Climate change and ocean deoxygenation within intensified coastal ocean upwelling circulations

Andrew Bakun
Rosenstiel School of Marine and Atmospheric Science
University of Miami
USA

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subtitle: ***Silvery "first responders" of neritic ecosystems – Can sardines save our skins?***

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“. . . without speculation there is no good and original observation”

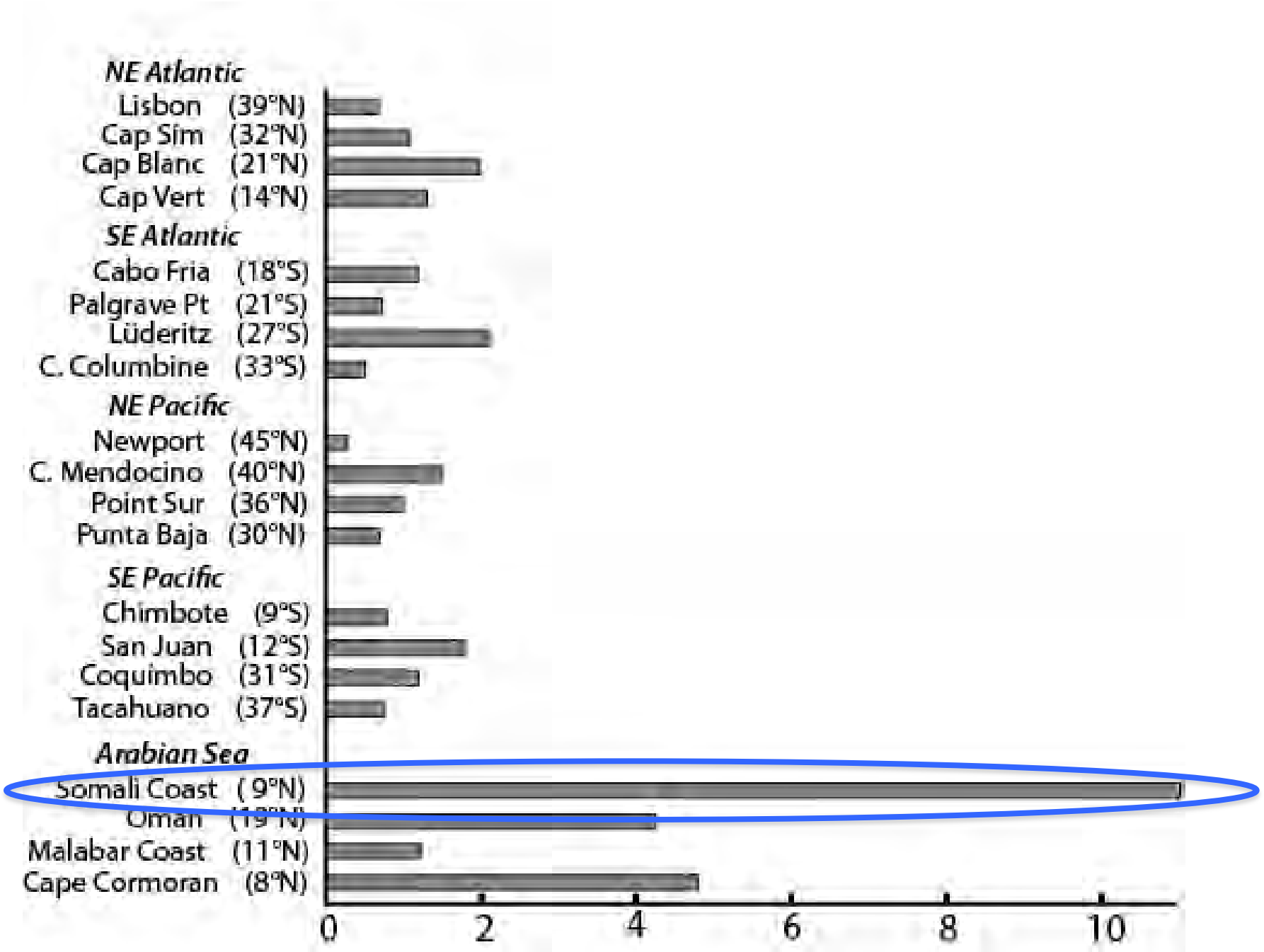
Charles Darwin, Letter to A. R. Wallace (22 Dec 1857). In Alfred Russel Wallace and Sir James Marchant (ed.), *Alfred Russel Wallace: Letters and Reminiscences* (1916), 109.

The most intense coastal upwelling systems in the world's oceans:

1. Somalia

2. Namibia

Special example
3. Oregon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Cabo Fria (18°S)
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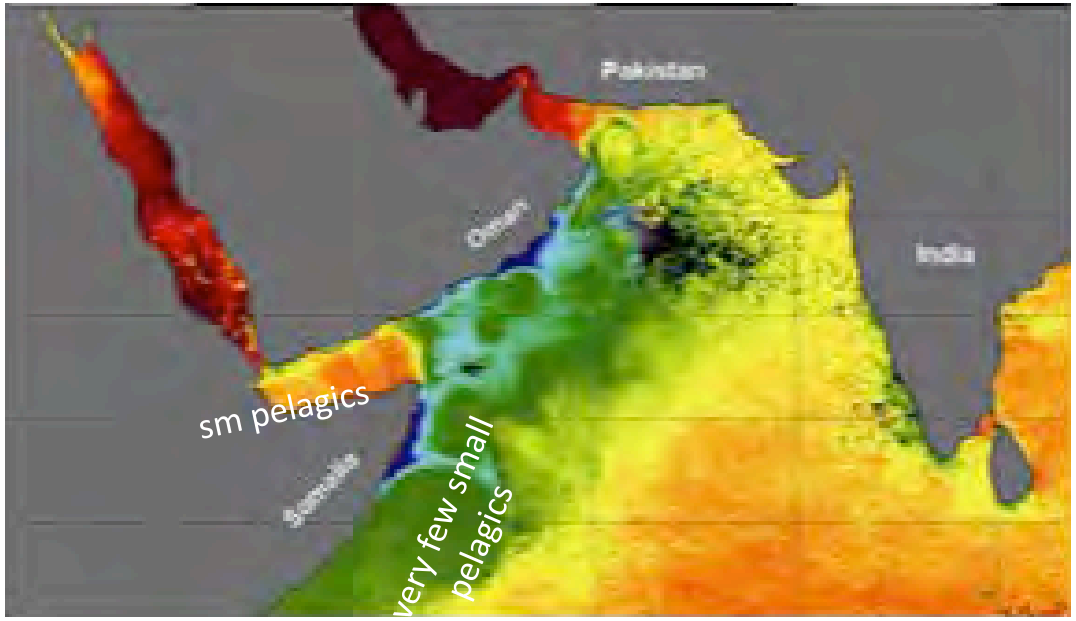
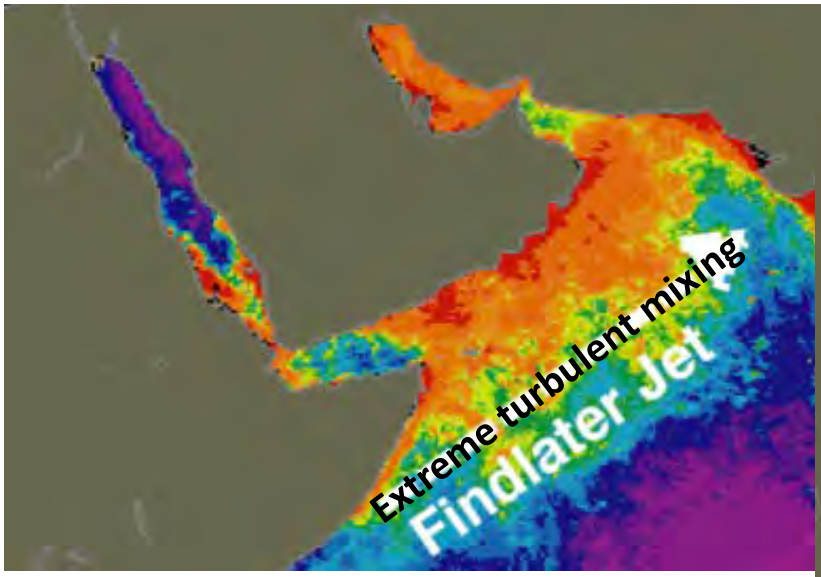
C. Columbine (33°S)
NE Pacific
Newport (45°N)
C. Mendocino (40°N)
Point Sur (36°N)
Punta Baja (30°N)
SE Pacific
Chimbote (9°S)
San Juan (12°S)
Coquimbo (31°S)
Tacahuano (37°S)
Arabian Sea
Somali Coast (9°N)
Oman (19°N)
Malabar Coast (11°N)
Cape Cormoran (8°N)
0
2
4
6
8
10

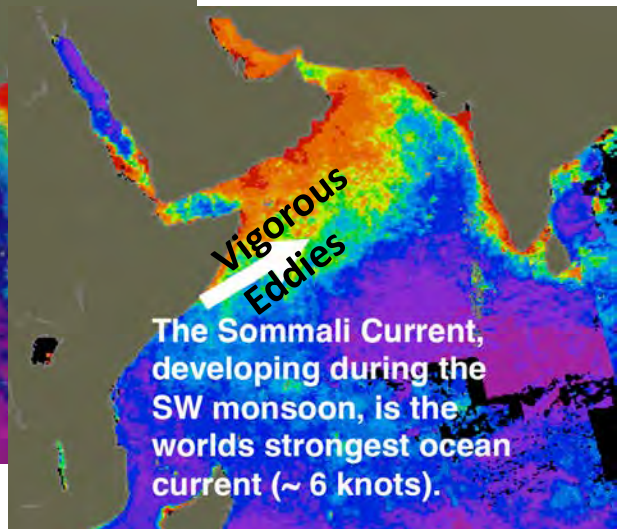
1. Somalia



SST in July 2003 (**Southwest Monsoon**), from the MODIS satellite. Source: NASA Goddard Earth Sciences (2007a).



Chlorophyll



Huge quantities of unoxidized organic production spewed directly outward into the Arabian Sea proper producing:

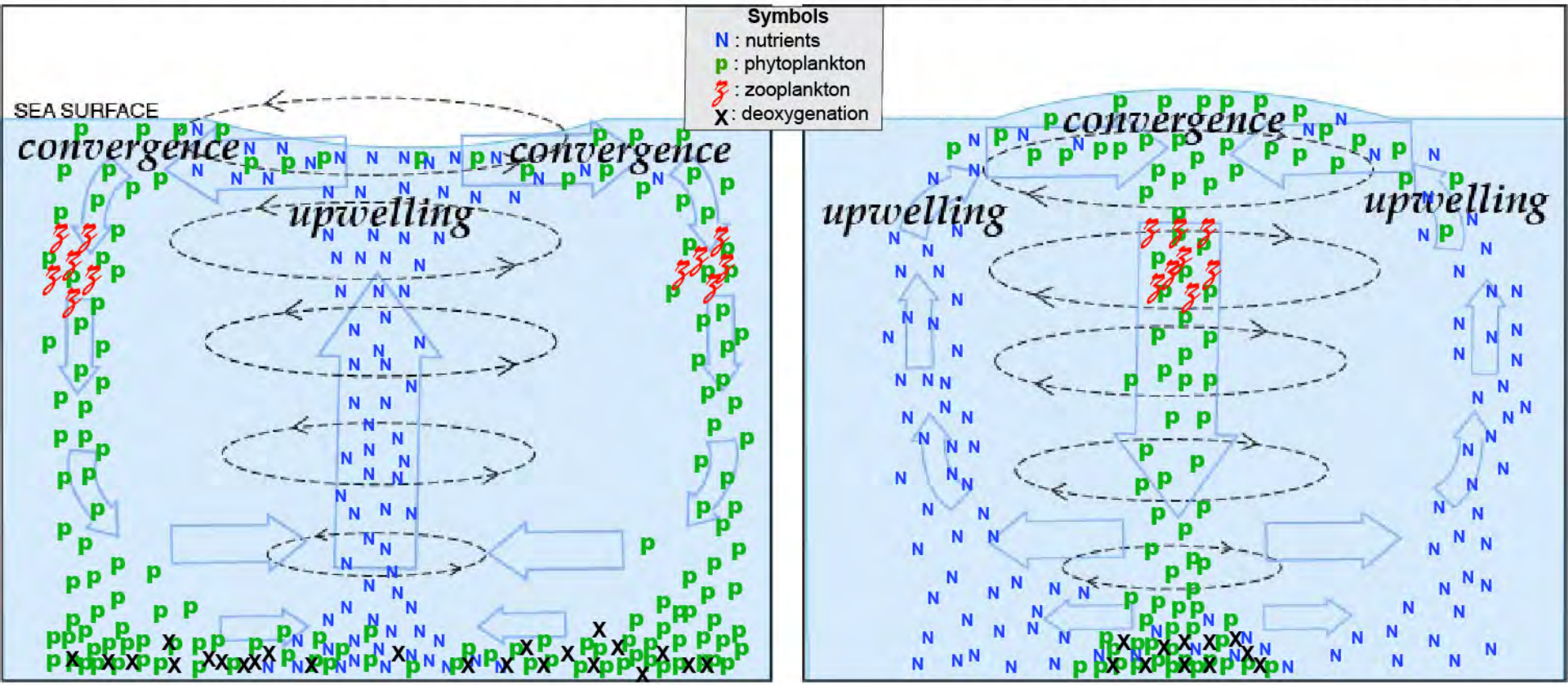
severe hypoxia at depths as shallow as 50 to 125 meters over large areas of the northern Arabian Sea;

thickest low-oxygen layer to be found anywhere in the world's oceans;

one of the top three water-column denitrification sites in the world's oceans;

one of the world's most important zones of oceanic methane emissions.

very scattered, widely spread, very patchy, intense near-surface patches of deoxigenation.


(a) Actively-forced Cyclonic Eddy
(b) Actively-forced Anticylonic Eddy
Symbols
N : nutrients
p : phytoplankton
z : zooplankton
X : deoxygenation
SEA SURFACE
convergence
convergence
upwelling
convergence
upwelling
upwelling

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Open ocean dead zones in the tropical North Atlantic Ocean

J. Karstensen[1], B. Fiedler[1], F. Schütte[1], P. Brandt[1], A. Körtzinger[1], G. Fischer[2], R. Zantopp[1], J. Hahn[1], M. Visbeck[1], and D. Wallace[3]

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
[2]Faculty of Geosciences and MARUM, University of Bremen, Bremen, Germany
[3]Halifax Marine Research Institute (HMRI), Halifax, Canada

Correspondence to: J. Karstensen (jkarstensen@geomar.de)

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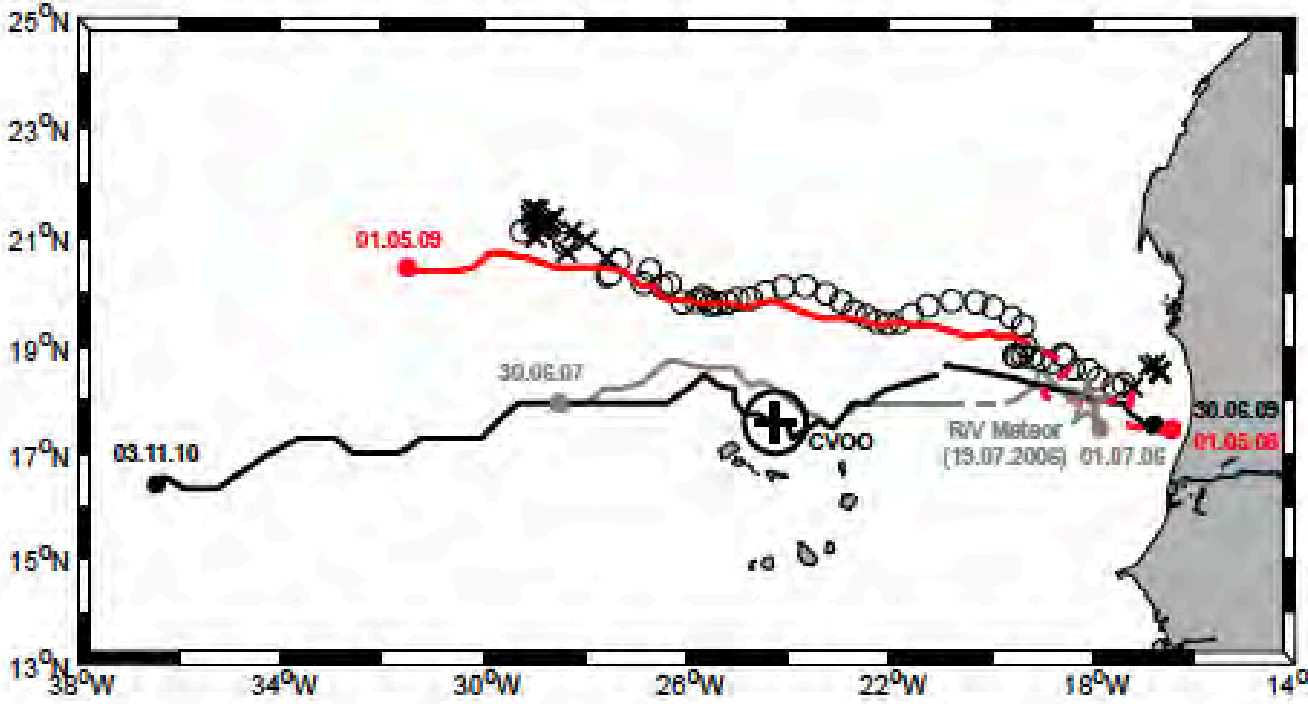
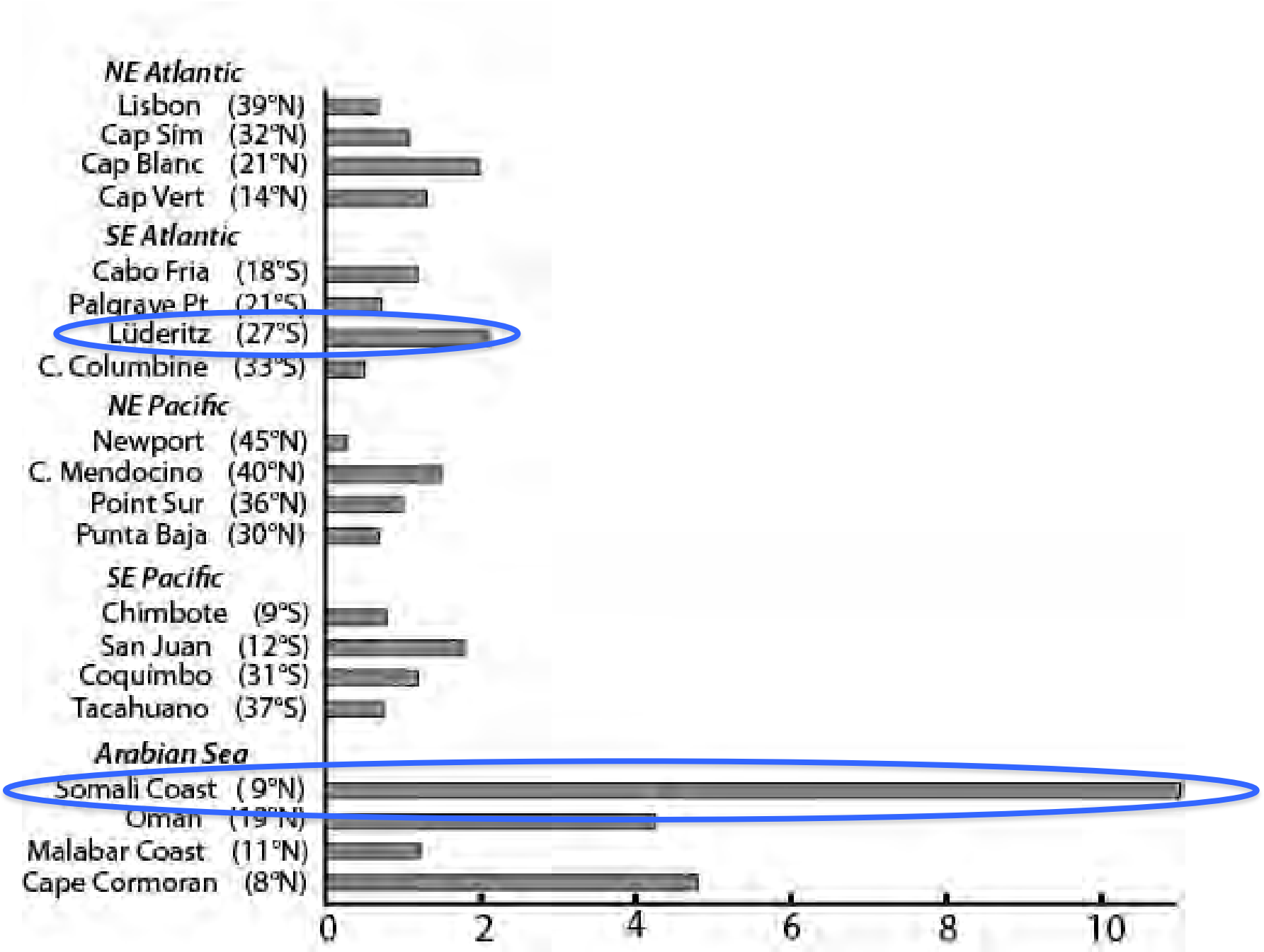
Abstract. Here we present first observations, from instrumentation installed on moorings and a float, of unexpectedly low ($< 2\,\mu mol\,kg^{-1}$) oxygen environments in the open waters of the tropical North Atlantic, a region where oxygen concentration does normally not fall much below $40\,\mu mol\,kg^{-1}$. The low-oxygen zones are created at shallow depth, just below the mixed layer, in the euphotic zone of cyclonic eddies and anticyclonic-modewater eddies. Both types of eddies are prone to high surface productivity. Net respiration rates for the eddies are found to be 3 to 5 times higher when compared with surrounding waters. Oxygen is lowest in the centre of the eddies, in a depth range where the swirl velocity, defining the transition between eddy and surroundings, has its maximum. It is assumed that the strong velocity at the outer rim of the eddies hampers the transport of properties across the eddies boundary and as such isolates their cores. This is supported by a remarkably stable hydrographic structure of the eddies core over periods of several months. The eddies propagate westward, at about 4 to 5 km day^{-1}, from their generation region off the West African coast into the open ocean. High productivity and accompanying respiration, paired with sluggish exchange across the eddy boundary, create the "dead zone" inside the eddies, so far only reported for coastal areas or lakes. We observe a direct impact of the open ocean dead zones on the marine ecosystem as such that the diurnal vertical migration of zooplankton is suppressed inside the eddies.

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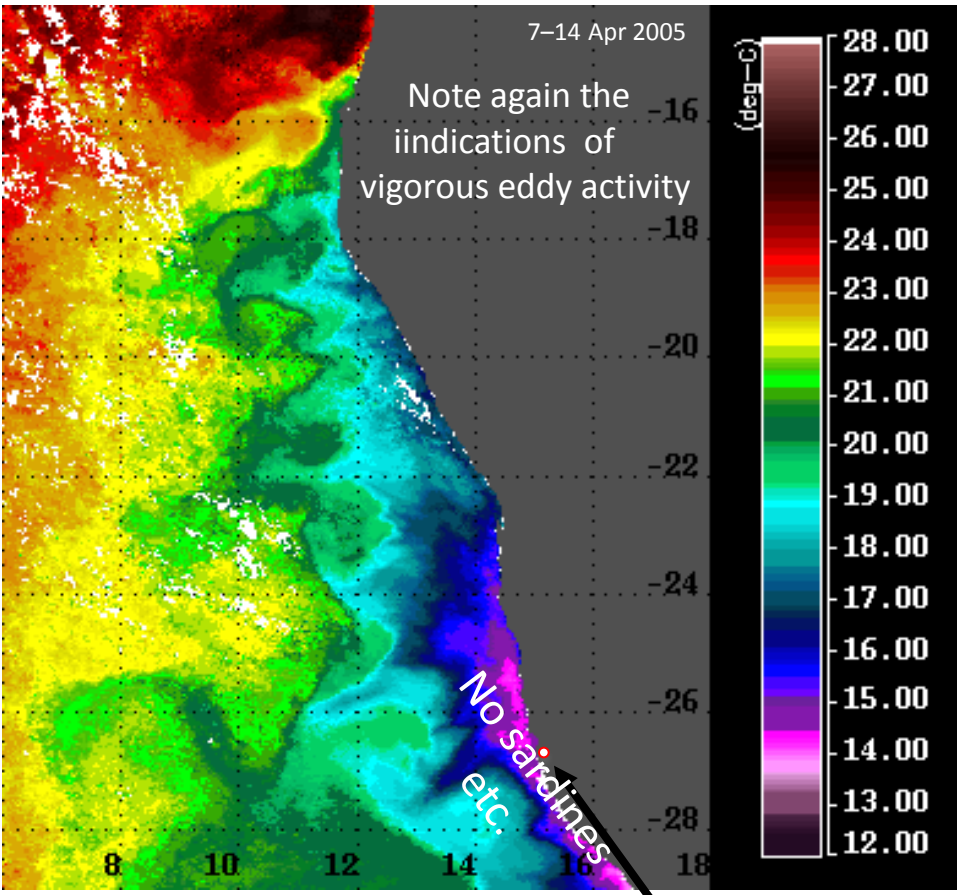
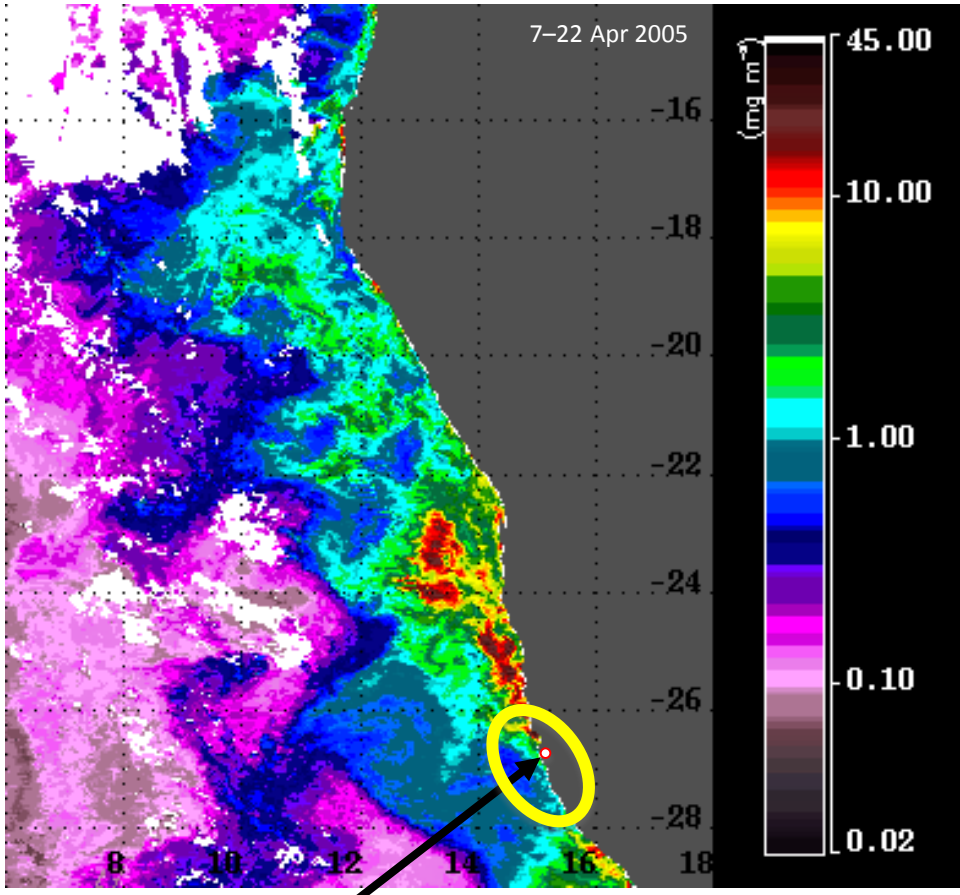
2. Namibia

