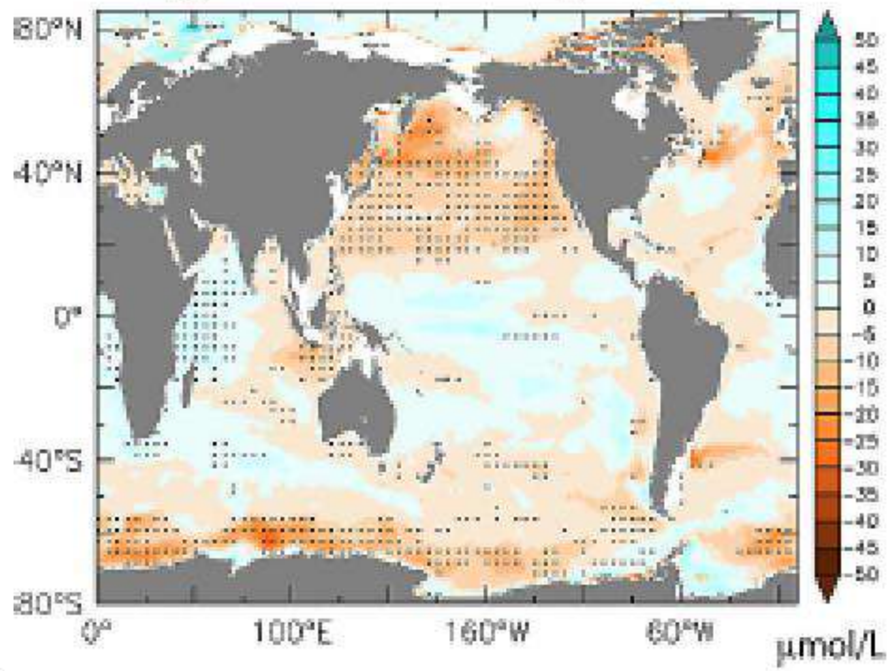


Bograd et al. 2015

10 Earth System Models project in 2100 widespread oxygen decline at intermediate depths

RCP 8.5   Oxygen concentration changes at 200-600 m (1990s-2090s)   RCP 2.6





Bopp et al. 2013
Biogeosciences

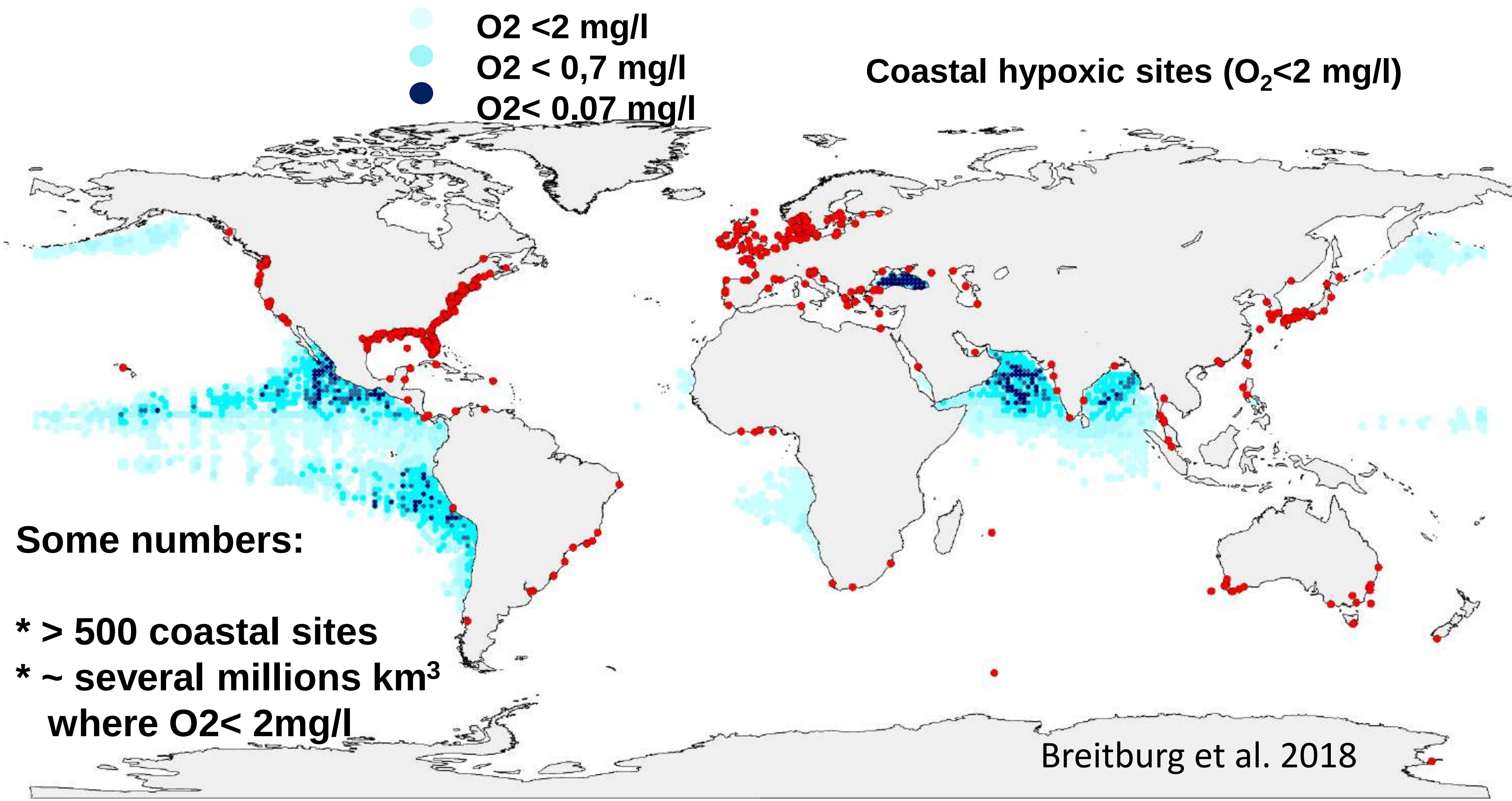
GO$_2$NE
Global Ocean Oxygen NEtwork

Nutrient-driven hypoxia is pervasive in the coastal ocean as well.

United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

Dead zones are exacerbated by climate change.



Some numbers:

* > 500 coastal sites
* ~ several millions km^3 where O2< 2mg/l

Breitburg et al. 2018

Oxygen is essential to most life

Ocean deoxygenation affects nearly all biogeochemical and biological processes in the ocean

Structure
- Body Size
- Taxonomic Composition
- Biodiversity
- Distributions

→

Function
- Physiology
- Production
- Respiration
- Food Webs
- C Burial
- Recruitment
- Foraging Behavior

→

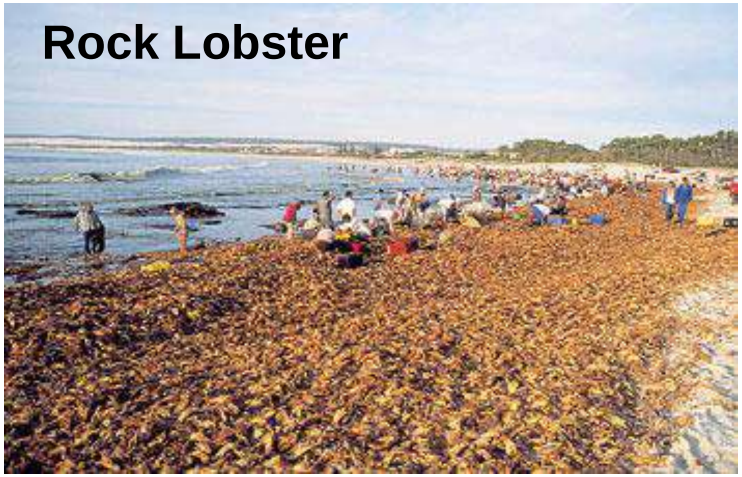
Ecosystem Services
- Fisheries
- C sequestration
- Recreation
- Tourism

AND…. thermal & CO_2 tolerances

Ocean Deoxygenation alters ecosystems

Major loss of biodiversity is inevitable. Big & active animals are the first to go

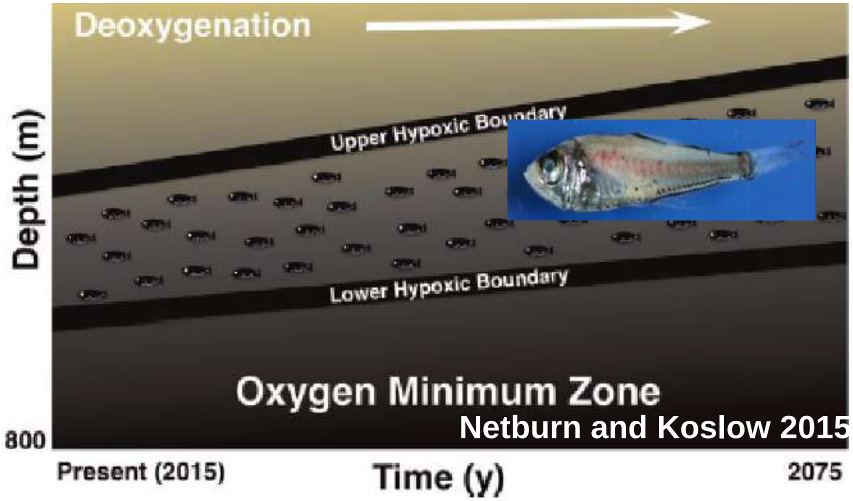
Rock Lobster



Crabs

Habitat Compression: **Intolerant species become subject to overfishing or predation**

