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COASTAL UPWELLING IN CESM

…and eastern boundary currents: Quantifying the sensitivity to resolution and coastal wind representation in a global climate model

R. Justin Small (NCAR)

Enrique Curchitser (Rutgers)

Brian Kauffman (NCAR)

Kate Hedstrom (U. Alaska)

Bill Large (NCAR)

OMWG meeting

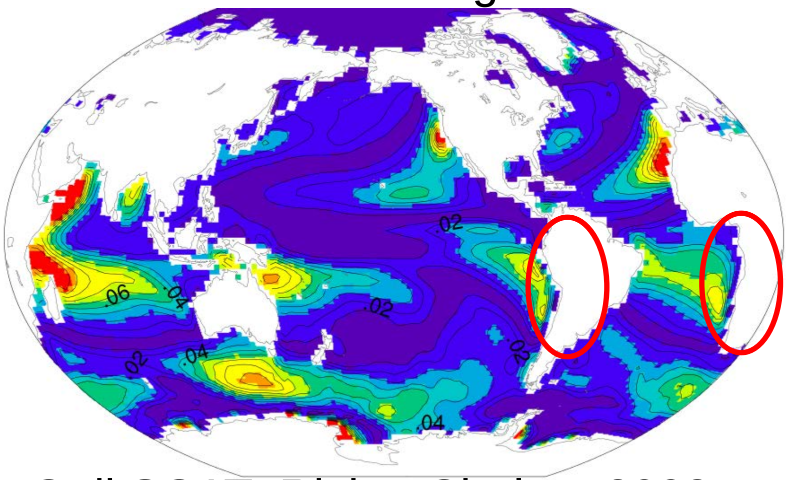
January 15-16, 2015

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

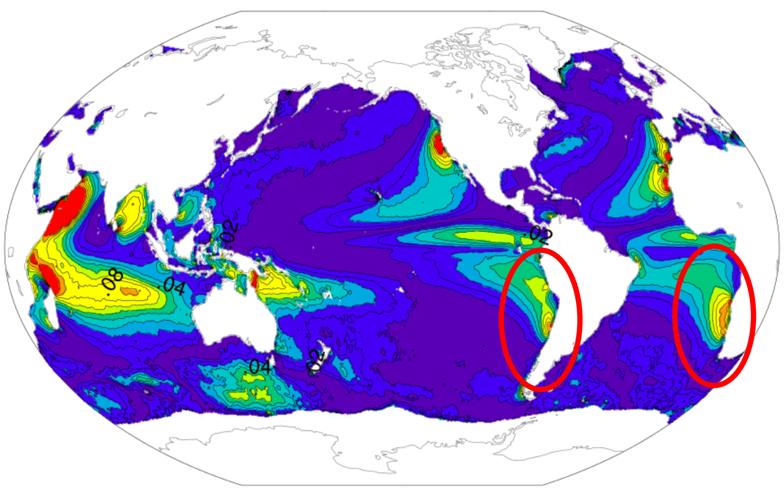
Wind stress & atmosphere resolution

CCSM4-2deg



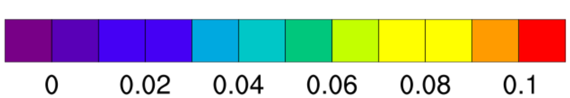
With a 2deg atmosphere model, wind stress is too weak adjacent to eastern boundaries

QuikSCAT Risien Chelton 2008



Absolute value of meridional wind stress TAUY, in June-July-August (JJA). Shows strength of upwelling favorable wind stress.

Only CAM cells over pure ocean shown (no land cells)



Nm^{-2}

Consequences of weak coastal winds

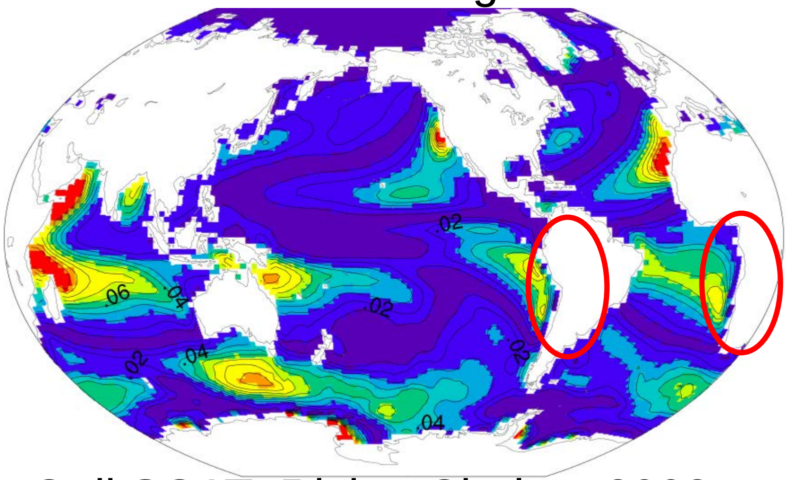
- Weak coastal upwelling
  - Ekman offshore transport weak
- Weak or no Equatorward “coastal jet”
  - Yoshida 1955, Charney 1955, **Fennel et al. 2012, Junker 2014**
- Strong wind stress curl
- Ekman pumping driven upwelling
  - Picket and Paduan 2003, Junker 2014
- Countercurrents by Sverdrup balance

$$\beta\rho_0 \int_{-H}^{0} v\,dz = \nabla \times \tau$$

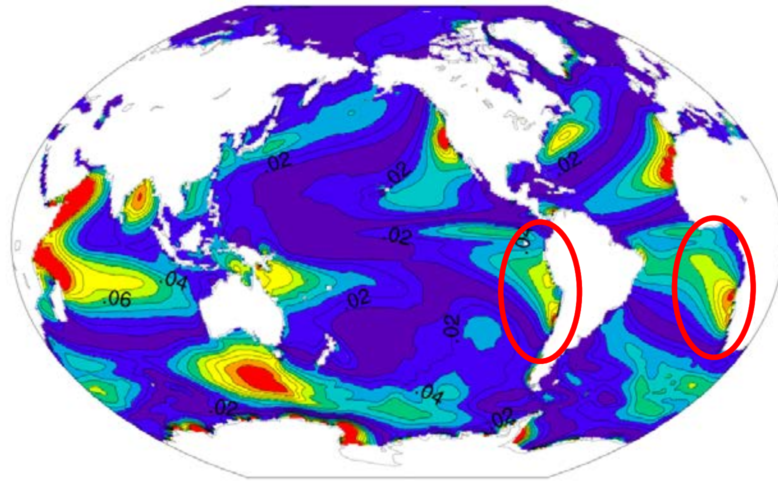
→ Southward transport if curl is negative

