Fossil fuel $CO_2$ emissions:
- cause atmospheric & ocean warming
- cause ocean acidification
- can promote ocean hypoxia

Changes affect many marine organisms

Potentially large consequences for ocean ecosystems and society
Ocean heat content increasing with global temperature

Domingues et al. 2008 (Nature)
Animals distributions are changing with ocean warming

Monterey Bay rocky intertidal animals –
Warm water species increased, Cold water species declined

Southern Species Increased
Northern Species Declined

Barry et al. 1995, Sagarin et al. 1999
Ocean Warming is Causing Coral Bleaching and Death

Estimated loss of living coral colonies from reefs in 1997-1998 = 16% worldwide
Threshold temperature – above which bleaching manifests itself (1-2°C above the long-term summer maximum temperatures).

WHAT DOES THE FUTURE HOLD?

Hoegh-Guldberg (1999)
Hypoxic (low oxygen) waters are more common off Oregon.

Dissolved oxygen profiles during the upwelling season (mid-April to mid-October) in the upper 800 m of the continental shelf and slope of Oregon.
Oxygen levels in many ocean areas is declining (hypoxia)

Warmer surface waters inhibit mixing of oxygen to depth

Stramma et al. 2010
CO\textsubscript{2} emissions cause Ocean Acidification.
Fossil fuel CO$_2$ in the oceans (1994)

Anthropogenic CO$_2$ concentration (μmol kg$^{-1}$)

[Sabine et al. Science, 2004]
Ice Ages

Variation in CO₂ and ocean acidity (pH)

CO₂ on Earth

- CO₂ emissions rising
- Ocean becoming more acidic

Atmospheric, Ocean CO₂, & Ocean pH

CO₂ Time Series in the North Pacific Ocean

Doney et al. 2009

Global CO₂ Increase

Increase in Ocean Acidity due to added CO₂

Doney et al. 2009

Percent Change in Acidity
Ice Ages

Change in ocean pH over 25 million years

- Estimated from boron isotopes in seabed foraminifera
- Note speed and size of current pH change

Turley et al 2005
Options for organisms faced with warming, hypoxia, and ocean acidification?

- Migration
- Tolerance & Acclimation
- Adaptation (linked to evolutionary history, generation time)
- Extinction

What to do...?
Ocean change affects physiological function

- Photosynthesis
- Calcification *
- Respiration
- Acid - Base Balance
- Metabolism

Vampire Squid
Ocean change may be more difficult for deep-sea animals

Deep-Sea Animals

- Low metabolic rates
- Low enzyme function
- Evolved in highly stable deep-sea environment
- Food-limited – "Living on the edge"

Deep-sea Octopus
Stress increases the ‘cost of living’

Energy budgets - If the cost of living (e.g. shells) increases, less is available for growth and reproduction.
Ocean chemistry and the future of coral reefs?

Predicted aragonite saturation ($\Omega$) [a measure of the amount of minerals available to make coral skeletons] is shown over a global map of existing coral reef locations (pink dots) for various atmospheric CO2 levels. Note that $\Omega$ decreases drastically with higher CO2 levels.

280 ppm is the preindustrial level of CO2 in the atmosphere. During 2011 CO2 is ~390 ppm. Most climate models indicate that we will reach ~800 ppm CO2 by 2100.

Corals grow best when carbonate minerals are abundant ($\Omega > 3$), and cease to grow at low mineral levels ($\Omega \sim 2$) and can dissolve at very low levels ($\Omega < 1$).

On the right, there is a count of the mineral conditions for the locations of all global coral reefs. Note that the preindustrial climate (280 ppm CO2) all reef locations had mineral conditions favorable to growth (high $\Omega$).

As CO2 levels rise through this century, ALL existing reef are expected to have marginal or poor conditions for coral growth.
Low carbonate saturation associated with low calcification rate

Hoegh-Guldberg et al. 2007
Will Ocean Acidification disrupt energy flow through marine food webs?

Pteropod = Salmon food

Sockeye Salmon
Marine Communities are Biological Networks

Primary Production

Phytoplankton

Zooplankton

Large zooplankton

Squid

Seabirds

Humans

Fish

Mammals

Marine Food Web

Detritus / Bacteria

Seafloor Animals
A worrisome storyline

Rising atmospheric CO₂

Decreasing ocean pH, Ω, [CO₃²⁻]

Altered physiology, population changes

Changing benefits

Food web changes, ecosystem shifts

Socioeconomic consequences
Conclusions

What we know:
• Carbon dioxide emissions causing ocean change
• Warming, hypoxia, acidification
• Stressful for many organisms

What we expect:
• Food webs will be affected
• Ecosystem services (e.g. fisheries) will change

What we don’t know:
• Long term effects
• Sensitive life stages
• Acclimation and adaptation
• Multiple Stressors
• Ecosystem tipping points?
Perception of ocean health
It's blue, so it must be okay...?
Value the oceans
Mass extinctions during Earth history

- 5 major mass extinctions with >70% extinction of all species
- 10+ million years to recover (rediversify)
Ecosystem-based management of marine resources

Nutrient inputs:
- Industry
- Agriculture
- Animal farms
- Sewage treatment plants
- Development

Feeding
- Young of the year
- Eggs
- Ages 1 - 2 years
- Age 2 years and above

ian.umces.edu/press
Mass extinctions and ocean acidification: biological constraints on geological dilemmas

J. E. N. Veron


[Diagram showing geological time scale with key events and timeframes.]
Latitudinal range of carbonate (coral) reefs
No correlation with temperature, so $\Omega$ (ocean chemistry) is more important

For hundreds of millions of years, at the edge of their range, shallow-water reef-building calcifiers have been “trying” to compete ecologically in low-$\Omega$ conditions.

What is the probability that they will succeed in doing in the next decades what they have been unable to do for hundreds of millions of years?

Field Survey of Natural CO₂ Venting Sites in Italy

- Echinoderms conspicuously absent, shell dissolution
- Seagrasses thrive

Jason Hall-Spencer et al. 2008
Outside the vents – abundant calcifiers e.g. sea urchins
At high CO$_2$ there are almost no calcifiers, fleshy algae and invasive species dominate.

250 taxa now examined including macroalgae (Porzio in press, JEMBE), seagrasses, foraminifera, sponges, nematodes, polychaetes, molluscs, crustaceans, chaetognaths, bryozoans.