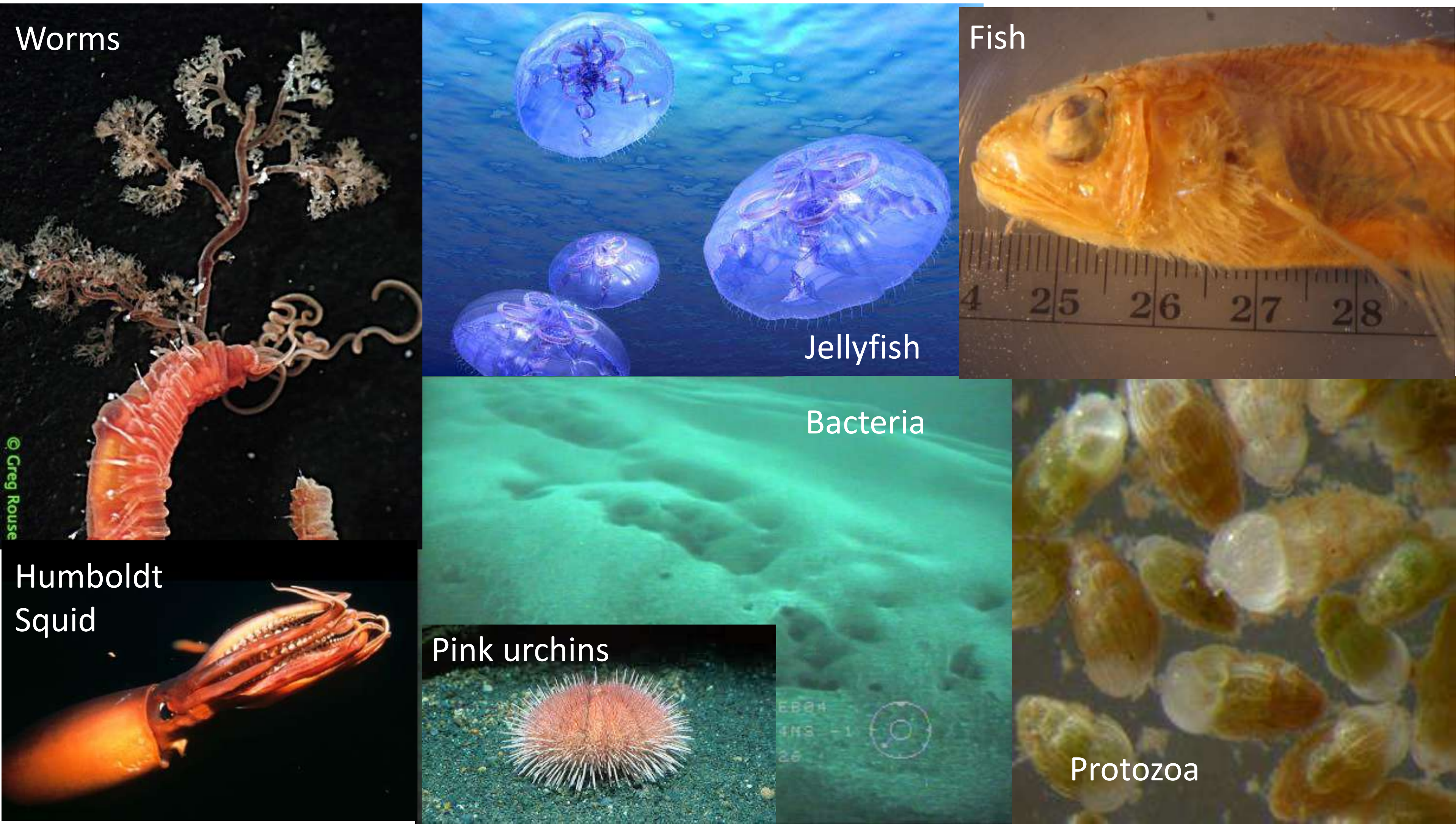
Upward Migration of Midwater Taxa

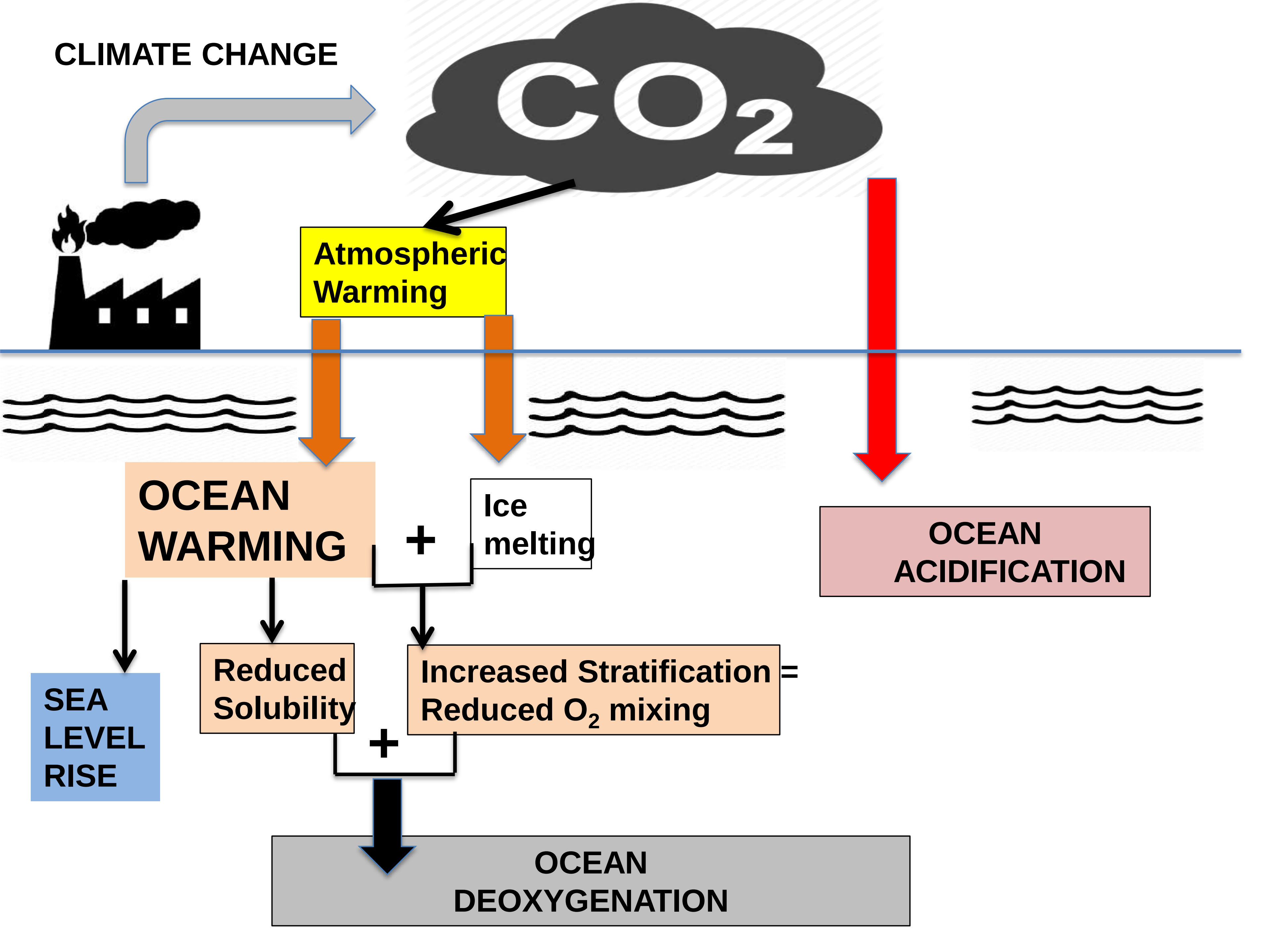


Netburn and Koslow 2015

Shoaling of Billfish

Some Species Cope with Ocean Deoxygenation





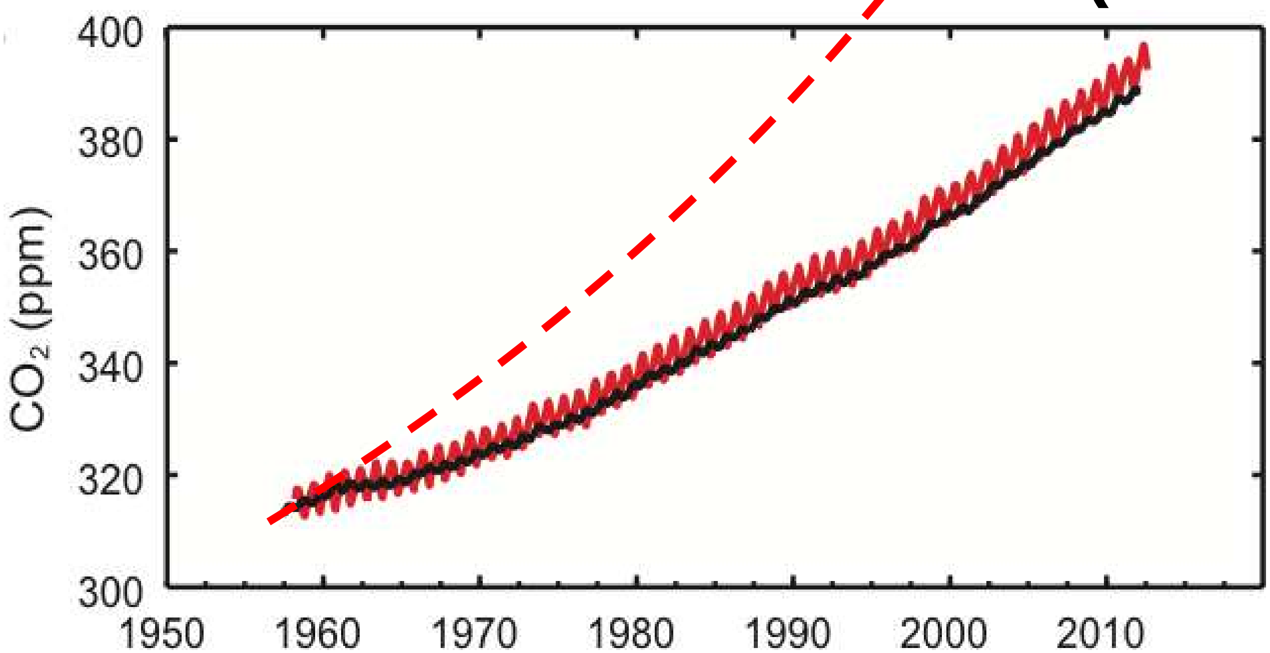
CLIMATE CHANGE
CO2
Atmospheric Warming
OCEAN WARMING
+
Ice melting
OCEAN ACIDIFICATION
SEA LEVEL RISE
Reduced Solubility
Increased Stratification = Reduced O2 mixing
+
OCEAN DEOXYGENATION