Wind stress & atmosphere resolution

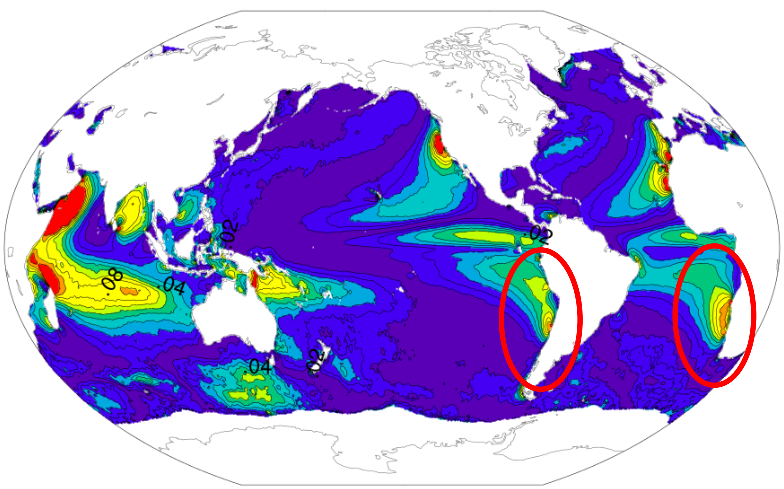
CCSM4-2deg



CCSM4-0.5deg



QuikSCAT Risien Chelton 2008

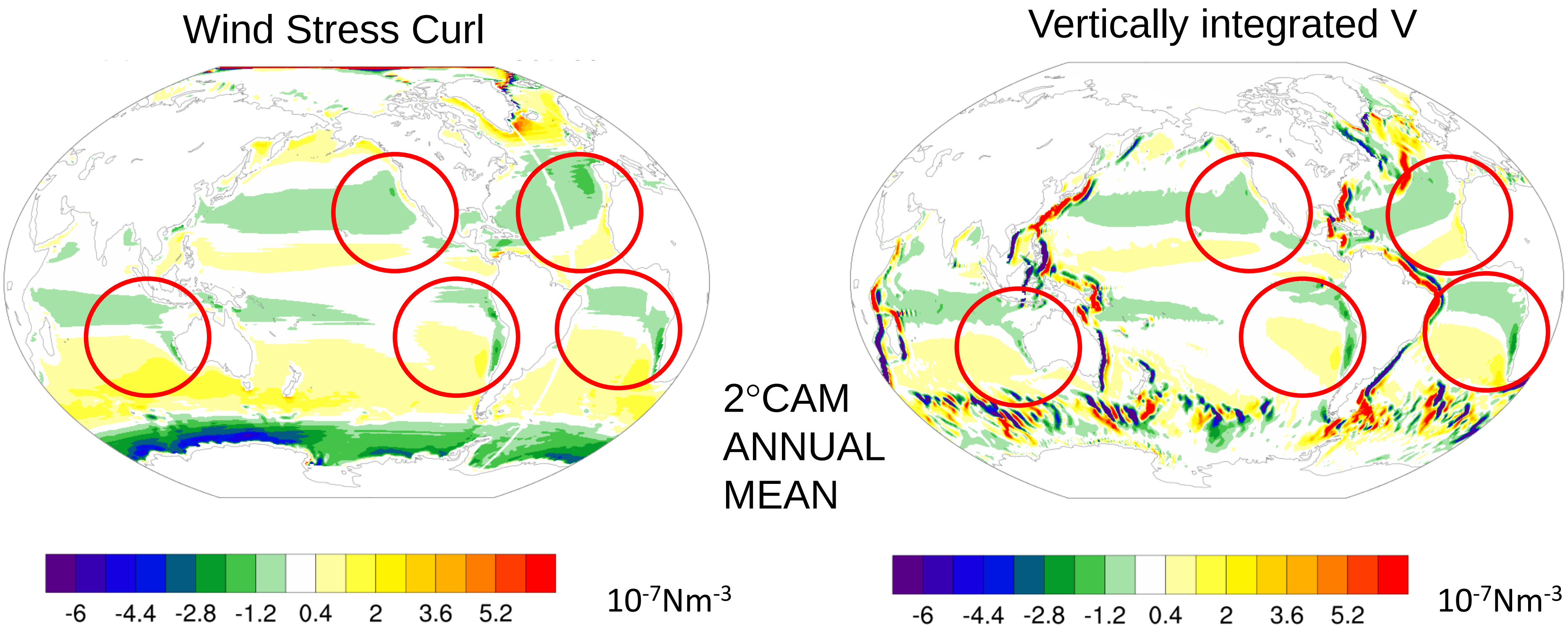


Notable improvement when going to a 0.5deg atmosphere

Nm^{-2}

Absolute value of meridional wind stress TAUY, in June-July-August (JJA)

Eastern boundary Sverdrup balance

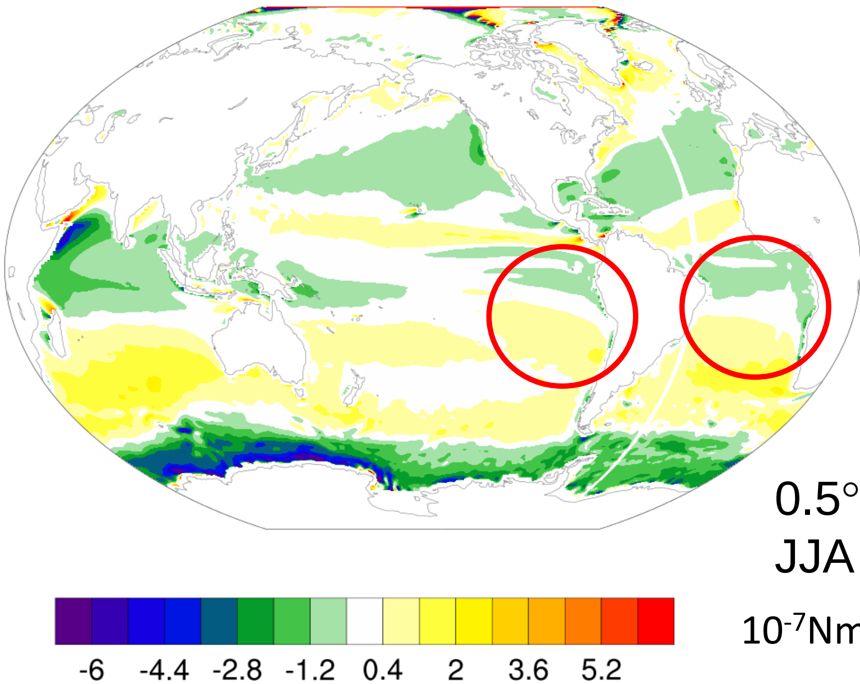


Right panel: Depth-integrated meridional current to 500m multiplied by $\beta\rho_0$ where β is the meridional gradient of Coriolis force, ρ_0 is a reference ocean density. Under Sverdup balance this should equal the curl of the wind stress shown in **left panel**

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.

