Winds, Coastal Circulation, Climate Variability and Hypoxia off the Pacific Northwest

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with lots of help from:

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Outline

- coastal upwelling ecosystems
  - on eastern boundaries of ocean basins
  - wind-driven upwelling
- low-oxygen in eastern boundary currents
  - hypoxia and anoxia
  - upwelling source water and winds
- climate change?
- new technologies for ocean observing
California Current

Canary Current

Humboldt Current

Benguela Current

Coastal Upwelling Ecosystems

1% of surface area, but > 20% of wild caught seafood

The California Current is a prototypical “eastern boundary current” upwelling region.
Wind Forcing and Large-Scale Circulation

Huyer (1983)

summertime winds blow toward the equator
Equatorward winds force surface water offshore and upwelling of deep, low-oxygen, nutrient-rich water

Satellite chlorophyll and temperature

Barth (2007)
Low-Oxygen zone formation

1. Primary production >> surface respiration (very high export)
2. Bottom respiration >> air-sea exchange
3. Poorly flushed surface and bottom water
Upwelling and hypoxia animation

Thanks to Alan Dennis (COAS/OSU)
What are hypoxia zones?

Areas of the coastal ocean where dissolved oxygen levels are \( \leq 1.4 \text{ ml/l} \)

(1 ml/l = 1.33 mg/l = 44\( \mu \text{M} \) = 15% saturation)

The Biologist = mg/g   The Oceanographer = ml/l
The Chemist = \( \mu \text{M} \)   The Physiologist = % Saturation

Courtesy of L. Levin (SIO)
What happens when DO drops to such low levels?

Modified from Rabalais et al. 2002

- Dissolved Oxygen
  - 1.4 ml l⁻¹
  - 1.0 ml l⁻¹
  - 0.5 ml l⁻¹
  - 0 ml l⁻¹

- Fish
- Mobile Inverts
- Sessile Inverts
- Large Infauna
- Hypoxia-tolerant Infauna

- Stressed
- Absent or Dead
The Oregon ‘Dead Zone’

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COAS 50th Anniversary
July 18, 2009
Most hypoxic zones of concern occur in enclosed estuaries and/or at mouths of polluted rivers.
Over 400 sites worldwide experiencing hypoxia
Off Oregon, hypoxia develops on the open continental shelf

Dissolved Oxygen (ml l⁻¹)

Depth of Measurement (meters)

- Hypoxia: < 1.43 ml/l
- "Severe" hypoxia: < 0.5 ml/l

2002 - ▲
2003 - ◆
2004 - □
2005 - ○
2006 - +

R/V Elakha
Hypoxia extends to within 1 km of the surf zone.

Encompasses important shallow ecological and fishery habitats.
Ecosystem impacts of hypoxia

Normal Inner-Shelf Rockfish Community

Dungeness crab piles in intertidal

Invertebrate die-offs & anoxia

Grantham et al. (2004); Chan et al. (2008)
Low oxygen on the shelf influenced by:

- changes in upwelling sourcewater properties
- strength and persistence of winds

both of which are influenced by climate change!
In 2002, anomalously low DO sourcewater led to hypoxia over the shelf.
Supercharged upwelling of 2006

Cumulative wind stress since Spring Transition

Equatorward, Upwelling favorable

Barth/Pierce (OSU)
Is hypoxia/anoxia a normal feature of the system?

Dissolved oxygen (ml l⁻¹)

Depth (m)

1950 to 1999

Chan et al. (2008, Science)
Is hypoxia/anoxia a normal feature of the system?

Chan et al. (2008, Science)
Is hypoxia/anoxia a normal feature of the system?

Dissolved oxygen (ml l⁻¹)

1950 to 1999
2000 to 2005
2006

N ~ 4000 hydrocasts

Chan et al. (2008, Science)
Deep low oxygen zones in the global ocean

(World Ocean Atlas) at 200 m
Depth of the Oxygen Minimum Zone

Helly and Levin (2004)

central Oregon

Eastern Pacific

DO < 0.5 ml/L
California Current
Canary Current
Humboldt Current
Benguela Current
Upwelling-driven shelf hypoxia occurs in other (but not all) major upwelling ecosystems.