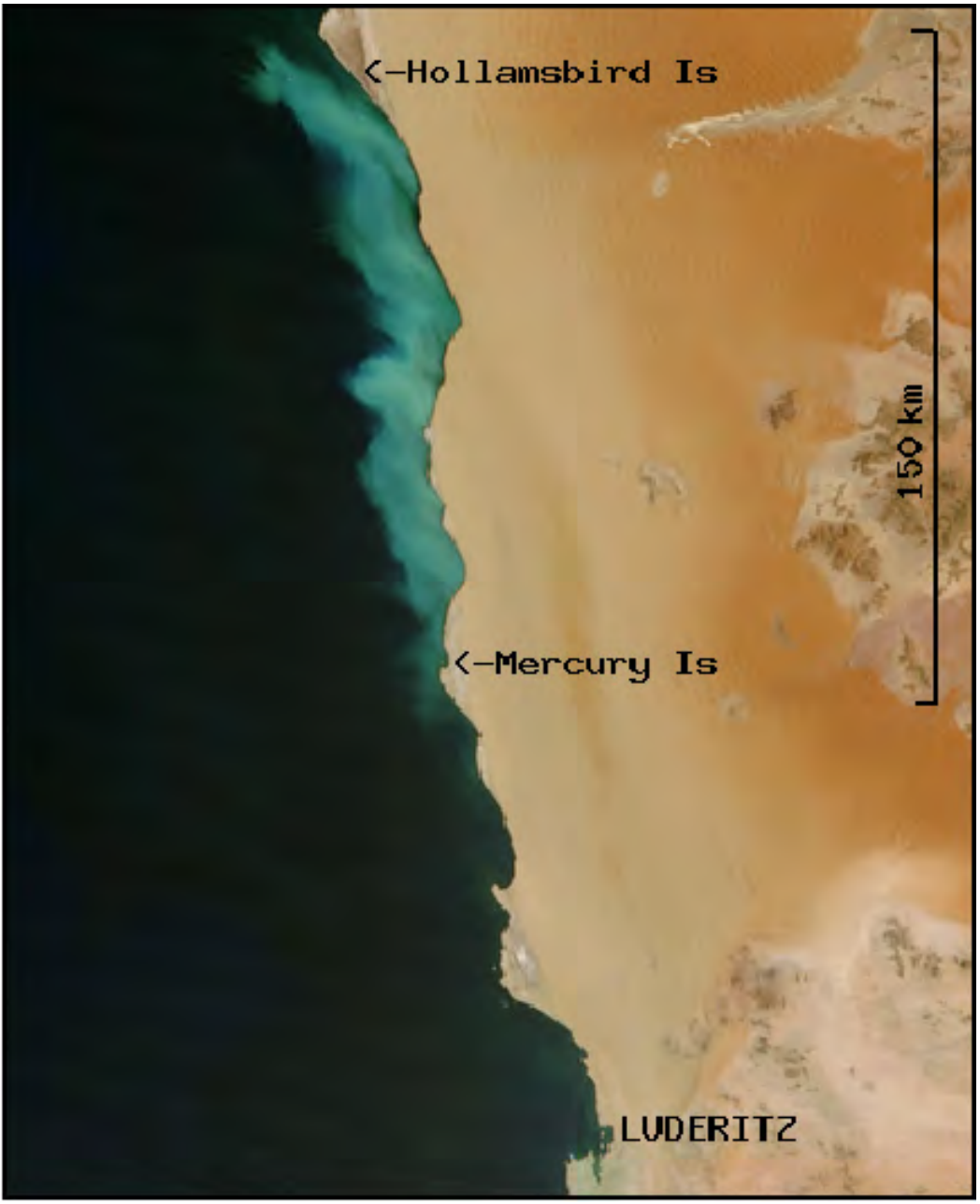
Sea Surface Temp (° C)

Chlorophyll Pigment (mg m^{-3})





Lüderitz, Namibia (the strongest zone of <u>sustained</u> (year round) upwelling in the world)



Satellite (“quasi-true color) image of the Namibian Desert coast, showing the surface manifestation of an eruption (9 Jan 2003)

The “milky-turquoise”-colored area is produced by reflective micro-particles of elemental sulfur produced as the toxic hydrogen sulfide is oxidized as it passes through the oxyginated waters near the sea surface

In addition to the toxic effects of the hydrogen sulfide, this strips the oxygen from the water column producing an even longer lasting adverse biological effect

MECHANISM:

1.Massive deposition and anoxic decomposition of organic matter

2. Effervescence of bubbles of CH_4 and CO_2

3. H_2S diffuses into bubbles and is carried upward in an eruption

4. Eruption triggered by episode of low hydrostatic pressure

5. H_2S oxidized to elemental sulfur (visible from satellite)

EFFECTS:

H_2S

highly toxic

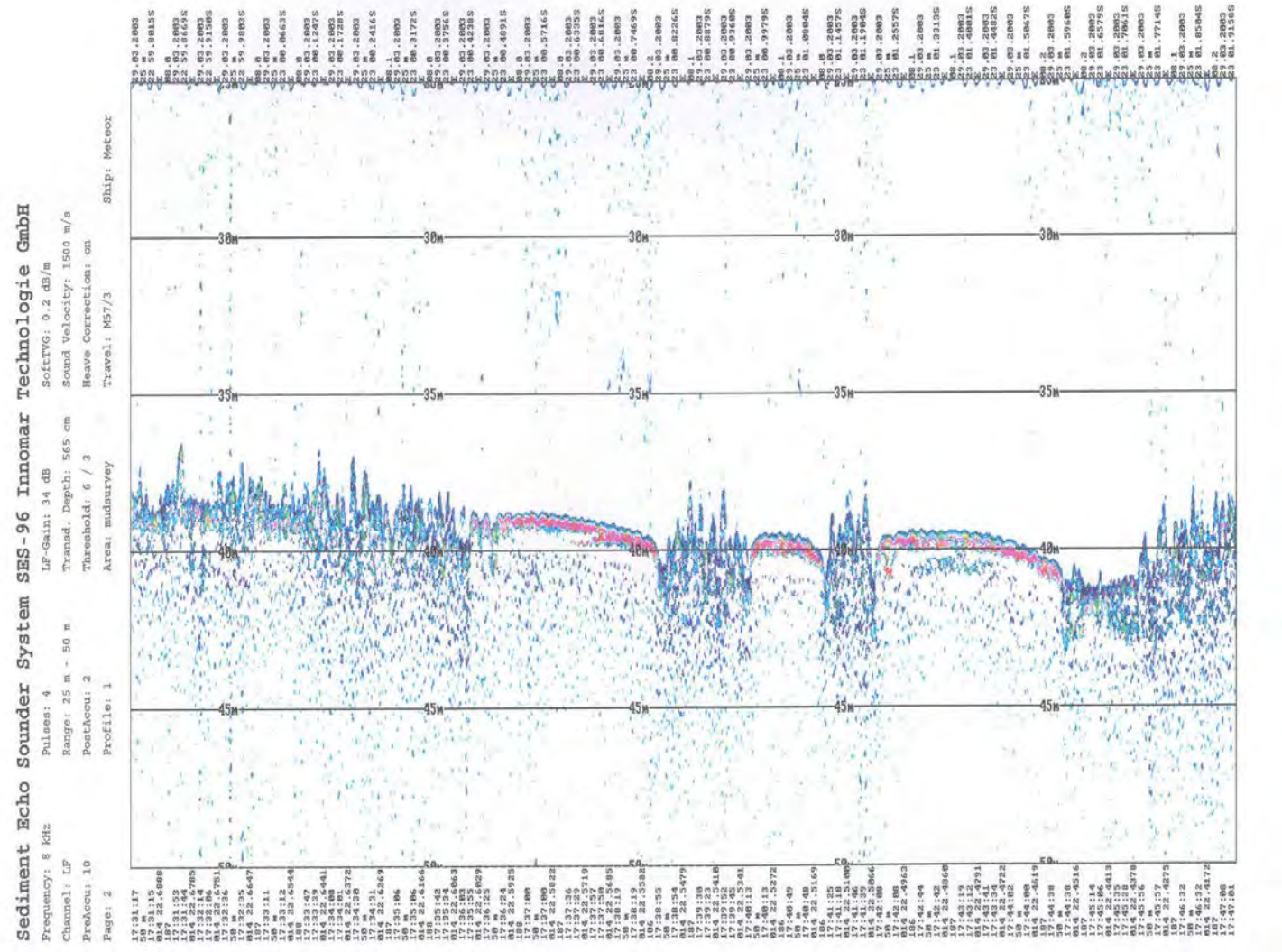
strips dissolved oxygen from the water column

Injection of nutrients

CH_4 is a particularly potent greenhouse gas (GWP=21)

GWP (Global Warming potential): ratio of the global warming effect produced by one unit mass of a greenhouse gas to that produced by one unit mass of CO_2

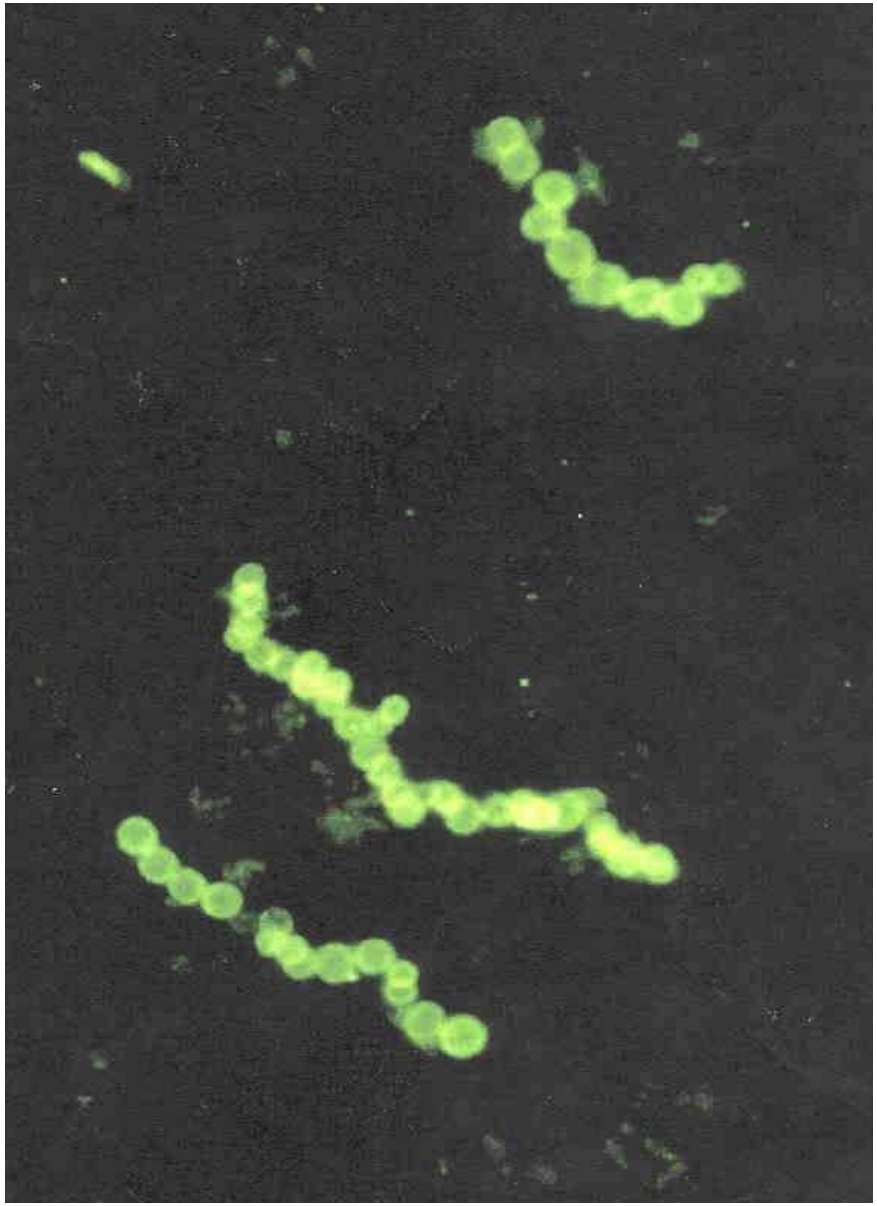
R. Endler
IOW (Baltic Sea Research Inst)



Acoustic trace: new emissions –> methane layer disappears at eruptive points, bubbles emanating from the surface

Thiomargarita namibiensis

“Sulphur pearl of Namibia”

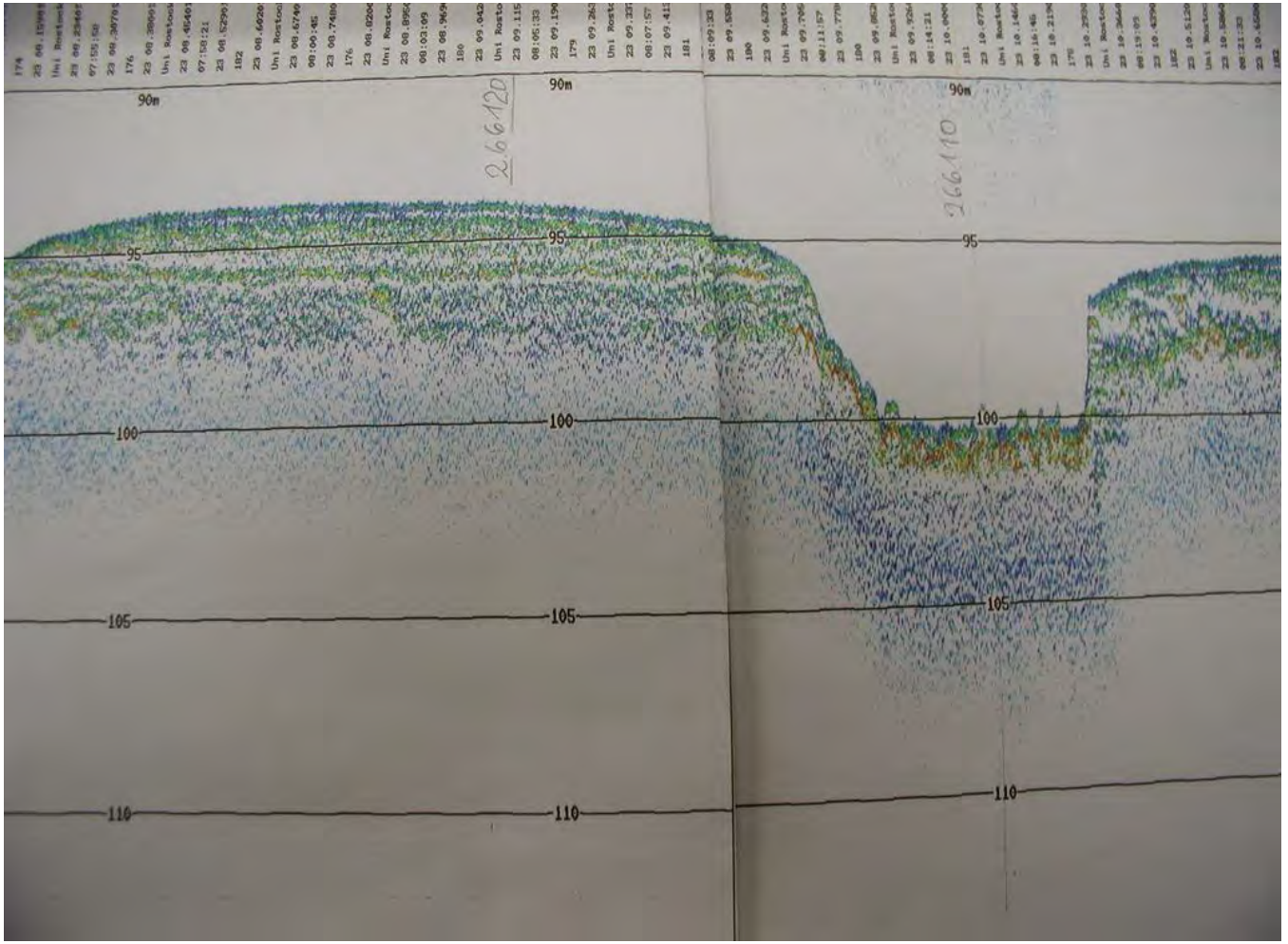


- largest known bacteria in world! (a single bacterium can be seen with the naked eye)
- discovered 1997
- occur at & near the surface of diatomaceous layer, where sustain themselves by oxidizing sulphide with nitrate from the water column above

ROV footage of bacteria mats at 47m water depth
-> bubble craters from which methane escapes from the sediment.
Methane generated within the sediment is present as free gas in extensive pockets below the diatomaceous mud belt.

Sediment seisimic survey: Pelican Point Crater

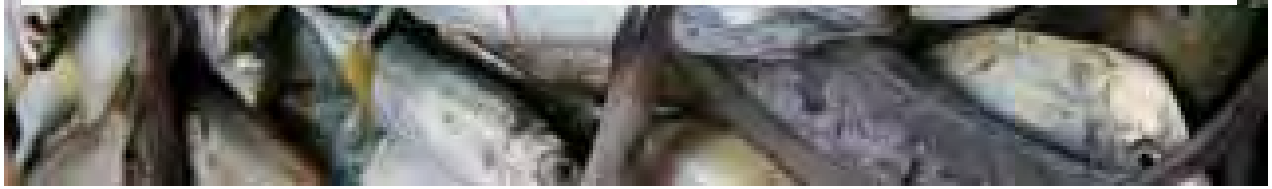
R. Endler
IOW (Baltic Sea Research Inst)



Crater: 3km long & 6m deep → mud displaced during an eruption event, pressure change causes release of methane beneath the sediment, carrying hydrogen sulphide into the water column.

It has been estimated (Hamukuaya et al. 1998) that 2 billion hake were lost in one hypoxic outbreak that took place in 1994 (two billion hake representing a thousand large, readily marketable food fish for every man, woman and child living in Namibia.)

Hamukuaya H, O'Toole MJ, Woodhead PJM. Observations of severe hypoxia and offshore displacement of cape hake over the Namibian shelf in 1994. S Afr J Mar Sci. 1998;19:57-59.



For a full year and a half after initiating regularly monitoring of eruptions there was nearly contiually one or more eruption episodes underway somewhere along the Namibian coast

Then the eruptions ceased entirely for a full year, at least – suggesting a degree of transient dynamic equilibrium that could be somehow abruptly be switched from one state to another

During that year the Namibian National Marine Resources Information Center put a notice on their website of an apparent “minor rebound” of sardine reproductive activity along the Namibian coast

$$\frac{dp}{dt} = r_{(p)growth}p - r_{advection}p - r_{deposition}p - zc_{grazing}p - sc_{filtering}p + A_H\left(p_{>\lambda} - p\right) \quad (1)$$

$$\frac{dz}{dt} = r_{(z)growth}z - r_{advection}z - r_{predation}z + A_H\left(z_{>\lambda} - z\right) \quad (2)$$

$$\alpha \equiv r_{(p)growth} - r_{advection} - r_{deposition} - zc_{grazing} - sc_{filtering} - A_H \quad (3)$$

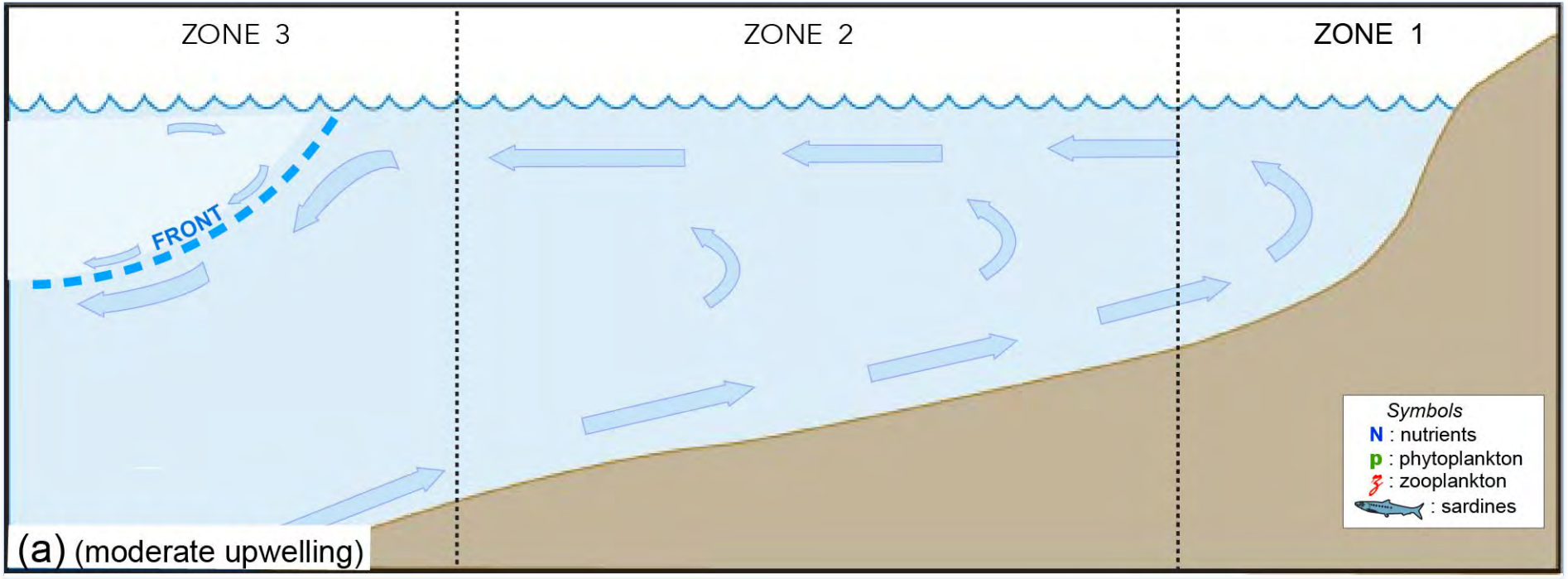
$$\gamma \equiv r_{(z)growth} - r_{advect} - r_{predation} - A_H \quad (4)$$

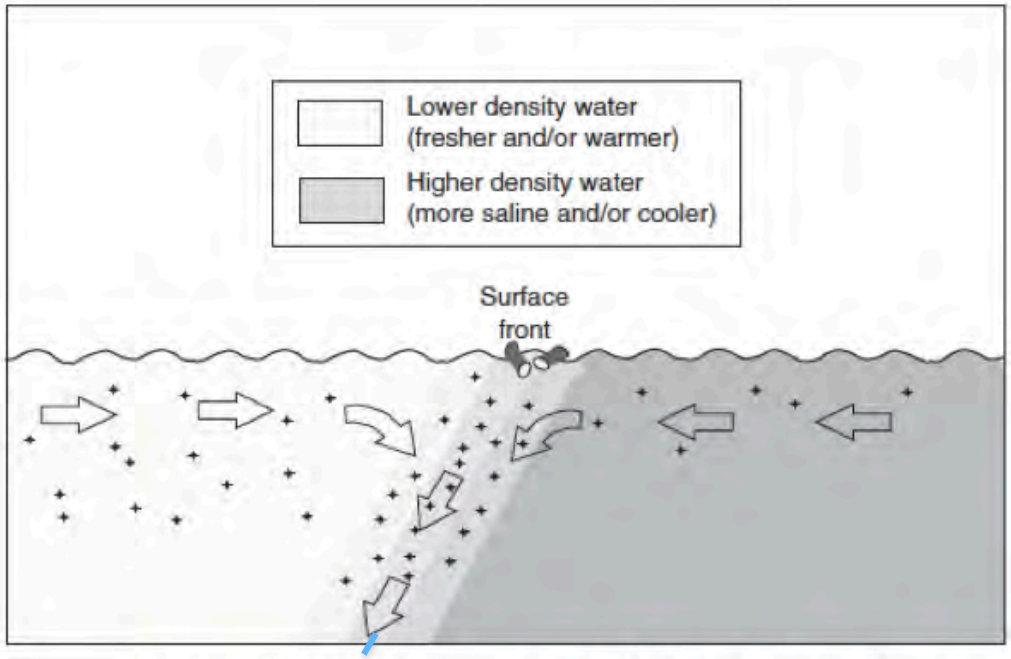
$$\frac{dp}{dt} = \alpha p + A_H p_{>\lambda} \quad (5)$$

$$\frac{dz}{dt} = \gamma z + A_H z_{>\lambda} \quad (6)$$

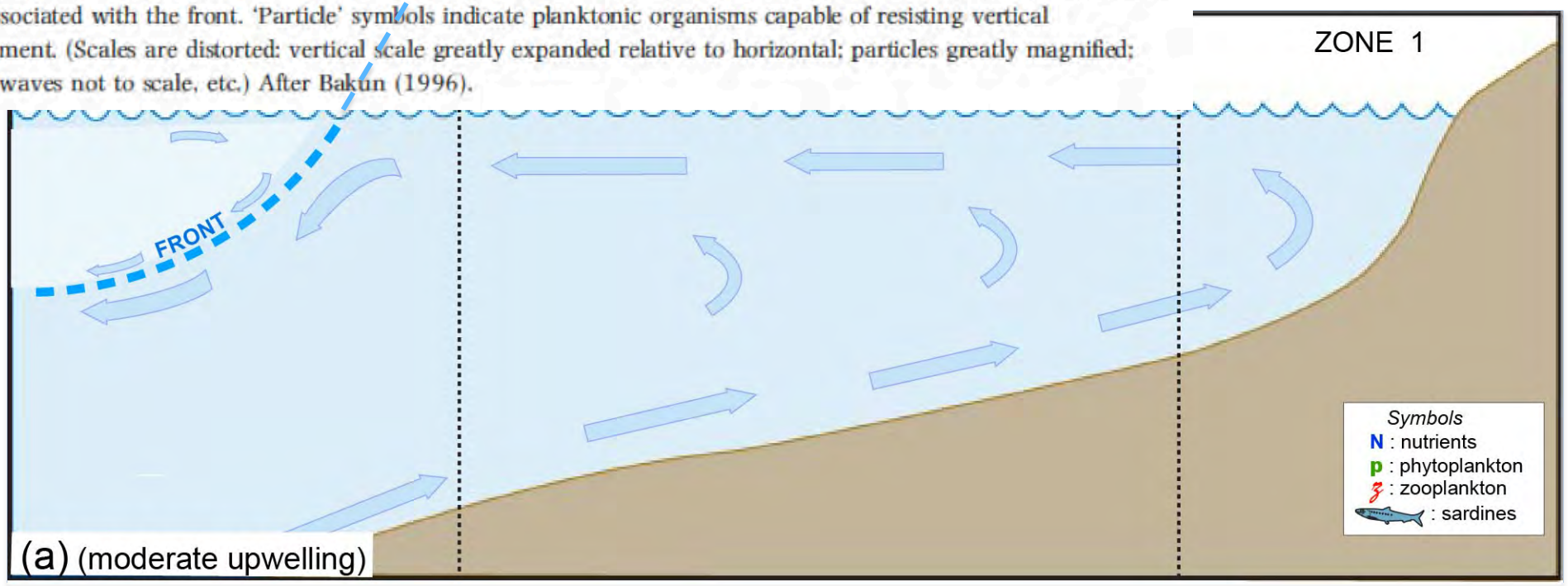
$$\frac{dp}{dt} = \left(\frac{dp}{dt}\right)_{t=to} e^{\alpha t} \quad (7)$$

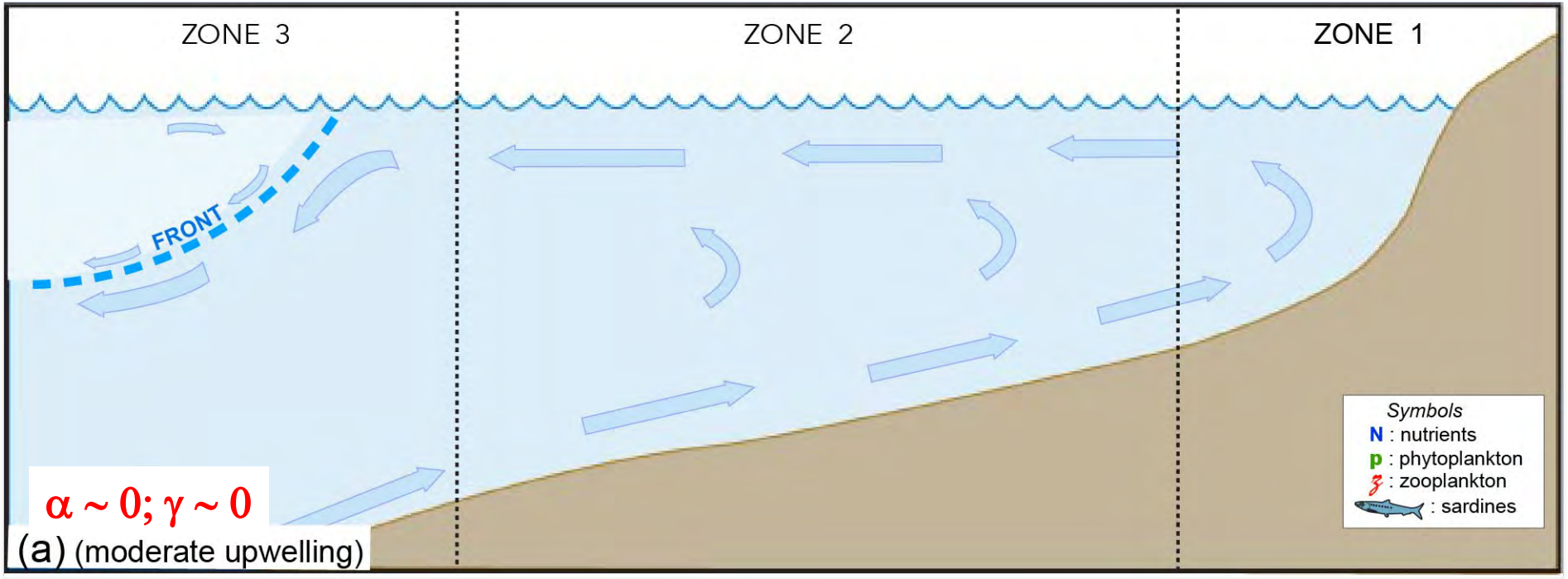
$$\frac{dz}{dt} = \left(\frac{dz}{dt}\right)_{t=to} e^{\gamma t} \quad (8)$$


ZONE 3
ZONE 2
ZONE 1
FRONT
Symbols
N : nutrients
p : phytoplankton
z : zooplankton
: sardines
(a) (moderate upwelling)



5 Schematic diagram of a convergent front between waters of differing density. Arrows indicate density-driven
ssociated with the front. 'Particle' symbols indicate planktonic organisms capable of resisting vertical
ement. (Scales are distorted: vertical scale greatly expanded relative to horizontal; particles greatly magnified;
waves not to scale, etc.) After Bakun (1996).