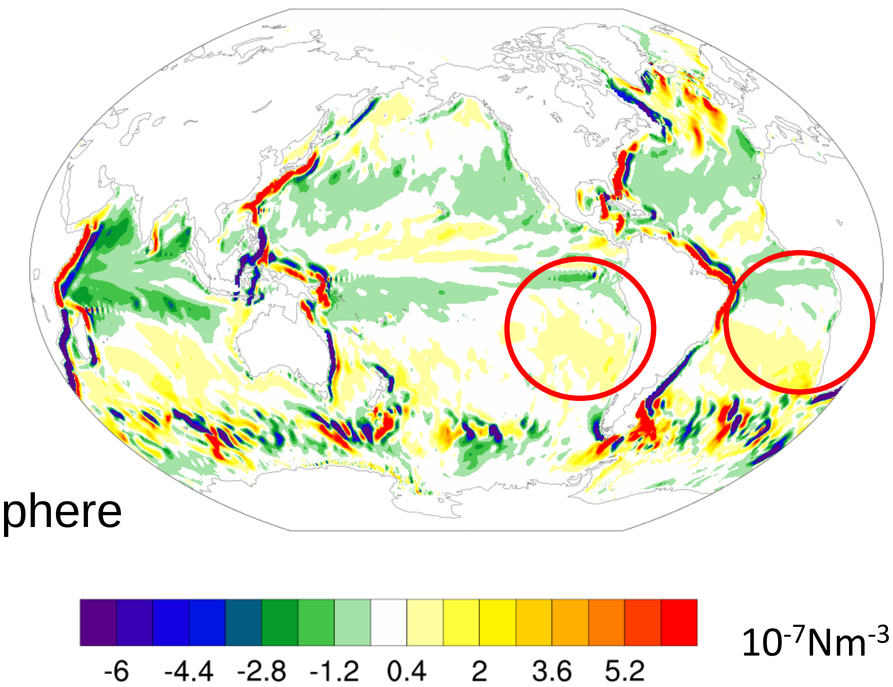
Eastern boundary Sverdrup balance

Wind Stress Curl



10^{-7}Nm^{-3}

Vertically integrated V



10^{-7}Nm^{-3}

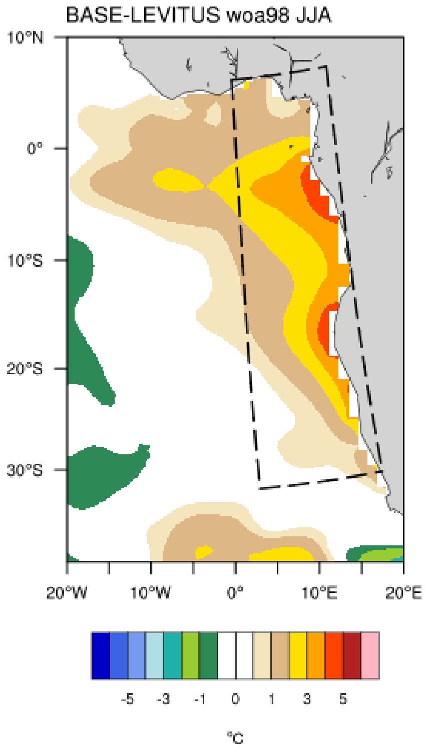
0.5°atmosphere
JJA

Right panel: Depth-integrated meridional current to 500m multiplied by $\beta\rho_0$ where β is the meridional gradient of Coriolis force, ρ_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

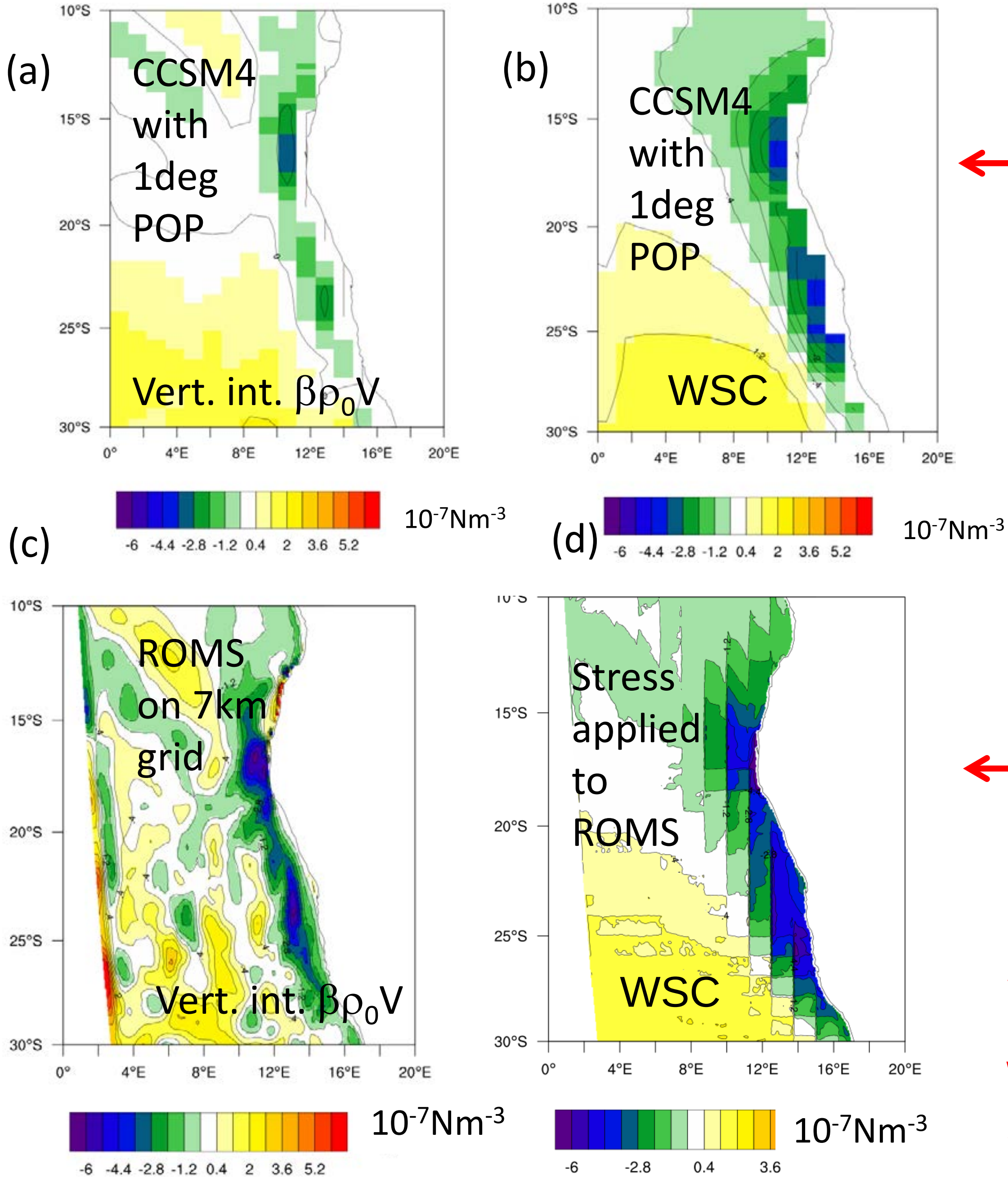
- However, SST errors are still large in Benguela in CCSM4 with atmosphere at 0.5deg.
- So we embedded a high-resolution (7km) ROMS nest in the Eastern boundary region.



SST bias in CCSM4 with 0.5deg atmosphere.

ROMS domain shown as dashed line.

Does use of a hi-resolution ocean disrupt Sverdrup balance?



Simulation with non-eddy resolving ocean model

Note southward flow in both cases.

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

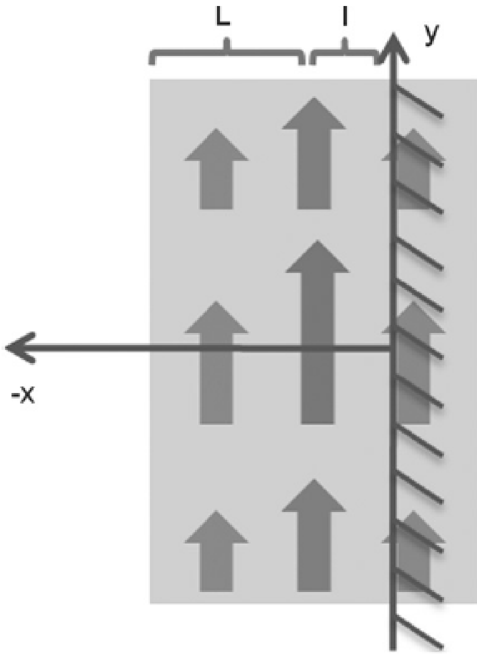
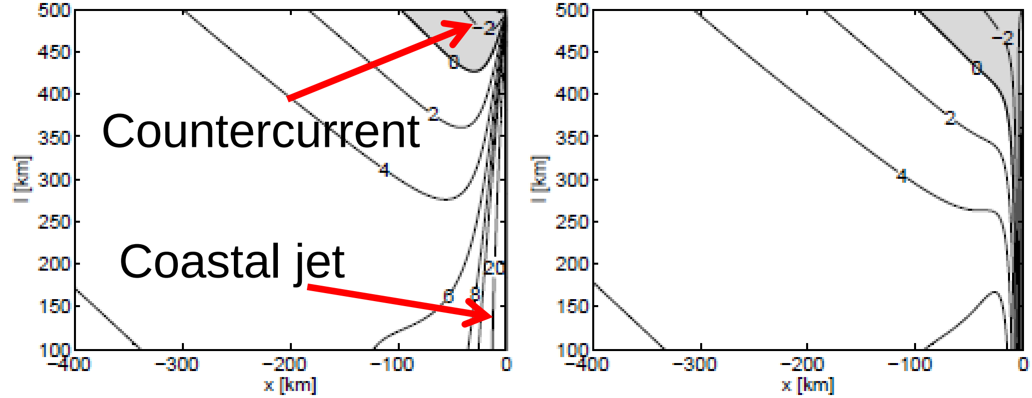


Fig. 7. Sketch of the wind patch with cosine shape in both meridional and zonal directions. The distance of the wind maximum to the boundary and the width of the band are controlled by the parameters l and L, respectively.

