The Changing Ocean, Ecosystem Consequences and Solutions

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Rising CO₂

An New Trajectory
Carbon dioxide emissions are changing the climate – on land but also in the ocean.
CO₂ is not the only emission causing warming of the planet
A Warming Atmosphere

Northern Hemisphere Land Temperature Anomalies, January-December

The hottest year since 600s
Observed change in surface temperature 1901–2012
The ocean has absorbed >93% of the heat resulting from CO$_2$ emissions

(Gleckler et al. 2016)
THE OCEAN as CLIMATE MITIGATOR

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

Roemmich et al. 2015
• Species on the Move (towards the poles)
• Higher Metabolic Rates Exceeding Physiological Thresholds

Warming
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 > 1.4°C has allowed a Lithodid crab invasion in the Palmer Deep, Antarctica.

Neolithodes yaldwyni

**BIODIVERSITY CONSEQUENCES**

- < 850 m No crabs
- > 950 m With crabs

Warming-Induced Coral Bleaching

Caused by corals expelling symbiotic algae
In Feb 2018 – 20°C warmer than normal!
Warming causes:
Melting glaciers and ice sheets
Expansion of seawater
= Sea Level Rise
Storm Surge, Flooding

Coastal Squeeze

Regional MSL trends from Oct...
Ocean Deoxygenation

A warming ocean holds less oxygen

Warming raises oxygen thresholds for living organisms

A warmer ocean is more stratified

Enabling less ventilation

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

Rising Fe and N deposition in the N. Pacific

Enhanced Upwelling in Eastern Boundary currents

Helm et al. 2011 GRL

Ito et al. 2016

Sydeman et al. 2014
A warmer ocean may release more methane via dissociation of gas hydrates on margins

Methane release fuels microbial oxygen consumption (by aerobic methanotrophs)

See Boetius & Wenzhoffer 2013 Nature Geosciences
The ocean has lost 2% of its oxygen since the 1960s, but not uniformly. Much loss has occurred in the North Pacific at 150-700 m.
As a result, low oxygen areas are expanding.

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

At 200 m the hypoxic area (with $< 70 \mu$M 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

Oxygen loss of 0.67 μM/y 1956-2004

26.9 isopycnal

British Columbia

Oxygen (mol L⁻¹)

1978-2010

Crawford and Pena 2013

Oregon

50 m 1960-2010

Pierce et al. 2012

So. Califoarnia Bight

1984-2012

Stn. 93.110 26.5 isopycnal

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

Dead zones are exacerbated by climate change.

Some numbers:

* > 500 coastal sites
* ~ several millions km³ where O₂ < 2 mg/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 & CO₂ tolerances
Ocean Deoxygenation alters ecosystems

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

Habitat Compression: Intolerant species become subject to overfishing or predation

Upward Migration of Midwater Taxa

Shoaling of Billfish
Some Species Cope with Ocean Deoxygenation

- Worms
- Jellyfish
- Fish
- Bacteria
- Pink urchins
- Protozoa
- Humboldt Squid
Atmospheric Warming

Reduced Solubility

Increased Stratification = Reduced O₂ mixing

Ice melting

SEA LEVEL RISE

OCEAN ACIDIFICATION

OCEAN WARMING

OCEAN DEOXYGENATION

CLIMATE CHANGE
The ocean absorbs 26% of annual CO$_2$ emissions.

Slowing the greenhouse effect:

(without sinks) 500 ppm
(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.

Turley et al. (2006)

Image_ J. Zachos
Ocean Acidification in the Upper Ocean

Coral Reefs

Pelagic Systems

Shellfish Aquaculture
Ocean Acidification is Occurring in the Deep Ocean!
Thermohaline circulation is transporting CO$_2$ downward, causing acidification of deep waters

$\Omega_{\text{arag}} = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{\text{sp}}}$

Norwegian corals
Pacific corals
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

Deoxygenation
Acidification
Warming
Sea Level Rise
Change in POC fluxes

Levin & Le Bris 2015
Bopp et al. 2013
HETEROGENEITY BEGETS BIODIVERSITY & RESOURCES

carbon sequestration
nutrient cycling

pharmaceuticals
industrial agents

Mn nodule Fields

Hydrothermal Vents

Seamounts

Canyons

Upwelling systems
Oxygen minima

Methane Seeps

Cold water coral & sponge reefs

habitat,
trophic support,
nursery grounds

genetic resources
biomaterials
Climate change will interact with growing human disturbance to reduce resilience.
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
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.

14 coastal countries do not mention the ocean at all!

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?

Gallo et al. 2017
Nature Climate Change
Some marine topics or ecosystems were included by many countries; others were not

<table>
<thead>
<tr>
<th>Topic</th>
<th>Countries/Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean Warming</td>
<td>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</td>
</tr>
<tr>
<td>Ocean Acidification</td>
<td>Antigua and Barbuda, Bangladesh, Comoros, Dominica, Eritrea, Iraq, Kiribati, Marshall Islands, Mauritania, Nauru, Niue, Palau, Seychelles, Tonga</td>
</tr>
<tr>
<td>Ocean Deoxygenation</td>
<td>Mauritania</td>
</tr>
<tr>
<td>Mangroves</td>
<td>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</td>
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<tr>
<td>Coral Reefs</td>
<td>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</td>
</tr>
<tr>
<td>Blue Carbon</td>
<td>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</td>
</tr>
</tbody>
</table>

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

- Fisheries Support
- Storm Buffering
- Carbon Sequestration
- Biodiversity
- 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