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α ~ 0; γ ~ 0
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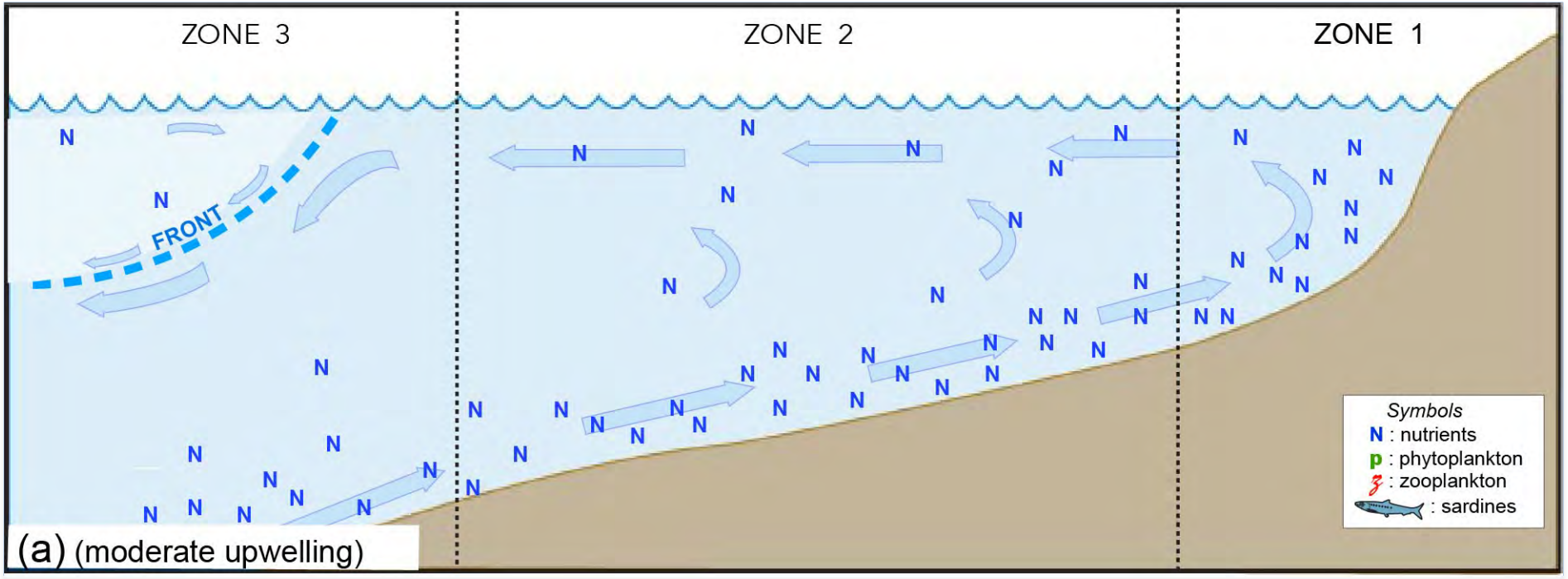
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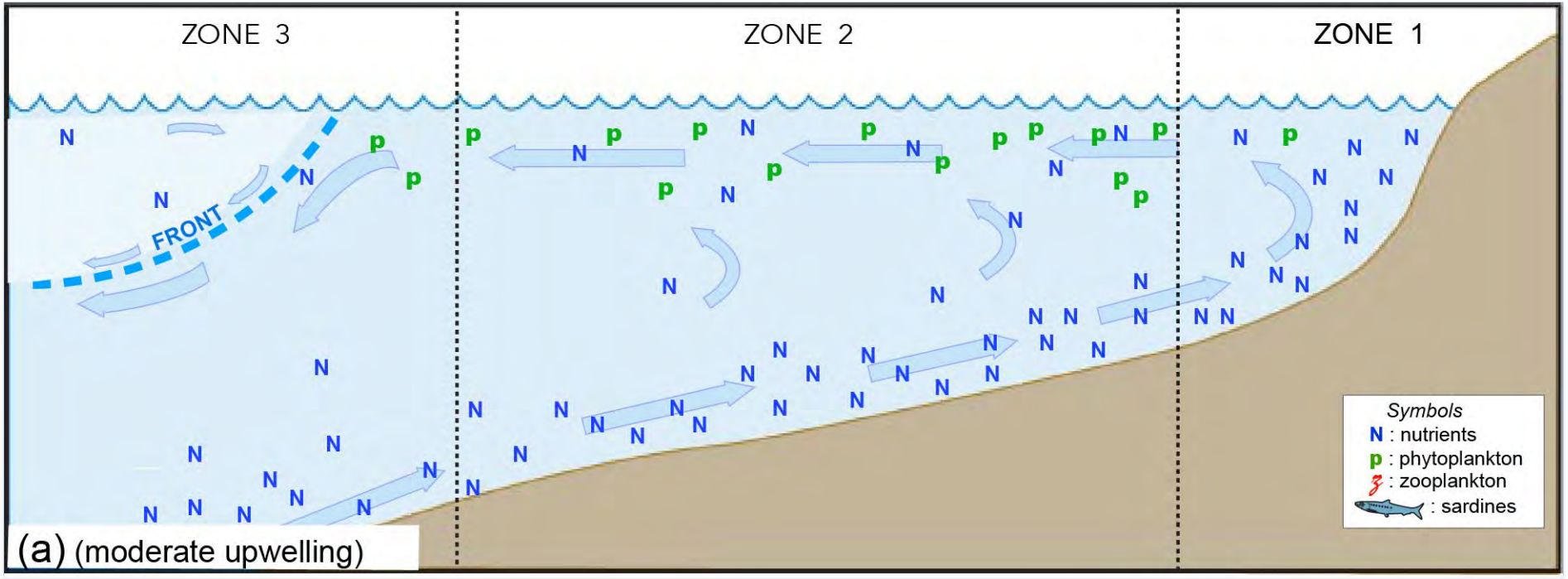
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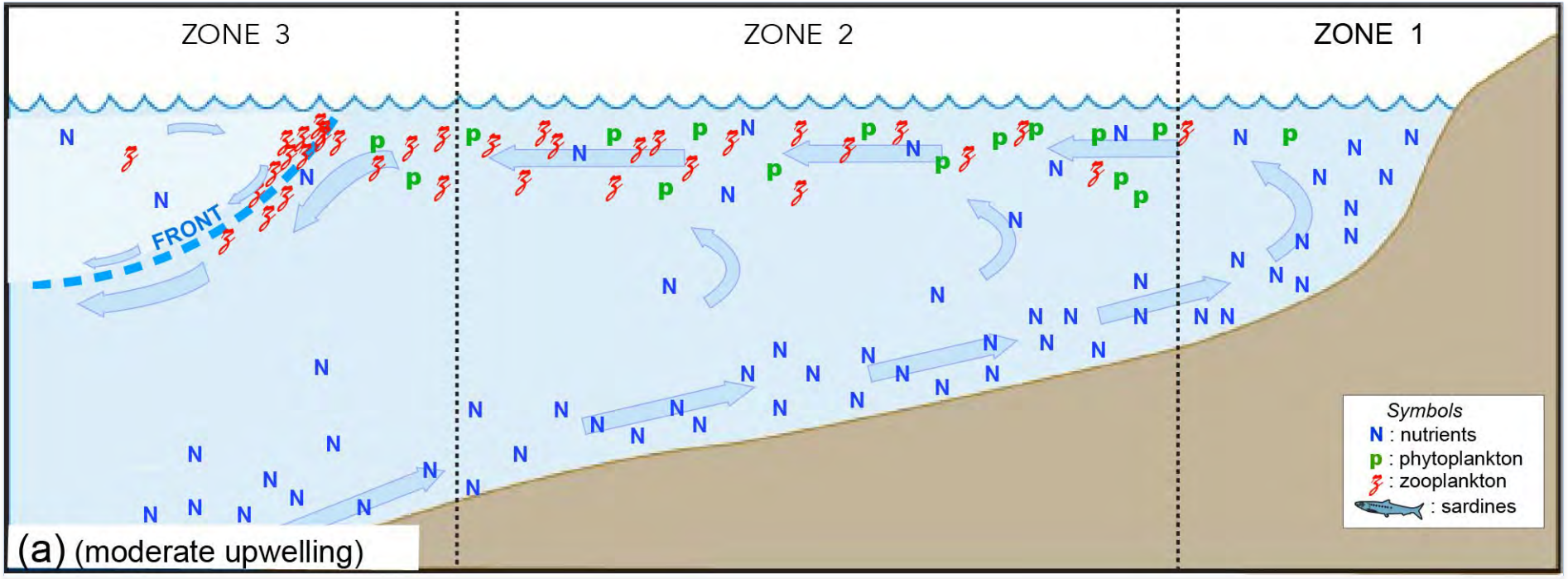
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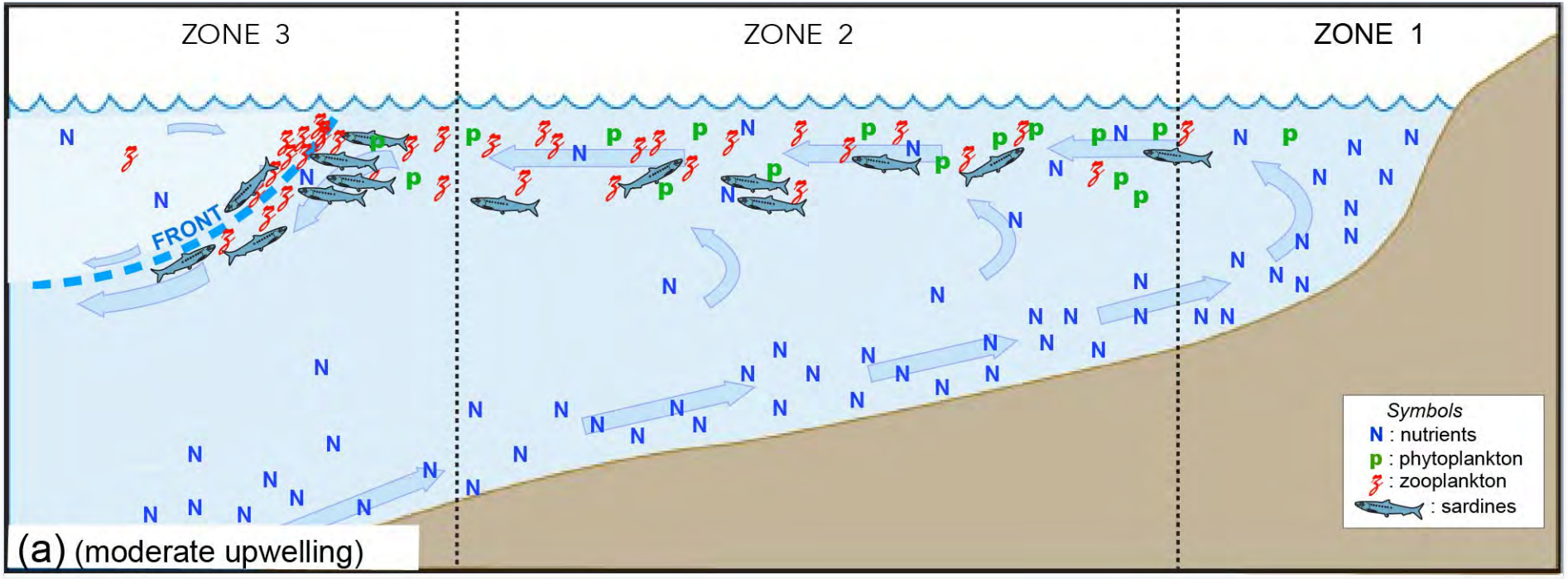

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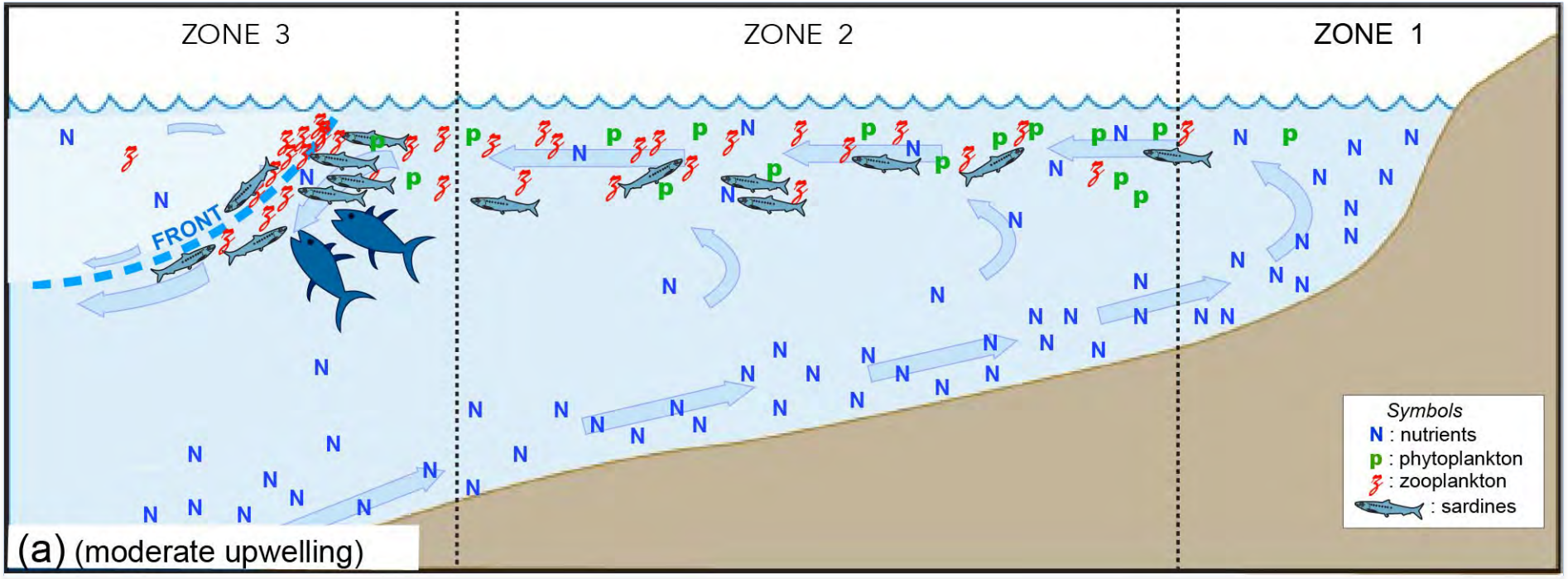

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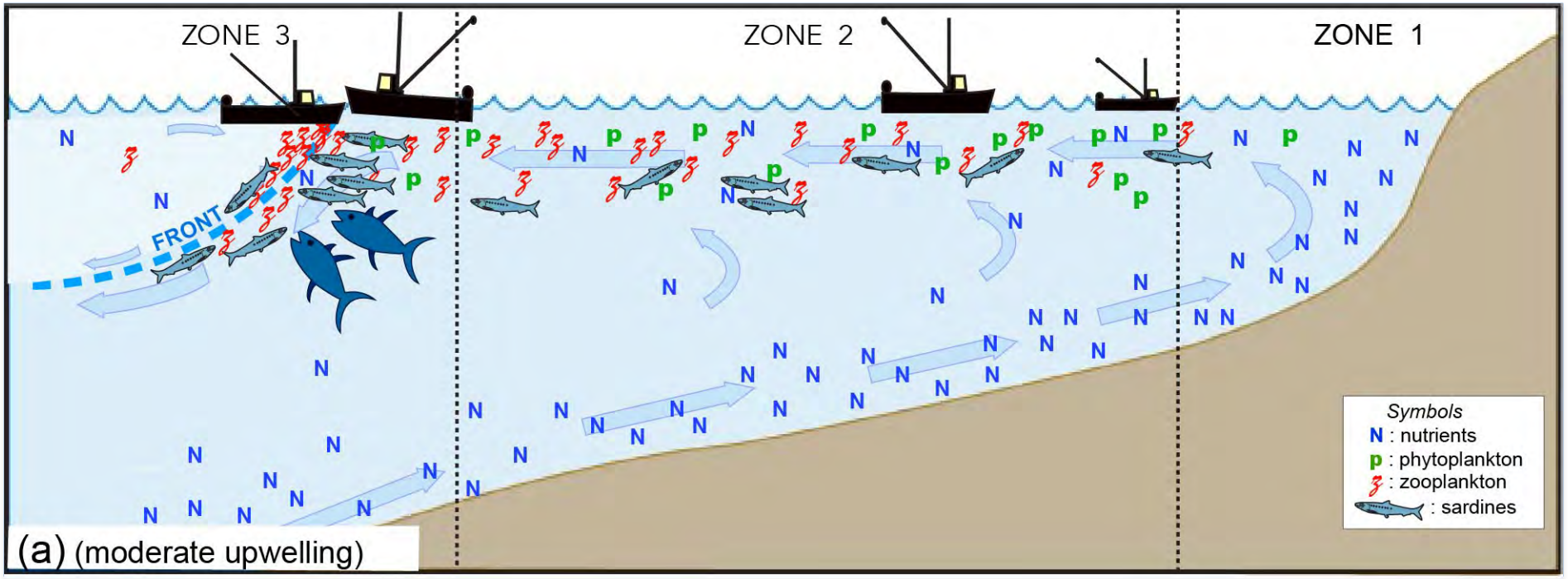