Fennel et al. 2012
Junker 2014

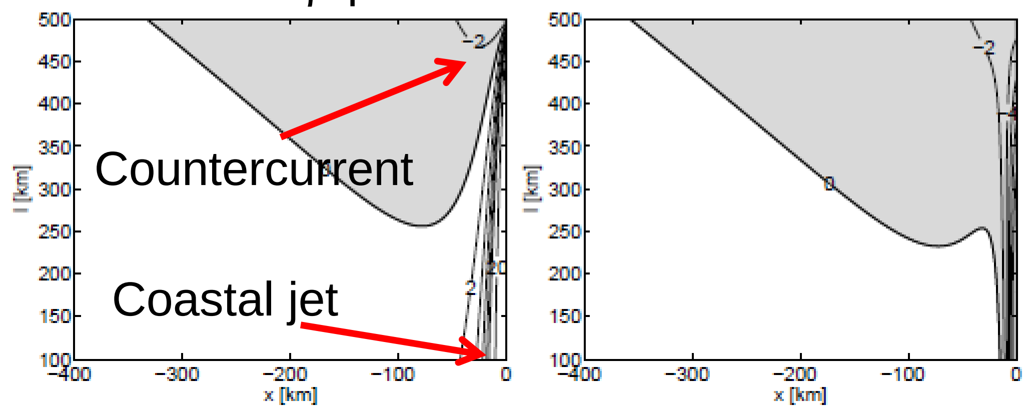
f-plane model



(a) $z = 10\,\mathrm{m}$ (b) $z = 100\,\mathrm{m}$

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 $l \gtrsim 420\,\mathrm{km}$, introduces a poleward flow beside the PUC that is observed at $z = 100\,\mathrm{m}$ in the very vicinity of the coast.