The ocean absorbs 26% of annual CO_2 emissions

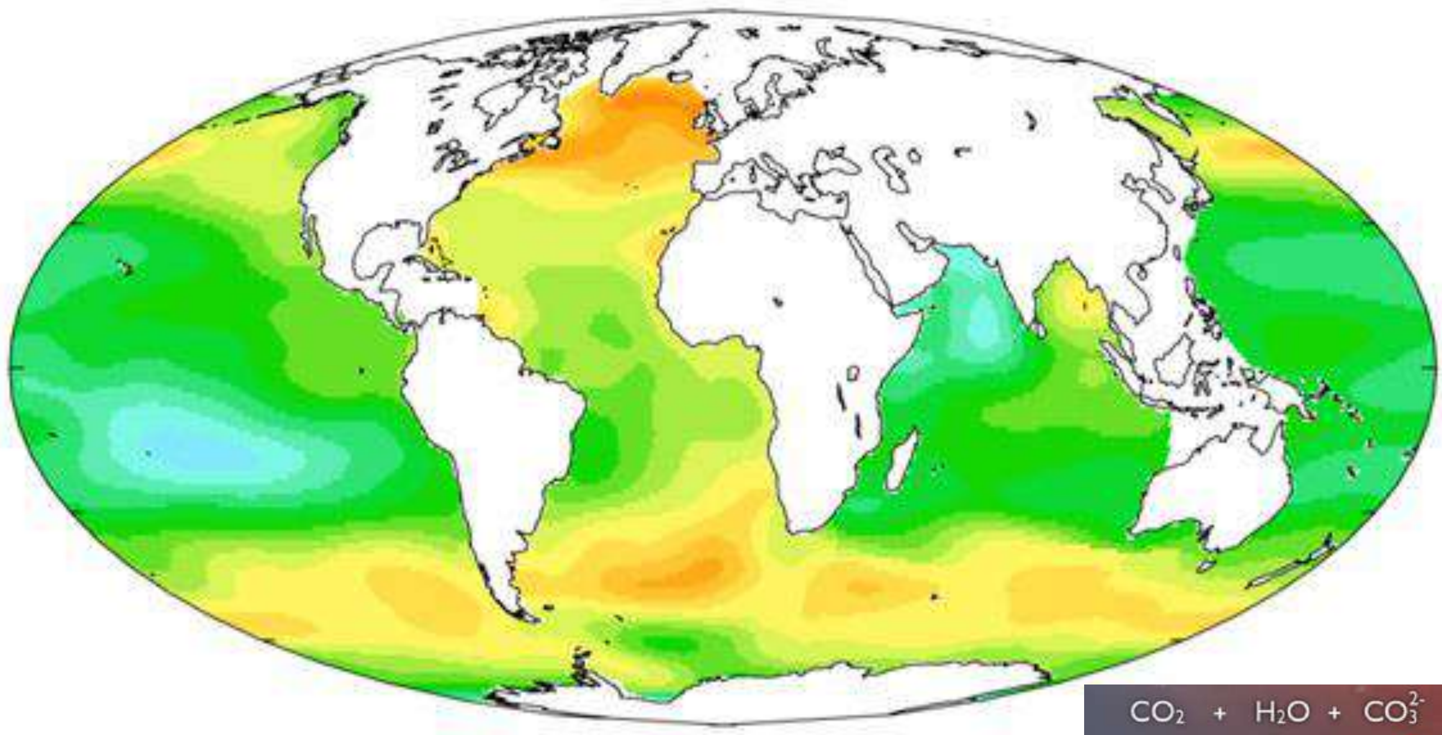
(without sinks) 500 ppm

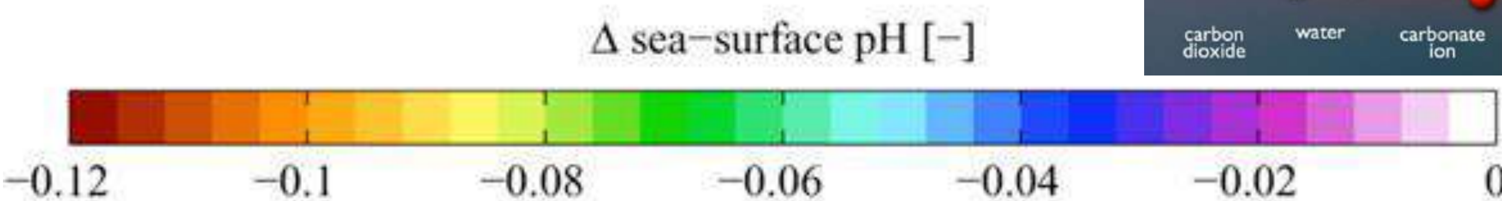
Slowing the greenhouse effect

(with sinks) 409 ppm

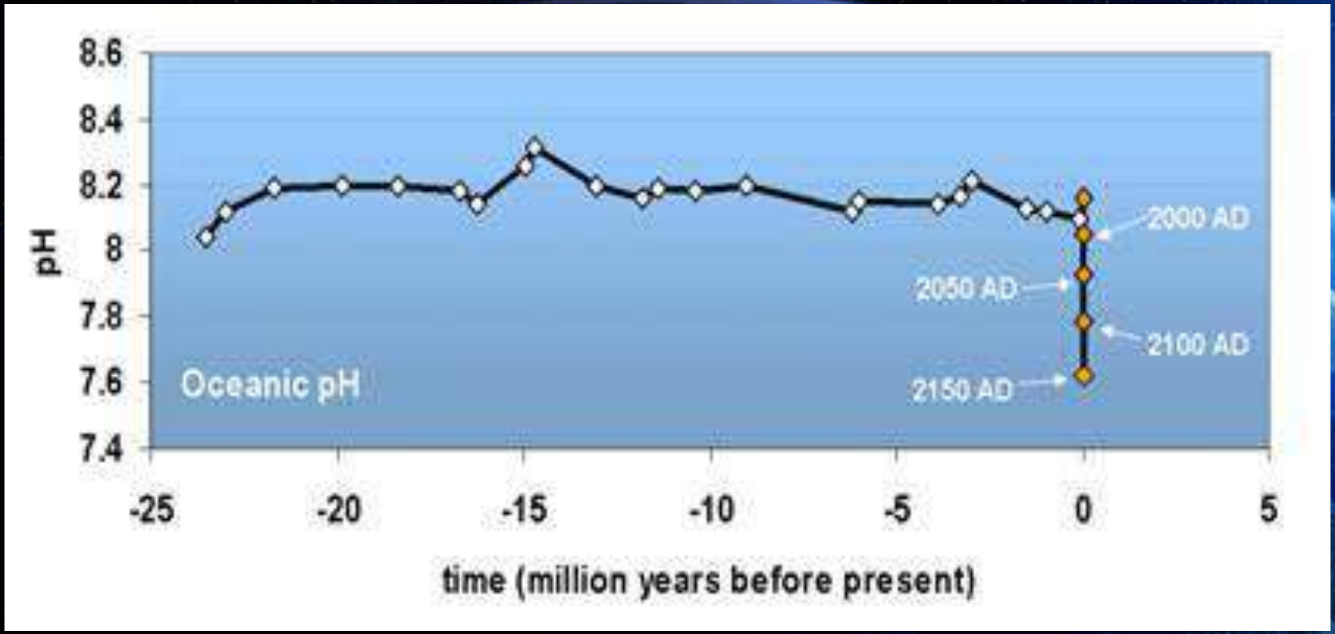


Direct ocean uptake of CO_2 lowers the pH of the ocean and reduces carbonate saturation





Ocean acidification is intensifying rapidly and at a rate unprecedented for millions of years

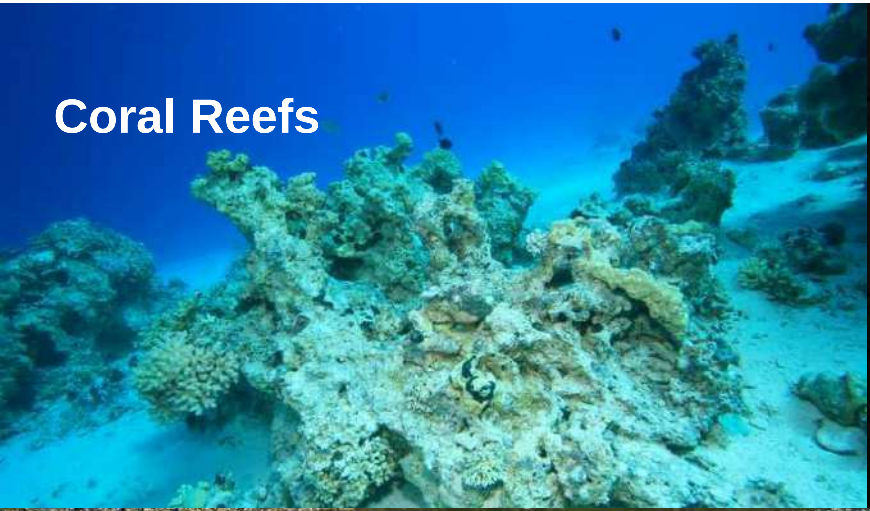


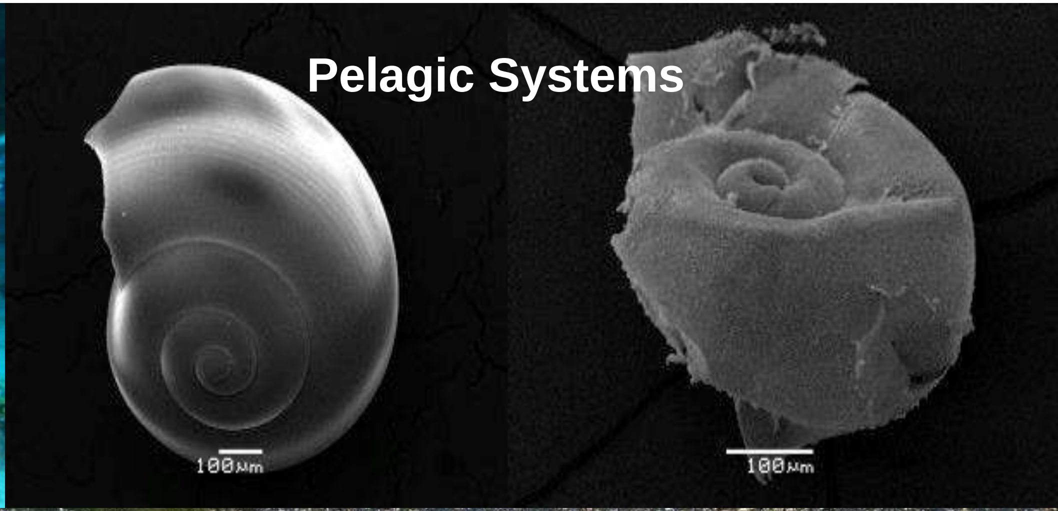
Acidification is 10 times faster than at any time during at least the last 65 million years

Image_ J. Zachos

Turley et al. (2006)

Ocean Acidification in the Upper Ocean

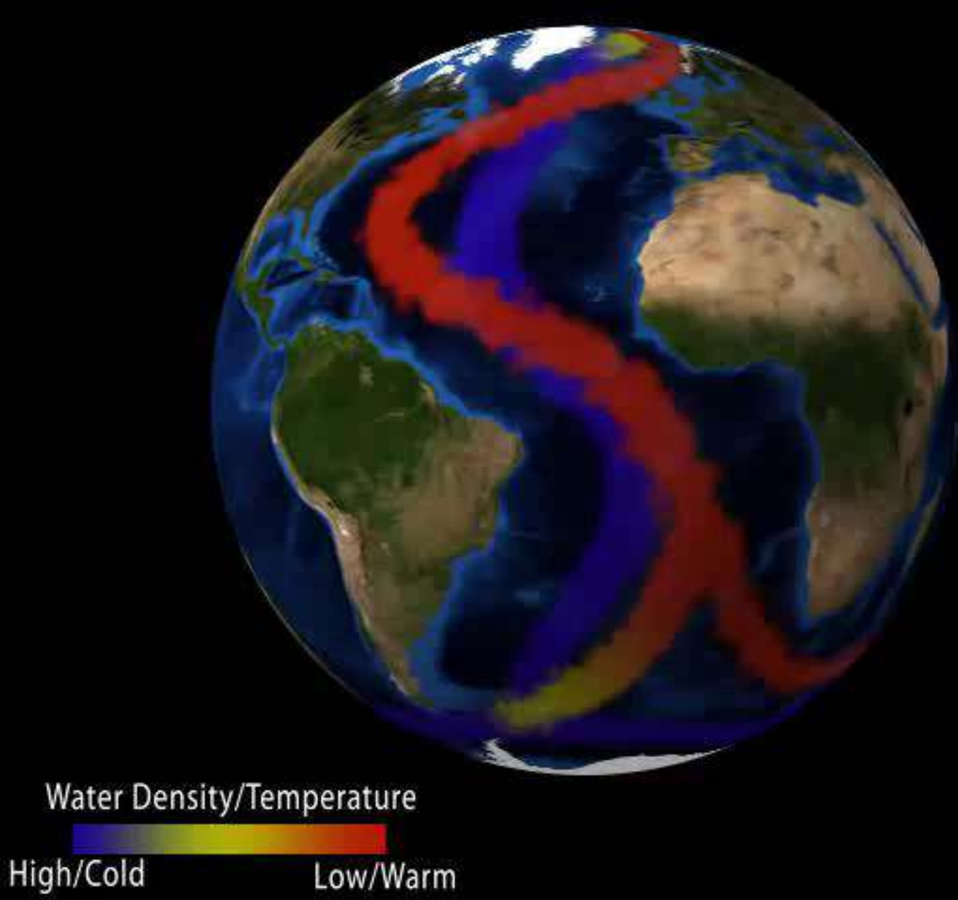


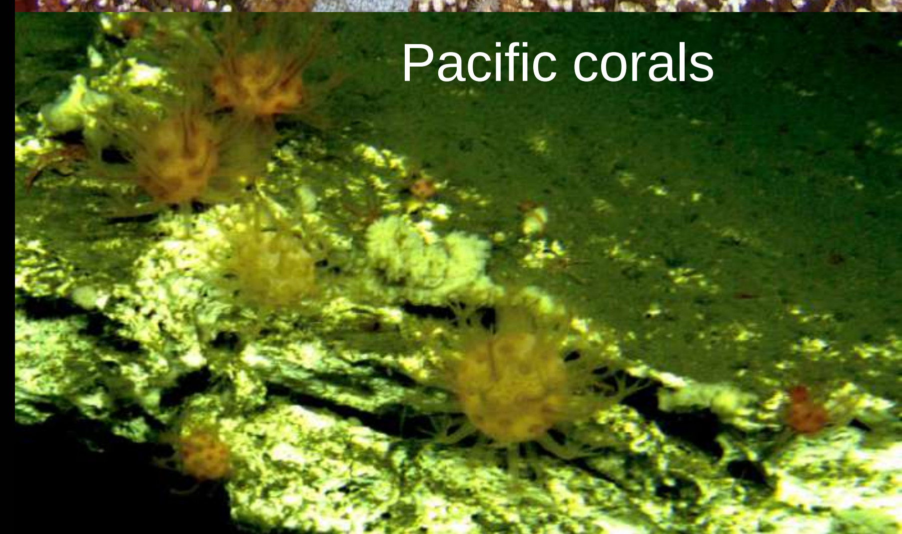


Ocean Acidification is Occurring in the Deep Ocean!

