COASTAL UPWELLING IN CESM
...and eastern boundary currents:
Quantifying the sensitivity to resolution and coastal wind representation in a global climate model

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Outline of talk & Summary

• 1. Global view: Sensitivity to atmosphere resolution
  • Sverdrup balance issues at low resolution

• 2. Benguela: Sensitivity to ocean resolution (part 1)
  – High resolution does not improve SST if wind profile is poor

• 3. Benguela: Sensitivity to coastal wind profile
  – Adjusting the wind stress curl

• 4. Benguela: Sensitivity to ocean resolution (part 2)
  – High resolution gives “realistic” coastal and upwelling jet if wind profile is improved

• 5. Remapping issues, and other upwelling examples

With a 2deg atmosphere model, wind stress is too weak adjacent to eastern boundaries.

Only CAM cells over pure ocean shown (no land cells)
Consequences of weak coastal winds

• Weak coastal upwelling
  – Ekman offshore transport weak

• Weak or no Equatorward “coastal jet”

• Strong wind stress curl

• Ekman pumping driven upwelling
  – Picket and Paduan 2003, Junker 2014

• Countercurrents by Sverdrup balance

\[ \beta \rho_0 \int_{-H}^{0} v dz = \nabla \times \tau \]
Southward transport if curl is negative
Absolute value of meridional wind stress $\tau_{AU}$, in June-July-August (JJA)
Eastern boundary Sverdrup balance

**Wind Stress Curl**

**Vertically integrated V**

Right panel: Depth-integrated meridional current to 500m multiplied by $\beta\rho_0$ where $\beta$ is the meridional gradient of Coriolis force, $\rho_0$ is a reference ocean density. Under Sverdrup balance this should equal the curl of the wind stress shown in left panel.

With a 2deg atmosphere in CCSM4, approximate Sverdrup balance holds in eastern boundaries and sub-tropical gyres. General southward flow at eastern boundaries tends to produce a warm SST error by flux of heat poleward. Similar with 1deg atmosphere.
Eastern boundary Sverdrup balance

Right panel: Depth-integrated meridional current to 500m multiplied by $\beta \rho_0$ where $\beta$ is the meridional gradient of Coriolis force, $\rho_0$ is a reference ocean density. Under Sverdup balance this should equal the curl of the wind stress shown in left panel.

With a 0.5deg atmosphere in CCSM4, Sverdrup balance is less appropriate in eastern boundaries (especially Benguela). Southward flow is less pronounced.
Nested high-resolution ocean

• However, SST errors are still large in Benguela in CCSM4 with atmosphere at 0.5deg.

• So we embedded a high-resolution (7km) ROMS nest in the Eastern boundary region.

SST bias in CCSM4 with 0.5deg atmosphere.

ROMS domain shown as dashed line.
Does use of a hi-resolution ocean disrupt Sverdrup balance?

(a) CCSM4 with 1deg POP

Vert. int. $\beta \rho_0 V$

(b) CCSM4 with 1deg POP

WSC

Simulation with non-eddy resolving ocean model

Note southward flow in both cases.

(c) ROMS on 7km grid

Vert. int. $\beta \rho_0 V$

(d) Stress applied to ROMS

WSC

Simulation with eddy resolving ROMS

No, a high resolution ocean model is also in approximate Sverdrup balance in this case.

Wind stress curl dominates solution in both cases.
Linear theory of coastal upwelling systems

Fennel et al. 2012
Junker 2014

f-plane model

Coastal jet

Countercurrent

β-plane model

Coastal jet

Countercurrent

Figure 5.6. Meridional velocity $v$ [cm s$^{-1}$] from the analytical $f$-plane model as a function of the distance of the wind maximum to the eastern boundary $l$ and the zonal coordinate $x$ for two depth levels 20 days after the onset of the wind. The currents are calculated in the middle of the wind band, i.e. at $y = 0$. Negative currents (poleward directed) are shaded gray. High WSC, i.e. for $l \geq 420$ km, introduces a poleward flow beside the PUC that is observed at $z = 100$ m in the very vicinity of the coast.