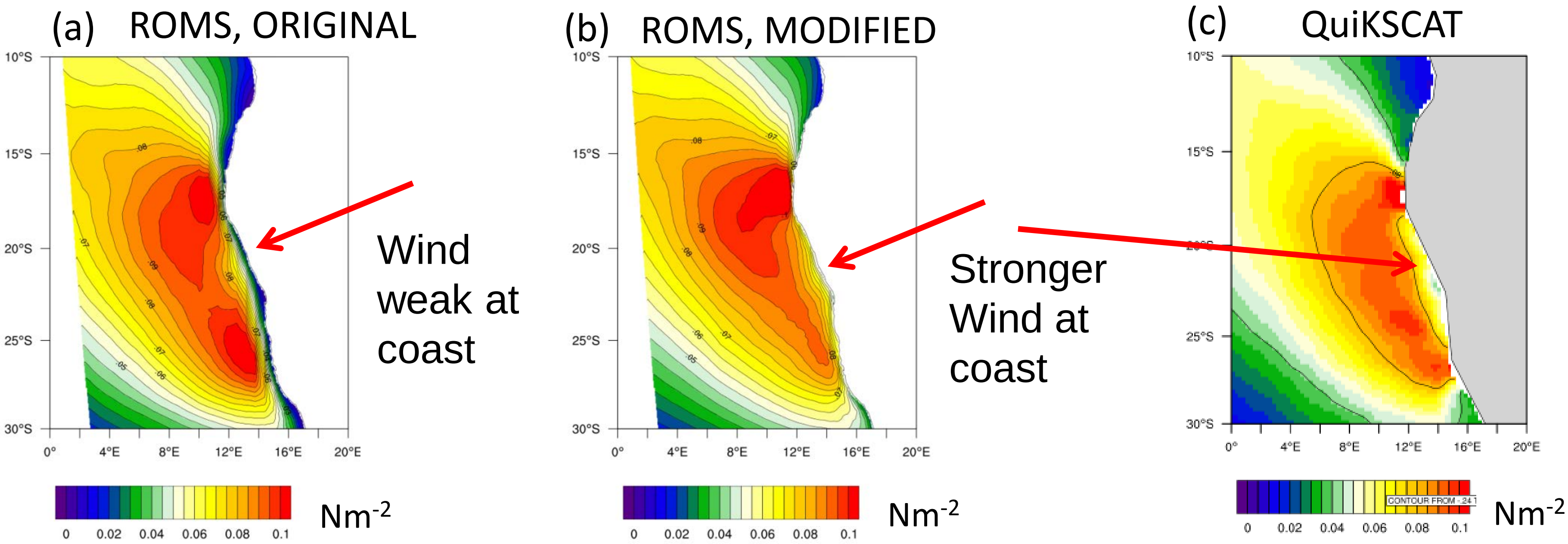
β-plane model



(a) $z = 10\,m$ (b) $z = 100\,m$

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

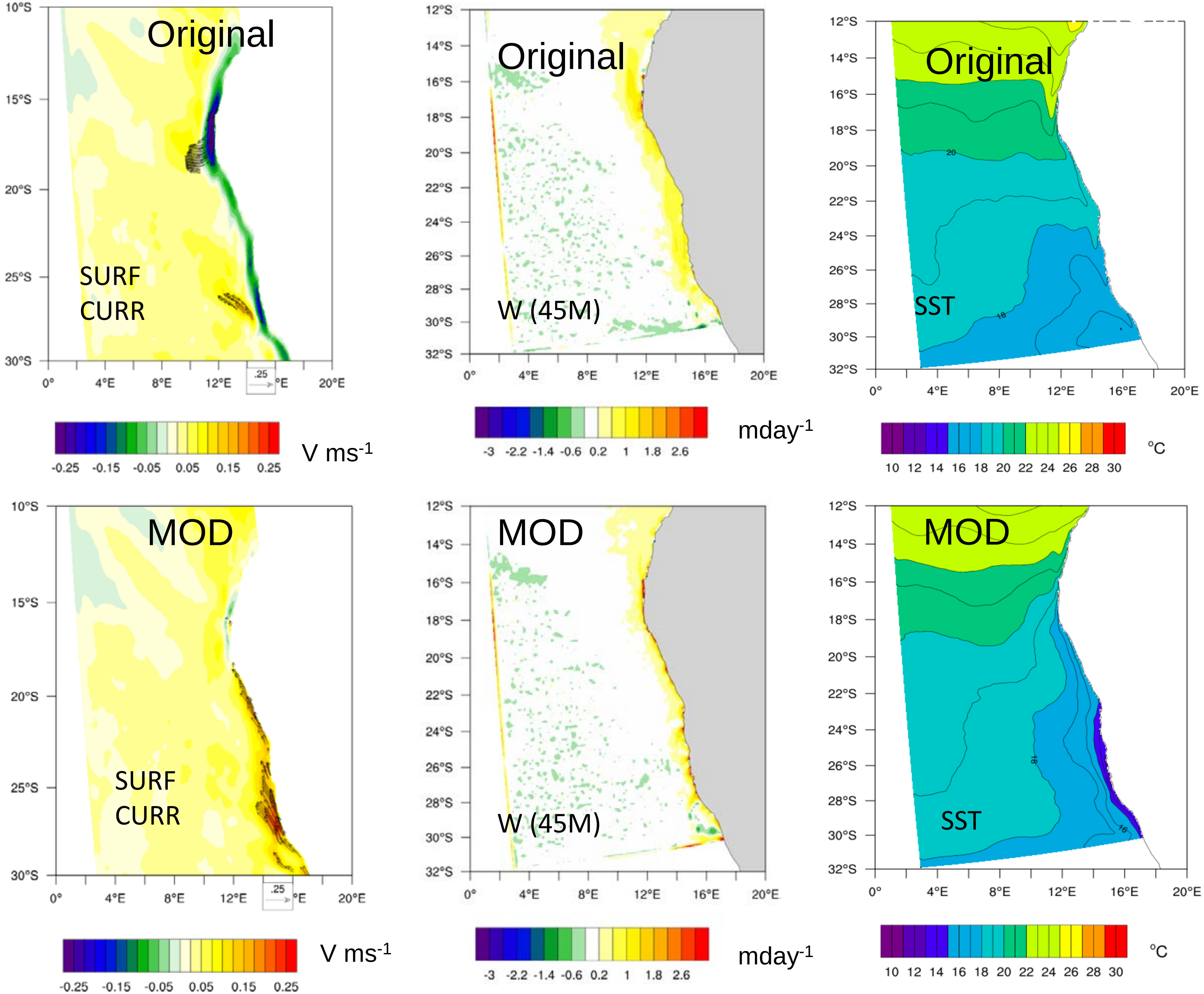
“Shifted wind” experiments



TAUY in JJA

Following **Capet et al 2004 (GRL),** the wind stress is modified **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.



Original experiment

Southward flow at coast, weak upwelling, no sign of upwelling SST front

Run with shifted winds

Dramatic changes! northward flow, coastal upwelling, cool SST

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.

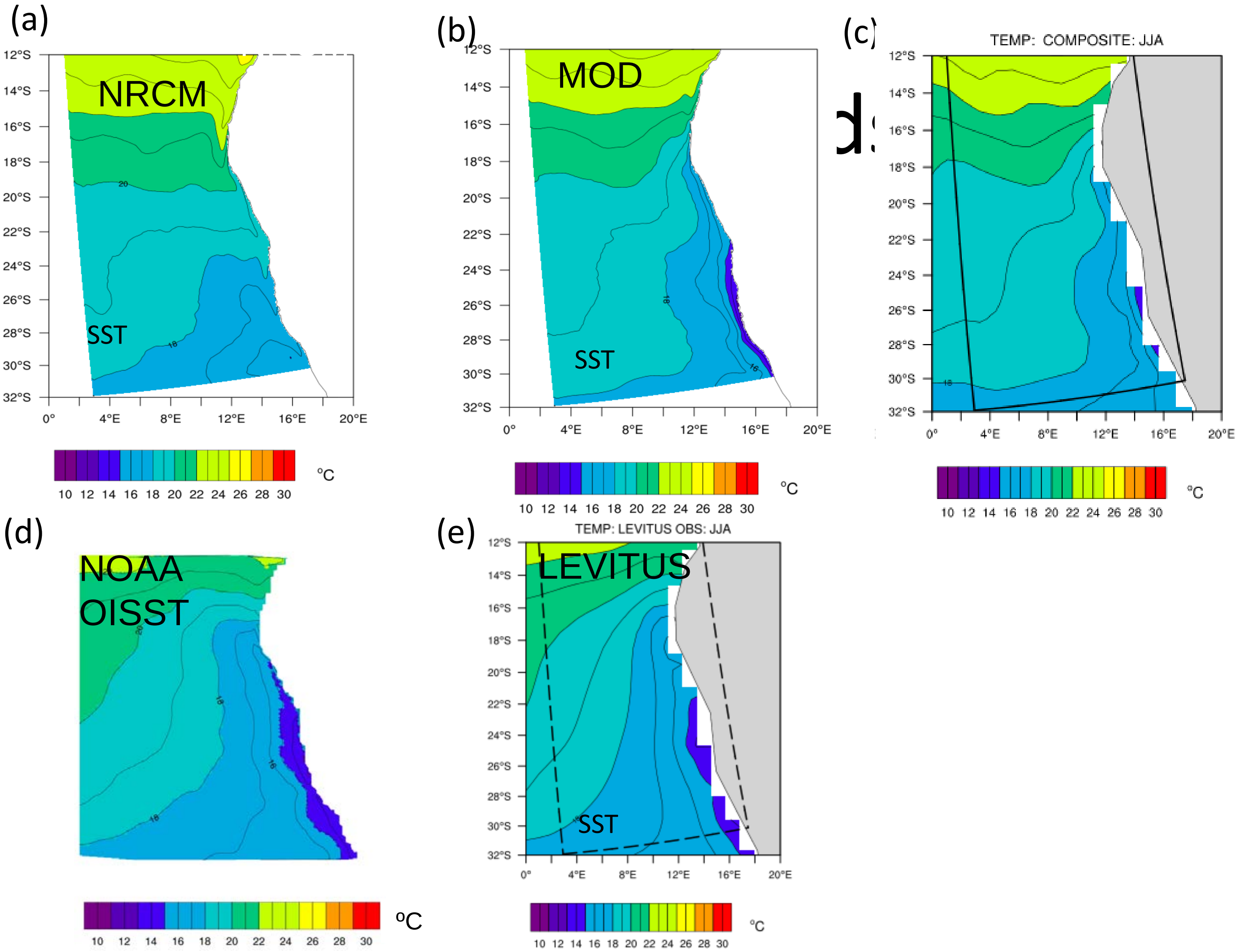
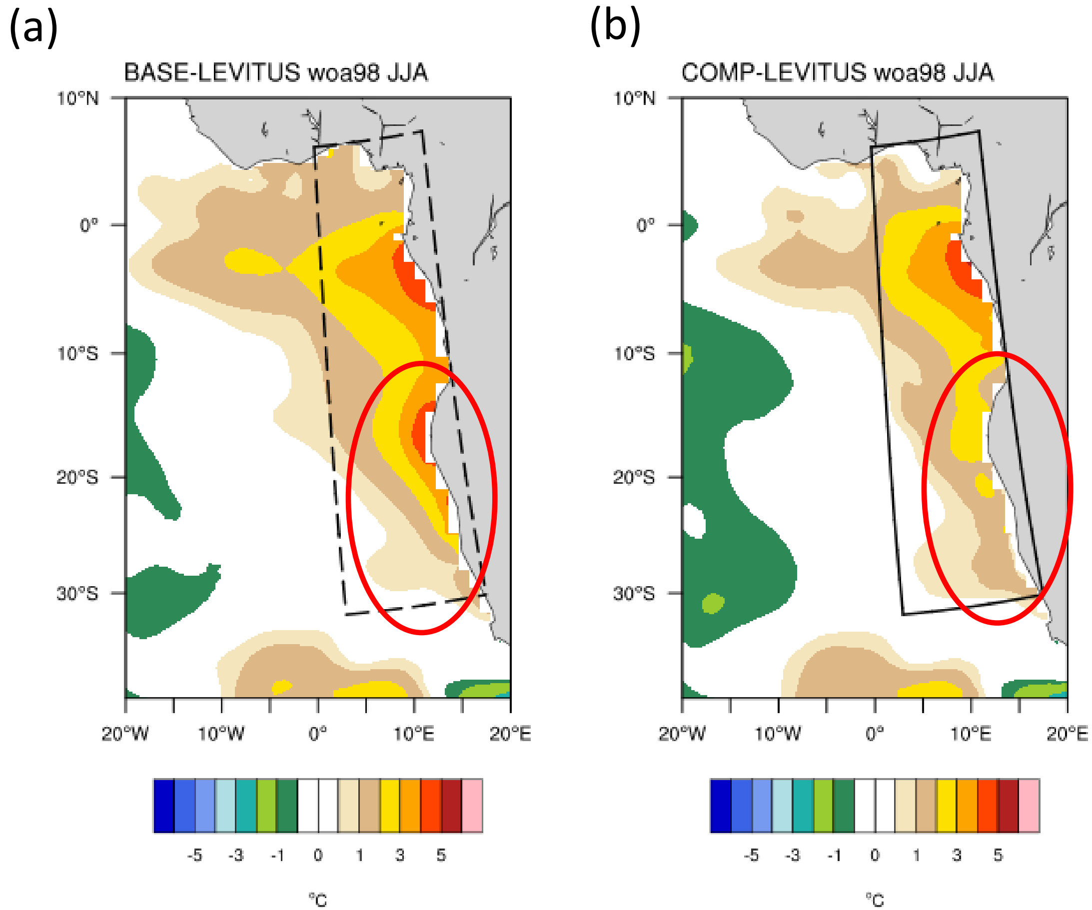


Fig. 15. Top-level temperature (taken as SST) from a) ROMS part of nRCM-0.5 b) from ROMS part of nRCM-MOD experiment, c) from composite SST of nRCM-MOD, d) from the NOAA analysis of observed SST (Reynolds et al 2007), e) from Levitus gridded onto POP grid.