Thermohaline circulation is transporting CO_2 downward, causing acidification of deep waters

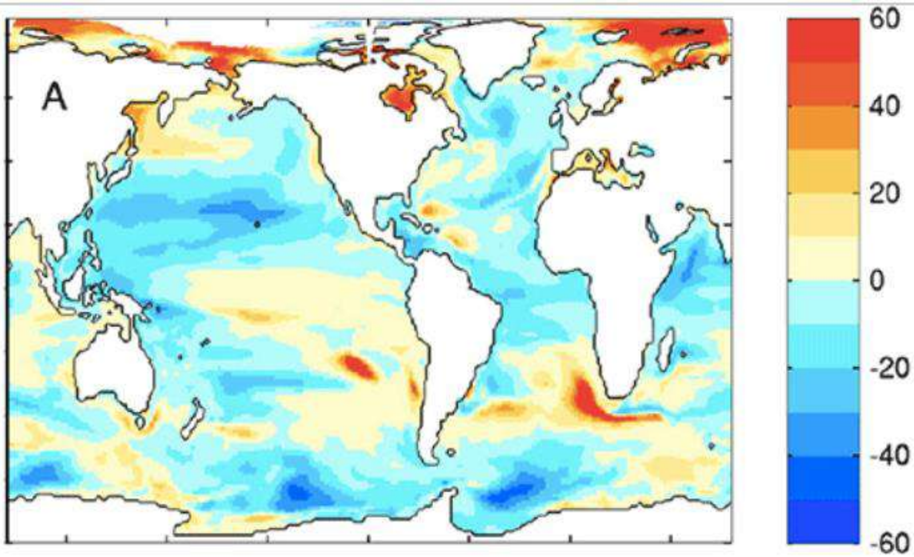
Ω_{arag} = $[Ca^{2+}][CO_3^{2-}]/Ksp$



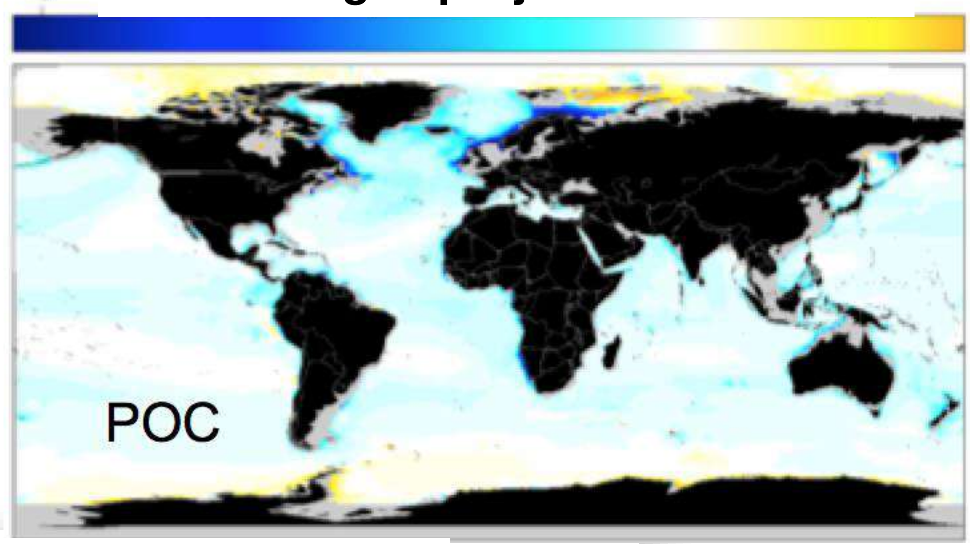


Warming and increased stratification causes a loss of food supply to the deep sea

Projected Change in Primary Production

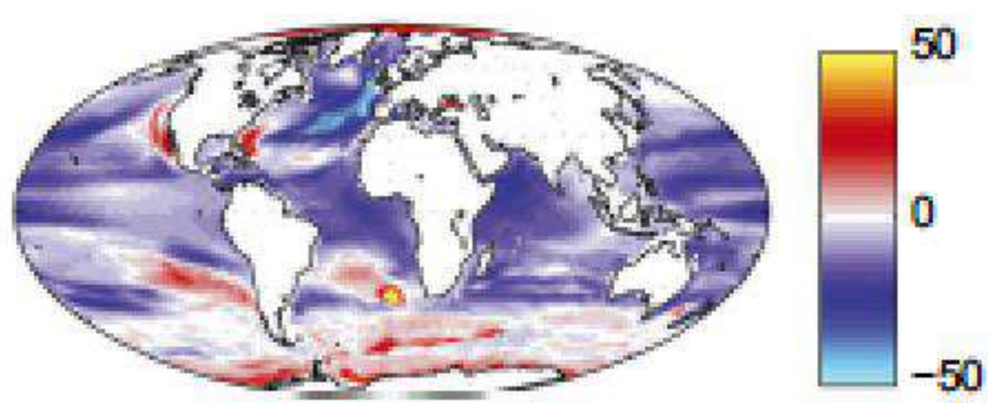


Seafloor Particulate Organic Carbon Flux changes projected for 2100



Stock et al. 2017

Faunal Biomass change under RCP 8.5



Jones et al. 2014

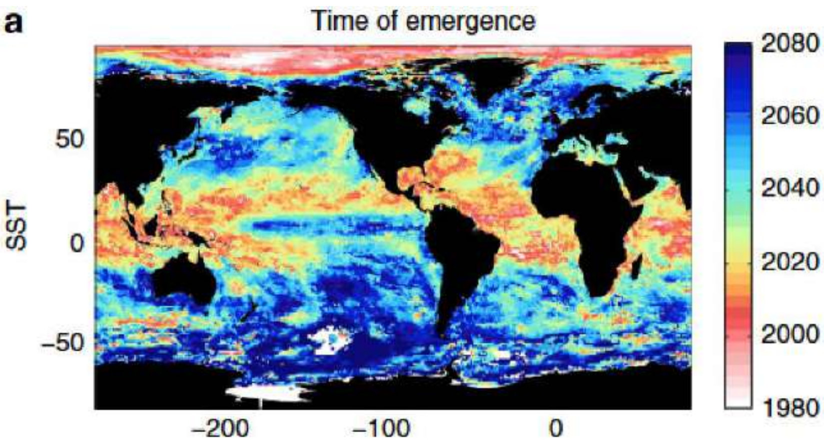
Climate change is occurring against a backdrop of natural variability.

- How do we know when change is due to man-made warming?

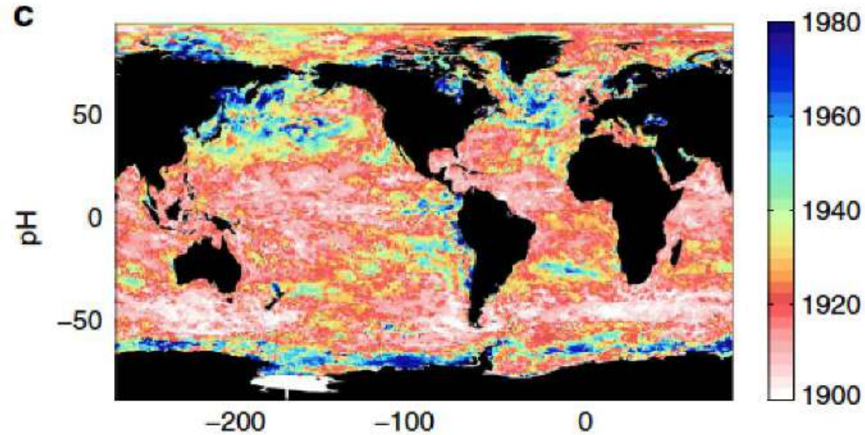
We can map time of signal emergence (exceeding natural variability) over the next century

Can this predict time of change in habitat suitability?

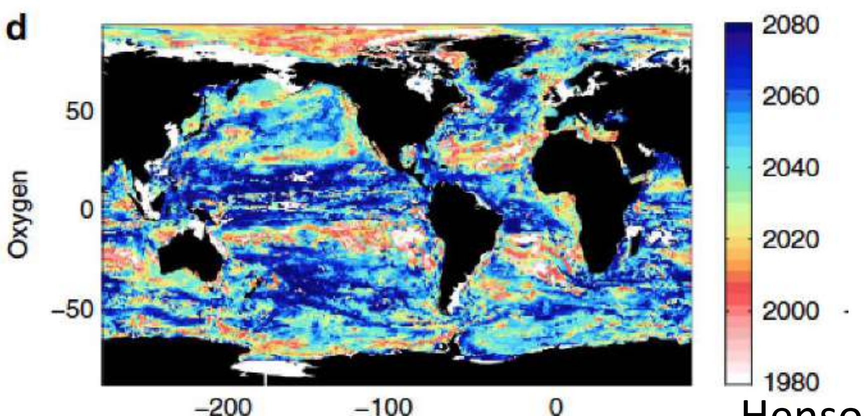
Sea Surface Temperature



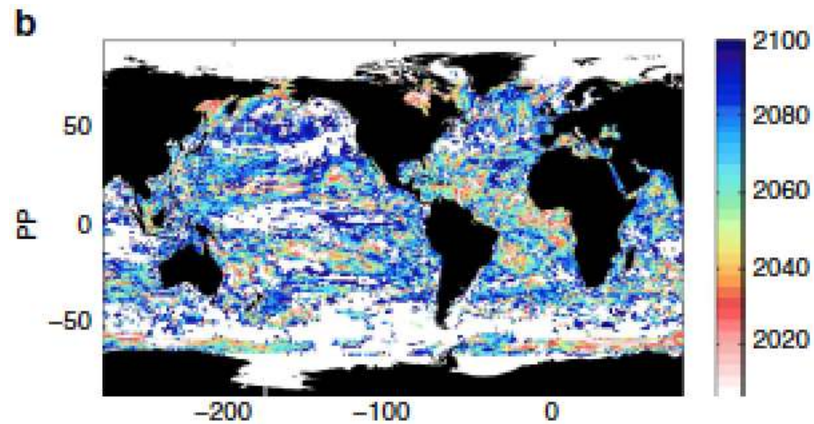
Ocean Acidification:



Ocean Deoxygenation:

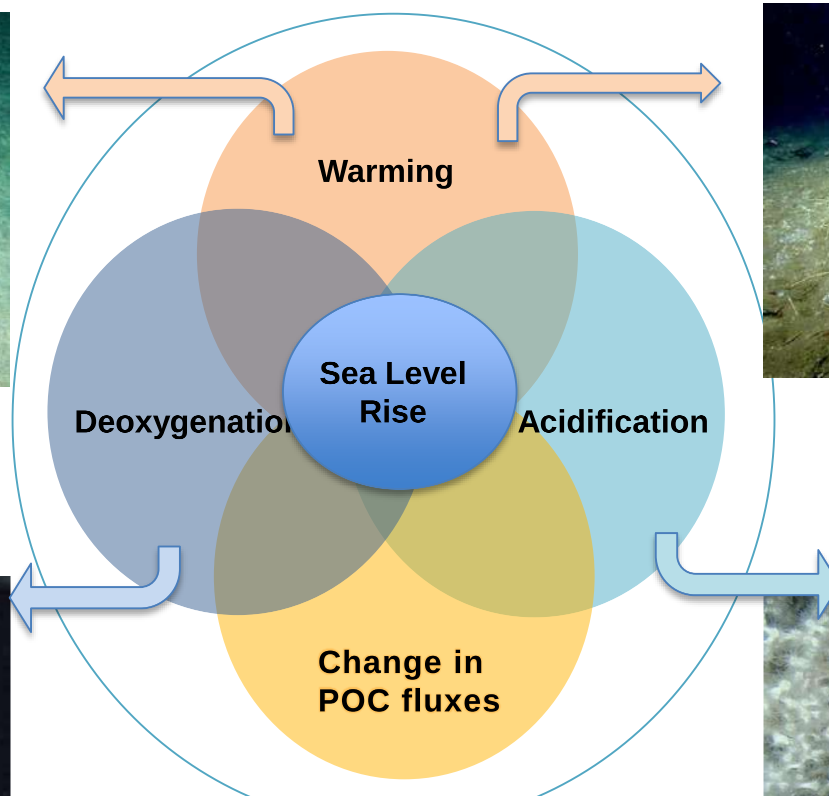


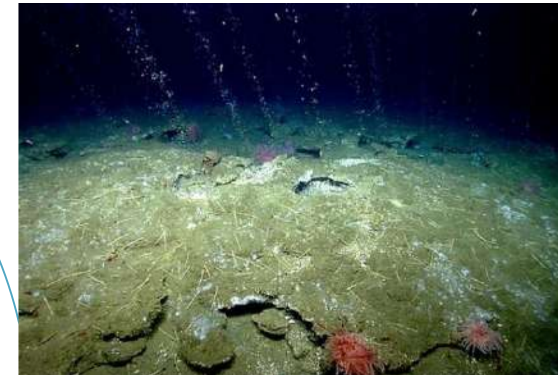
Primary Production

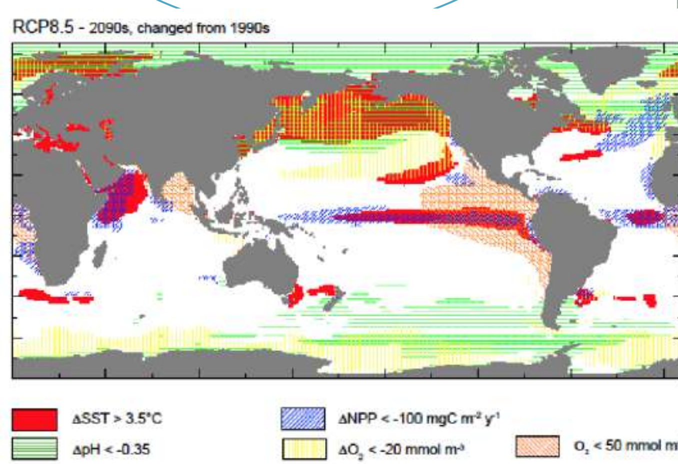


Henson et al. 2017

A Multi-Stressor Ocean





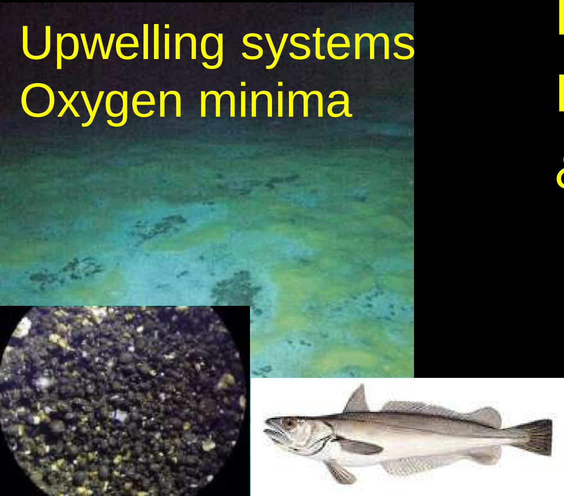


Levin & Le Bris 2015

Bopp et al. 2013

HETEROGENEITY BEGETS BIODIVERSITY & RESOURCES

Upwelling systems
Oxygen minima



Seamounts

carbon sequestration
nutrient cycling

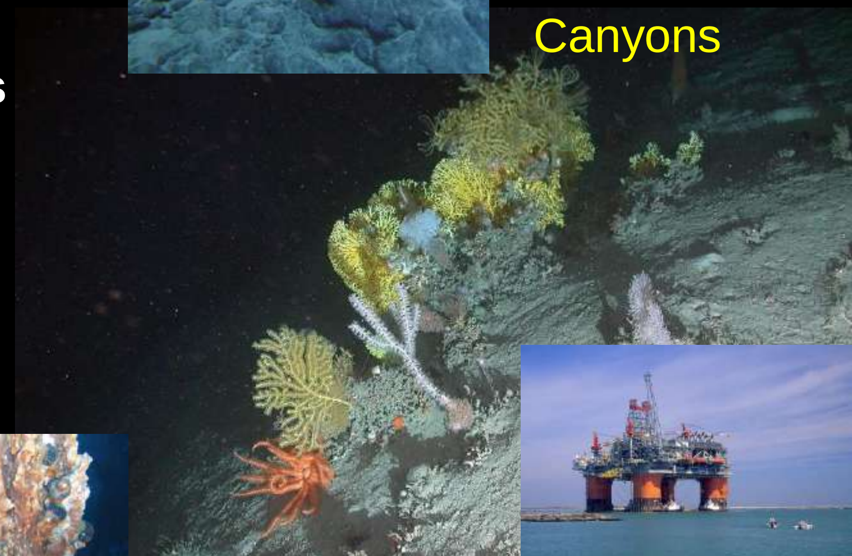
pharmaceuticals
industrial agents

genetic resources
biomaterials

habitat,
trophic support,
nursery grounds

Mn nodule Fields

Canyons

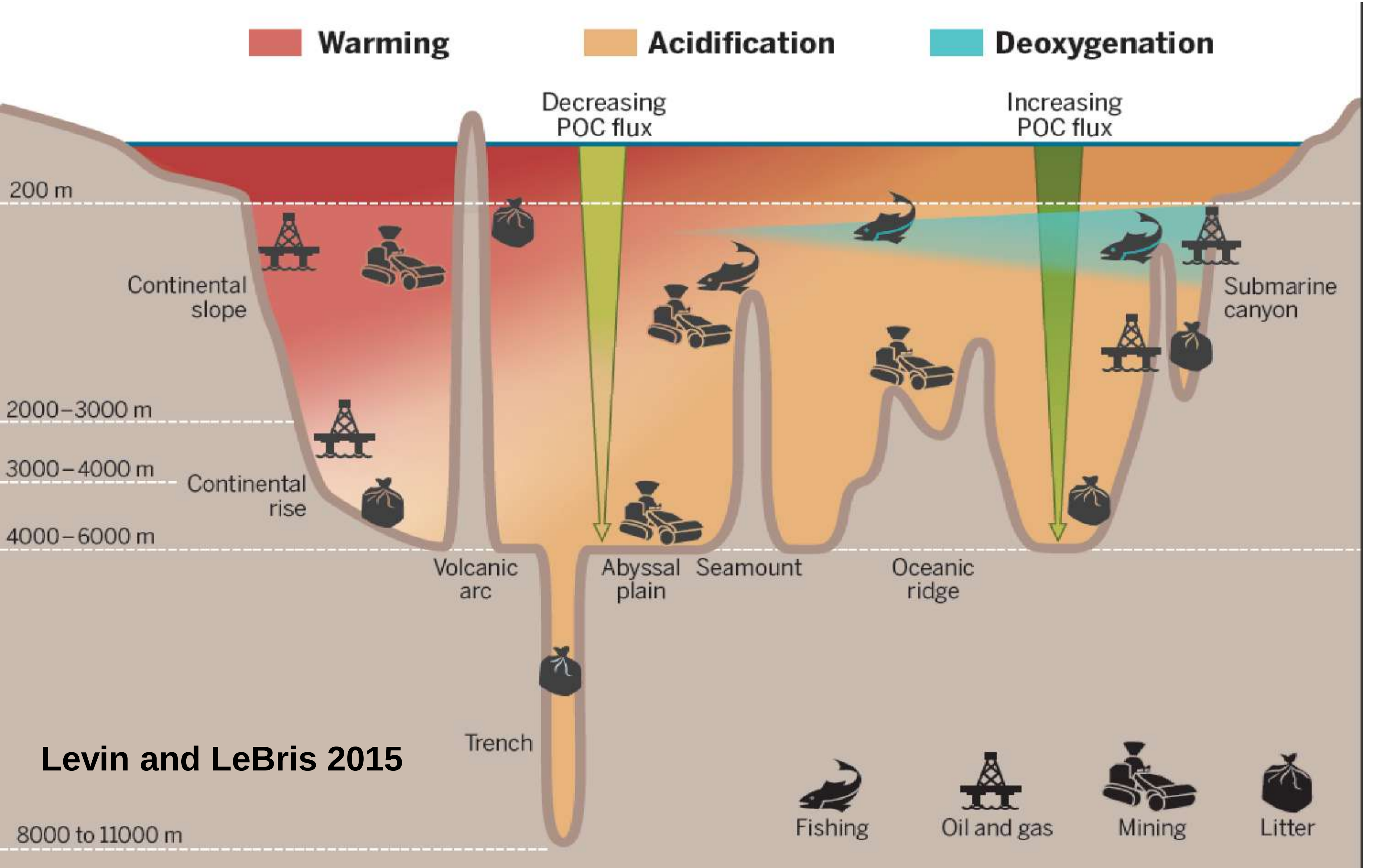


Methane Seeps

Hydrothermal Vents

Cold water coral & sponge reefs

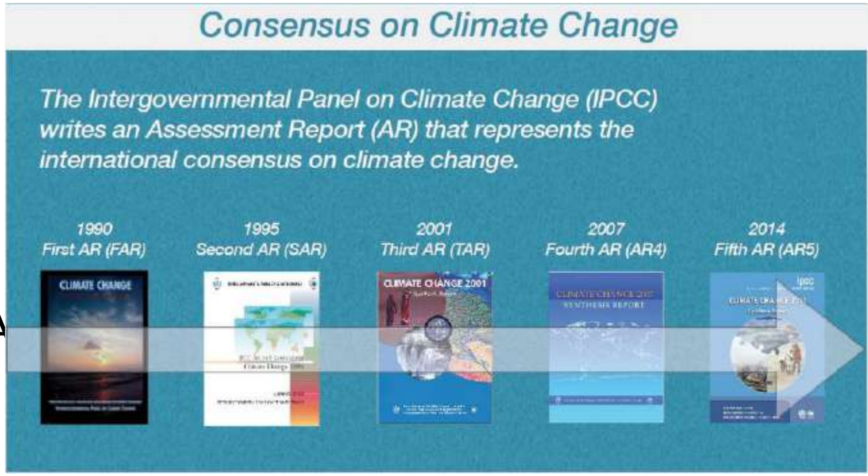
Climate change will interact with growing human disturbance to reduce resilience



Levin and LeBris 2015

Climate change in the ocean is a cumulative stressor that should be incorporated into policy and resource management