Figure 5.7. Same as 5.6 but for the stationary part of the meridional velocity on the $\beta$-plane. The friction parameter is $\nu = 0.02 f$. Negative currents (poleward directed) are shaded gray. The WSC induced poleward flow is observed already for lower WSC values on the $\beta$-plane, and the overall poleward directed flow is enhanced.

Fig. 7. Sketch of the wind patch with cosine shape in both meridional and zonal directions. The distance of the wind maximum to the boundary and the width of the band are controlled by the parameters $l$ and $L$, respectively.
“Shifted wind” experiments

(a) ROMS, ORIGINAL
(b) ROMS, MODIFIED
(c) QuiKSCAT

Following Capet et al 2004 (GRL), the wind stress is modified \textit{ad-hoc} near the coast to reduce wind stress curl and strengthen coastal winds.

The modified wind stress is applied to ROMS embedded in CCSM4.
Left: Time-mean surface current (arrows) and meridional velocity (color). Only vectors with magnitude > 0.1 ms\(^{-1}\) shown. Middle: vertical velocity at 45m. Right: SST. All for JJA season.

Run with shifted winds

Dramatic changes! northward flow, coastal upwelling, cool SST

Original experiment

Southward flow at coast, weak upwelling, no sign of upwelling SST front
Fig. 15. Top-level temperature (taken as SST) from a) ROMS part of nRCM-0.5 b) from ROMS part of nRCM-MOD experiment, c) from composite SST of nRCM-MOD, d) from the NOAA analysis of observed SST (Reynolds et al 2007), e) from Levitus gridded onto POP grid.
Effect on SST bias

Bias of SST in June-July-August in the south-eastern Atlantic in a) CCSM4 with 0.5deg atmosphere and b) simulation of ROMS embedded in CCSM4 and “shifted winds”.

Big improvement in circled region (removing “bullseye”) but still a warm bias
Modified wind experiments with high and low-res ocean

Plots show SST difference between case with “modified winds” and unmodified wind case. Left: with ROMS embedded in CCSM4. Right: CCSM4 with no ROMS. All data mapped onto 1deg POP grid.

- Improvements are very weak when using a 1deg POP model instead of ROMS
Remapping issues, and more upwelling examples
Issues of remapping winds onto ocean grid near coast

• Near coast, winds on atmosphere cells over ocean, over land, and over partial land are all equally weighted in remapping.

• Does reduced wind speed over land (due to high drag at surface) bias winds over coastal ocean low?
Fig. 6. ROMS SST difference between experiments, JJA. a) NRCM ("shifted wind") minus NRCM- 0.5. b) ROMS with new regridding minus NRCM- 0.5.
• Technique also applied to high-resolution “ASD” run
  – Caused very little difference – only affected innermost 25km
  – WSC issue much wider
Application to high-resolution CESM

From QuikSCAT & CAM5-SE, 0.25deg

QuikSCAT

CAM5

Absolute value of TAUY in JJA

Wind stress curl, JJA

From QuikSCAT & CAM5-SE, 0.25deg

QuikSCAT

CAM5

Strong WSC leads to strong Ekman pumping upwelling but weak coastal upwelling – “compensation” -surface currents do not look like “shifted wind” case
Application to other regions

Absolute value of TAUY

Wind stress curl
Way Forward

• More shifted wind experiments
Fig. 10. Wind stress at coastal points as a function of latitude. The stress is the magnitude of time-averaged vector components, at the closest data point to the west Africa coastline. a) in ROMS part of nRCM-0.5. b) corresponding field from nRCM-MOD. C) from QuikSCAT.
Way Forward

- More shifted wind experiments
- Discuss coastal winds with AMP group
Way Forward

• More shifted wind experiments
• Discuss coastal winds with AMP group
• Analysis of “ASD” suite of runs at varying resolution
  – Does high-res atmosphere, low-res ocean really fix the Peru-Chile and California Current systems (Gent et al. 2010)?
Acknowledgements


• Recommended papers
Additional Slides
Climate model view of Benguela

CMIP5 Multi-model mean (Provided by Roberto Mechoso, Matt Masarik). Long term, annual mean SST difference from observations.

