Ocean Acidification & Rising Ocean Temperatures

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https://www.rnrf.org/2018cong/
Recent U.S. & International Scientific Assessments

Climate Science Special Report
Fourth National Climate Assessment (NCA4), Volume I
This report is an authoritative assessment of the science of climate change, with a focus on the United States. It represents the first of two volumes of the Fourth National Climate Assessment, mandated by the Global Change Research Act of 1990.

https://science2017.globalchange.gov/

Second State of the Carbon Cycle Report (SOCCR2)
SOCR2 is an authoritative decadal assessment of carbon cycle science across North America, developed by over 200 experts from the U.S., Canadian and Mexican governments, national laboratories, universities, private sector, and research institutions.
SOCR2 is a Sustained Assessment Product of the U.S. Global Change Research Program.

https://carbon2018.globalchange.gov/

Fourth National Climate Assessment (NCA4), Volume II: Impacts, Risks, and Adaptation in the United States
The National Climate Assessment (NCA) assesses the science of climate change and variability and its impacts across the United States, now and throughout this century.

https://nca2018.globalchange.gov/

GLOBAL WARMING OF 1.5 °C
an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

https://www.ipcc.ch/report/sr15/
Human Perturbation to Global Carbon Cycle

Global Carbon Project: Le Quéré et al. Earth System Science Data 2018

Fossil-fuel emissions
Billion tons C/yr (GtC)

Global

Cumulative changes 1870–2017

- Fossil fuels and industry
- Land-use change
- Ocean
- Land
- Atmosphere

Ocean carbon uptake ~40% of human emissions
Rising Atmospheric CO₂ & Ocean Warming

Atmospheric CO₂ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

Pre-industrial atmosphere CO₂

Temperature Anomalies over Land and over Ocean

https://data.giss.nasa.gov/gistemp

https://www.esrl.noaa.gov/gmd/ccgg/trends/
Ocean Climate Change Signals

Climate Science Special Report 2017
Climate Thresholds

Schellnhuber et al. Nature Climate Change 2016

The diagram illustrates tipping elements possibly switched within the Paris range. It shows the temperature anomaly (°C) over time, from -20,000 years ago to the present day, and projecting to 2050. The Paris range is highlighted, indicating key climate thresholds such as WAIS, Greenland, Arctic summer sea ice, Alpine glaciers, Coral reefs, Amazon rainforest, Boreal forest, THC, Sahel, ENSO, EAIS, Permafrost, and Arctic winter sea ice. The RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios are also depicted, showing different climate trajectories.
Total greenhouse gas emissions CO2 + CH4+N2O+CFCs (GtCO2-equivalent/yr)

- **Emissions Reductions to Meet Climate Goals**

**Paris Agreement & Nationally Determined Contributions (NDC)**

- **No policy baseline**
- **Current policy scenario**
- **Unconditional NDC scenario**
- **Conditional NDC scenario**

**2°C range**
- Turquoise area shows pathways limiting global temperature increase to below 2°C by 2100 with about 66% chance

**1.5°C range**
- Green area shows pathways limiting global temperature increase to below 1.5°C by 2100 with about 66% chance

- **Remaining gap to stay within 2°C limit**
  - Medan estimate of level consistent with 2°C: 40 GtCO2e (range 38-45)

- **Remaining gap to stay within 1.5°C limit**
  - Medan estimate of level consistent with 1.5°C: 24 GtCO2e (range 22-30)

- **UNEP Emissions Gap Report 2018**
Surface Warming & Primary Productivity

DSS

Global Sea Surface Warming (°C)

ΔNPP

Global Net Primary Productivity Change (%)

RCP 4.5 (10)
RCP 4.5 (9)
RCP 6.0 (5)
RCP 8.5 (10)

Ensemble of CMIP5 Models
Bopp et al. Biogeosciences 2013
Surface Acidification & Subsurface Deoxygenation

Ensemble of CMIP5 Models

Bopp et al. Biogeosciences 2013
Ocean Warming & Poleward Shifts in Species Distributions

Sea Surface Temperature; Northeast Continental Shelf

Pershing et al. NCA4 2018


Poleward shifts for many species from climate (& fishing pressure)

Walsh et al. PLoS ONE 2015
Geographic Shifts in Distributions & Abundances

Poleward shifts in species distributions

Regional trends in abundance
- physiology
- phenology
- predator-prey mismatch
- disease