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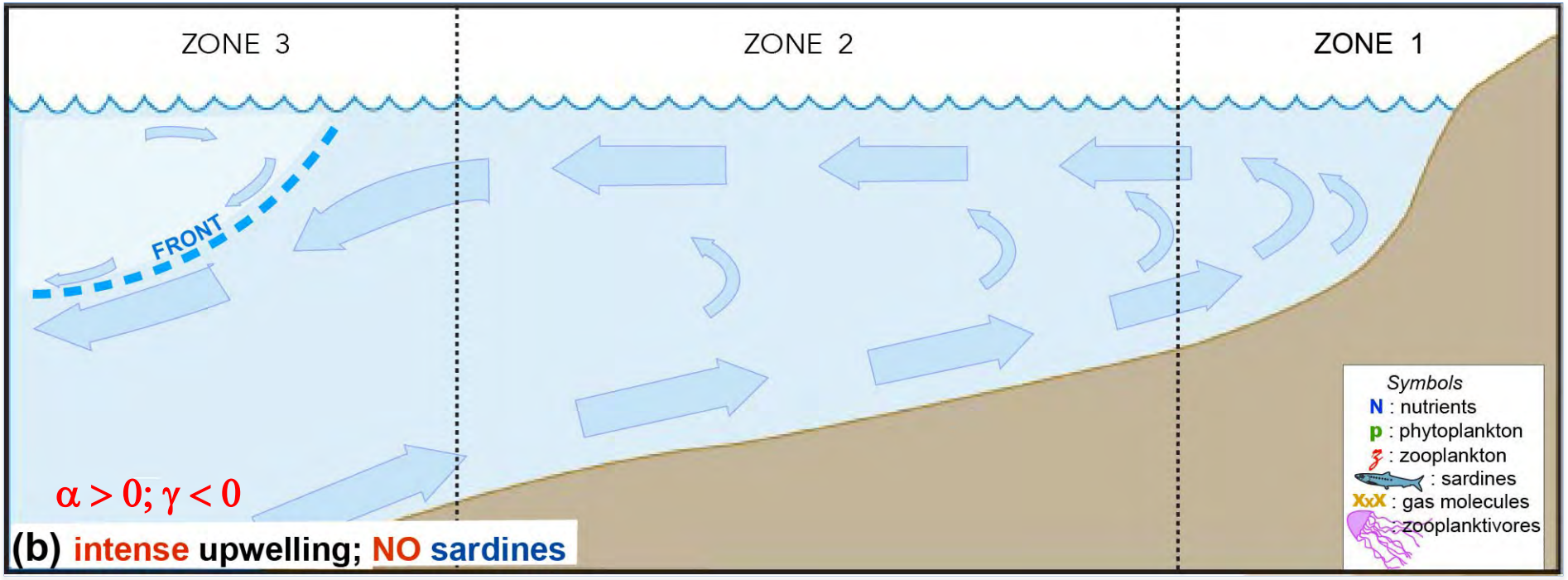
ZONE 3
ZONE 2
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FRONT
α > 0; γ < 0
(b) intense upwelling; NO sardines
Symbols
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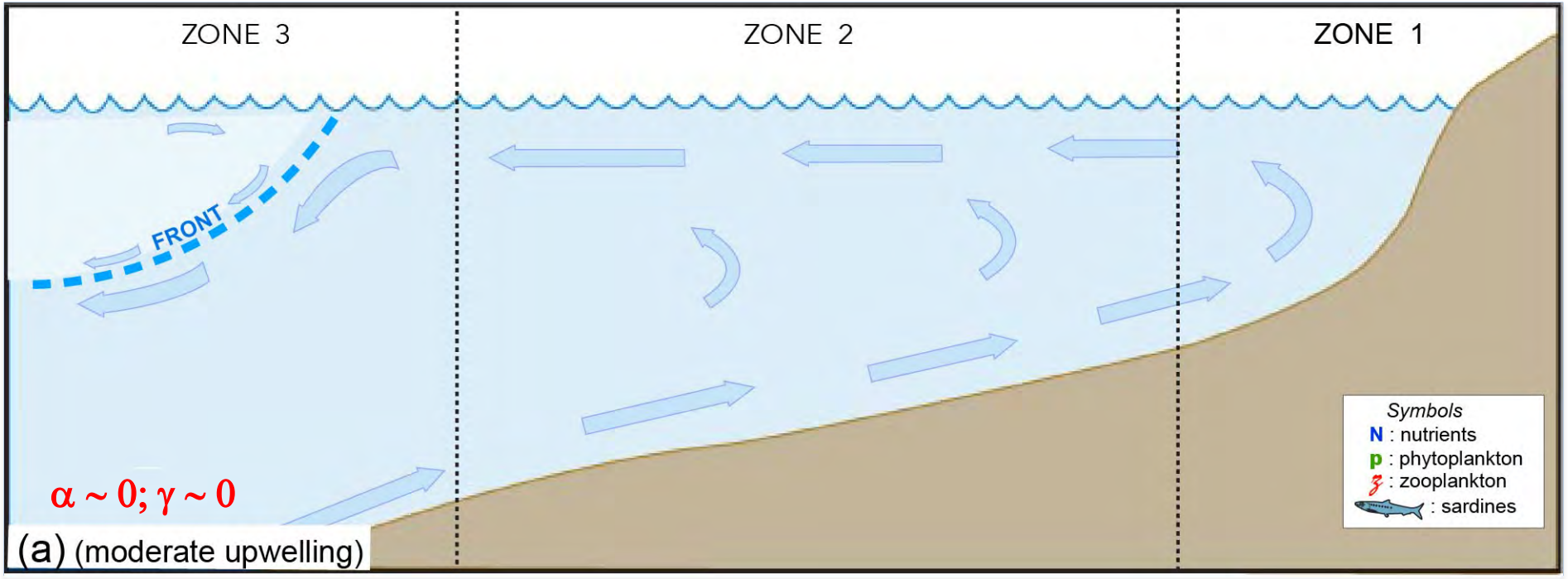
Z : zooplankton
: sardines
XxX : gas molecules
: zooplanktivores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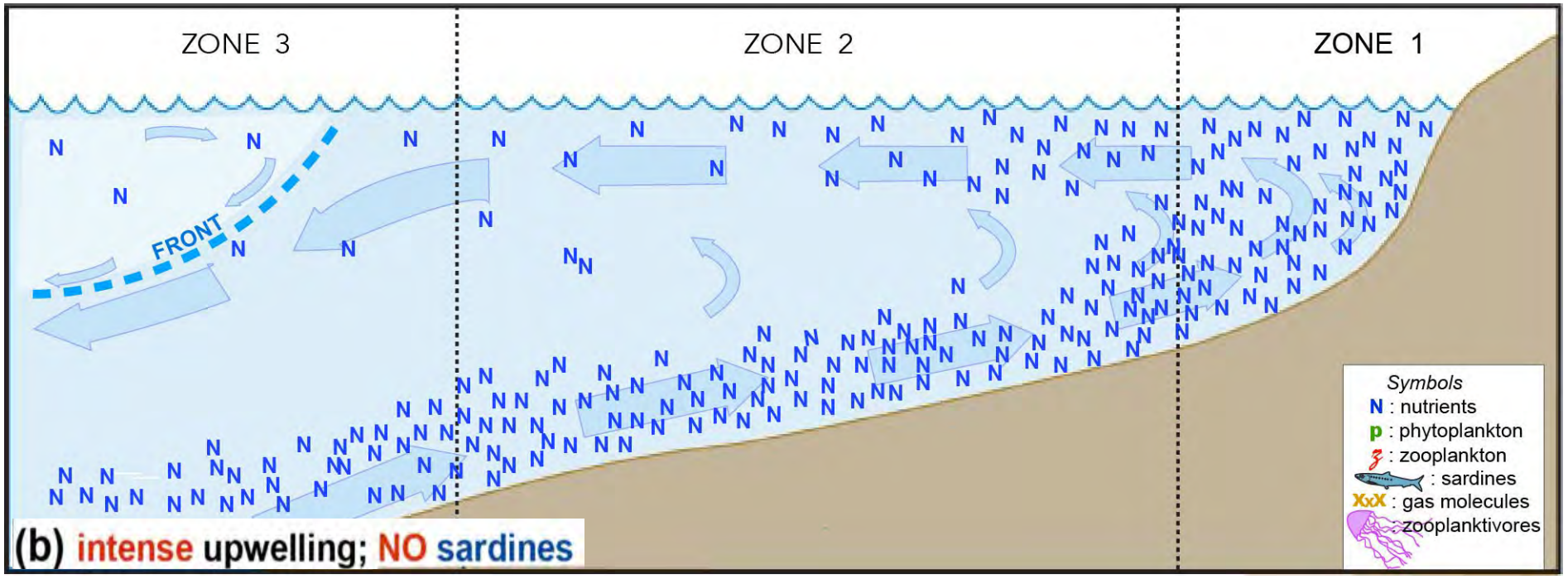
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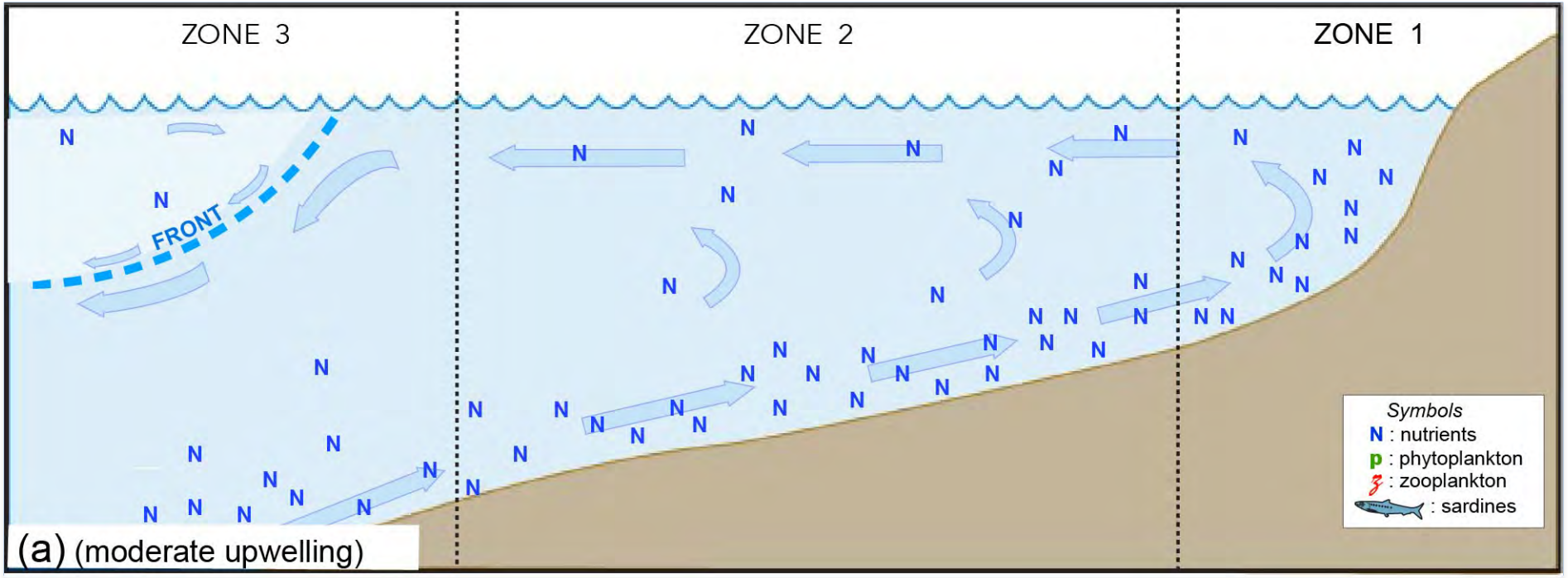
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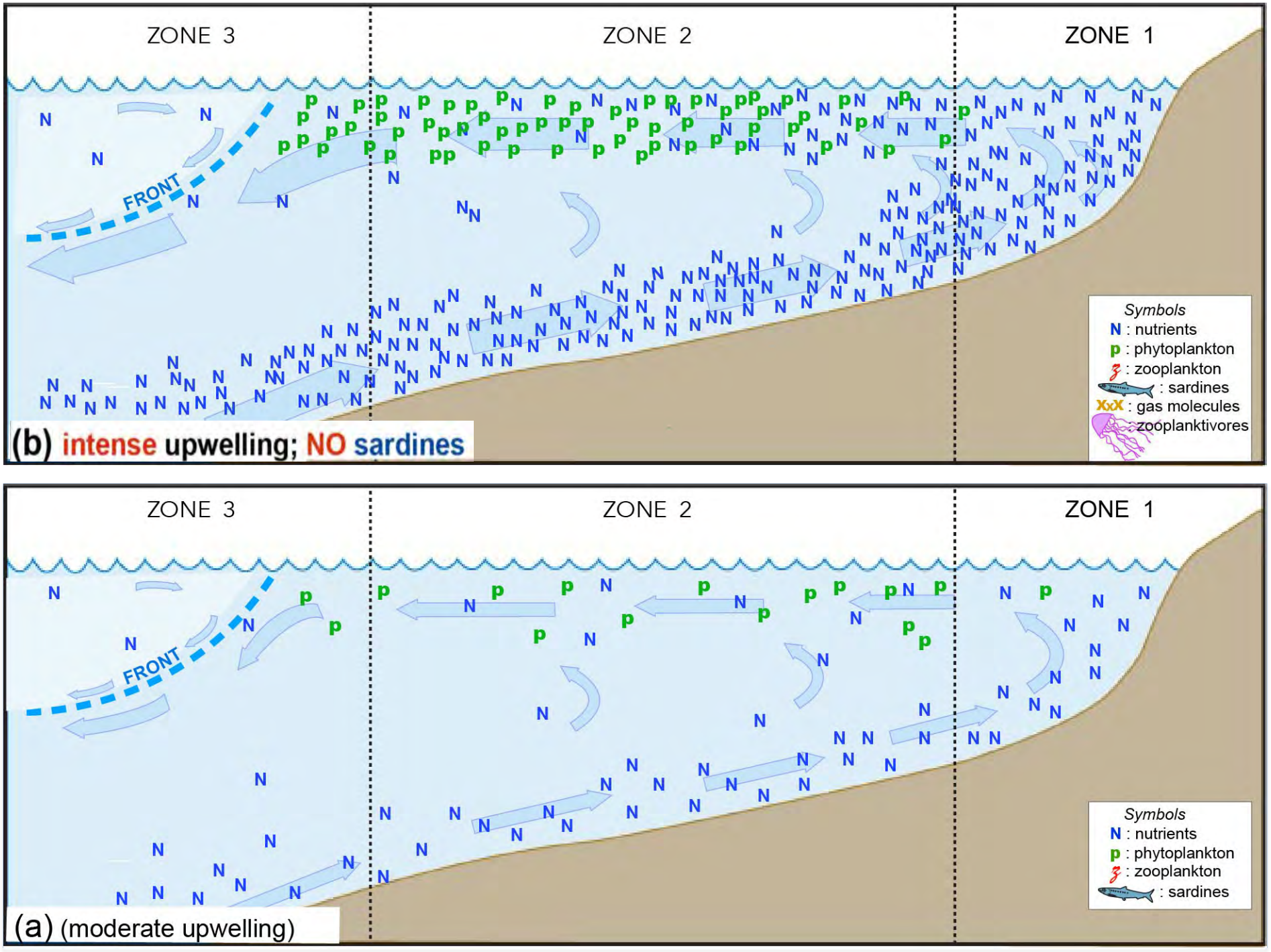
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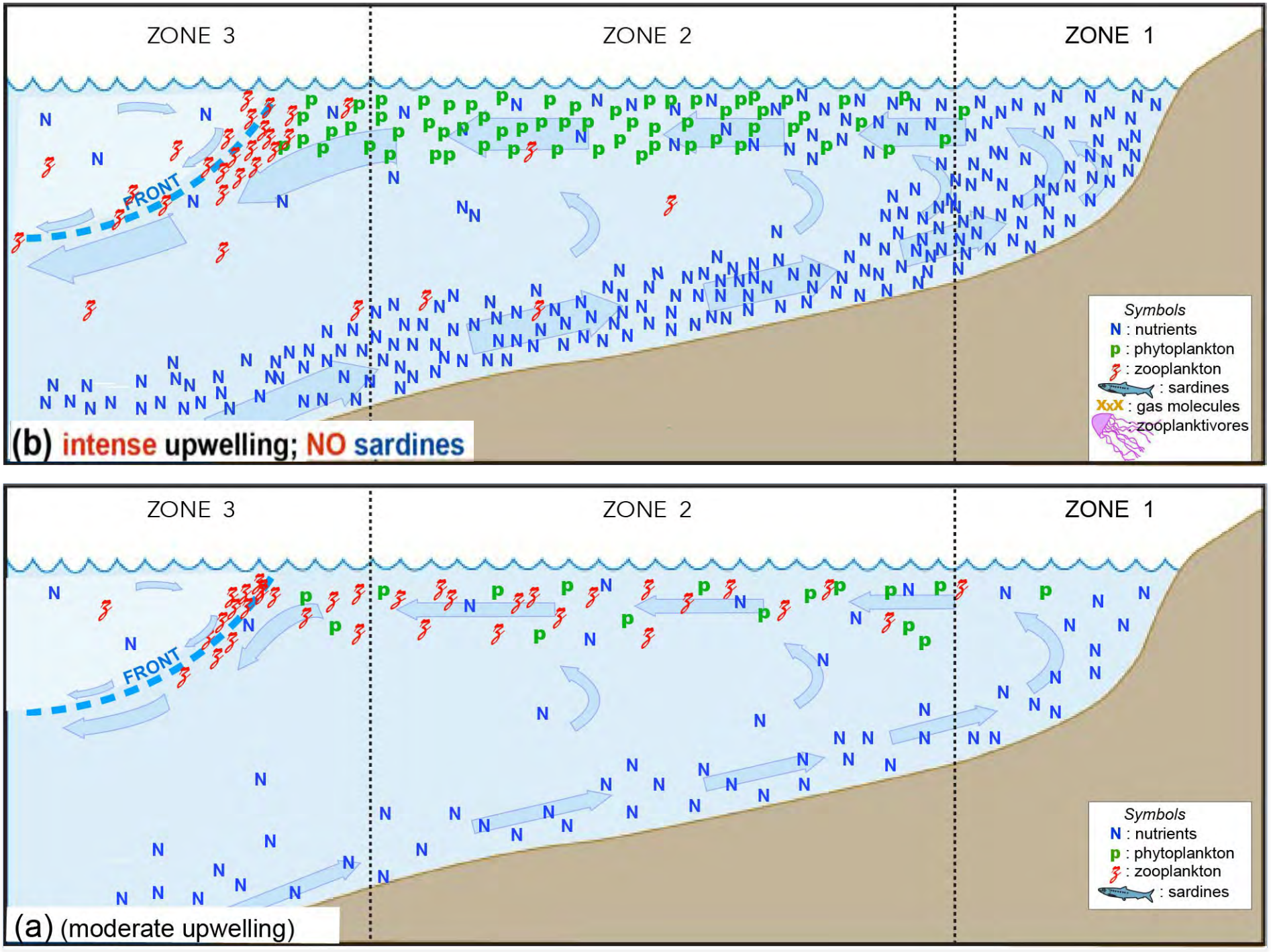
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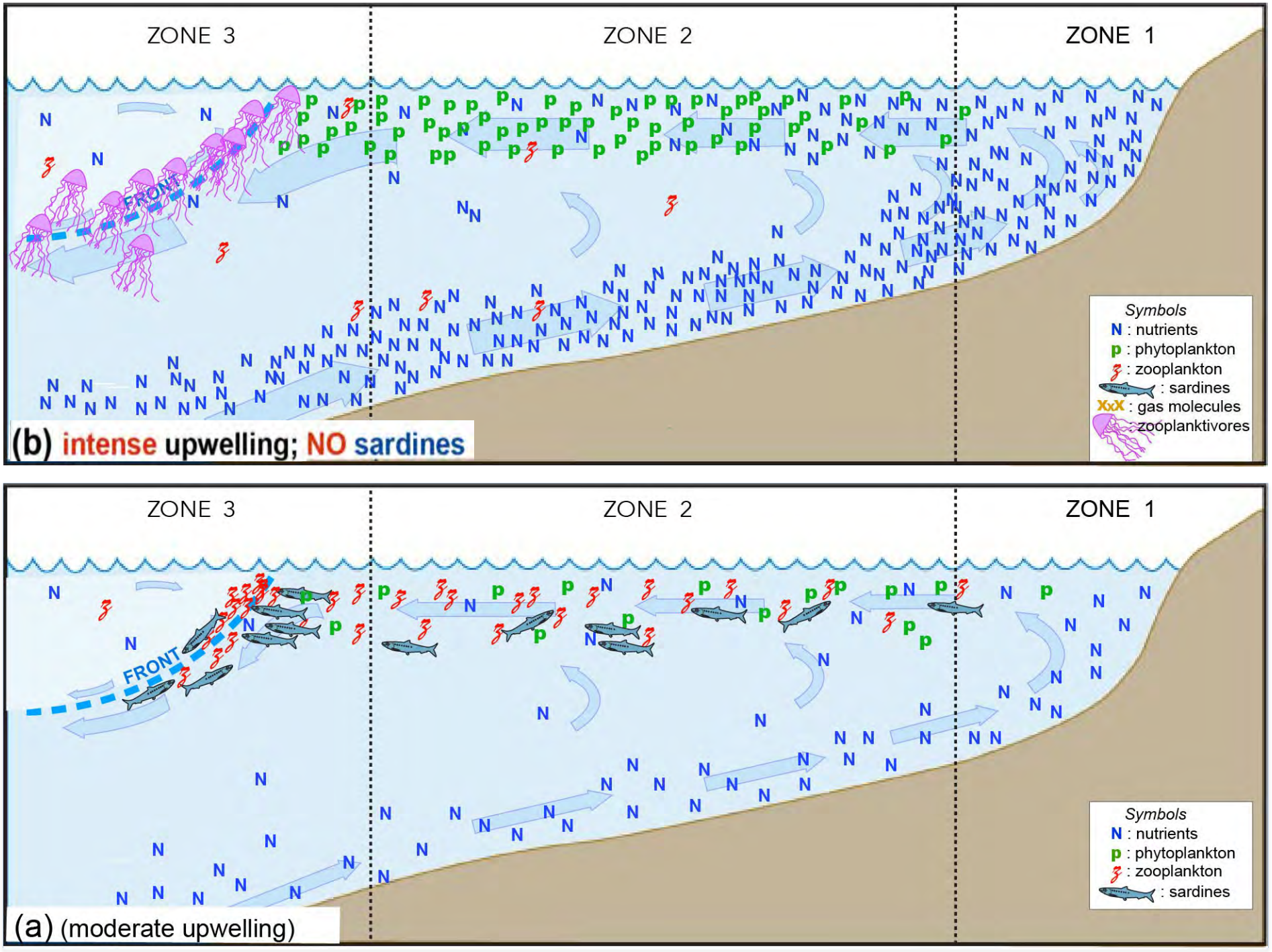
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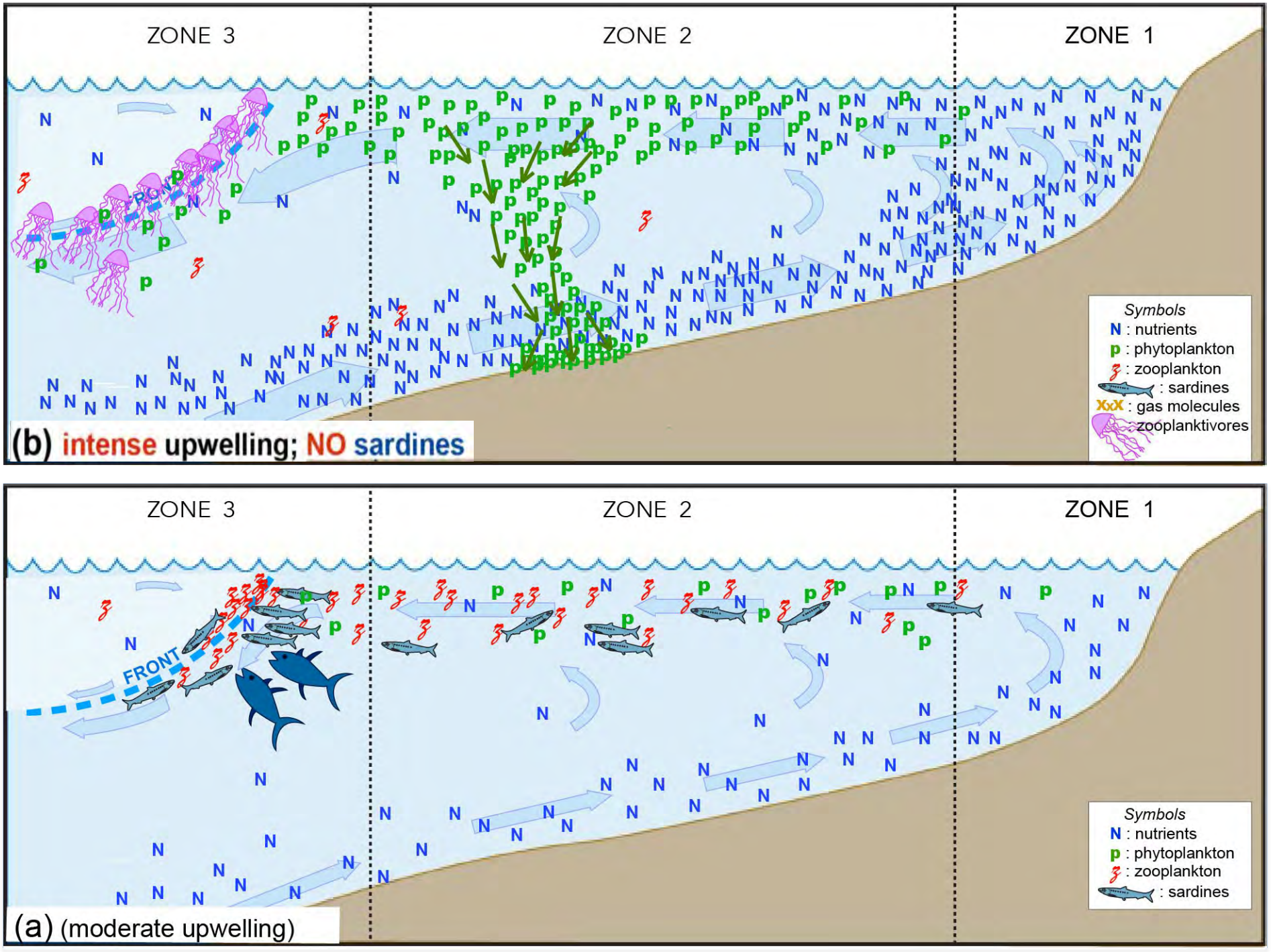
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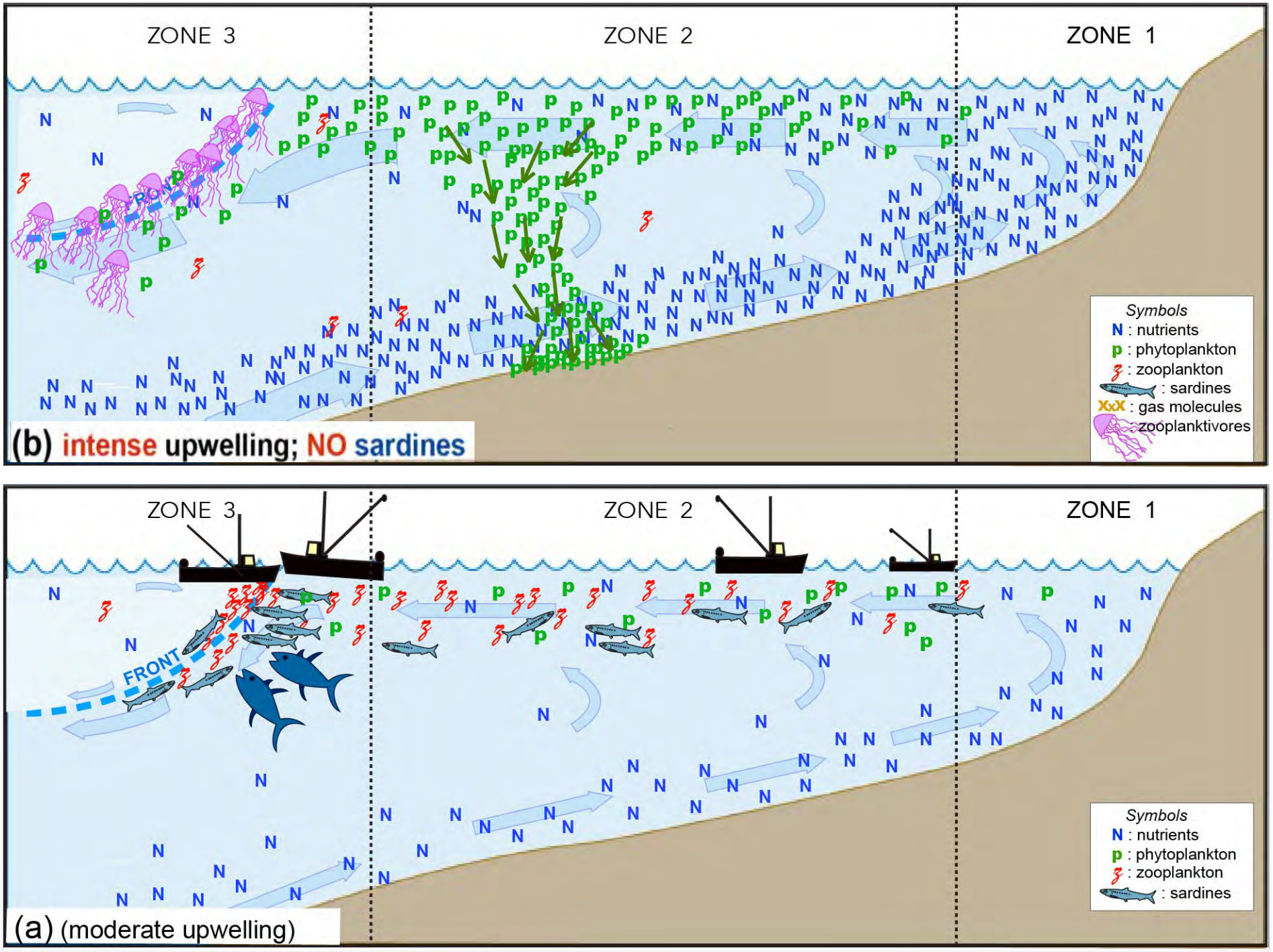
ZONE 3
ZONE 2
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(b) intense upwelling; NO sardines
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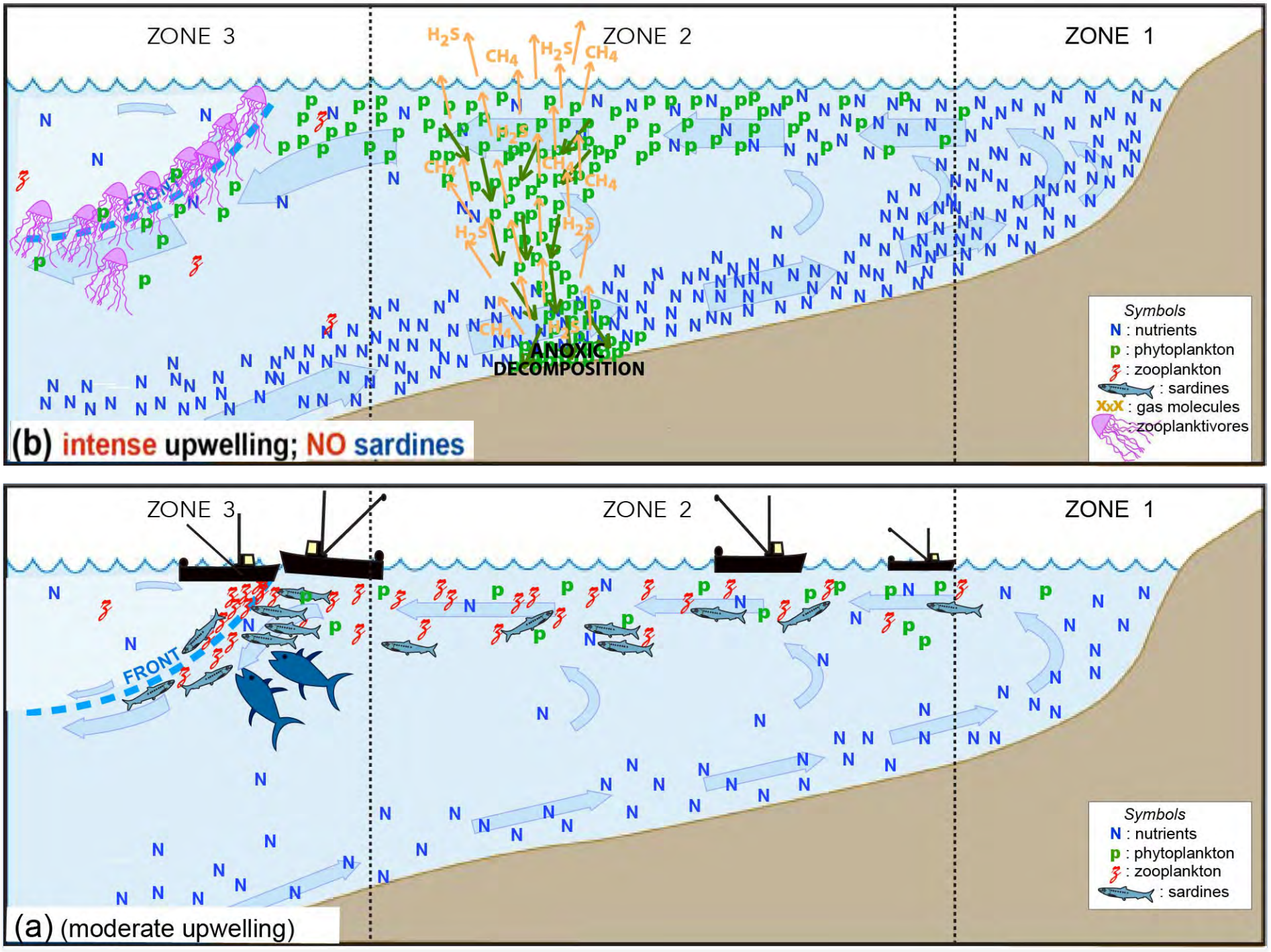
ZONE 3
ZONE 2
ZONE 1
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CH_4
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ANOXIC
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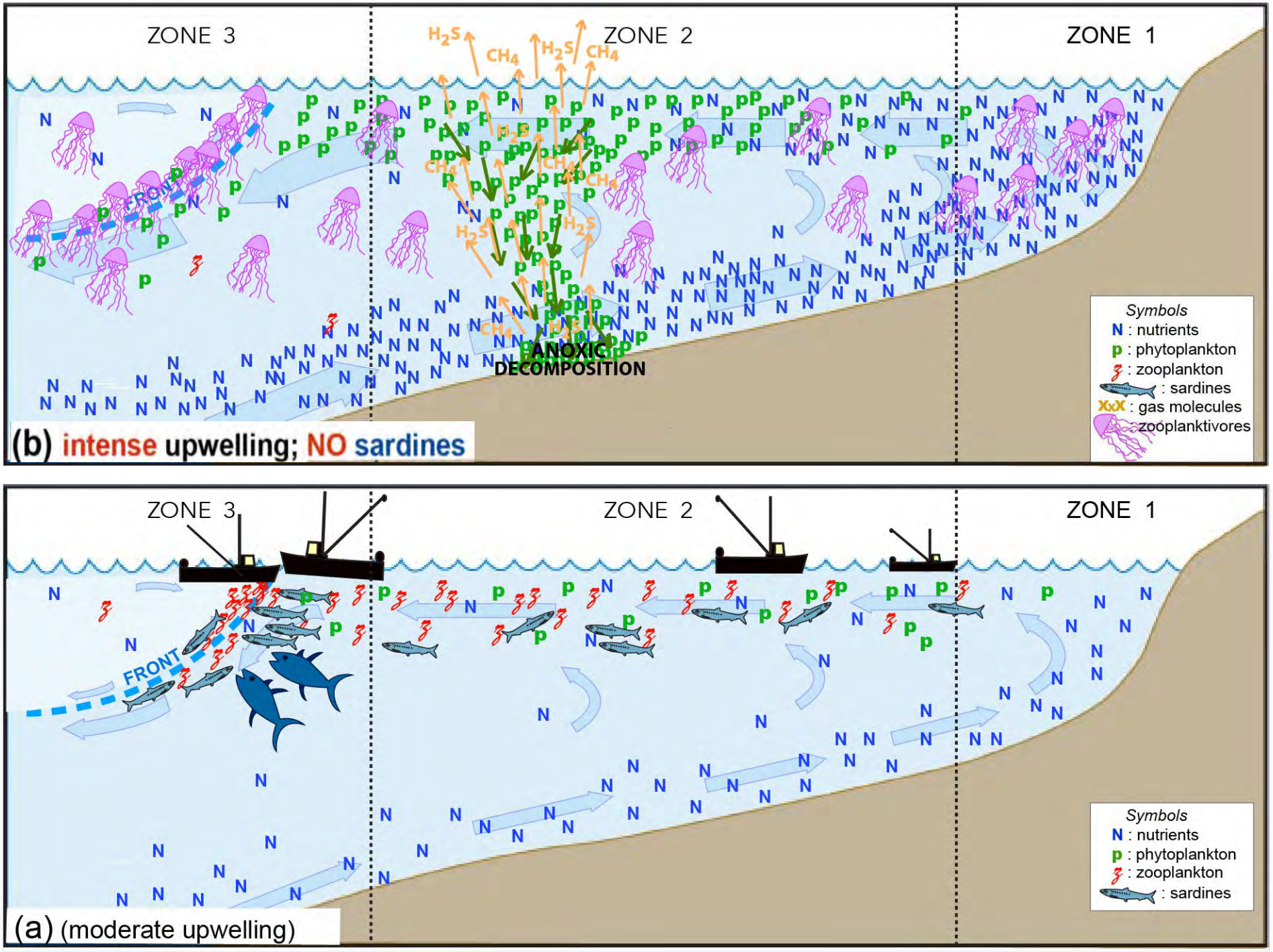
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What about the earlier suggestion that sardine abundance might be a “significant variable” in a “triggerable instability”?