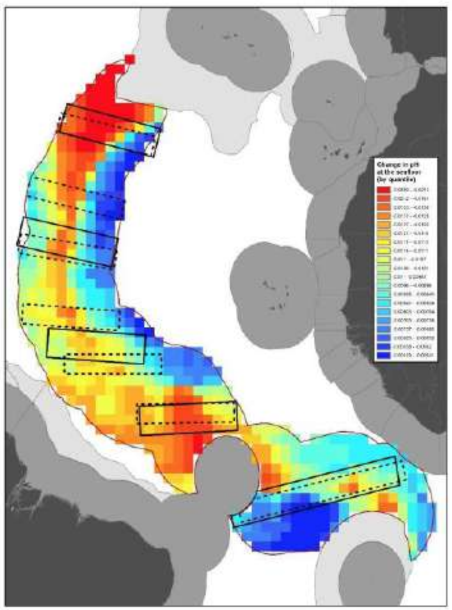
UNFCCC - IPCC



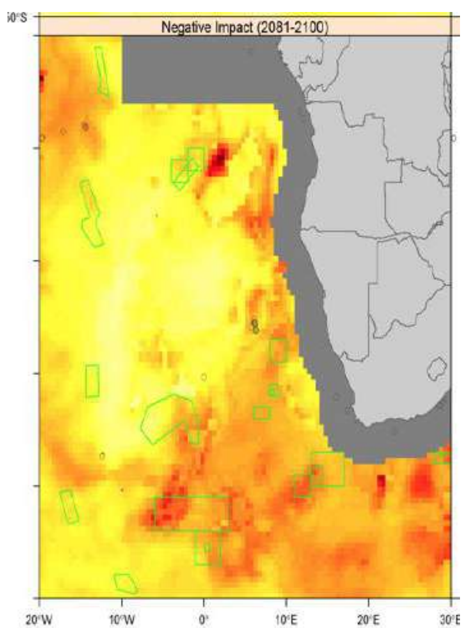
International Seabed Authority - APEIs

FAO/RFMO VMEs, Fishing Grounds

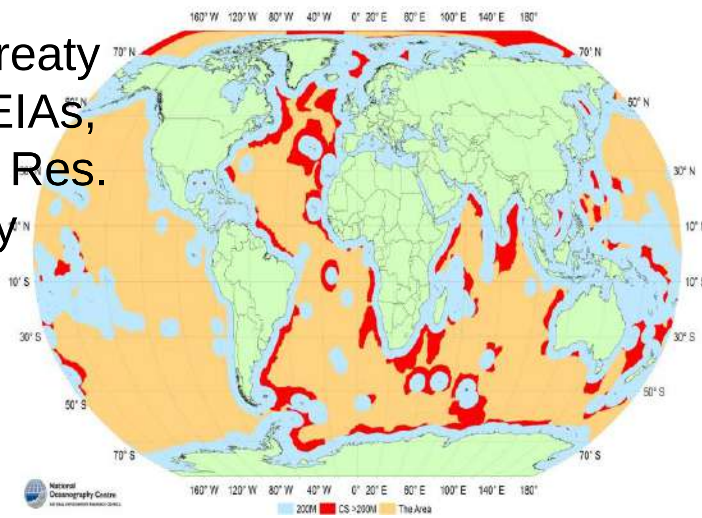
pH projection for 2100 On the Mid Atlantic Ridge



Projected exposure to Climate hazard in SEA



BBNJ Treaty
MPAs, EIAs,
Genetic Res.
Capacity
Building

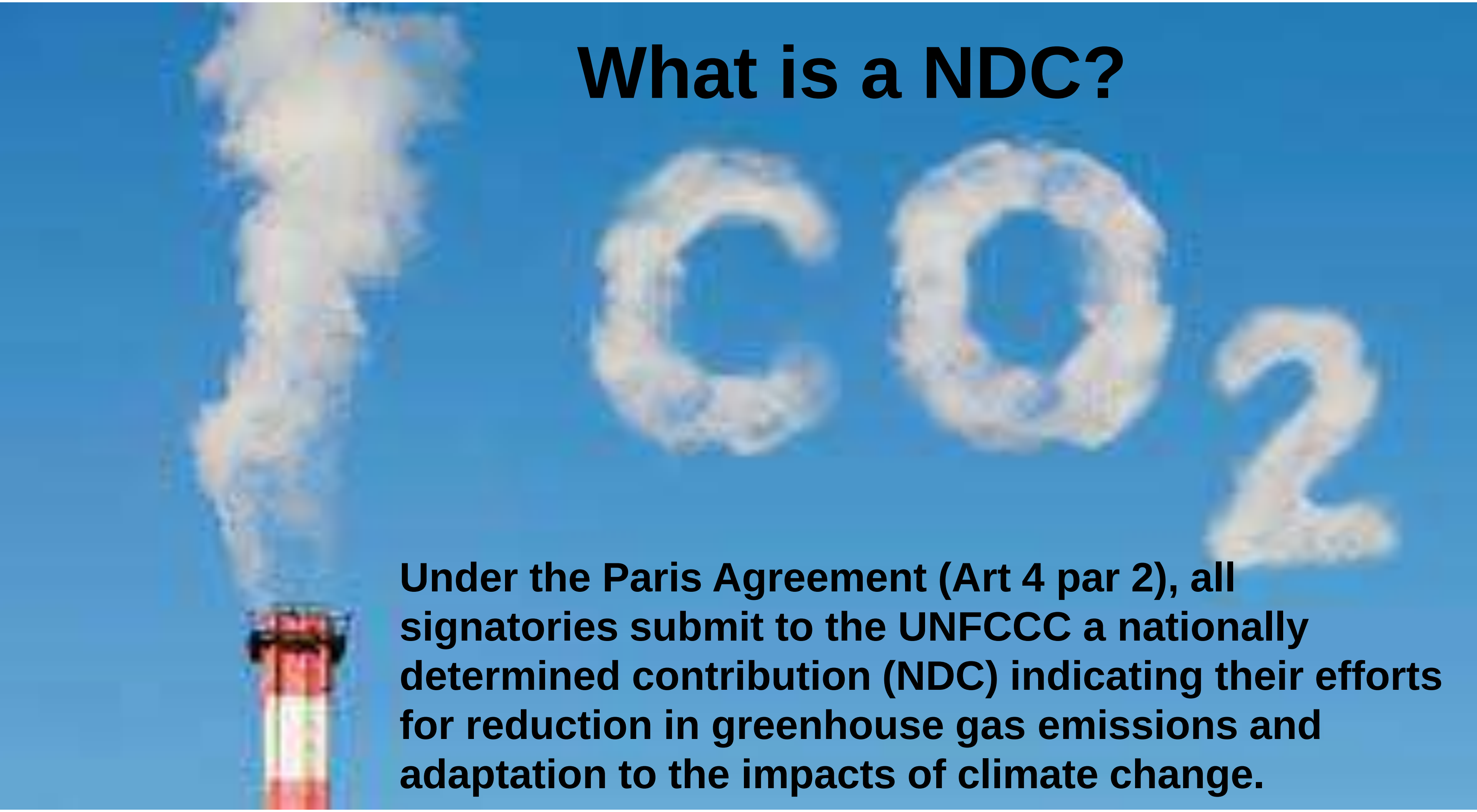


To What Extent are the Ocean Roles Recognized in International Climate Actions?

Nationally Determined Contributions (NDC)

Gallo, Victor, Levin, 2017; Nature Climate Change

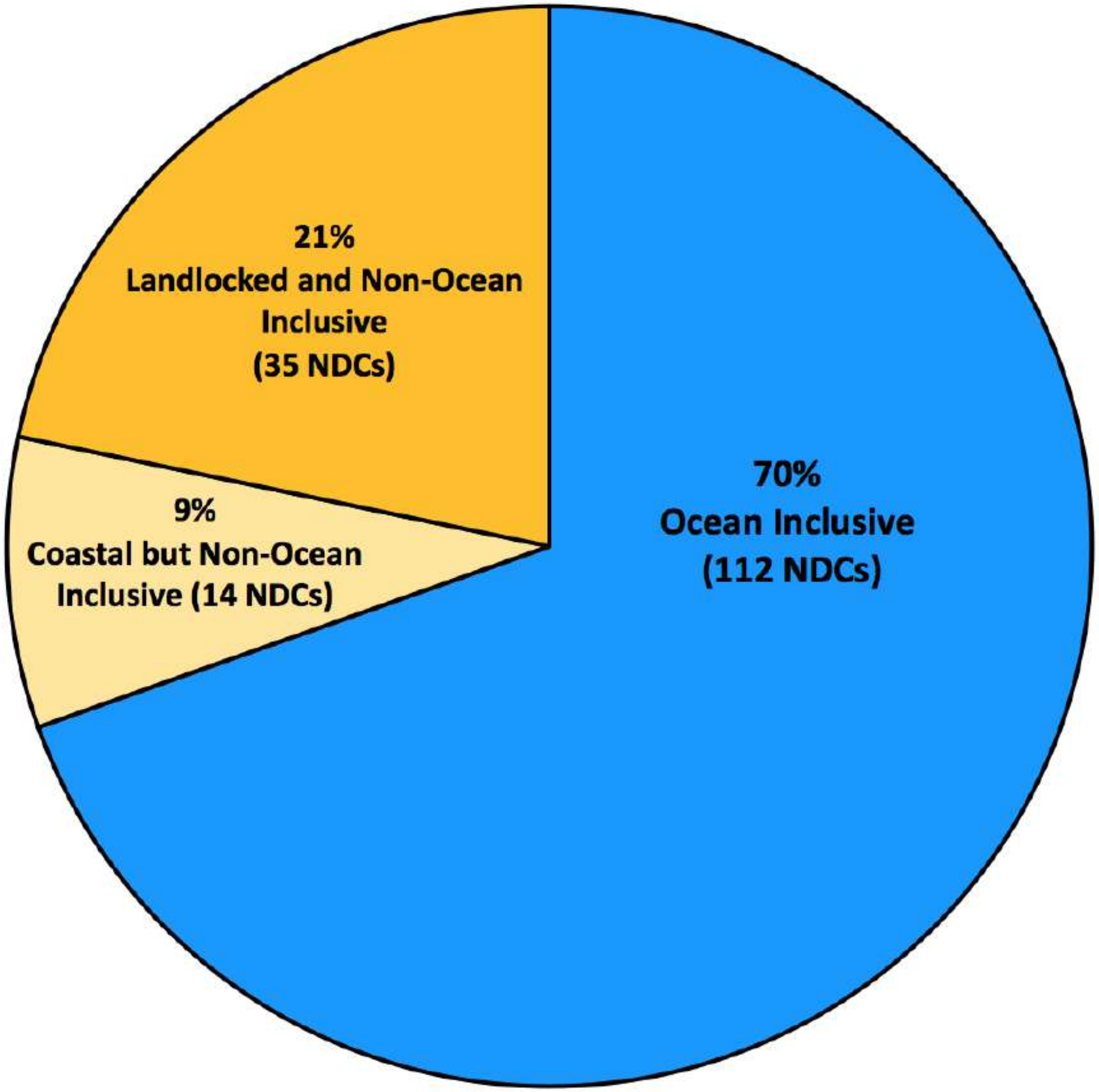
What is a NDC?



Under the Paris Agreement (Art 4 par 2), all signatories submit to the UNFCCC a nationally determined contribution (NDC) indicating their efforts for reduction in greenhouse gas emissions and adaptation to the impacts of climate change.

Nationally Determined Contributions reflect how countries think about climate problems and their priorities

70% of Nationally Determined Contributions include the ocean

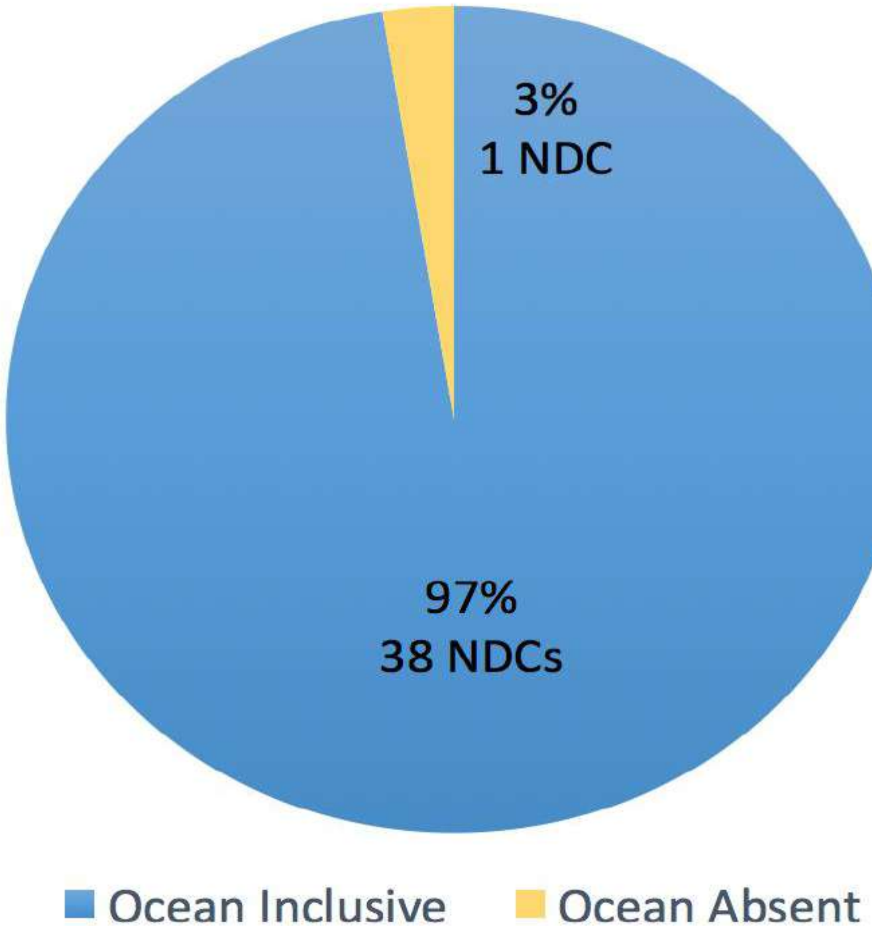


In the past marine issues were rarely raised at the international climate negotiations.

