Investigating the upwelling intensification hypothesis using climate-change simulations

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What are the consequences of long-term climate change for upwelling systems?

Fisheries production

- 2.5 Billion people
- 7.0 Billion people

- ~25% of global landings; source of good, quality protein.
Broad hypotheses concerning ecosystem responses

What physical changes might impact the structure of upwelling ecosystems?

Changes in water-column **stratification**.

Changes in the **properties of the source waters** (particularly $O_2$, $NO_3$, $Si$, $pH$) and the relative contribution of different masses (e.g., the California Undercurrent).

Changes in **mesoscale and submesoscale** processes (with emphasis on physical-biological interactions).

*Changes in the magnitude of upwelling winds.*
Previous results emphasized the influence of remote forcing.
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Earlier model analysis of the long-term changes in the Eastern Pacific revealed two surprises:

1. *Nutrient supply may be enhanced* in the future as a result of the decreased ventilation of the source waters supplied to the region.

2. *Intensification of the large-scale, upwelling favorable winds was not apparent*… at least in the single model run analyzed.

(Rykaczewski and Dunne, 2010)
Surprising results: the magnitude of winds changes little

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Global Climate Change and Intensification of Coastal Ocean Upwelling

Andrew Bakun

A mechanism exists whereby global greenhouse warming could, by intensifying the alongshore wind stress on the ocean surface, lead to acceleration of coastal upwelling.
This is a captivating hypothesis, involving:

**global warming,**
**atmospheric science,**
**oceanography,** and
**ecological impacts**

all tied together with a fairly intuitive explanation.
Bakun suggested that global warming would enhance summertime upwelling winds in eastern boundary currents.

Differential heating of the surface air over the landmass relative to the ocean…

…will result in intensification of the thermal Low over the Southwest, generating a stronger pressure gradient.
Supporting evidence and qualifications...

Early observations supported Bakun hypothesis.
Supporting evidence and qualifications...

Early observations supported Bakun hypothesis.

“...sufficiently attractive to gain general acceptance, even though empirical support was weak.”

Bakun noted the following qualifications in his proposal:

- Intensification should be limited to the main upwelling season and the core of the upwelling zone.

- Interannual and decadal variability is present.

- Impacts on the ecosystem may not be straightforward.

- Positive feedback likely given the expectation of cooler coastal waters.
Observational records of ocean winds are available:

- archived vessel reports (Beaufort and anemometer, since 1946 and earlier)
- coastal stations and buoys (since 1970s)
- data-based reanalyses targeted towards meteorological efforts (since 1948, with some earlier evidence)
- satellite estimates (since 1979)
Issues with reliance on an observational approach

Two major issues with observational datasets come to mind:

1. Although the duration of observational time series has increased, so too has our recognition of decadal scale variability. *Time series are short.*

2. The magnitude of historical climate change is rather small relative to what is expected in the future. *The “signal” is relatively weak.*
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Models can be useful in examining the concept

Atmosphere-ocean coupled climate models (IPCC-style) alleviate some of these issues:

- Not limited by data length or magnitude of historical forcing.
- Not limited by data quality or methodology.
- Offer comprehensive and quantitative results, as well as the ability to test each step (not just the final result).
Method: Analysis of multiple climate models

I picked models from the IPCC AR5 generation that met the following basic requirements:

- Simulations of conditions during the “historical period,” roughly 1850 to 2005.

- Simulations of conditions from year 2006 to 2100 at RCP 8.5.

- Surface air temperature, sea-level pressure, and surface wind stress available at monthly resolution.

26 models fit the bill: US$^5$, Japan$^4$, France$^4$, Germany$^2$, Australia$^3$, Italy$^3$, Norway$^2$, Canada, China, Russia.

Initial analysis was limited to the “summer” months: June-August.
A note on Representative Concentration Pathways (RCPs)

RCP 8.5 offers the largest “signal to noise”.

While once viewed as “overly pessimistic”, it appears increasingly realistic.

(Peters et al., 2013)
### Process Prediction

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**Upwelling Intensification Hypothesis Report Card**
Bakun’s step #1: Global temperatures will rise in the future.

All 26 models project significant warming over the coming century.
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Step #2: Increased warming of the land relative to the ocean

Bakun’s step #2: The continental surface will warm to a greater extent than the ocean surface.
Step #2: Models consistently support the expectation

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Bakun’s step #2: The continental surface will warm to a greater extent than the ocean surface.
In all 26 models, the degree of future warming of the surface air over land exceeds that over the coastal ocean.

A multi-model ensemble can be constructed from the 26 models. This ensemble supports the hypothesis that the heating of the land mass will be enhanced.
# Upwelling Intensification Hypothesis Report Card

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Step #3: Intensification of continental low relative to NPH

Bakun’s step #3: The thermal low over southwestern North America will intensify relative to the North Pacific High.
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5 of 26 models displayed the pressure changes described by Bakun.

10 of 26 showed the opposite changes.
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Bakun’s step #5: Equatorward, upwelling-favorable wind stress will increased as a consequence of future global warming.

1851-1880 wind stress  

2071-2100 wind stress  

(difference)
Step #5: Ensemble winds indicate less upwelling, on average.

Bakun’s step #5: Equatorward, upwelling-favorable wind stress will increase as a consequence of future global warming.

1851-1880 wind stress  2071-2100 wind stress  (difference)

California meridional wind stress (normalized, June-August)

less upwelling

more upwelling
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**Step #5: results are sensitive to latitude and season**
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Dry air is comprised of nitrogen and oxygen.

Air density decreases as air is heated.

If density of an air mass is low relative to neighboring masses, it is likely to rise and local pressure will decrease.

But…

*Mist air is less dense than dry air.* Addition of water vapor decreases air density.
Water ($\text{H}_2\text{O}$) weighs less than nitrogen ($\text{N}_2$).

One mole of dry air weighs 28.97 g, while one mole of water vapor weighs 18 g.

An air mass becomes heavier if water vapor is removed; lighter as water vapor is added.

Why is this relevant?

Density and SLP increase as air becomes arid.
As the atmosphere warms with climate change, the difference in humidity between oceanic and continental air masses will increase.

Oceanic air masses have an unlimited supply of water vapor from which to draw; continental air masses do not.

24 of 26 models display an increase in the relative humidity gradient.
While warming of surface air masses over land is enhanced relative to those air masses over the ocean, this does not result in an intensified pressure gradient.

Increased aridity of the continental air masses acts to counteract an intensification of the thermal low.

Changes in winds appear to be more sensitive to secular trends in latitude and seasonality—likely a response to the poleward migration of atmospheric pressure systems.

Conclusions: Reconfiguration of the hypothesis is warranted