Pershing et al.
NCA4 2018
Fishing Fleet Responses to Distribution Shifts

Adaptation strategies: catch diversity & high mobility may buffer fishing communities from effects of environmental change

Young et al. ICES Journal of Marine Science 2018
Exposure & sensitivity of species abundance, productivity & range to climate & acidification

Hare et al. PLoS One 2016
Projected Future Effects

Thermal habitat range shifts

RCP 2.6
RCP 8.5

Low uncertainty
High uncertainty

Pershing et al. 2018

Projected changes in fishery catch potential 2041–2060 relative to 1991–2010 under a higher scenario (RCP8.5)

Morley et al. PLoS ONE 2018

Pershing et al. 2018 4th National Climate Assessment
Range extension of oyster disease outbreaks

Climate may influence HAB composition & frequency

Burge et al.
Annual Review
Marine Science
2014

Coral Bleaching

Global extent of mass bleaching of corals in 2015 and 2016

severe >30%
moderate <30%
minimal

Hughes et al. Science 2018
Ocean & Coastal Oxygen Loss

- Coastal nutrient eutrophication & hypoxia exacerbated by warming & stratification

- Warming (solubility), biological consumption & reduced ventilation

Schmidtko et al. Nature 2017

Breitburg et al. Science 2018

Kelly et al. Science 2011
Rising Atmospheric Carbon Dioxide (CO₂) & Ocean Acidification

Ocean uptake of CO₂ causes:
- elevated CO₂ & inorganic carbon used by plants & phytoplankton
- acidification (lower pH)
- reduced carbonate ion used to build shells & corals

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}^+ + \text{HCO}_3^- \\
\text{H}^+ + \text{CO}_3^{2-} \rightarrow \text{HCO}_3^- 
\]

See also Fennel et al. 2018
2nd State of the Carbon Cycle Report
**Acidification Biological Impacts**

Negative impacts of CO$_2$ on mollusks

**Present**

- ~390 ppm CO$_2$
- Calcification: Positive effect
- Growth: Positive effect

**Future (estuaries)**

- ~750 ppm CO$_2$
- Calcification: Positive effect
- Growth: Positive effect
- ~1500 ppm CO$_2$
- Calcification: Positive effect

**Calcifiers**
- Calc. algae
- Coral
- Cocco.
- Mollusk
- Echino.
- Crustacean

**Non-Calcifiers**
- Fish
- Fleshy algae
- Seagrass
- Diatom

Kroeker et al. Global Change Biology 2013

Talmage et al. PNAS 2010
US Northeast Fisheries (Landings Value)

Gledhill et al. Oceanography 2015
Cooley & Doney
Environ. Res. Letters 2009
U.S. Northeast Scallop Fishery

Integrated assessment model: biology, chemistry & socio-economics

- CO₂ & Climate
- Planktonic larvae
- Reproduction & Recruitment
- Adult Mortality
- Harvest
- Demand & Fuel Costs
- Management


Sensitivity to acidification & warming

Sensitivity to management
Food-Web Dynamics

Busch et al.
ICES Journal of Marine Science
2013

Marshall et al.
Global Change Biology
2017
Arctic Climate Change & Acidification

Mathis et al. Oceanography 2015

Sea-ice extent
Sept. 2018

nsidc.org/arcticseaice/
Alaskan Integrated Risk from Ocean Acidification

Mathis, Cooley et al.
Prog. Oceanogr. 2015
Ecosystem Services & Public Goods

- Food provision
  - Fisheries
  - Mariculture
- Artisanal fishing opportunity
- Natural products
- Carbon storage
- Coastal protection
- Tourism and recreation
- Coastal livelihoods and economies
  - Livelihoods
  - Economies
- Sense of place
  - Iconic species
  - Lasting special places
- Clean waters
- Biodiversity
  - Habitats
  - Species

Ocean Health Index
Halpern et al. Nature 2012
Coastal and marine organisms

Ecosystem services and sectors

Marine Ecosystem Thresholds

Hoegh-Guldberg et al.
IPCC 1.5 °C Special Report
NMFS Climate Science Strategy

Climate Changes
- ↑ atmospheric CO₂
- ↑ temperature
- Δ precipitation
- Δ wind patterns

Physical/Chemical Changes
- ↑ ocean temperature
- ↑ stratification
- Δ circulation
- ↓ sea ice
- ↑ incidence of hypoxia
- Δ freshwater input
- ↑ sea level
- ↑ ocean acidification