CCSM4 1° model (from Gent et al. 2011). Long term, annual mean SST difference from Hurrell et al. 2008 observations.

Warm Sea Surface Temperature (SST) errors in eastern boundary regions may be due to:

1. Poor representation of Clouds, cloud-radiation feedbacks and cloud-SST feedbacks
2. Remote teleconnections of errors from Equatorial region to eastern boundary
3. Problems with Coastal upwelling, eastern boundary currents and eddies
Regional ocean model view


Difference between satellite (Envifish) and model-derived (left) summer and (right) winter SSTs (i.e., model − satellite SST). The contour interval is 0.5°C, and the thick black line is 0°C.


Cold SST errors in eastern boundary regions may be due to:

1. Extrapolation of strong winds to narrow coastal zone where satellite observations not available
2. Lack of coupling
3. Errors in surface heat flux components
Vorticity terms (m² s⁻¹) in the 15-yr time-averaged Sverdrup balance in (left) ECCO–GODAE and (right) HiGEM: (a),(b) V (using integration depths of 1400 and 1000 m, respectively), (c),(d) , and (e),(f) the Sverdrup error, . The yellow border in (e) and (f) indicates the edge of the masked regions not included in the determination of any integrated quantities.

Normalized difference Δ between $V_g$ and the wind-derived transport, as defined by (10). The transport $V_g$ is computed with $h$ given by the depth of $\sigma_v$ 26.24, 27.24, and 27.25 for the North Pacific, Southern Hemisphere and north Indian, and North Atlantic basins. The value of Δ shown here is the min difference taking into account the uncertainty on $V_g$, with yellow indicating exact agreement. Areas where the given isopycnals were not present in the mean are shown in dark gray. The mean 5-db geostrophic streamfunction is contoured in black at 10–dyn cm intervals.

Gray and Riser 2014. A global analysis of Sverdrup balance using absolute geostrophic velocities from Argo. JPO.
Is Sverdrup balance appropriate here?


Fig. 27. Sea level elevation [m] with respect to the eastern boundary derived from the measured wind stress field assuming a Sverdrup balance.
Upper ocean Heat budget

Thermodynamic budget, vertically averaged over top 50m of ocean, for April-May-June climatology.

Original case, ROMS in CCSM4

“Shifted wind” case, ROMS in CCSM4

More cooling by advection

Strongly damped by air-sea fluxes

Tendency is similar

Total advection  Sfc. Heating +Mix  Adv+Heat+Mix  Temp. tendency

Thermodynamic budget, vertically averaged over top 50m of ocean, for April-May-June climatology.
Comparison with forced ocean runs

Schmidt, Fennel, Junker et al

*MOM4 regional model forced by QSCAT winds, NCEP states.*

Nrcm Run with shifted winds
“Shifted wind” experiments

Wind stress curl structure is modified – much narrower but still strong in the modified experiment.
Vertical sections
Fig. 12. Meridional velocity sections vs longitude and depth. a), b) are along the line shown in c). d,e) are along the line shown in f). Left panels: from nRCM-0.5. Middle panels: from nRCM-mod. Shading in right panels shows the surface velocity from c) nRCM-0.5 and f) nRCM-MOD.
Fig. 13. Potential temperature sections (°C) vs longitude and depth. a), b) are along the northern line shown in Fig. 12c). b, ed) are along the southern line shown in Fig. 12f). Left panels: from nRCM-0.5. Middle panels: from nRCM-MOD. Note change of temperature color range from upper row to lower row.
So why are global climate model and regional ocean model simulations so different?

• In the narrow coastal upwelling/coastal jet zone –
  – Wind representation, curl
  – Coupling

• Outside the narrow coastal zone
  – Many factors…
  – Deficiencies in stratocumulus representation,
  – Possible teleconnection of errors from coastal zone or from Equatorial region