Ocean action can play an important role in meeting the goals of the Paris Agreement

Gallo et al. 2017
Nature Climate Change

All SIDS Countries with submitted NDCs -- Except Micronesia -- Included the Ocean

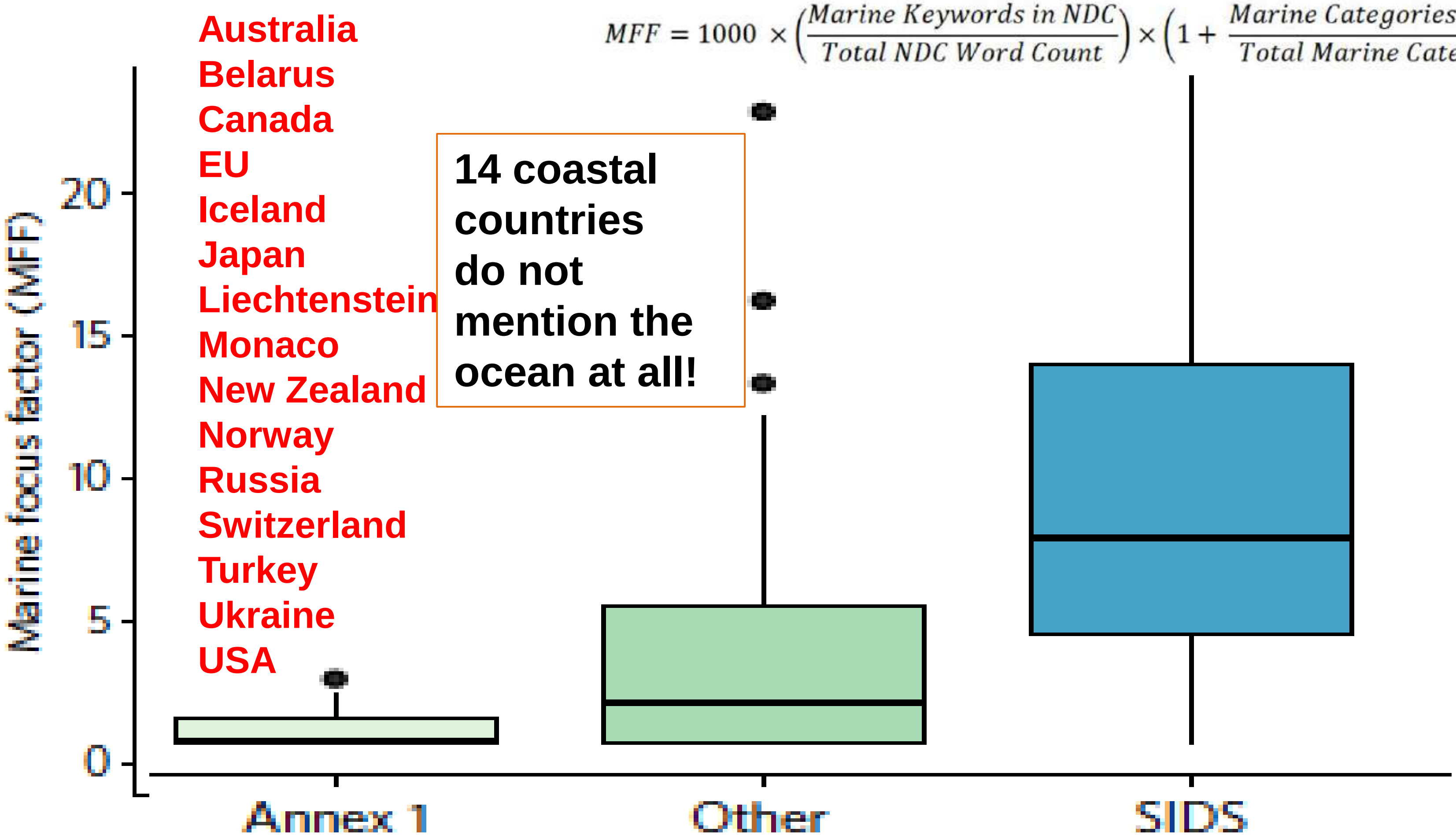


"Ocean" = coastal, marine, or oceanic

Who Recognizes the Critical Importance of the Ocean?

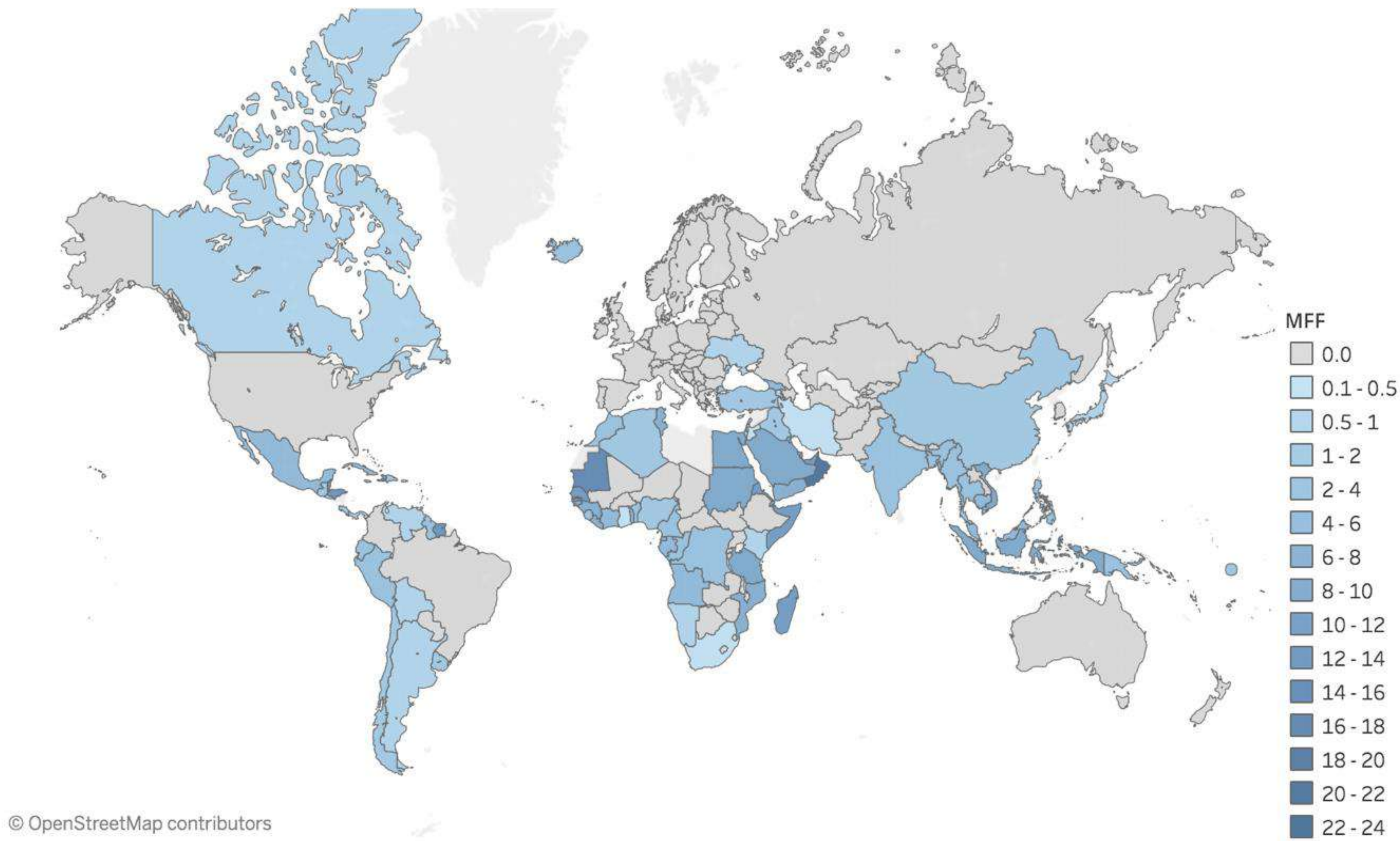
Annex 1 NDCs underrepresent the ocean while SIDS NDCs have a Marine Focus twice as high as other coastal countries

$$MFF = 1000 \times \left(\frac{Marine\ Keywords\ in\ NDC}{Total\ NDC\ Word\ Count}\right) \times \left(1 + \frac{Marine\ Categories\ in\ NDC}{Total\ Marine\ Categories}\right)$$



Gallo et al. Nature Climate Change 2017

Differences in Marine Focus within NDCs



Gallo et al. 201
Nature Climate Change

What factors influence marine focus?

38% of the Variance in MFF accounted for

POSITIVE:

- **% of Population in Low-Lying Areas** **(<5 m Above Sea Level)**
- **Small Island Developing State (SIDS**

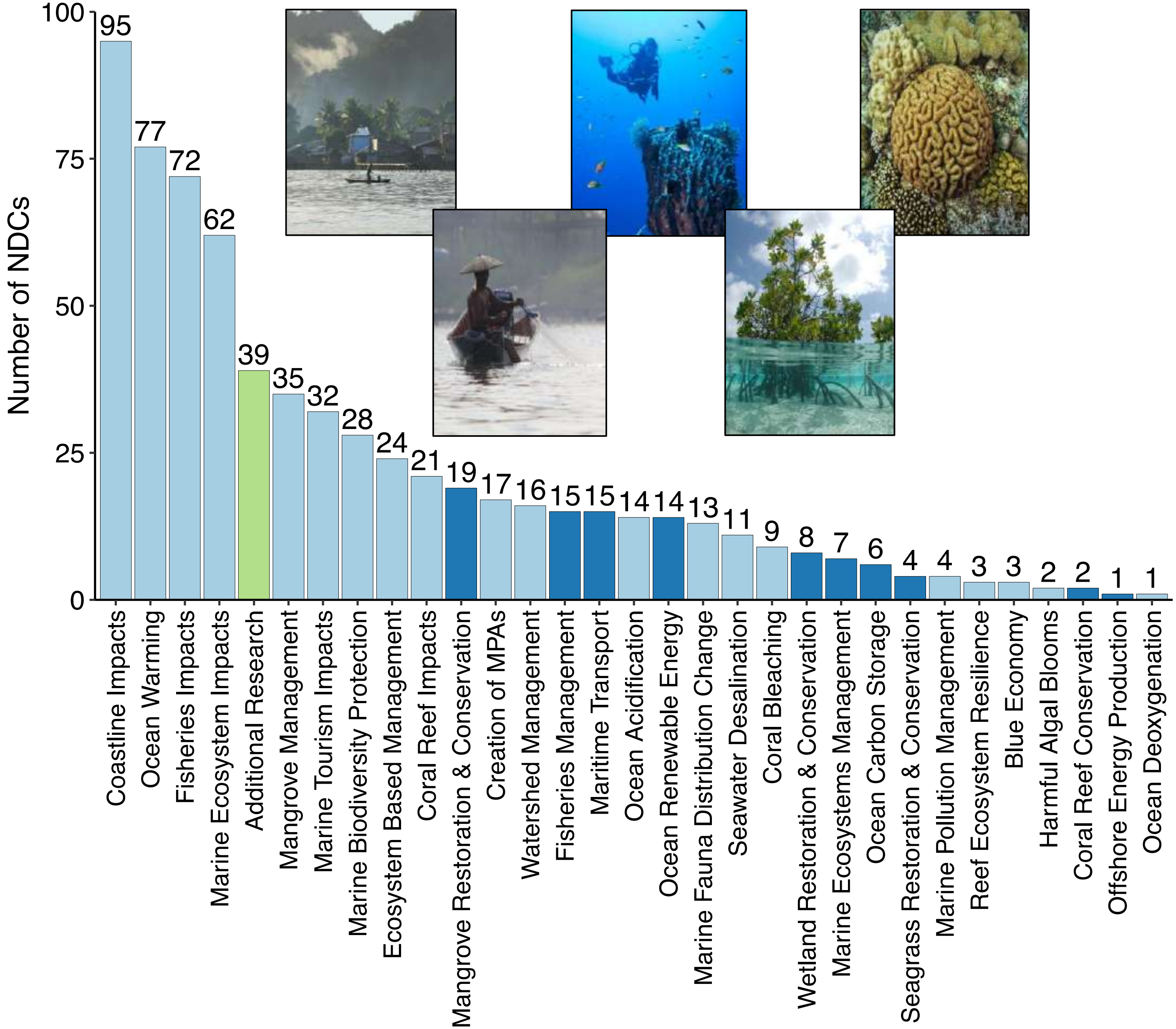
NEGATIVE:

- **EEZ:Land Area ratio**
- **Annex I party**

NO INFLUENCE:

- **Coastline Length**
- **Value of domestic fisheries landing**
- **GDP**
- **Fisheries: GDP**
- **Ocean Health Index**

What marine issues emerge?



