The Impacts of Climate Extremes on Ocean Ecosystems

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Acknowledgments

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The Impacts of Climate Extremes on Ocean Ecosystems

1. Climate extremes
2. Climate extremes in the marine environment
3. How climate extremes affect marine ecosystems
4. How we use high performance computing to understand and plan for climate impacts on marine ecosystems
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1. Climate extremes
   - Temperature
   - Precipitation
   - Droughts
   - Floods
   - Storms
The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable*

For simplicity, both extreme weather events and extreme climate events are referred to collectively as ‘climate extremes.’

Climate extremes can be defined quantitatively in two ways:
1. Related to a specific (possibly impact-related) threshold
2. Related to their probability of occurrence

*Field et al. 2012 Special IPCC Report on Extremes
Climate Extremes

**Absolute threshold:** usually in reference to a particular place

**Relative threshold:** < 10, 5, 1%, or even lower chance of occurrence for a given time of the year (day, month, season, whole year) during a specified reference period (generally 1961-1990) are often used

**Accumulation:** e.g. droughts and floods - the accumulation itself is the extreme.

**Compound:** two or more events occurring simultaneously, can lead to high impacts, even if the two single events are not extreme per se
Climate Extremes

*Field et al. 2012 Special IPCC Report on Extremes*
Climate Extremes on Land

Slide courtesy of Kevin Trenberth
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1. Climate extremes

2. Climate extremes in the marine environment
   – Temperature
   – Storms
   – Wave climate
   – Ocean acidification
   – Dust aerosols
   – Salinity, circulation patterns, etc.
Climate Extremes in the Ocean

Ocean Temperature

Ocean acidification

\[ \text{CO}_2 \]

\[ \text{CO}_2^{aq} \quad (\text{CO}_2 + \text{H}_2\text{O}) \]

\[ \text{H}_2\text{CO}_3 \]

\[ \text{HCO}_3^- + \text{H}^+ \]

\[ \text{CO}_3^{2-} + \text{H}^+ \]

Tropical storms

Wave climate
Thermal Stress

Degree Heating Week (DHW)

- Cumulative thermal stress over a rolling 12-week period for a given location
- Accumulation of excess heat when SST ≥ 1°C of climatological maximum SST

<table>
<thead>
<tr>
<th>°C above max</th>
<th>DHW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>1.0</td>
</tr>
<tr>
<td>Week 2</td>
<td>2.0</td>
</tr>
<tr>
<td>Week 3</td>
<td>0.8</td>
</tr>
<tr>
<td>Week 4</td>
<td>1.2</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Week 12</td>
<td>0.0</td>
</tr>
</tbody>
</table>
% of Reefs That Have Experienced Severe Bleaching

- 41%
- 22%
- 11%
- 38%
- 10%
- 7%
- 39%
- 23%
- 15%
- 7%
- 10%
- 11%
- 38%
- 41%
- 22%
Heat Stress – Degree Heating Weeks

DHW – 12 weeks ending on 09/09/2013

http://www.ospo.noaa.gov/Products/ocean/cb/dhw/index.html
Increases in storm frequency
Increases in storm frequency

2005 Composite:
Dennis, Emily, Katrina, Rita and Wilma

Tropical storms often damage shallow-water ecosystems.

Occasional disturbance tends to promote biodiversity, but when disturbances are too frequent, ecosystems can’t recover.
Wave Climate
Wave Climate

Grigg 1998 Coral Reefs
Significant Wave Height

Heller et al. 2013 Nature Climate Change
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1. Climate extremes
2. Climate extremes in the marine environment
3. How climate extremes affect marine ecosystems
   – Temperature: Coral bleaching events
   – Storm frequency: Kelp bed destruction
   – Wave climate: Ecosystem construction
   – Compound effects: Harmful algal blooms
   – Ocean acidification: Multiple impacts
   – Dust aerosols: Nutrients, toxins, pathogens
The stresses ecosystems feel

“Pulse” disturbance storms

“Press” disturbance PDO

“Ramp” disturbance acidification warming
Alternative Stable States

Bellwood et al. (2008) Nature
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Example: HPC to understand future impacts of climate on coral reefs
Coral bleaching has increased in frequency and severity since the mid 20th Century. During the 1997-1998 ENSO, ~30% of reefs worldwide experienced bleaching. Unless corals can adapt, bleaching frequency will exceed their capacity to recover by the middle of the 21st Century.

Coral bleaching in the Coral Triangle

Photos: Ray Berkelmans
Regional Ocean Model System
“Coral Triangle” Implementation

Horizontal res.: 1280 x 640
Vertical res.: 50 levels
Time step: 90 sec

Computational cost on Janus:
~ 40,000 SU/yr
- 1368 12-way compute nodes @ 134 Gflops/s

Data storage: 600 GB/yr (daily averages)
CT-ROMS 2004-2006

**Bathymetry:** global SRTM30_PLUS product with 30-sec resolution [Becker et al., 2009]

**Vertical resolution:** 50 terrain-following levels

**Atmospheric forcing:** Modern Era-Retrospective Analysis for Research and Applications (MERRA, Rienecker et al., 2011)

**Boundaries and initial conditions:** Simple Ocean Data Assimilation (SODA, Carton et al., 2000)

**Tidal boundary conditions:** global model of ocean tides TPXO 7.2 (Egbert and Erofeeva, 2002)

Castruccio et al. (in press) *JGR*
Sea surface temperature

Castruccio et al. (in press) *JGR*
Comparison of Degree-Heating-Weeks

ROMS

16 Jun 1998

20°N
10°N
0°
10°S
20°S
100°E 110°E 120°E 130°E 140°E 150°E 160°E

CoRTAD

16 Jun 1998

20°N
10°N
0°
10°S
20°S
100°E 110°E 120°E 130°E 140°E 150°E 160°E

29 Sep 1998

20°N
10°N
0°
10°S
20°S
100°E 110°E 120°E 130°E 140°E 150°E 160°E

29 Sep 1998

0
4
8
12
16

0
4
8
12
16
The Coral Triangle

Beyond Bleaching: “Connectivity” between reefs

Photos: Ray Berkelmans
Coral Spawning Events

Video: NOAA Flower Garden Banks

Photo: Bette Willis
Coral Life Cycle
Connectivity

Holding it all together

Recovery depends on how well “connected” coral communities are in terms of the transport of larvae from one reef to another.

If one reef gets hit, will it be reseeded with larvae from a healthy reef?
Connectivity

Realized connectivity

\[ a_{ij} = A_j' f'D_{ij}^t S_{ij}^t \]

- \( A_j' \) = area of adult corals at reef \( j \)
- \( f' \) = fecundity
- \( D_{ij}^t \) = potential connectivity between reef \( j \) and reef \( i \)
- \( S_{ij}^t \) = probability of larvae remaining in transit from reef \( j \) and reef \( i \)

\[ S_{ij}^t = e^{-M(\sigma)t - (1-s)R_{ij}} \]

- \( M \) = daily larval mortality rate as a function of temperature (\( \sigma \))
- \( t \) = dispersal time between reef \( i \) and \( j \)
- \( s \) = probability of settling on previous reefs
- \( R_{ij} \) = number of reefs encountered along the trajectory
Lagrangian Coherent Structures

Sep 14, 2004

[Map of oceanic currents with Lagrangian coherent structures marked in red and blue lines, showing the flow patterns in the area between 110°E to 140°E and 5°S to 5°N.]
Three Points

1. Climate extremes do affect the ocean
2. These extremes have significant impacts on ocean ecosystems
3. HPC is invaluable in designing ways to minimize those impacts
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THANK YOU
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