Effect on SST bias

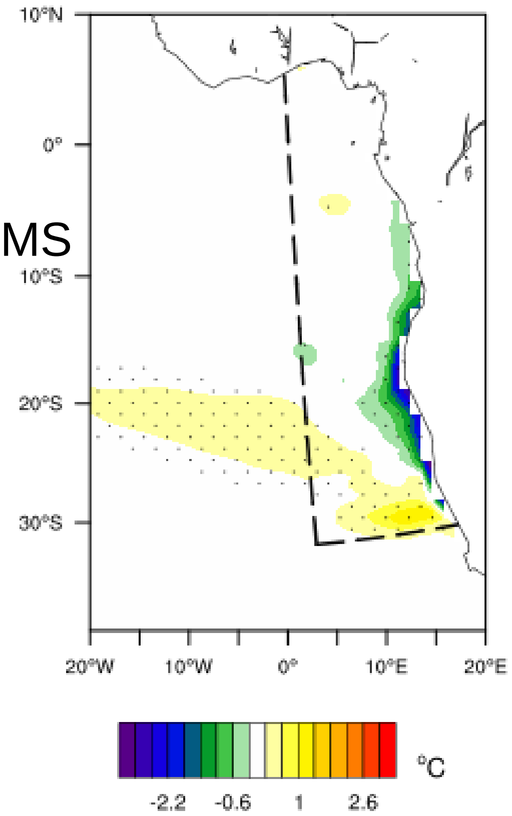


Bias of SST in June-July-August in the south-eastern Atlantic in a) CCSM4 with 0.5deg atmosphere and b) simulation of ROMS embedded in CCSM4 and "shifted winds".

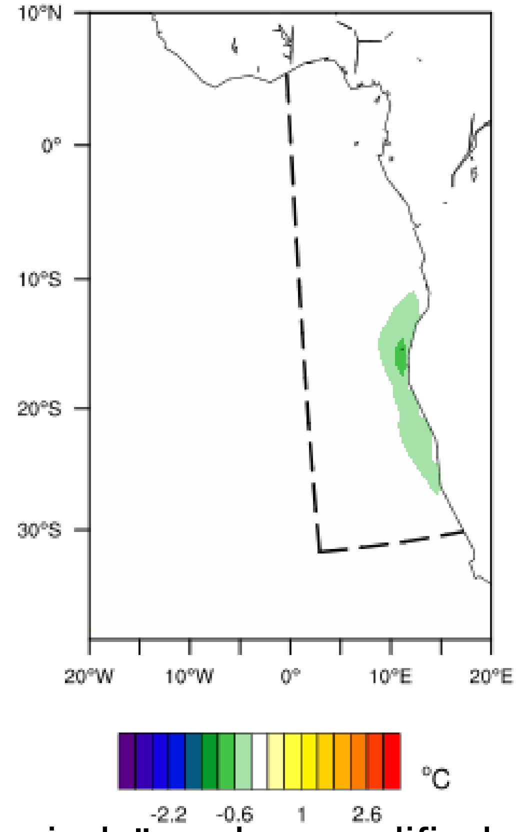
Big improvement in circled region (removing "bullseye") but still a warm bias

Modified wind experiments with high and low-res ocean

Run with ROMS and "shifted winds"



Run with 1deg POP only and "shifted winds"



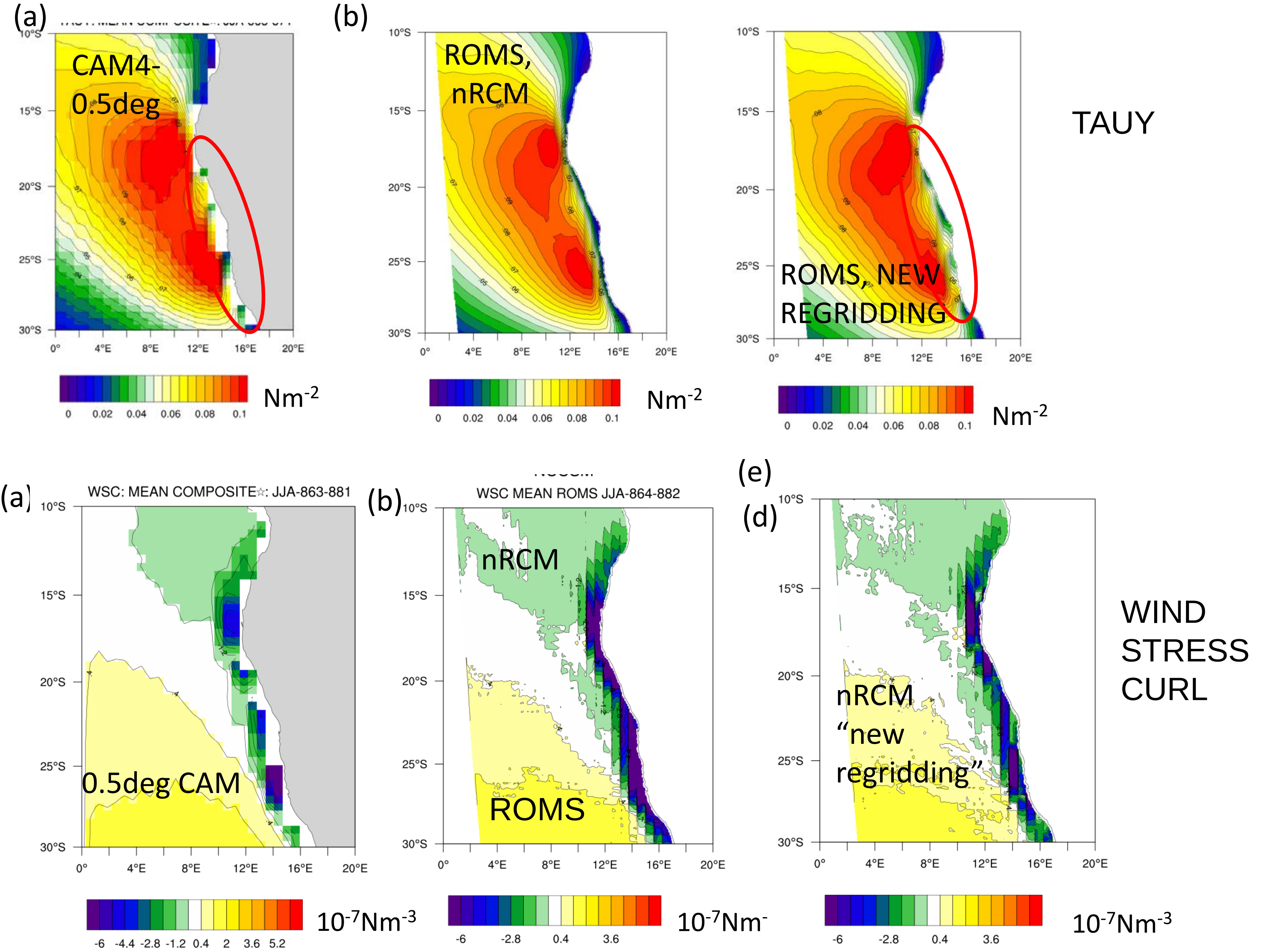
Plots show SST difference between case with "modified winds" and unmodified wind case. Left: with ROMS embedded in CCSM4. Right: CCSM4 with no ROMS. *All data mapped onto 1deg POP grid.*

- **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?