Dark Blue = Mitigation

Light Blue = Adaptation or Impacts

Green = Research Needs

Gallo et al. 2017 Nature Climate Change

Some marine topics or ecosystems were included by many countries; others were not

Ocean Warming	Angola, Antigua and Barbuda, Bahamas, Bahrain, Bangladesh, Barbados, Belize, Benin, Brunei Darussalam, Cabo Verde, Cambodia, Cameroon, China, Comoros, Congo, Costa Rica, Cuba, Democratic Republic of Congo, Djibouti, Dominica, Egypt, El Salvador, Eritrea, Equatorial Guinea, Fiji, Gambia, Georgia, Grenada, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iraq, Kiribati, Kuwait, Lebanon, Liberia, Madagascar, Malaysia, Maldives, Marshall Islands, Mauritania, Mauritius, Morocco, Mozambique, Myanmar, Nauru, Nigeria, Niue, Oman, Palau, Papau New Guinea, Qatar, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Sao Tome and Principe, Saudi Arabia, Senegal, Seychelles, Singapore, Solomon Islands, Somalia, South Africa, Sudan, Suriname, Tonga, Trinidad and Tobago, Tunisia, Tuvalu, United Republic of Tanzania, Vietnam, Yemen
Ocean Acidification	Antigua and Barbuda, Bangladesh, Comoros, Dominica, Eritrea, Iraq, Kiribati, Marshall Islands, Mauritania, Nauru, Niue, Palau, Seychelles, Tonga
Ocean Deoxygenation	Mauritania
Mangroves	Angola, Bahamas, Bahrain, Bangladesh, Benin, Brunei Darussalam, Cambodia, Cameroon, Congo, Côte d'Ivoire, Cuba, Djibouti, El Salvador, Fiji, Gabon, Grenada, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Kiribati, Liberia, Madagascar, Marshall Islands, Mauritius, Mexico, Myanmar, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Somalia, Sudan, Suriname, Thailand, United Republic of Tanzania, United Arab Emirates, Vietnam, Yemen
Coral Reefs	Barbados, Belize, Brunei Darussalam, Cuba, Djibouti, Dominica, Egypt, Eritrea, Grenada, Honduras, Iraq, Kiribati, Madagascar, Maldives, Mauritius, Mexico, Nauru, Niue, Palau, Papau New Guinea, Qatar, Saint Vincent and the Grenadines, Saudi Arabia, Solomon Islands, Somalia, Sudan, Tonga, Yemen
Blue Carbon	Angola, Antigua and Barbuda, Armenia, Bahamas, Bahrain, Bangladesh, Brunei Darussalam, China, Dominica, El Salvador, Guinea, Guyana, Haiti, Iceland, Kiribati, Madagascar, Marshall Islands, Mexico, Philippines, Saudi Arabia, Senegal, Seychelles, Solomon Islands, Suriname, Ukraine, United Arab Emirates, Vietnam

Gallo et al. 2017
Nature Climate Change

A Role for Scientists:
Ocean Research Needs in NDCs

Sea Level Rise and Coastal Zone Monitoring (12 countries):
Yemen, Guinea, Georgia, Cuba, Nauru, Lebanon, Sudan, Maldives, Malaysia, Tanzania

Fisheries (6 countries):
Mainstreaming climate change into fisheries management (Gambia, Tonga)
Climate smart fisheries (Liberia, Egypt, Peru, Senegal)

Blue carbon (3 countries):
Research on mangroves and seagrasses/ coral reef protections (Bahrain, Somalia and Singapore)

Climate Observation System (3 countries): Benin, Niue, Nauru

Oceanography and Climate (3 countries): Seychelles, Guinea-Bissau, Antigua and Barbuda

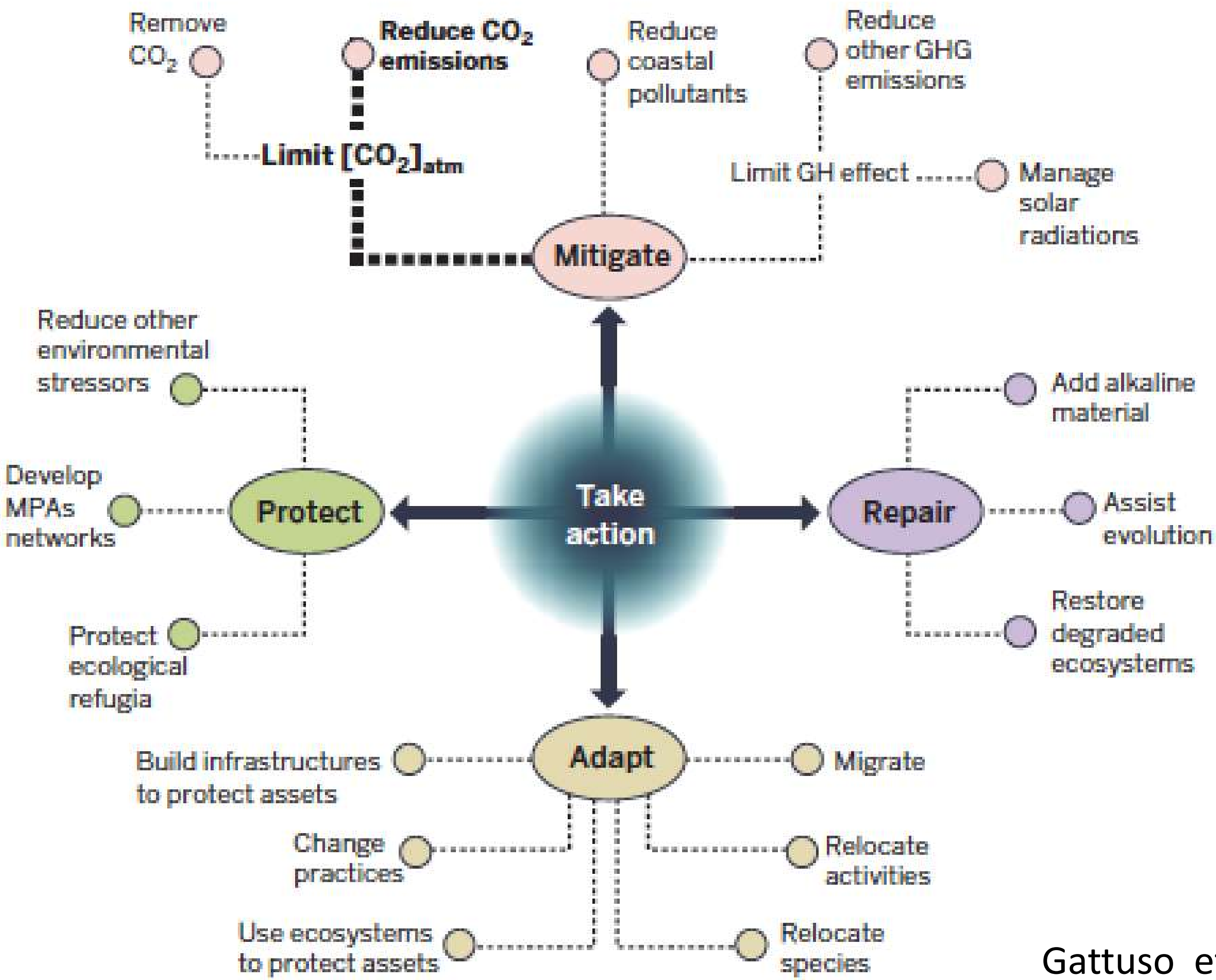
Biodiversity Research (2 countries): Vanuatu and Senegal

Ocean training and capacity building/ academic collaborations (3 countries): Brunei Darussalam, Gabo





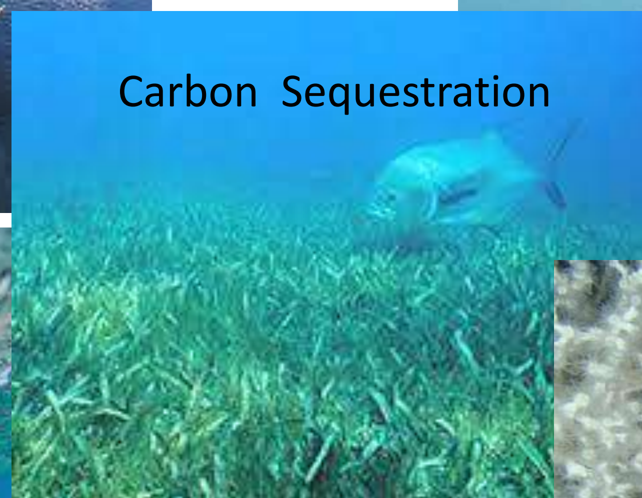

Opportunities and Solutions

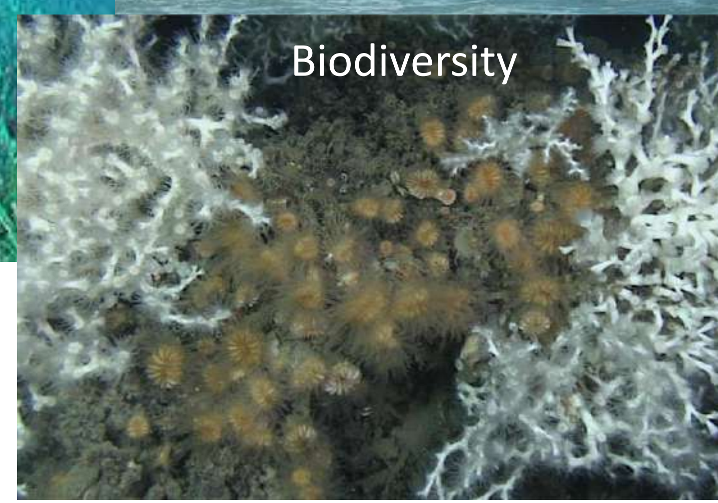


Gattuso et al. 2015

Enhance and Conserve our Multi-Protector Ecosystems:
Coral Reefs, Mangroves, Marshes & Seagrasses

Fisheries
Support





Recreation
and Livelihoods

To Take Home

- Rising greenhouse gas emissions are warming the planet.
- The ocean is the great mitigator, taking up heat and CO_2.
- This uptake is creating a warmer, less oxygenated and more acidic ocean, with rising sea level.
- Environmental changes are altering ecosystems
- We need to think creatively about addressing climate change through policy, management and science


Thank you
For
Listening!
Art by Lily Simonson