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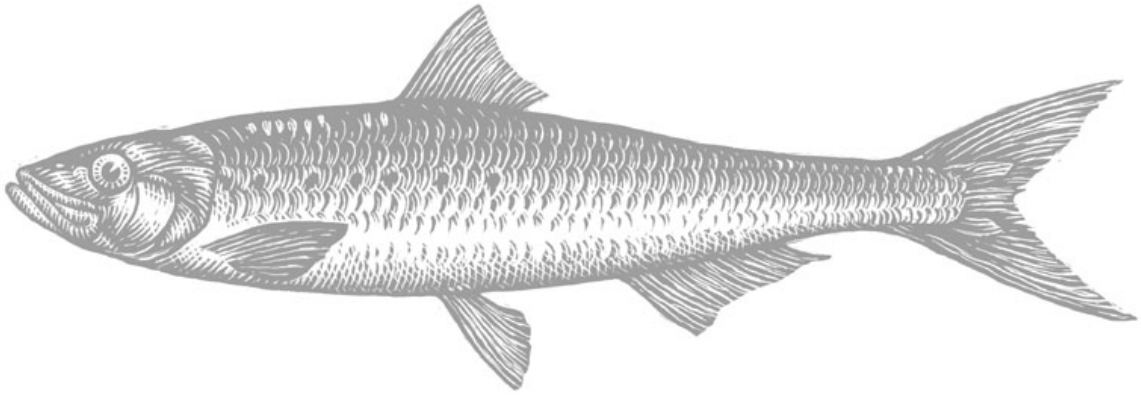
"... without speculation there is no good and original observation"

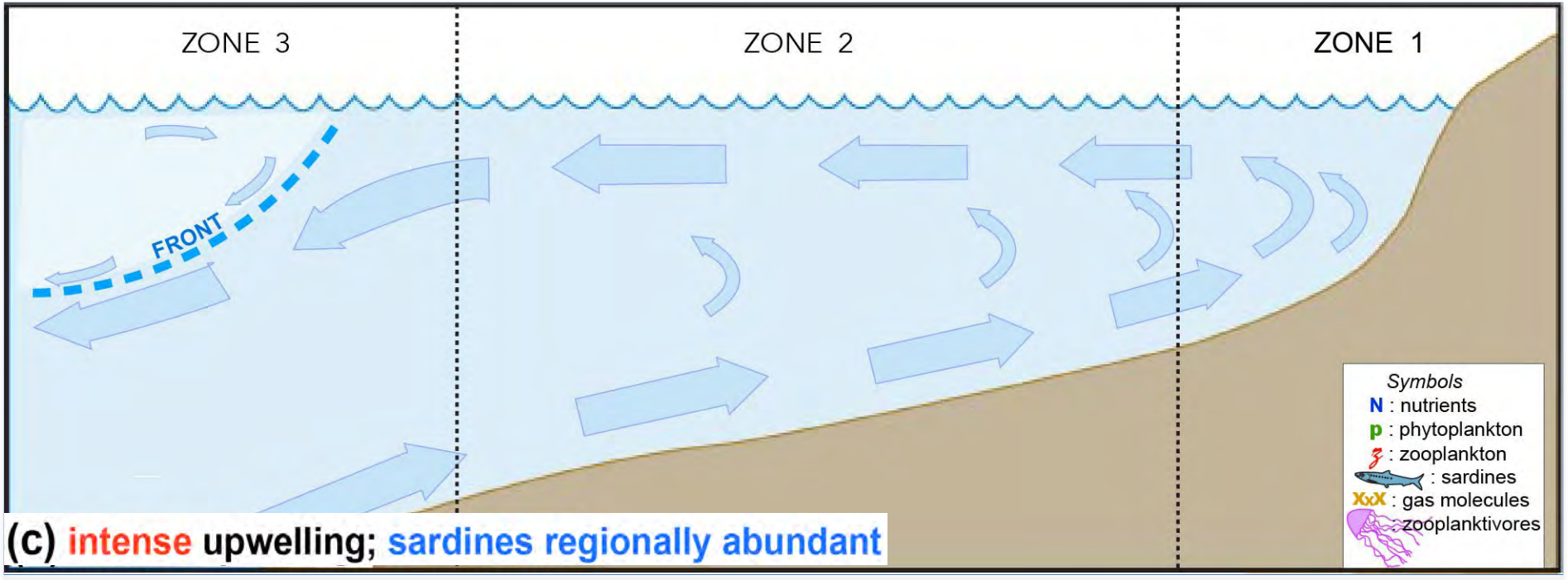
Charles Darwin, Letter to A. R. Wallace (22 Dec 1857). In Alfred Russel Wallace and Sir James Marchant (ed.), *Alfred Russel Wallace: Letters and Reminiscences* (1916), 109.

Sardine



Very strong swimmer and migrator

Very fine gillraker filter mesh



$$\frac{dp}{dt} = r_{(p)growth}p - r_{advection}p - r_{deposition}p - zc_{grazing}p - sc_{filtering}p + A_H\left(p_{>\lambda} - p\right) \quad (1)$$

$$\frac{dz}{dt} = r_{(z)growth}z - r_{advection}z - r_{predation}z + A_H\left(z_{>\lambda} - z\right) \quad (2)$$

$$\alpha \equiv r_{(p)growth} - r_{advection} - r_{deposition} - zc_{grazing} - sc_{filtering} - A_H \quad (3)$$

$$\gamma \equiv r_{(z)growth} - r_{advect} - r_{predation} - A_H \quad (4)$$

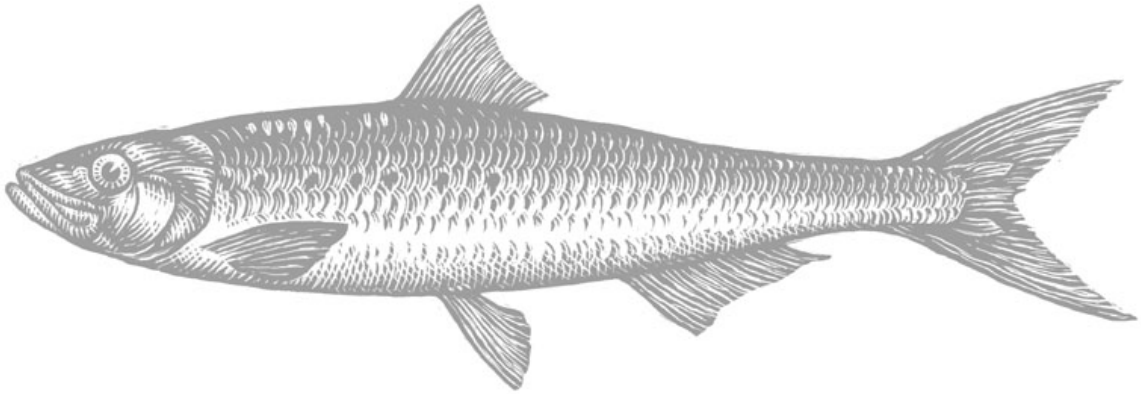
$$\frac{dp}{dt} = \alpha p + A_H p_{>\lambda} \quad (5)$$

$$\frac{dz}{dt} = \gamma z + A_H z_{>\lambda} \quad (6)$$

$$\frac{dp}{dt} = \left(\frac{dp}{dt}\right)_{t=to} e^{\alpha t} \quad (7)$$

$$\frac{dz}{dt} = \left(\frac{dz}{dt}\right)_{t=to} e^{\gamma t} \quad (8)$$

Sardine



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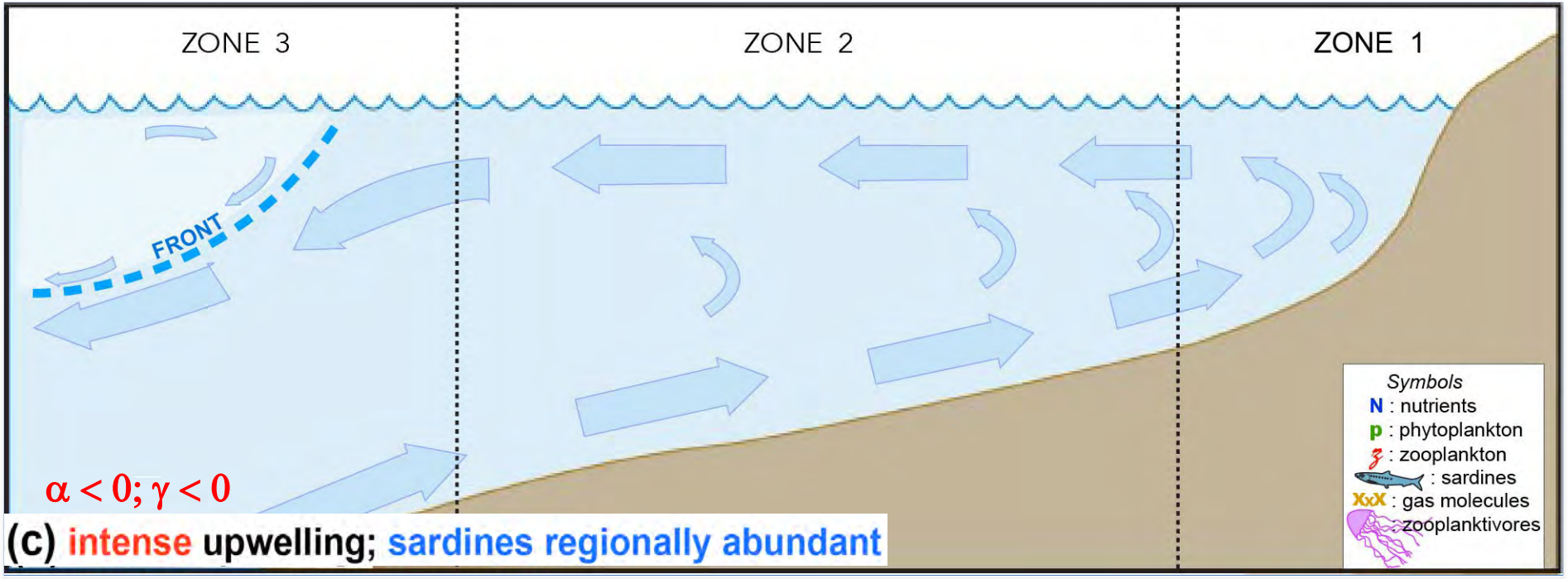