(a)
CAM4-0.5deg
(b)
ROMS, nRCM
ROMS, NEW REGRIDDING
TAUY
Nm-2
0 0.02 0.04 0.06 0.08 0.1
10°S 15°S 20°S 25°S 30°S
0° 4°E 8°E 12°E 16°E 20°E
(a)
WSC: MEAN COMPOSITE☆: JJA-863-881
0.5deg CAM
(b)
WSC MEAN ROMS JJA-864-882
nRCM
ROMS
(e)
(d)
nRCM "new regridding"
WIND STRESS CURL
10-7Nm-3
-6 -4.4 -2.8 -1.2 0.4 2 3.6 5.2
10-7Nm-
-6 -2.8 0.4 3.6
10-7Nm-3
-6 -2.8 0.4 3.6

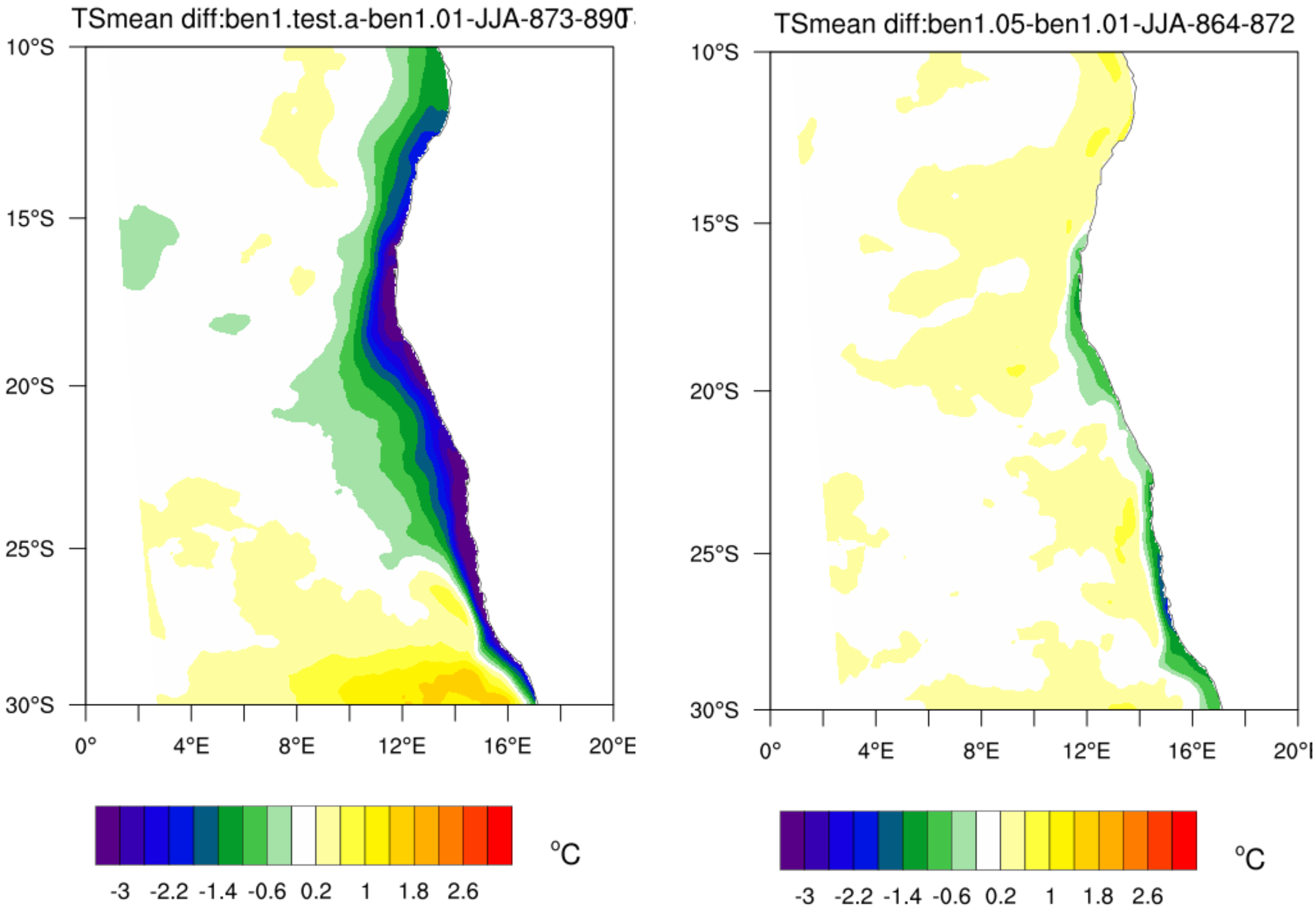
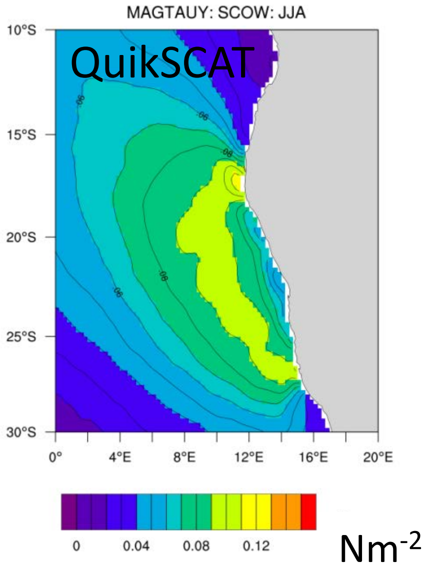
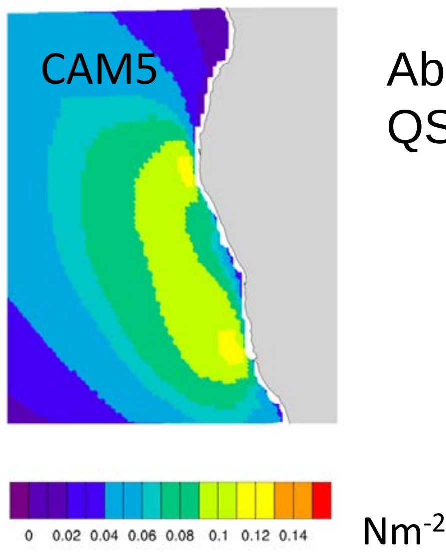


Fig.6. ROMS SST difference between experiments, JJA. a) NRCM ("shifted wind") minus NRCM- 0.5. b) ROMS with new regridding minus NRCM- 0.5.

