Warming up, turning sour, losing breath
- EBUS as hotspots of global change

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Acknowledgments:

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Eastern Boundary Upwelling Regions are hotspots of global change, as they are subject to the simultaneous exposure to multiple stressors.
OBJECTIVE:
To explore the biogeochemical sensitivity of EBUS to simultaneous stressors emanating from changes in:
- Atmospheric CO$_2$ (ocean acidification)
- Changes in upwelling (ocean acidification & deoxygenation)
- Changes in stratification (deoxygenation & ocean acidification)
1. Introduction
   *or why should we be concerned about multiple stressors in EBUS?*

2. Ocean acidification
   *or how the near-shore CalCS might become undersaturated soon*

3. Ocean warming and circulation changes
   *or how are ocean warming and circulation changing OA and O₂?*

4. Summary and outlook
The power of regional modeling

Regionalization of models permit us to increase resolution to the level needed to resolve the coastal processes.
The $N_2PZD_2+CNO_2$ model

Reduced remineralization rate when $O_2 < 5 \mu\text{mol kg}^{-1}$
No consideration of benthic denitrification

Gruber et al. (2006, 2011)
Modeling multiple stressors in EBUS

Perturbation simulations with Regional Ocean Modeling System (ROMS) with NPZD model for the California, Canary, and Humboldt CS

(5km/7km/15 km resolution)
Evolution of Aragonite saturation horizon and pH

Year 2005

A2-scenario
Evolution since 1750 and projection until 2050

Strong shoaling of the saturation horizon

Gruber et al. (2012)
Evolution of chemical habitats in the CalCS

Relative contribution of volumina with a particular $\Omega$ in the upper 60 m and the nearshore 50km

Habitats that are acceptable for most CaCO$_3$ forming organisms become rare, even though most of the upper 60m remains supersaturated.

Gruber et al. (2012)
1. Introduction
   
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   *or how are ocean warming and circulation changing OA and O₂?*

4. Summary and outlook
And now add changes in temperature and wind-stress

- Timeslice simulations
- Transient simulations

- $2x\tau, +2^\circ C$
- $2xCO_2, 2x\tau, +2^\circ C$

- $280 \ (1750)$
- $380 \ (2000)$
- $540 \ (2050)$

- $2xCO_2$
Response to doubling of wind-stress

Changes in winds (and temperature) lead to a complex pattern of changes in $\Omega_{\text{arag}}$ and oxygen.
Changes in winds and temperature lead changes in changes in both directions with regard to $\Omega_{arag}$ and oxygen.
Strongly contrasting responses to changes in winds and temperature.
As expected, $O_2$ and $\Omega_{\text{arag}}$ co-vary strongly, but with different slopes and intercepts.

Understanding the co-variability between $\Omega_{\text{arag}}$ and $O_2$
Adding wind…

Wind changes affects primarily the Canary CS, while the relationship remains in the CalCS.
Adding CO₂...

The increase in atmospheric CO₂ decreases $\Omega_{\text{arag}}$, while it has no impact on $O_2$ (in our model).
Adding wind and CO$_2$...

The joint impact is mostly driven by atmospheric CO$_2$, with wind changes enhancing the changes, particularly in the Canary CS.
The changes in $\Omega_{\text{arag}}$ and $O_2$ are a result of the balance between advection/mixing and local sources minus sinks (production & remineralization).
How can we understand the differences...

<table>
<thead>
<tr>
<th>EBUS</th>
<th>California CS</th>
<th>Canary CS</th>
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</thead>
<tbody>
<tr>
<td>Potential impacts of upwelling increase</td>
<td>Increase of coastal hypoxic &amp; acidification (at depth)</td>
<td>Decrease of coastal hypoxia &amp; acidification (shallow)</td>
</tr>
<tr>
<td>Main mechanisms</td>
<td>Upwelling/advection of low O\textsubscript{2}, low pH</td>
<td>Remineralization on the shelf</td>
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</tbody>
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*Basin scale forcing (e.g., depth/size of OMZ) + local environmental factors (e.g., shelf width) will strongly control the response of ocean acidification and coastal hypoxia to upwelling/stratification increase in EBUS*
Summary and Outlook

- The California Current System is bound to progress toward large and widespread *undersaturation* with regard to aragonite within the next few decades.

- Changes in *upwelling* and *ocean warming* will modify ocean acidification somewhat. They have much more substantial impacts on oxygen, albeit with large regional differences.

- EBUS are hotspots of change. They may provide an *ideal testbed* for studying the impact of multiple stressors on marine life and biogeochemistry.

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The Humboldt Current System is highly prone to become undersaturated in the upper ocean, while the Canary Current System will likely remain supersaturated.