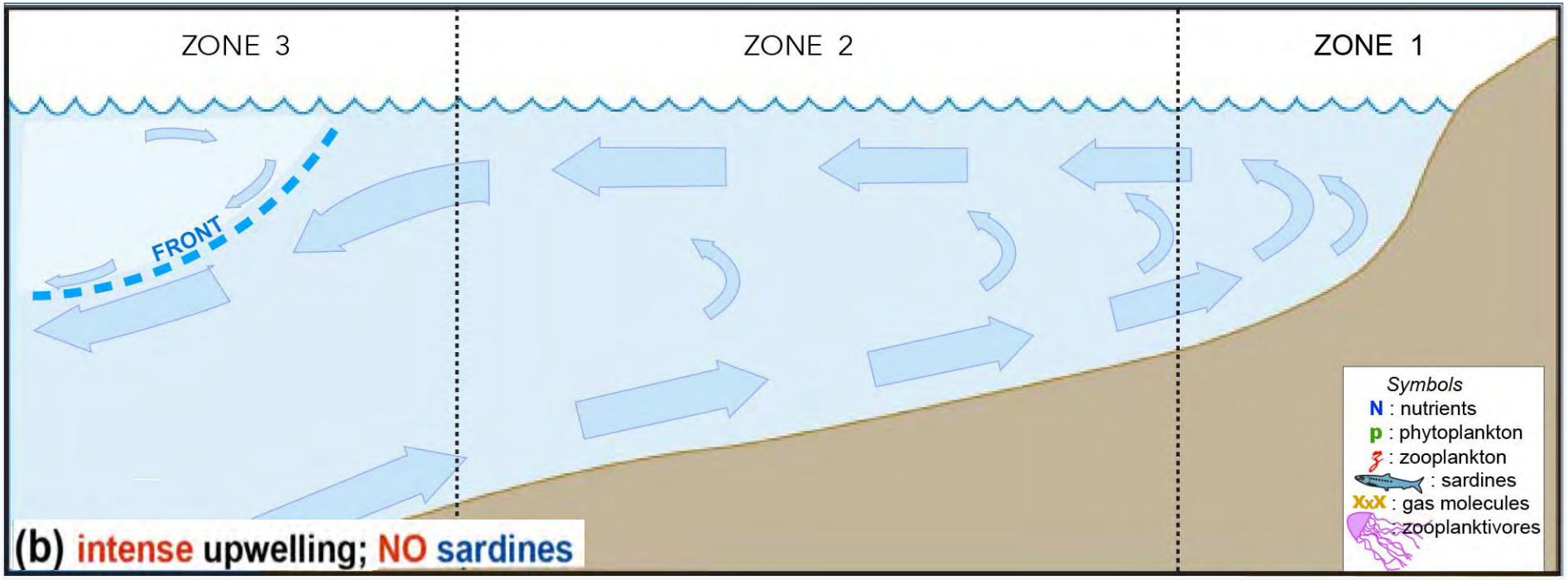
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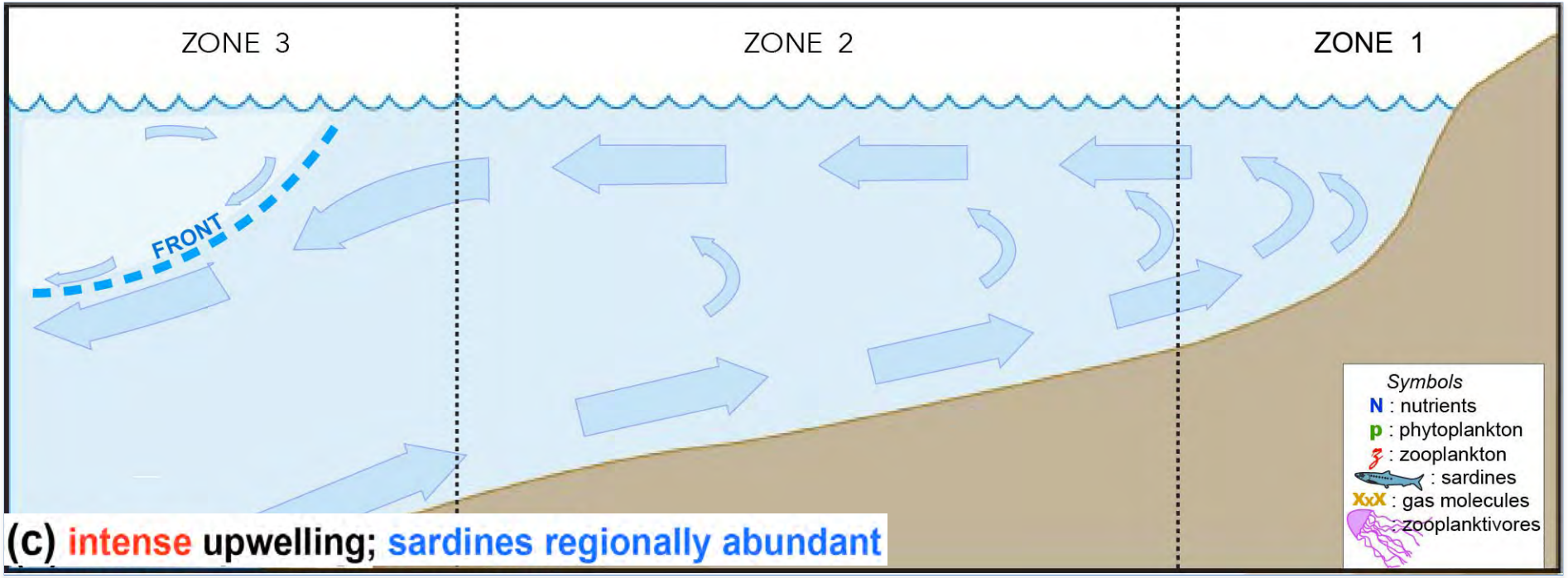
(b) intense upwelling; NO sardines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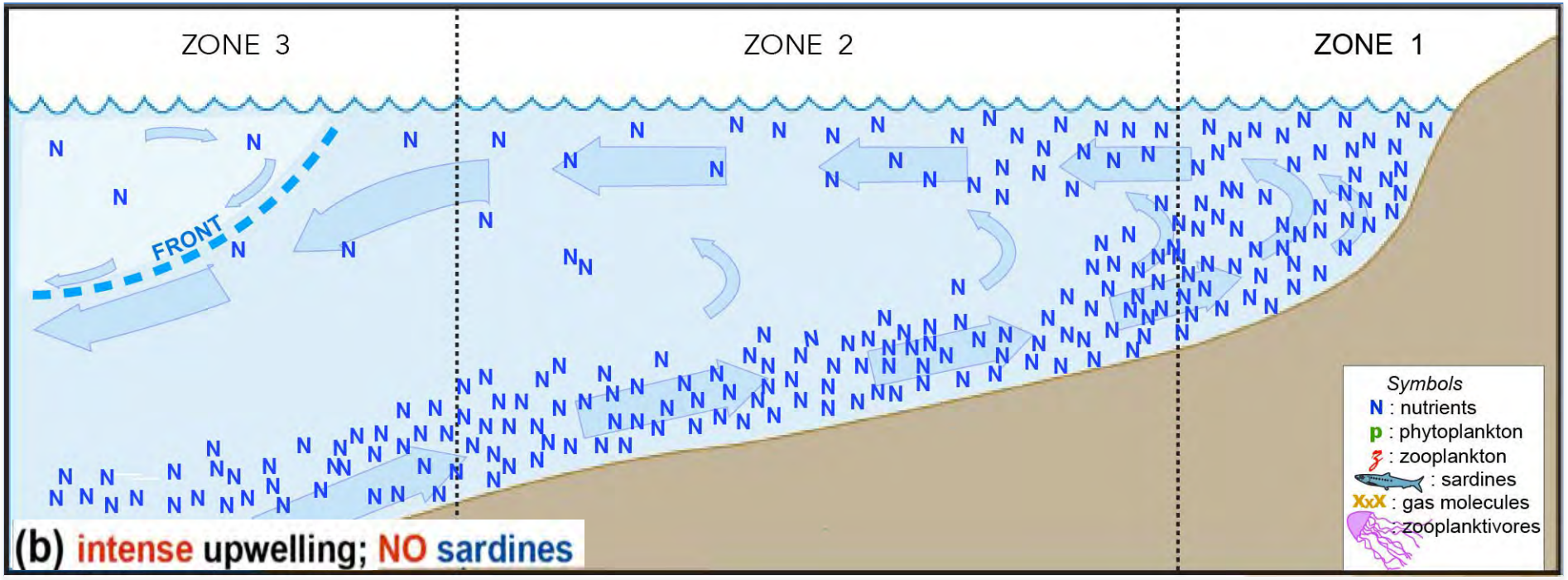
(c) intense upwelling; sardines regionally abundant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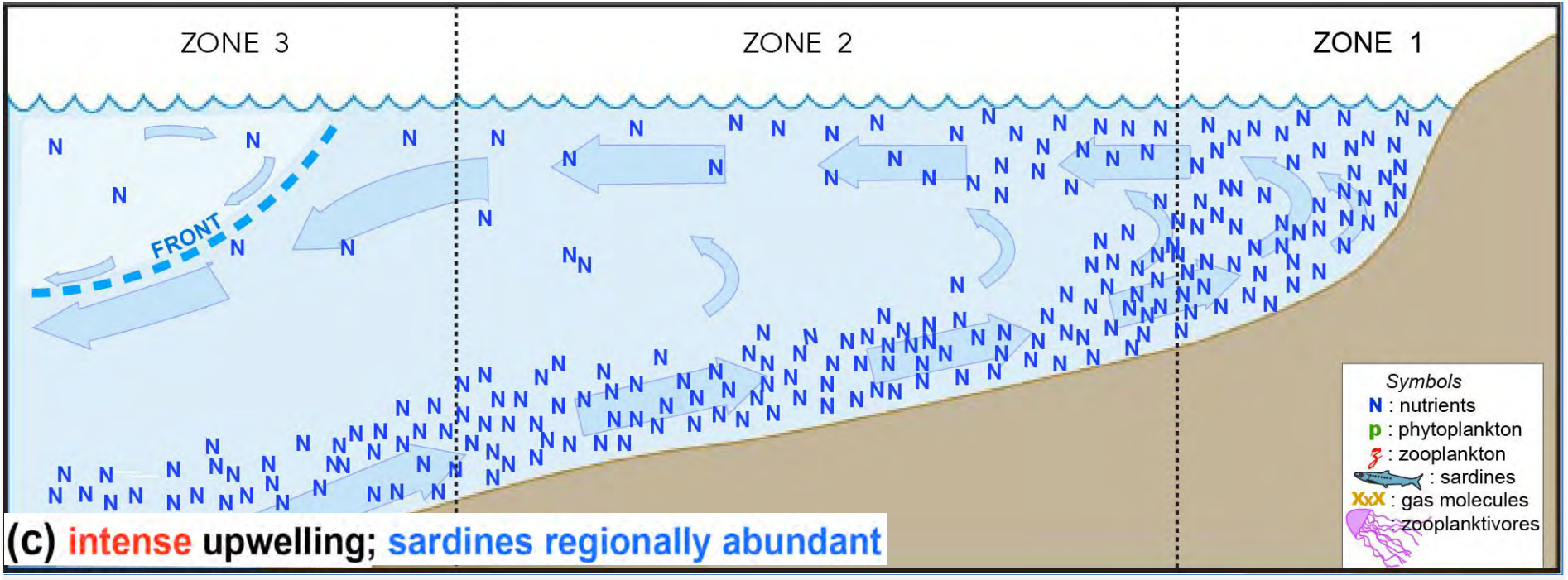
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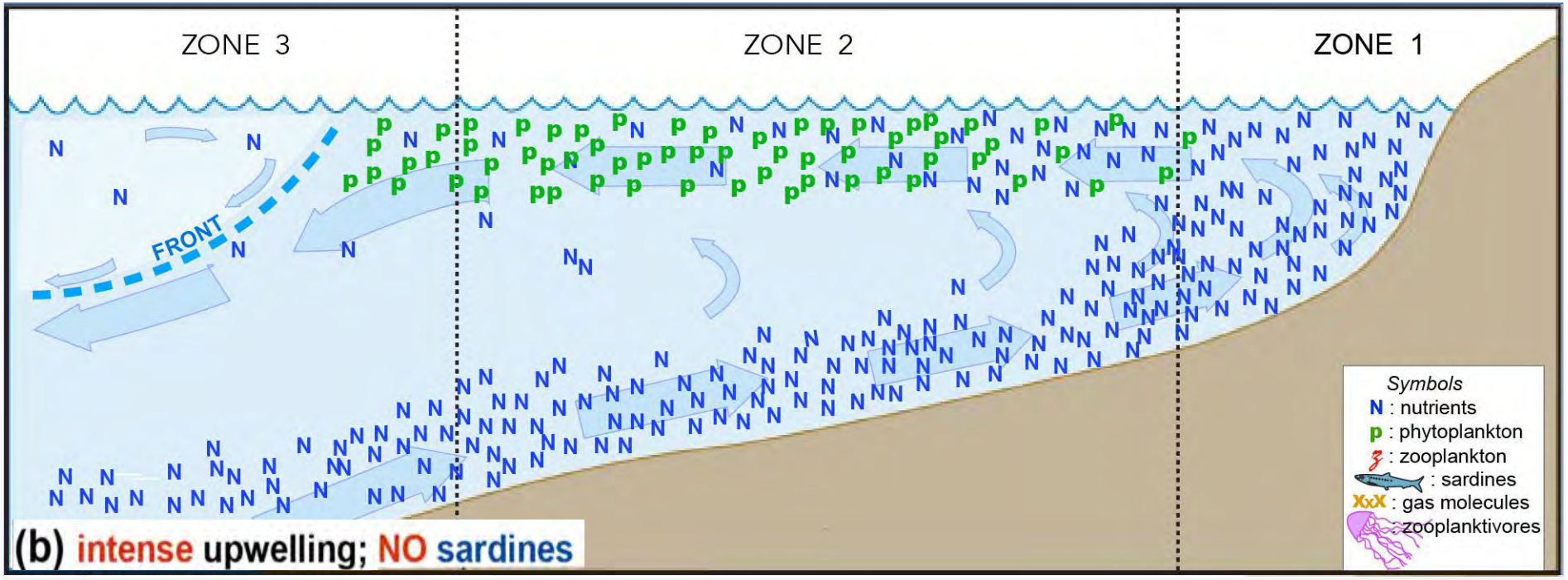
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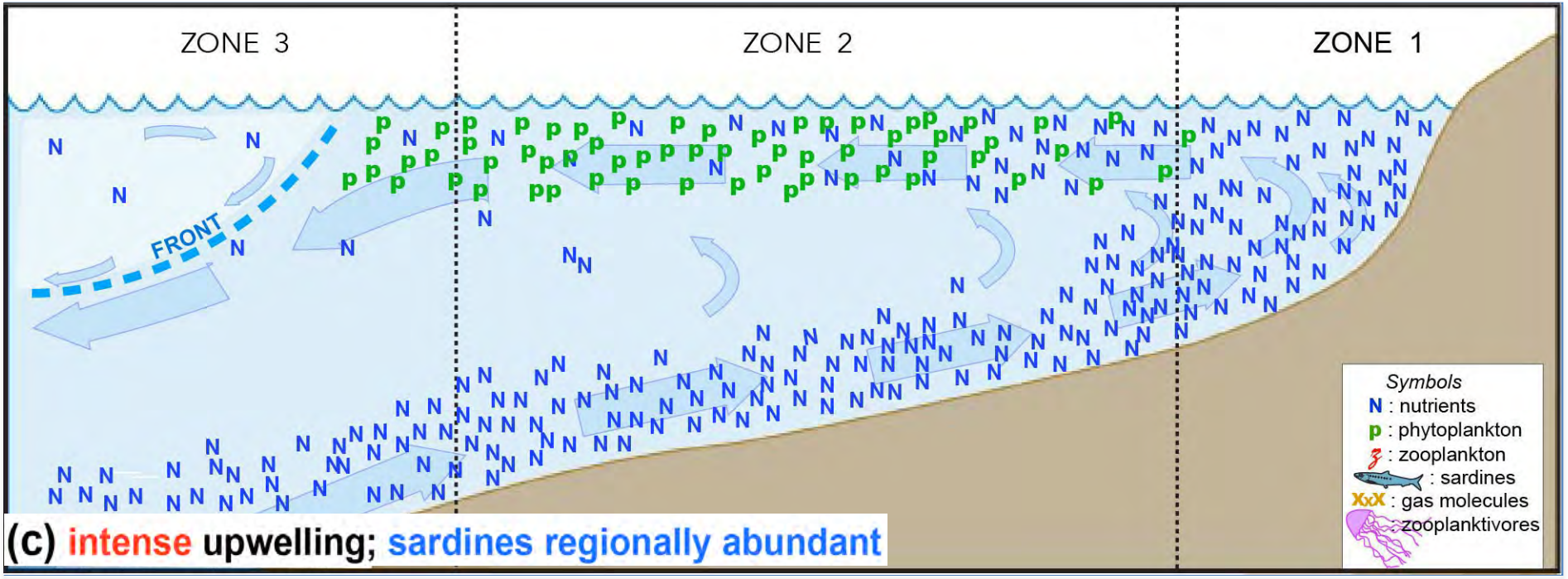
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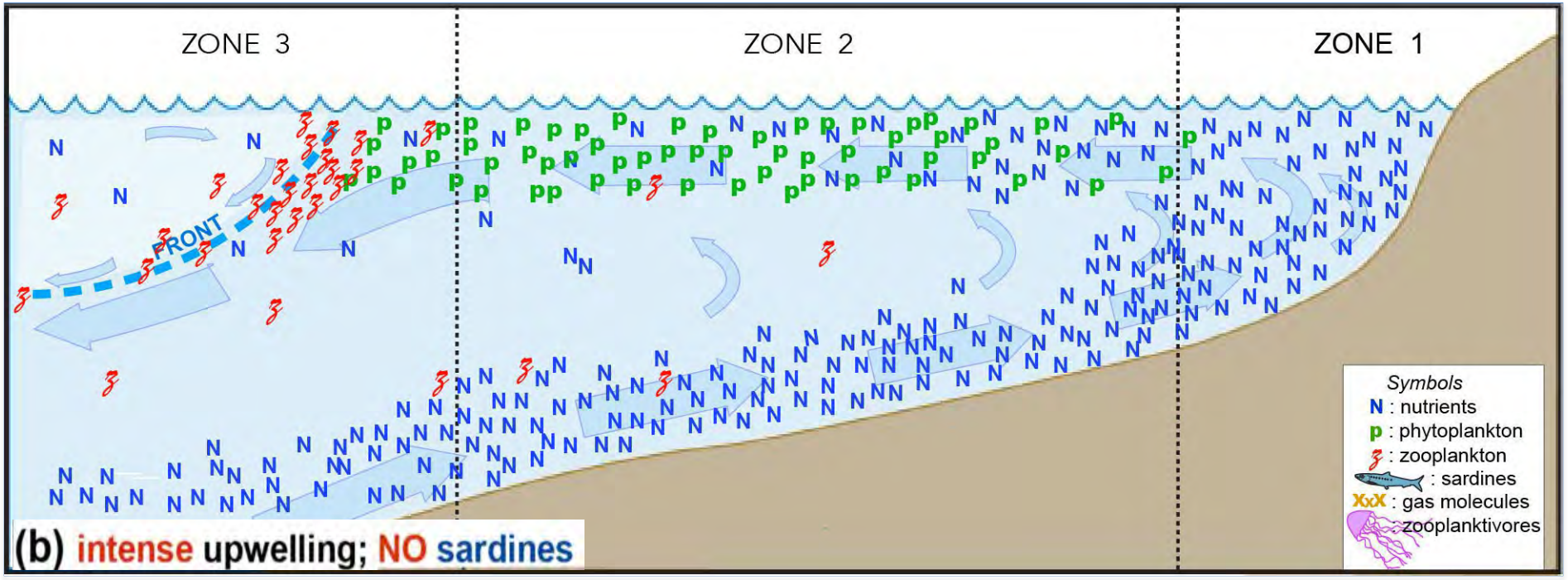
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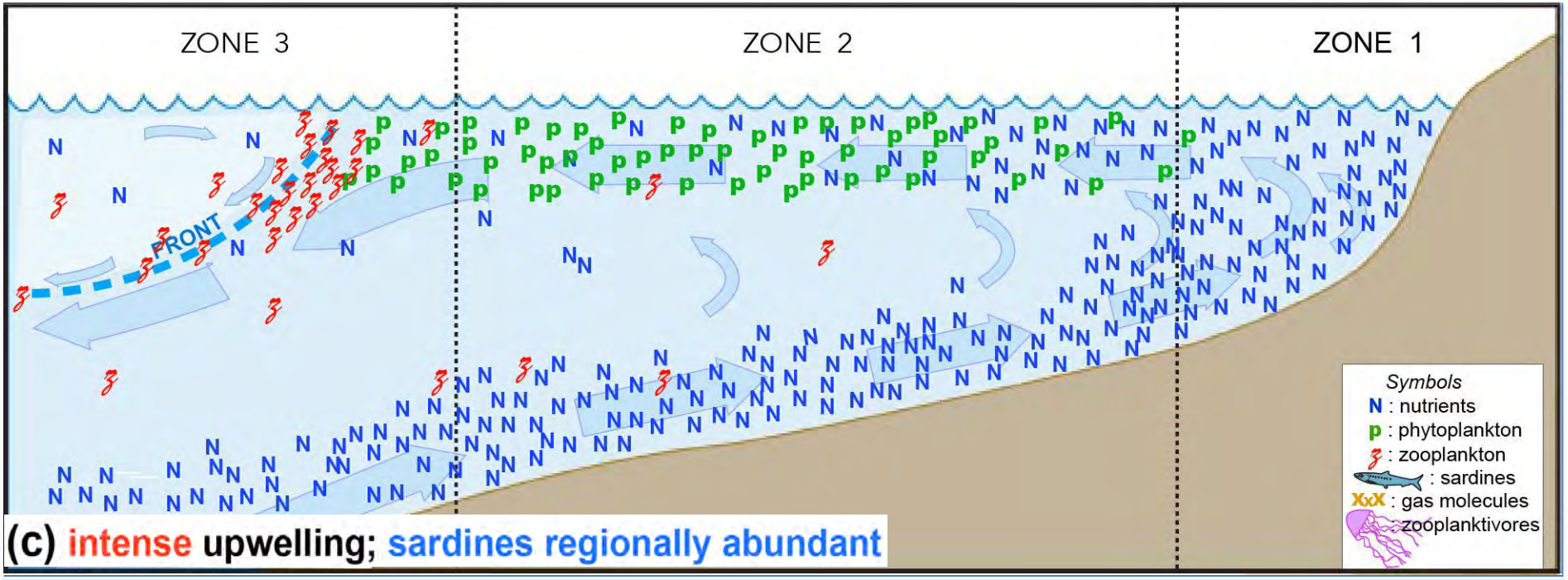
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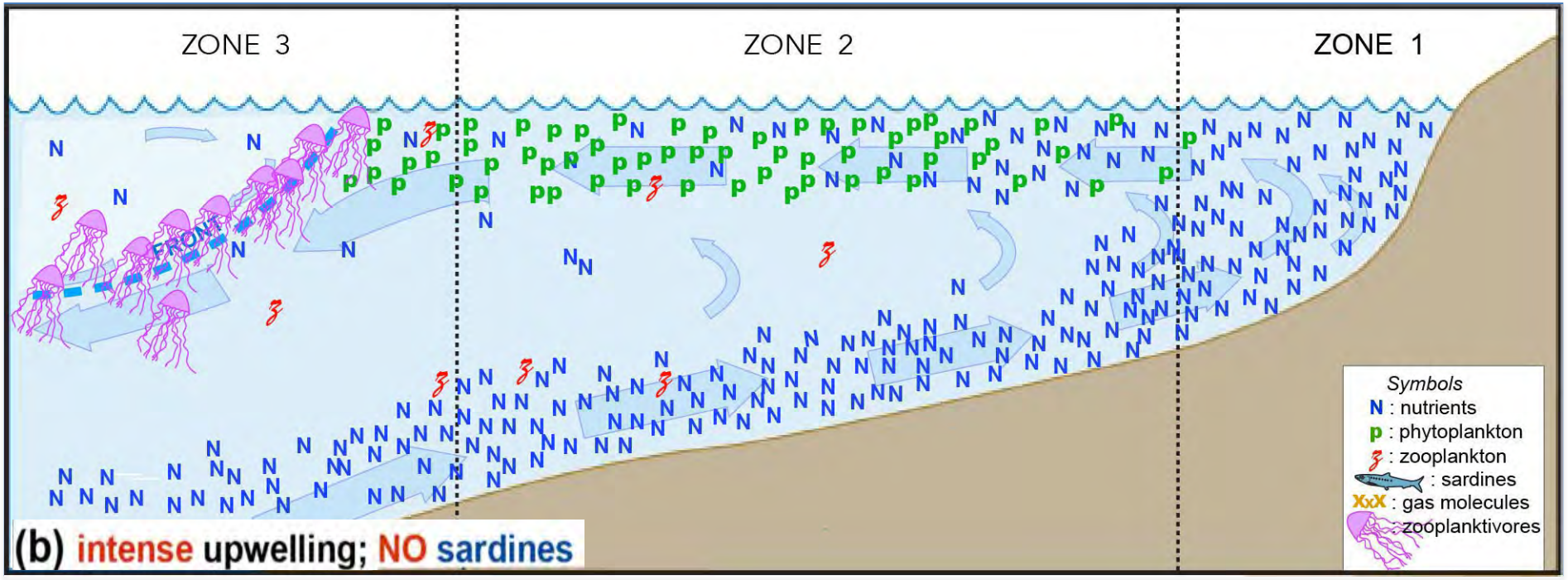
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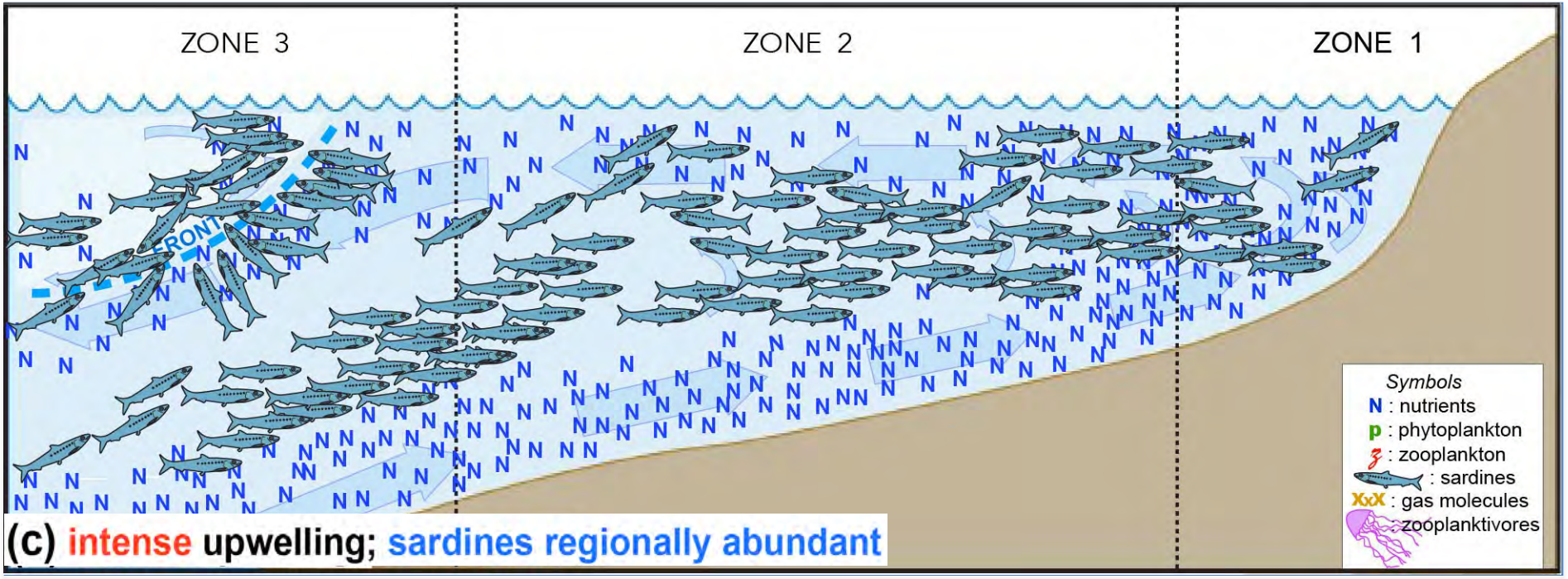
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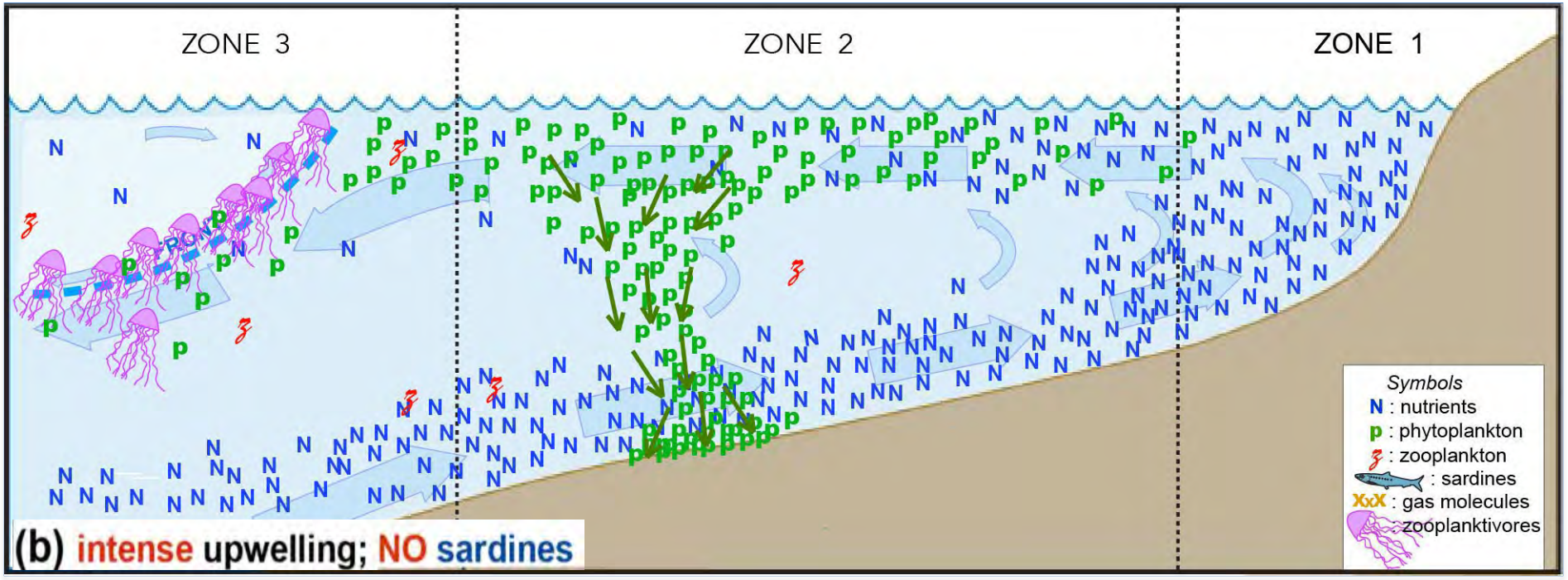
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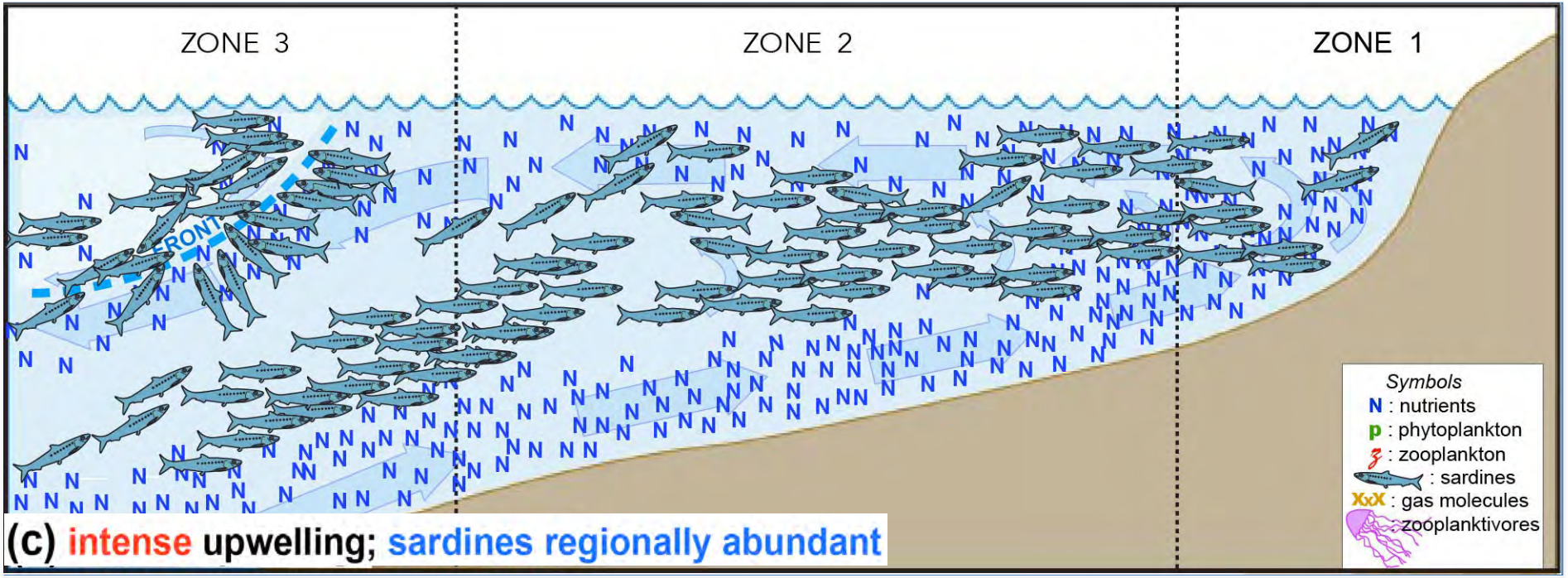
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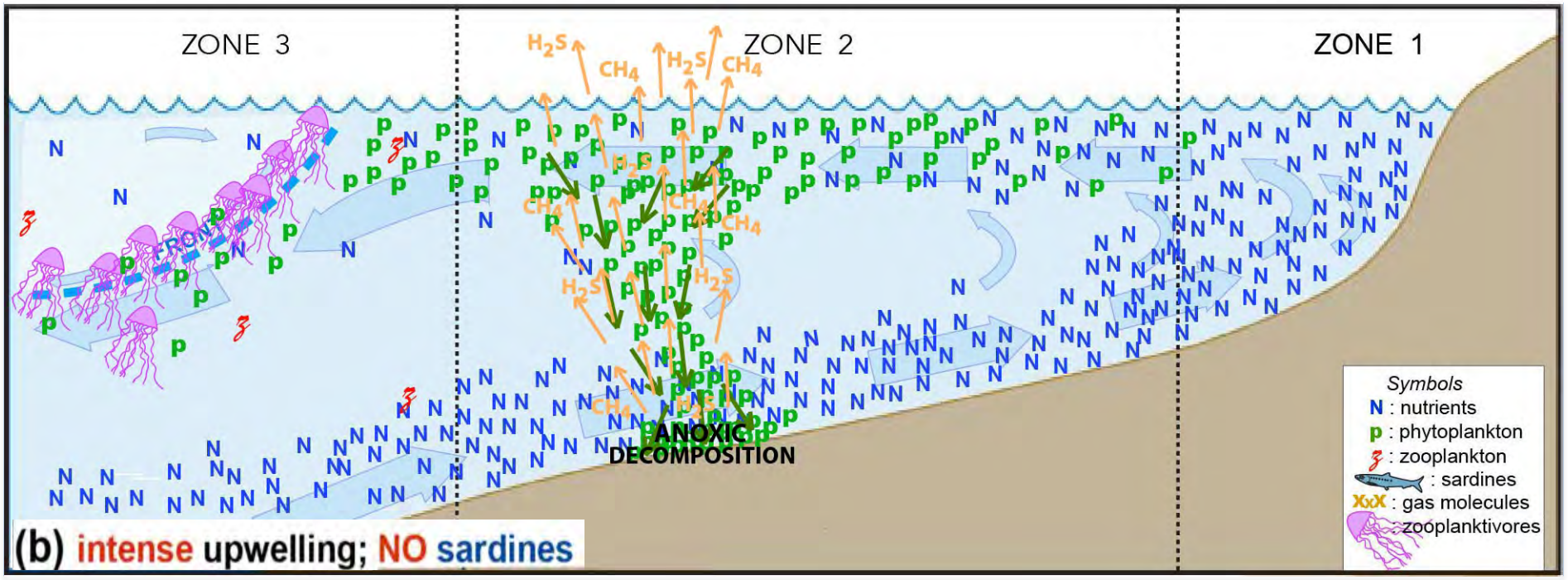
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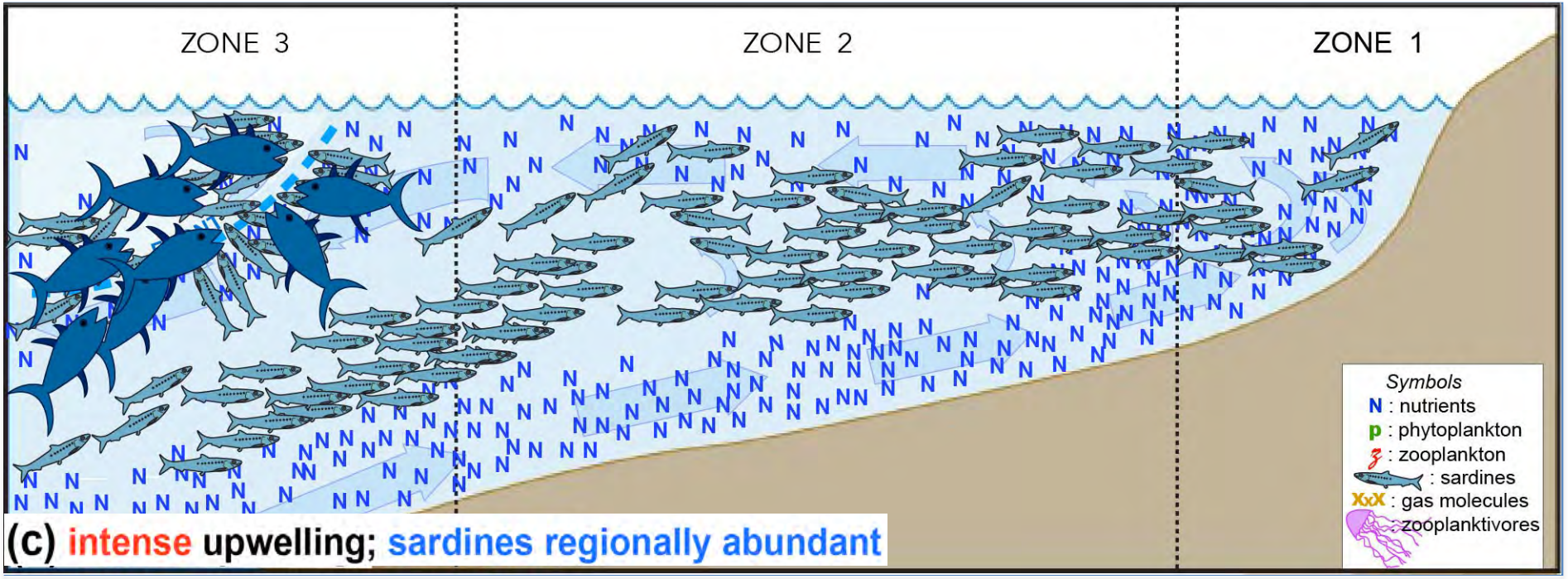
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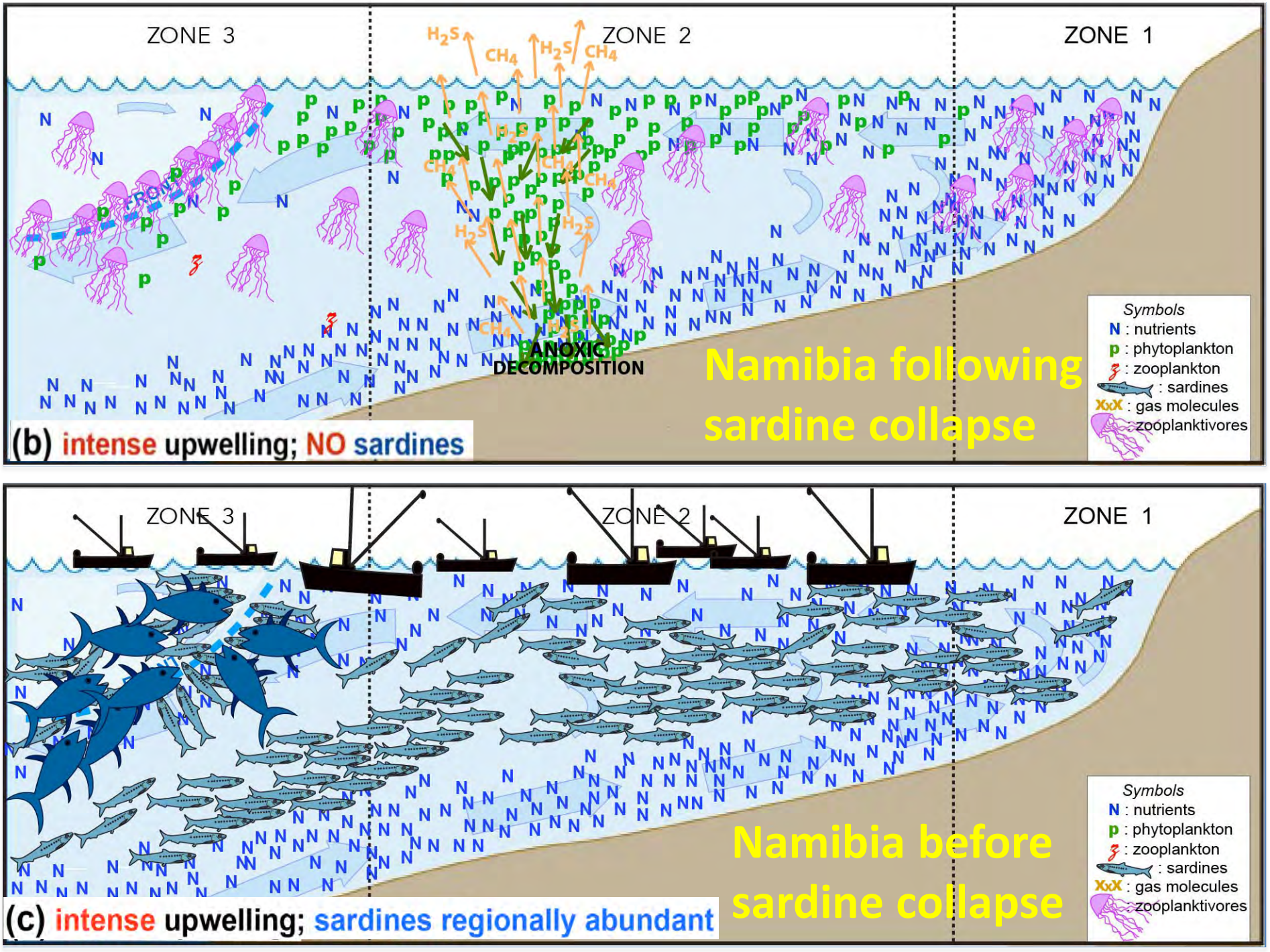
ZONE 3
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Namibia following
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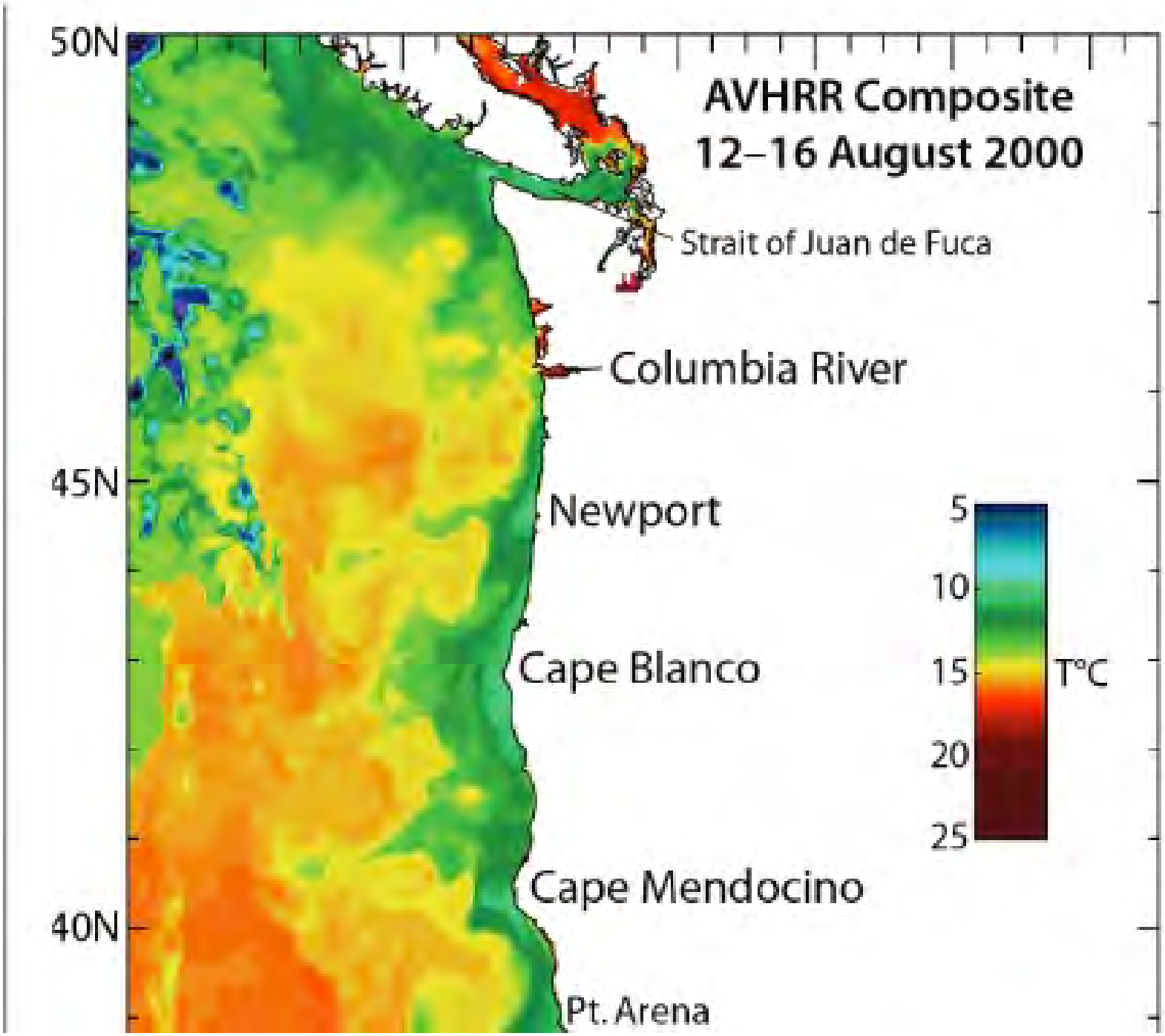
http://ceoas.oregonstate.edu/about/files/OceanOffOregon.pdf