Central Chile [August 2002 to July 2007] (Cornejo et al, in press)
Hypoxia in the Benguela Current

Walvis Bay (23S, 130m bottom depth) (Monteiro et al., 2006, GRL)

Lobster Walk Outs in S. Africa

Hypoxia-caused sulfur plumes off Namibia (Weeks et al., 2002)
Low oxygen on the shelf influenced by:

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Changes in upwelling sourcewater properties

50 years at Ocean Station Papa in 100-400m depth range:

- T increasing 0.005-0.012 C/yr (0.25-0.60 C in 50 years)
- DO decreasing 0.39-0.70 umol/kg/yr (0.45-0.80 ml/l in 50 years)

Whitney et al. (2007, PinO)
“Expanding Oxygen-Minimum Zones in the Tropical Oceans”

Fig. 1. Climatological mean (18) dissolved oxygen concentrations (μmol kg⁻¹ shown in color) at 400 m depth contoured at 20-μmol kg⁻¹ intervals from 10 to 230 μmol kg⁻¹ (black lines) using Ocean Data View (9) software. Analyzed areas (A to F, Table 1, and Fig. 2) are enclosed by black boxes.

Fig. 2. Dissolved oxygen concentration (μmol kg⁻¹ shown in color) maps (20, 21) versus time (1960–2006) and pressure (1 dbar = 1 m) with sample locations (white dots). (A) The eastern tropical North Atlantic (10° to 14°N, 20° to 30°W), contoured at 50 μmol kg⁻¹ (thick white line). (B) The central equatorial Atlantic (3°S to 3°N, 20° to 10°W), contoured at 120 μmol kg⁻¹ (thick white line). (C) The eastern tropical South Atlantic (18°S to 8°S, 2° to 12°E), contoured at 60 μmol kg⁻¹ (thick white line). (D) The eastern equatorial Pacific Ocean (5°S to 5°N, 105° to 115°W), contoured at 60 μmol kg⁻¹ (thick white line). (E) The central equatorial Pacific Ocean (5°S to 5°N, 165° to 175°W), contoured at 90 and 120 μmol kg⁻¹ (thick white lines). (F) The eastern equatorial Indian Ocean (5°S to 0°, 90° to 98°E), contoured at 60 μmol kg⁻¹ (thick white line).
Do we see trends in strength of upwelling? (Bakun, 1990)

“Increased Coastal Upwelling in the California Current System” Schwing and Mendelssohn (1997, JGR)

“Rapid 20th-Century Increase in Coastal Upwelling off Northwest Africa” McGregor et al. (2007, Science)

Caveats: records are relatively short and year-to-year and decadal variations are big!

elsewhere the Canary Current is warming (D. Barton, personal comm.)
What do regional climate models tell us?
Simulation with 2X CO₂ versus 1X CO₂ (560 vs 280 ppm)

Changes in upwelling-favorable winds (red = more)

April  May  June

Changes in land-sea temperature difference (red = land warmer)

July  August  Sept

Snyder et al. (2003, GRL)
Multi-IPCC model average sea-level pressure and surface wind difference between A2 (2070-2100) and BL (1970-2000)

Courtesy of R. Garreaud (U. Chile)
Autonomous Underwater Vehicle Gliders

cross-margin transect twice per week since April 2006

CTD dissolved oxygen chlorophyll fluorescence CDOM fluorescence light backscatter
Autonomous Underwater Glider

GPS, Iridium and Freewave Antennae in tail fin

Aanderaa Optical Dissolved Oxygen sensor

Glider Control and more batteries

Science Bay

Pitch Batteries

Air bladder

Optical Sensors (Chl, CDOM and Backscatter)

CTD

Displacement Pump

7 ft long
100 lbs in air
OSU Glider Operations

- 90 km cross-shelf
- strong currents (50+ cm/s)
- abrupt bathymetry
- historical observations

- April 2006– July 2009
- 1108 glider-days
- 405 sections
- 106,219 vertical profiles
- 25,855 km
  over 2/3 around the Earth!
Dissolved Oxygen from glider

Hypoxia

July 2006

Barth (OSU, unpublished data)
Summary

Increasing hypoxia on the mid to inner shelf in the northern California Current (even anoxia!)

Underwater gliders can conduct year-round repeat sampling in coastal and boundary current regions

Upwelled sourcewater dissolved oxygen content and wind stress contribute about equally to shelf hypoxia

Sourcewater dissolved oxygen decreasing

Ongoing Work: continue to investigate coastal winds, circulation changes