Biological Impacts
- Δ productivity
- Δ phenology & survivorship
- Δ species distribution
- Δ species abundance
- Δ community composition
- ↑ disease impacts
- ↑ invasive species impacts
- Δ food web structure
- ↓ biodiversity & resilience

Social Economic Impacts
- Δ fishing and other ocean activities (what, where, when)
- Δ revenues & economics
- Δ industries
- Δ subsistence use
- Δ community health & vulnerability
- ↑ human risks

International Impacts
- Δ transboundary species
- Δ migratory species
- Δ international agreements
- Δ partnerships
- Δ transportation patterns and risk
- Δ security & response requirements

Mitigation Efforts
- Actions to ↓ emissions, ↑ sequestration

Adaptation Efforts
- Actions to ↓ stressors, ↑ resilience, seek beneficial outcomes
Applying Principled Flexibility to Resource Management

Strategies
- Continuous monitoring
- Fully embrace precautionary principle – instead of MSY use “clearly sustainable”
- Minimize multiple stressors
- Incentivize adaptation and commit to adaptive management
- Preserve ecosystem connectivity
- Increase long term planning and coordination across governments and jurisdictions
- Enable management goals to reflect changing baselines

Processes
- Science based decision making
- Ecosystem based management
- Marine planning
- Assessing ecosystem services

Whit Saumweber
Center for Strategic and International Studies

NOAA Fisheries Climate Vulnerability Assessment
Extra Slides
Attribution & Detection of Human Climate Impacts

Climate Science Special Report 2017
Perturbations can alter response of complex social-ecological systems

Resilient systems:
- diversity
- connectivity
- adaptive capacity

Ecological Resilience, Adaptation & System Evolution

Stability landscape
Multiple stable states
Disturbance

Transboundary Stock Shifts

# of transboundary species by Exclusive Economic Zones (EEZs)
RCP8.5; 2100 relative to 1950-2014

# of EEZs with transboundary species relative to atmospheric temperature change

Pinsky et al. Science 2018
Ocean Climate Extreme Events

The diagram illustrates the increase in the probability of occurrence of extreme weather events as the climate changes from previous to new conditions. The graph shows a shift from Cold Weather to Hot Weather, indicating a decrease in the probability of colder events and an increase in hotter events.

The map highlights specific locations where extreme events have occurred:
- **2016**: Pacific Cod
- **2014**: Dungeness Crab
- **2015**: Humpback Whale
- **2012**: Sea Lion

Additional notes:
- Coral in Northern Mariana Islands and Guam
- American Lobster and Longfin Squid
- Florida Keys and Puerto Rico
- American Samoa and Republic of the Marshall Islands

The map uses colors to denote different regions affected by these extreme events, providing a visual representation of the geographic impact.
Ocean Anthropogenic CO$_2$

Gruber et al.
Global Biogeochemical Cycles
2009

Khatiwala et al.
Biogeosciences 2013
CO$_2$ & Carbon-Climate Feedbacks

- **No climate feedbacks**
- **With climate feedbacks**

Climate reduces effectiveness of land and ocean carbon sinks
Results in lower compatible fossil fuel emissions

**Climate Sensitivity**
\[
\Delta T = \alpha \Delta CO_2^{atm} \quad (K/ppm)
\]

Linear decomposition of cumulative ocean carbon inventory
\[
\Delta C = \beta \Delta CO_2^{atm} + \gamma \Delta T \\ (\beta \text{PgC/ppm}; \gamma \text{Pg C/K})
\]
Benthic Warming & Lobsters


Observed benthic Temperature

RCP8.5 \Delta Days > 20 \degree C

Upper thermal habitat limit

Days > 20 \degree C

Statistical downscaling from CMIP5 RCP8.5 models

Kavanaugh et al.
JGR Oceans 2017

Rheuban et al.
JGR Oceans 2017
Ocean Warming, Acidification & Deoxygenation

Doney Science 2010
Global & Regional Patterns of Ocean Warming

Temperature Anomalies over Land and over Ocean

Annual J-D 2017

L-OTI(°C) Anomaly vs 1951-1980

NASA GISS

https://data.giss.nasa.gov/gistemp
Arctic Sea Ice Extent (Area of ocean with at least 15% sea ice)

Sea Ice Extent, Sep 2018

Total extent = 4.7 million sq km