‘Dead Zone’ Reappears Off the Oregon Coast

By CORNELIA DEAN
Published: August 6, 2008

For the fifth year in a row, unusual wind patterns off the coast of Oregon have produced a large “dead zone,” an area so low in oxygen that fish and crabs suffocate.

The zone occupies a space roughly the size of Rhode Island.

This dead zone is unlike those in the Gulf of Mexico and elsewhere, which result from fertilizer, sewage or runoff from hog or poultry operations carried by rivers. The Oregon zone appears when the wind generates strong currents carrying nutrient-rich but oxygen-poor water from the deep sea to the surface near shore, a process called upwelling.

The nutrients encourage the growth of plankton, which eventually dies and falls to the ocean floor. Bacteria there consume the plankton, using up oxygen.

Jane Lubchenco, a marine biologist at Oregon State University, said the phenomenon did not appear to be linked to recurring El Niño or La Niña currents or to long-term cycles of ocean movements. That made Dr. Lubchenco wonder if climate change might be a factor, she said, adding, “There is no other cause, as far as we can determine.”

Readers’ Opinions

Forum: The Environment

The dead zone, which appears in late spring and lasts a matter of weeks, has quadrupled in size since it first appeared in 2002 and this year covers about 1,235 square miles, an area about as large as Rhode Island, Dr. Lubchenco said.

Is dead zone spreading to Washington?

Scientists have documented a large pool of oxygen-poor water off Oregon's coast, and reports of dead crab and fish from Washington suggest it may extend much farther north.

Moclips to the Quinault River: Several species of dead fish washed up on the beach. Tribal fishermen reported dead crab in pots.

Westport: Commercial fishermen also have reported dead crab in their pots.

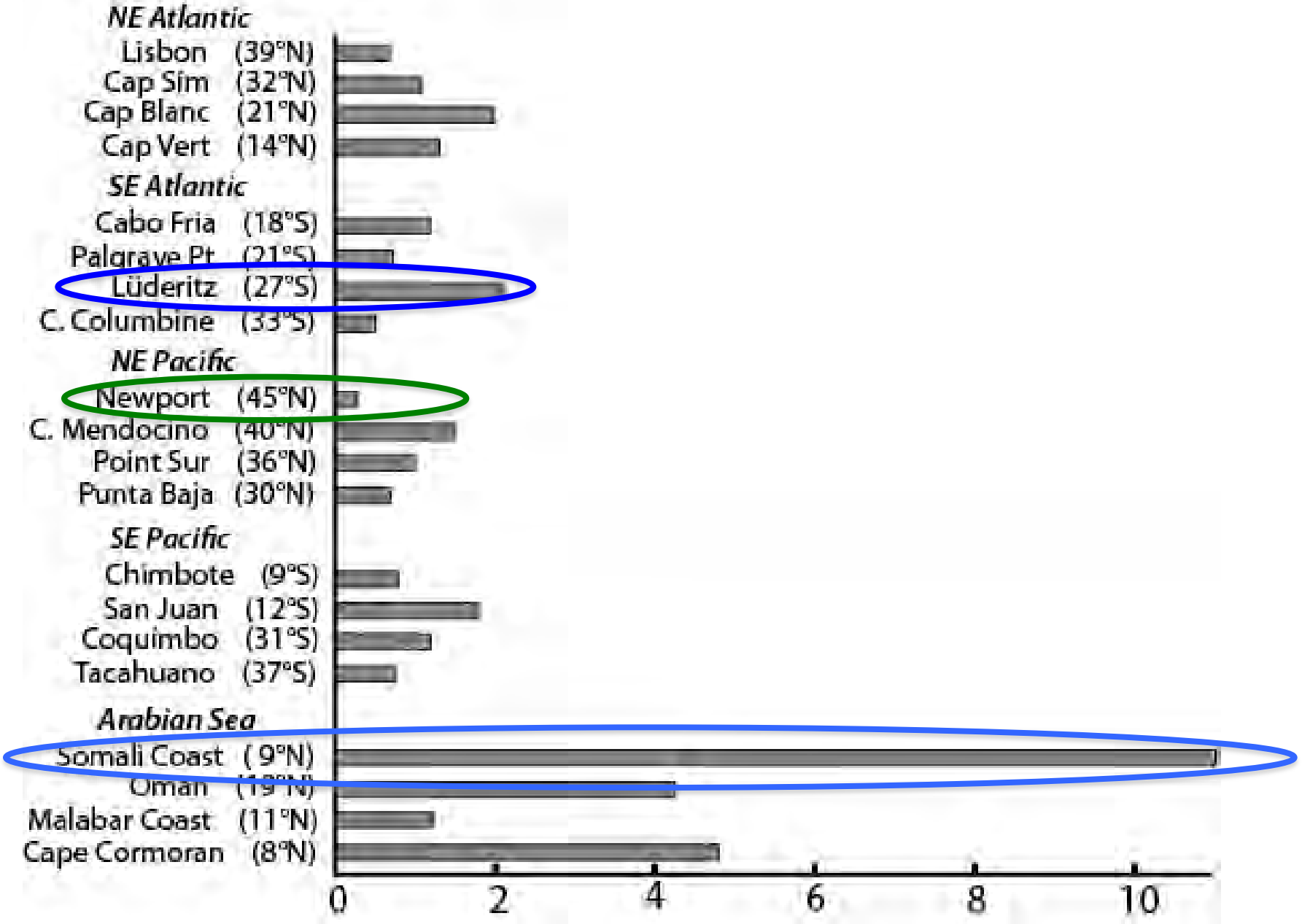
Kalaloch to Copalis: Preliminary data show low dissolved oxygen levels. Volunteers report large numbers of dead crab on the beach.

Sources: ESRI, TeleAtlas, Oregon State University

MARK NOWLIN / THE SEATTLE TIMES

“. . . without speculation there is no good and original observation”

Charles Darwin, Letter to A. R. Wallace (22 Dec 1857). In Alfred Russel Wallace and Sir James Marchant (ed.), *Alfred Russel Wallace: Letters and Reminiscences* (1916), 109.


NE Atlantic
Lisbon (39°N)
Cap Sim (32°N)
Cap Blanc (21°N)
Cap Vert (14°N)
SE Atlantic
Cabo Fria (18°S)
Palgrave Pt (21°S)
Lüderitz (27°S)
C. Columbine (33°S)
NE Pacific
Newport (45°N)
C. Mendocino (40°N)
Point Sur (36°N)
Punta Baja (30°N)
SE Pacific
Chimbote (9°S)
San Juan (12°S)
Coquimbo (31°S)
Tacahuano (37°S)
Arabian Sea
Somali Coast (9°N)
Oman (19°N)
Malabar Coast (11°N)
Cape Cormoran (8°N)
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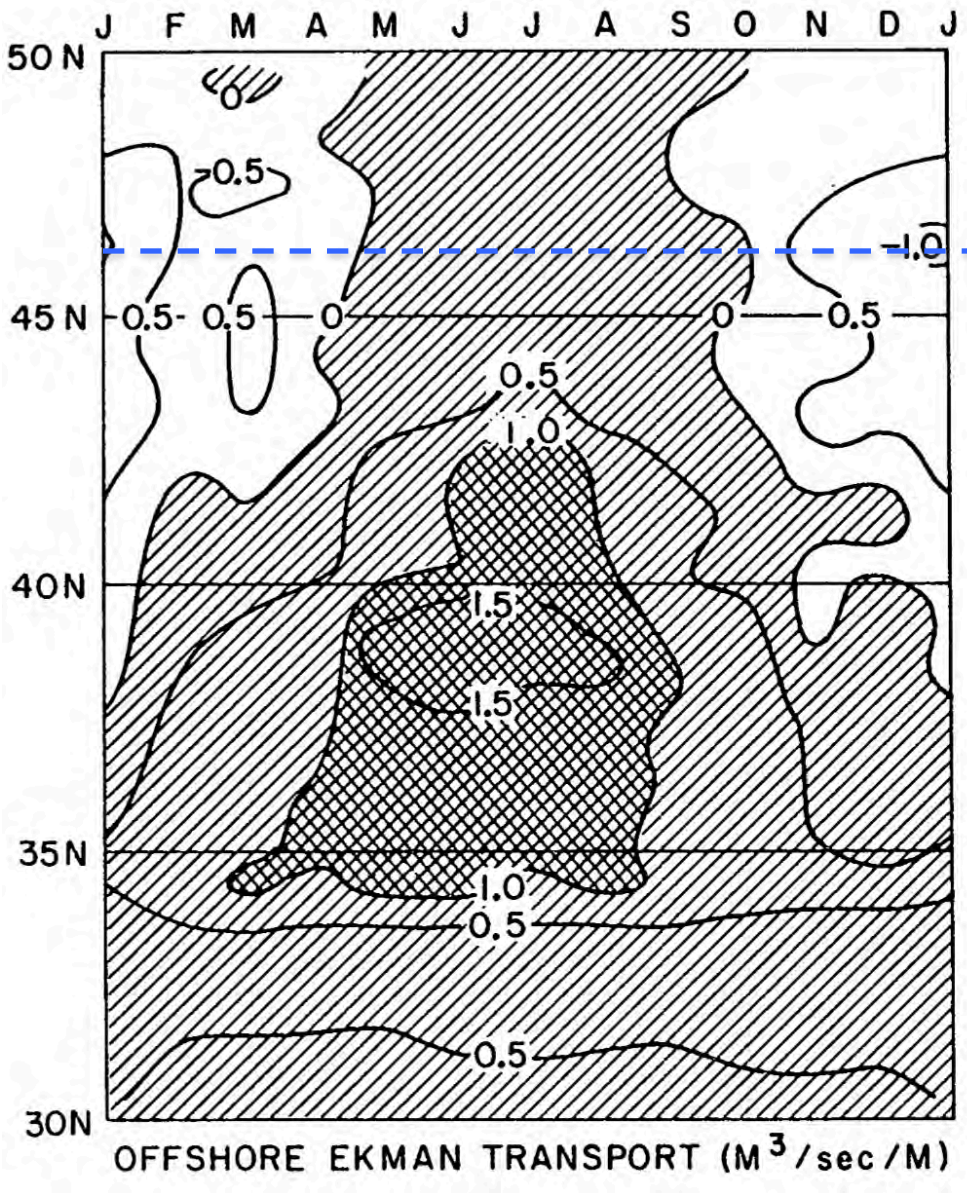
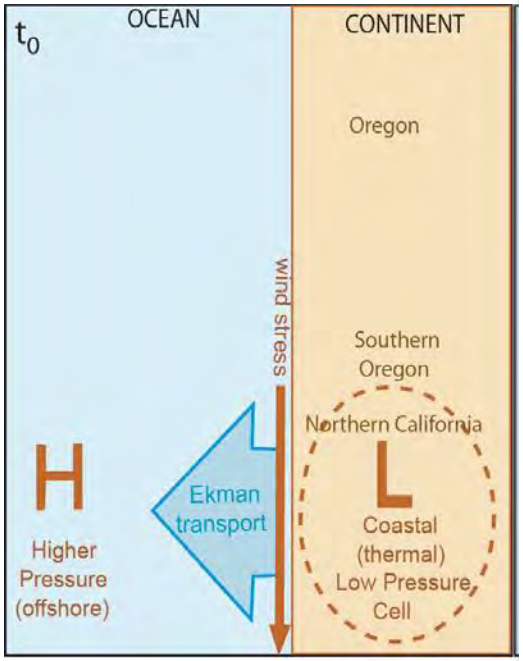
10

Bakun, A., D.R. McLain and F.V. Mayo. 1974. Fishery Bulletin. 72:843-844.




t_0
OCEAN
CONTINENT
Oregon
wind stress
Southern
Oregon
Northern California
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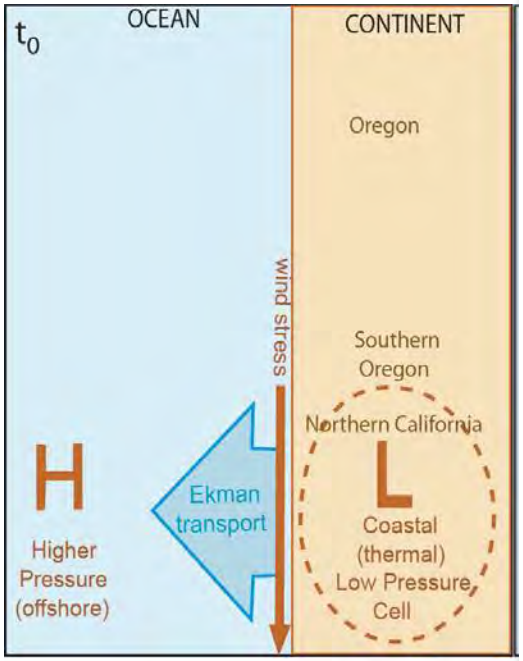
Higher
Pressure
(offshore)
Ekman
transport
L
Coastal
(thermal)
Low Pressure
Cell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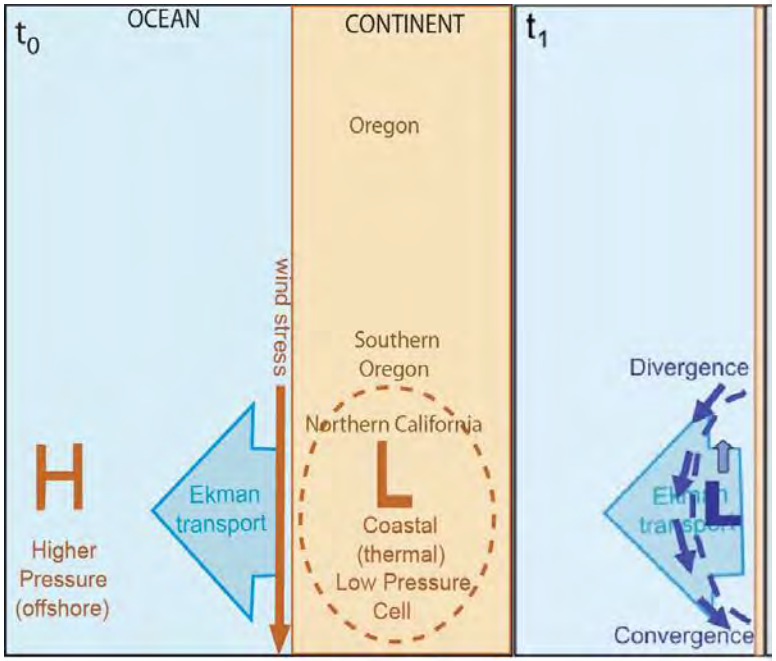
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t_1
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wind stress
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Higher
Pressure
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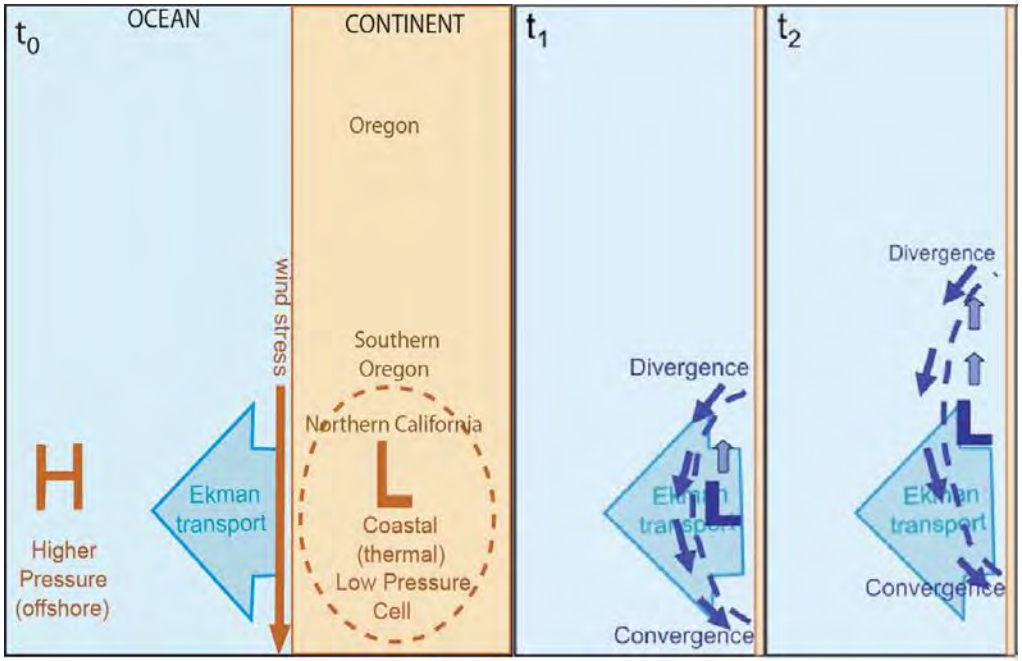
Low Pressure
Cell
Convergence


t_0
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wind stress
Southern Oregon
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Higher Pressure (offshore)
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Coastal (thermal) Low Pressure Cell
Divergence
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Ekman transport
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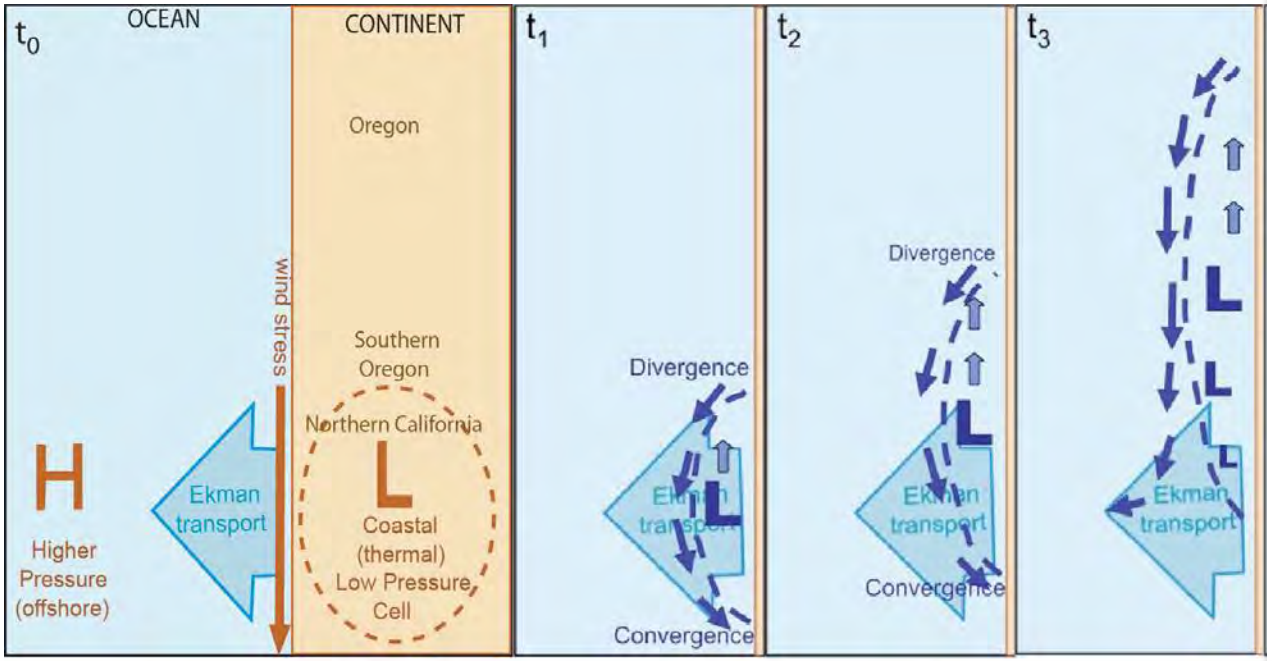
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Divergence
Convergence
t_2
Divergence
Ekman transport
Convergence
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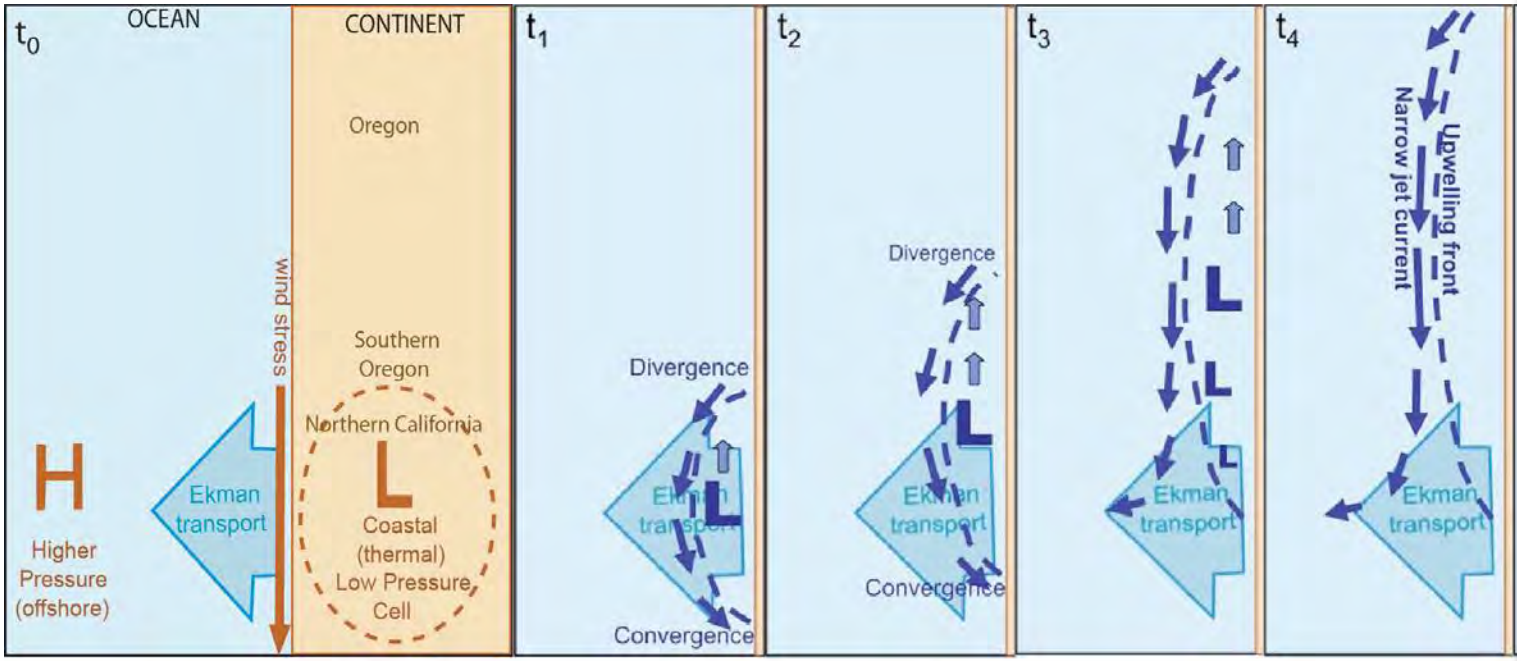
Ekman transport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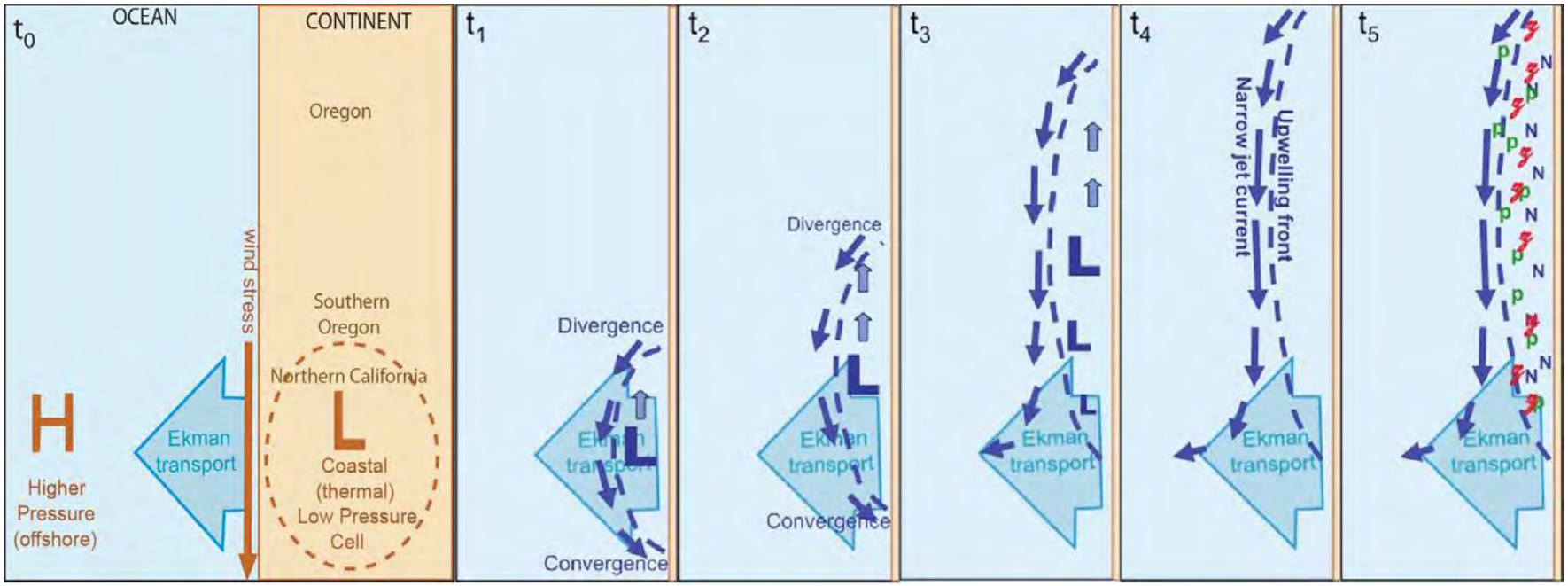
Low Pressure
Cell
t1
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Narrow jet current
Upwelling front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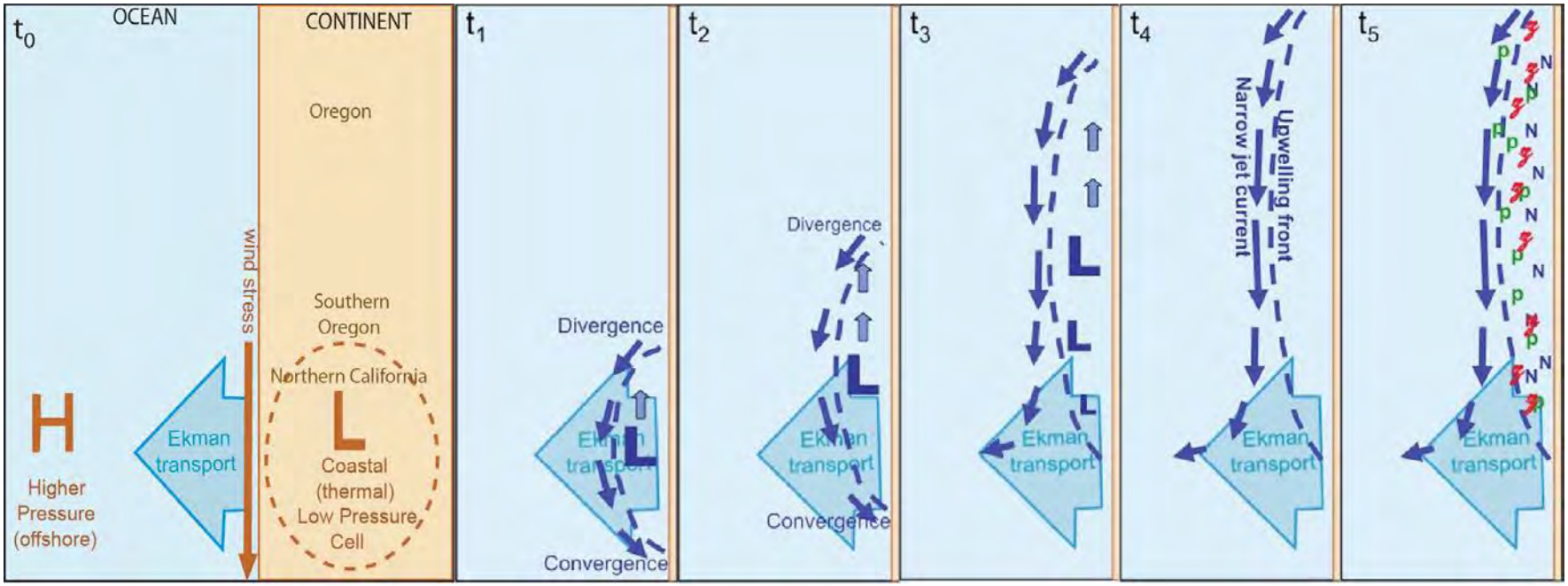
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Narrow jet current
Upwelling front
t5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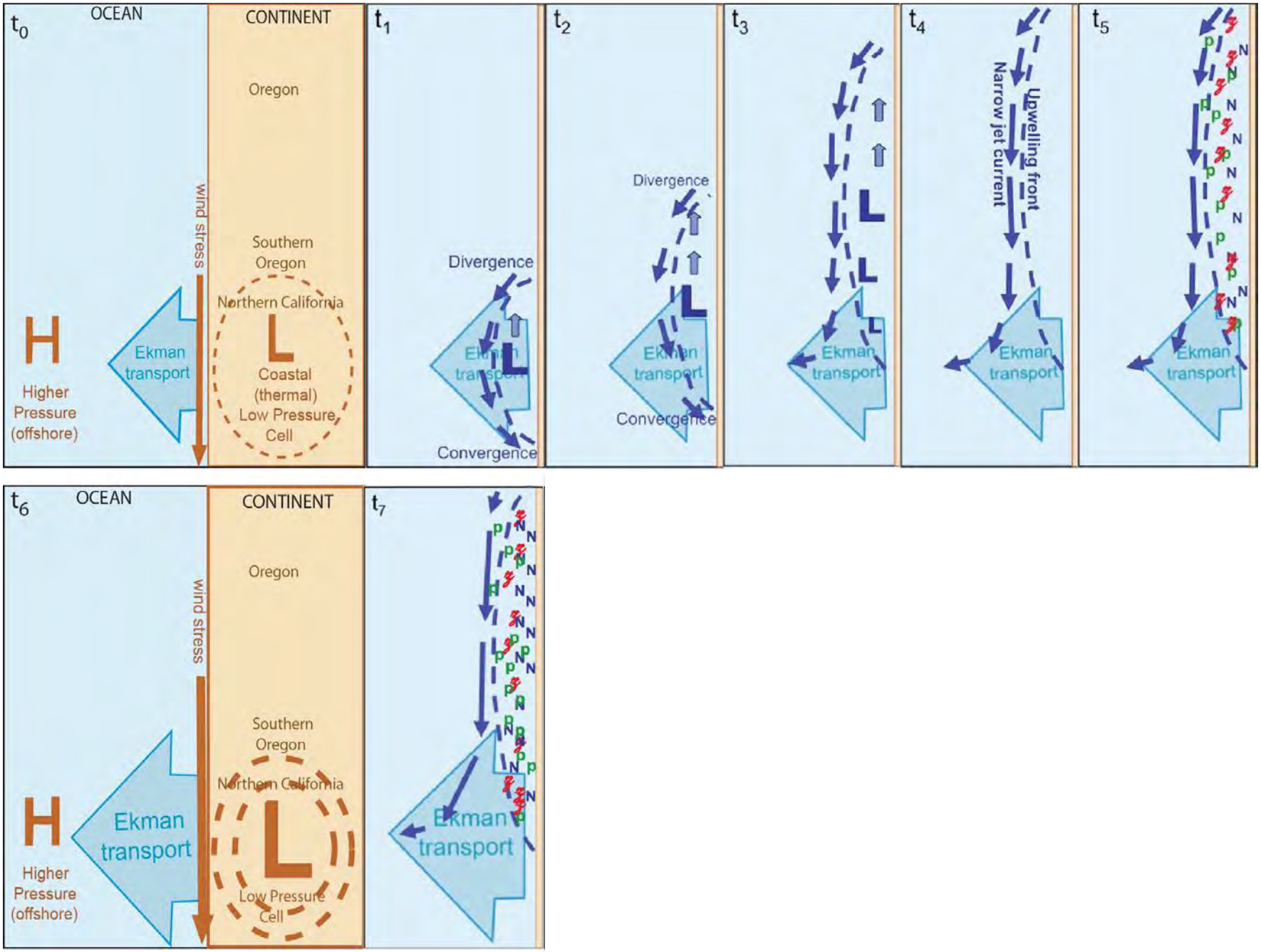
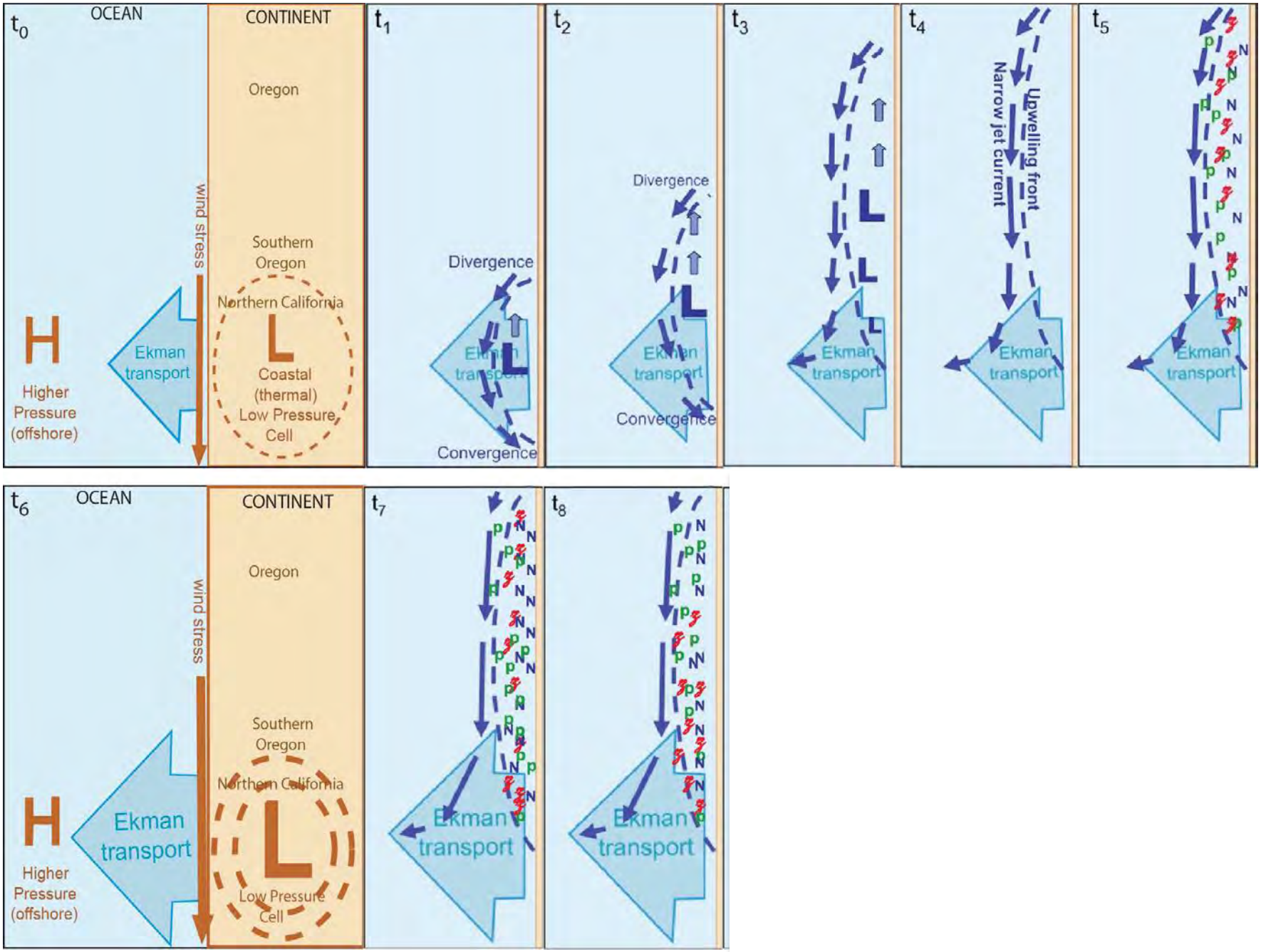
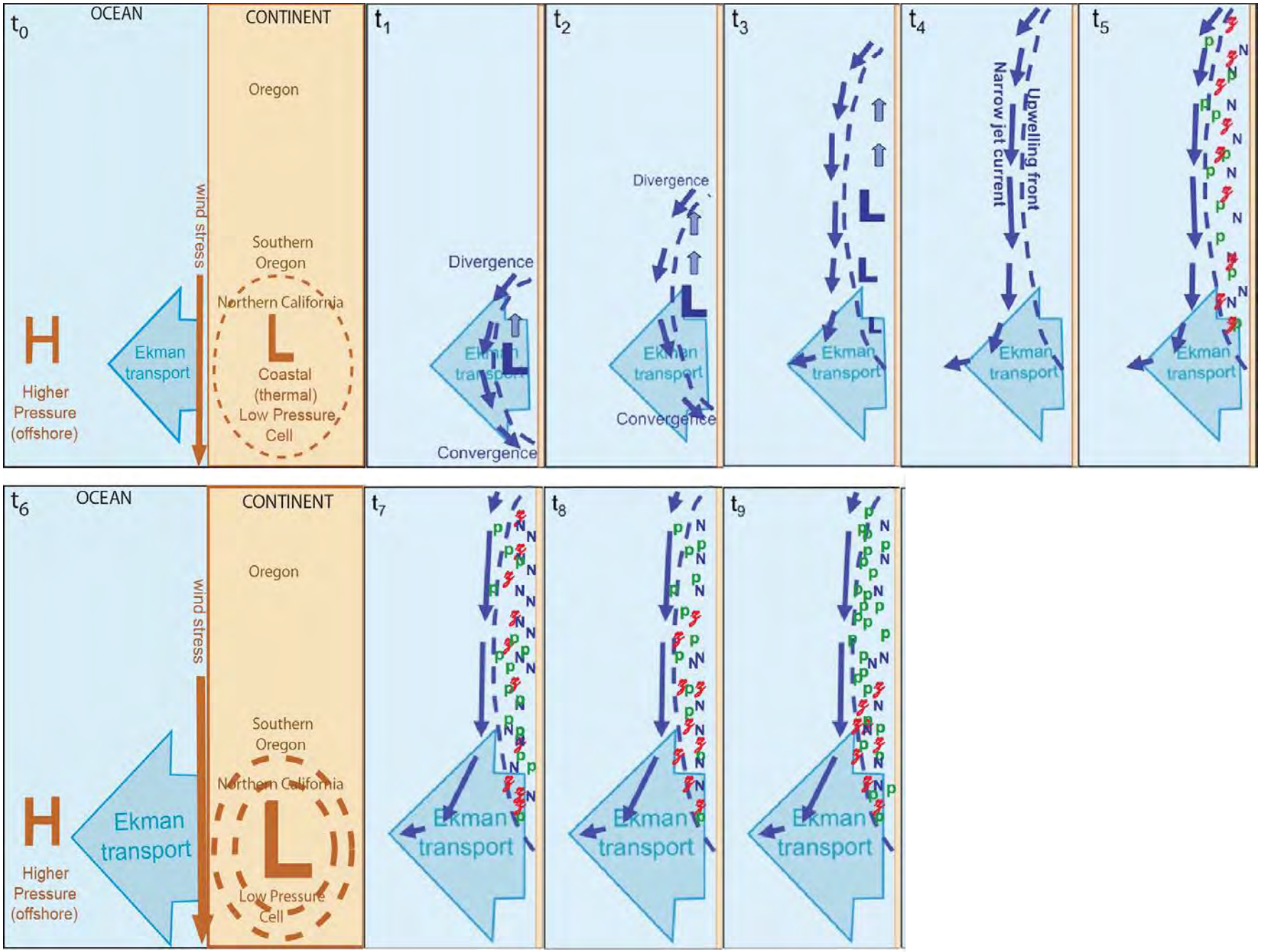
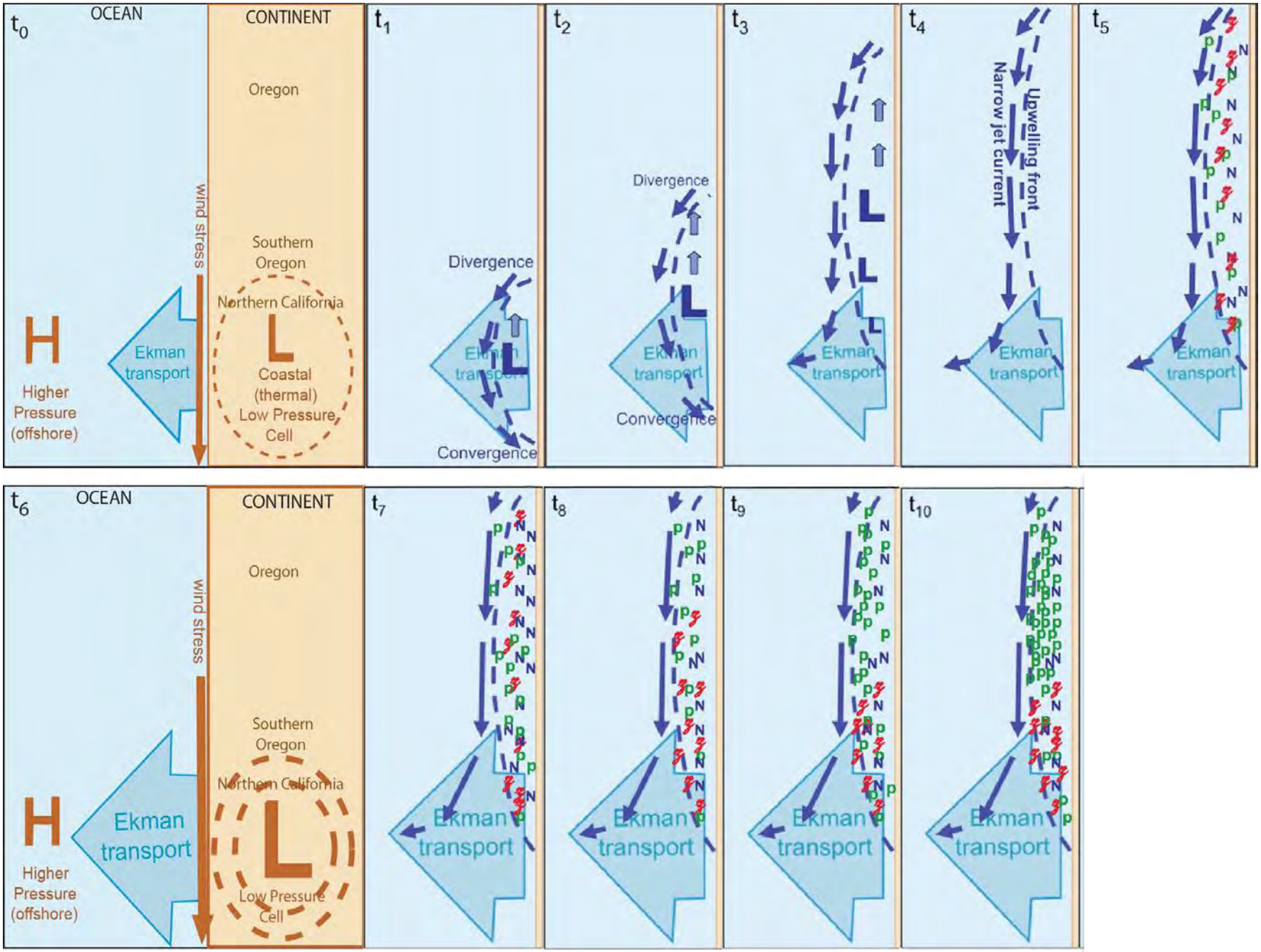
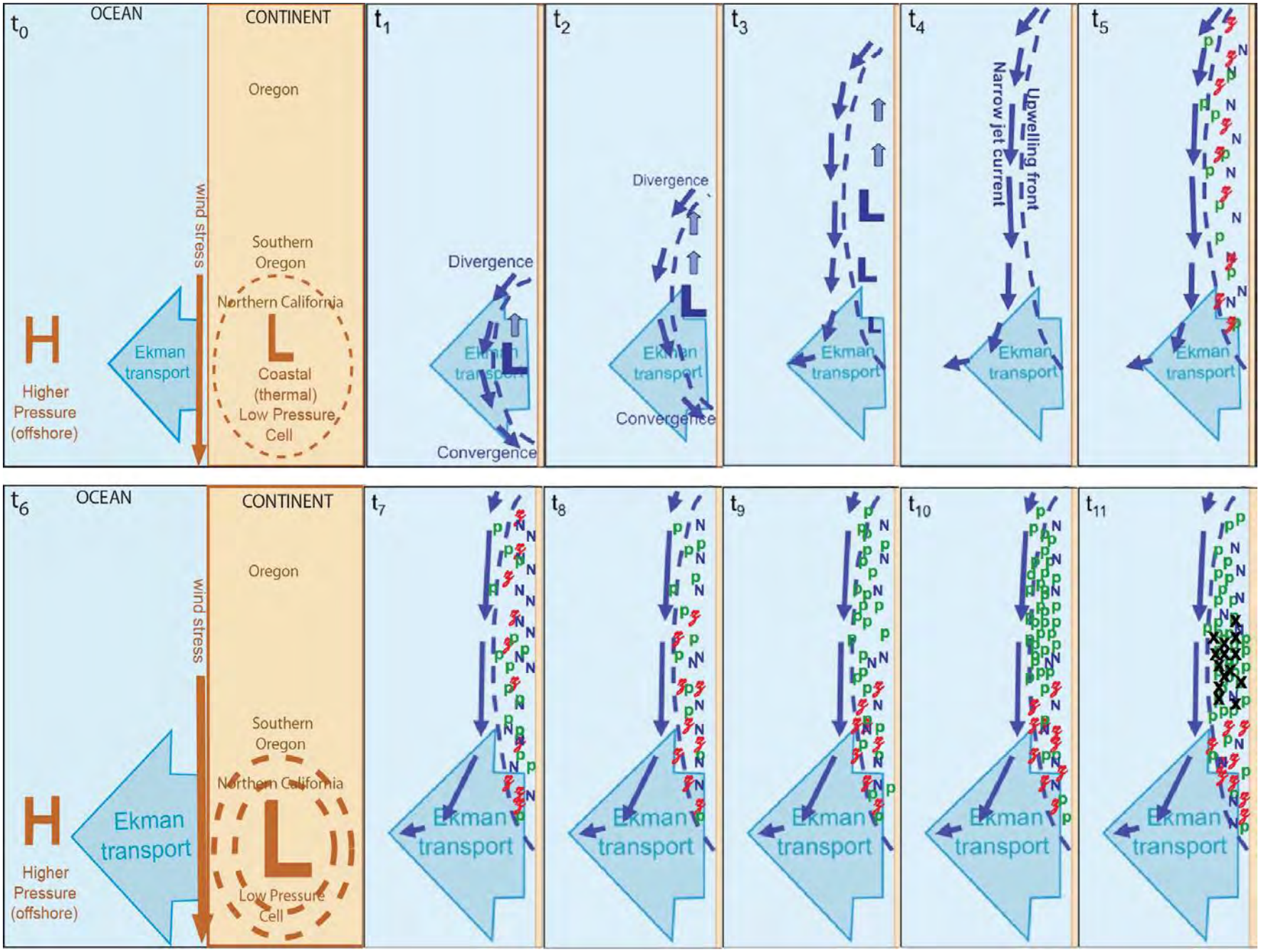
Coastal
(thermal)
Low Pressure
Cell
Higher
Pressure
(offshore)
t1
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Narrow jet current
Upwelling front
t5
t6
OCEAN
CONTINENT
Oregon
wind stress
Southern
Oregon
Northern California
H
Ekman
transport
L
Low Pressure
Cell
Higher
Pressure
(offshore)


t0
OCEAN
CONTINENT
Oregon
wind stress
Southern Oregon
Northern California
H
L
Ekman transport
Coastal (thermal) Low Pressure Cell
Higher Pressure (offshore)
t1
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Narrow jet current
Upwelling front
t5
t6
Low Pressure Cell
t7


t0
OCEAN
CONTINENT
Oregon
wind stress
Southern Oregon
Northern California
H
L
Ekman transport
Higher Pressure (offshore)
Coastal (thermal) Low Pressure Cell
t1
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Upwelling front
Narrow jet current
t5
t6
t7
t8
Low Pressure Cell


t0
OCEAN
CONTINENT
Oregon
wind stress
Southern
Oregon
Northern California
H
L
Ekman
transport
Coastal
(thermal)
Low Pressure
Cell
Higher
Pressure
(offshore)
t1
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Narrow jet current
Upwelling front
t5
t6
t7
t8
t9
Low Pressure
Cell


t0
OCEAN
CONTINENT
Oregon
wind stress
Southern Oregon
Northern California
H
L
Ekman transport
Coastal (thermal) Low Pressure Cell
Higher Pressure (offshore)
t1
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Narrow jet current
Upwelling front
t5
t6
t7
t8
t9
t10
Low Pressure Cell


t0
OCEAN
CONTINENT
Oregon
wind stress
Southern Oregon
Northern California
H
L
Ekman transport
Coastal (thermal) Low Pressure Cell
Higher Pressure (offshore)
t1
Divergence
Convergence
t2
Divergence
Convergence
t3
t4
Narrow jet current
Upwelling front
t5
t6
t7
t8
t9
t10
t11
Low Pressure Cell

From: Blended sea level anomaly fields with enhanced coastal coverage along the U.S. West Coast