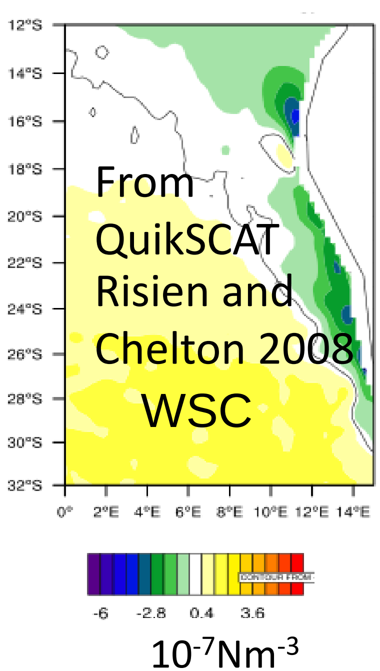
- Technique also applied to high-resolution “ASD” run
  - Caused very little difference – only affected innermost 25km
  - WSC issue much wider

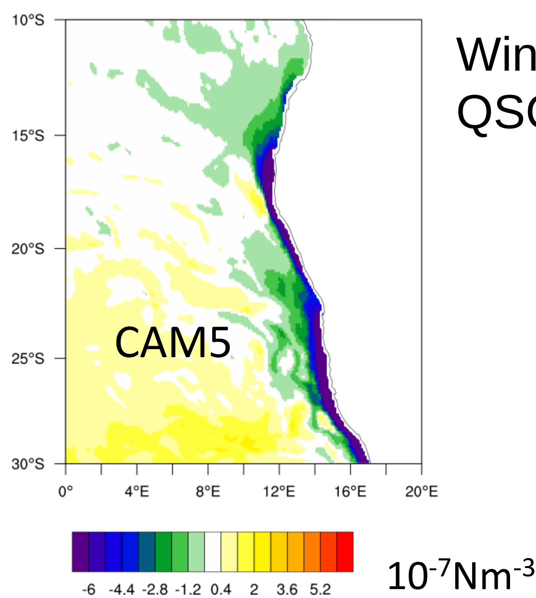
Application to high-resolution CESM





Absolute value of TAUY in JJA
QSCAT & CAM5-SE, 0.25deg

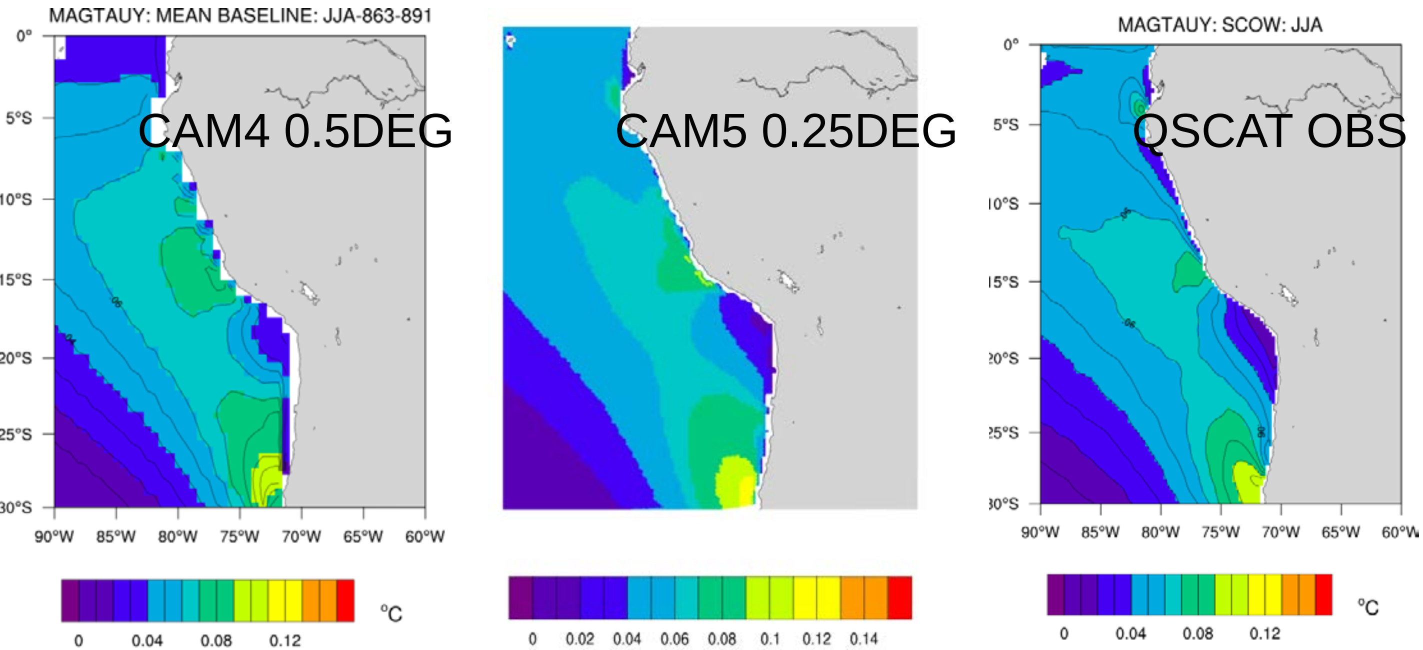




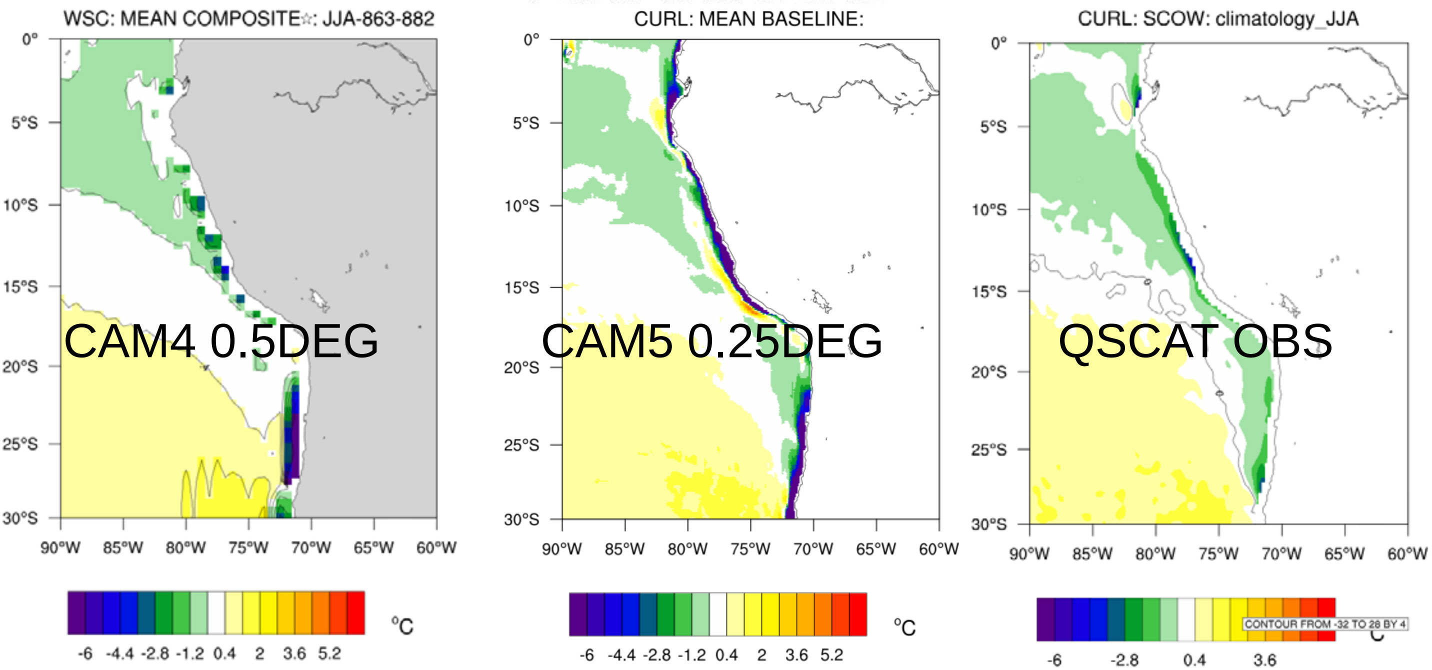
Wind stress curl, JJA
QSCAT & CAM5-SE, 0.25deg

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

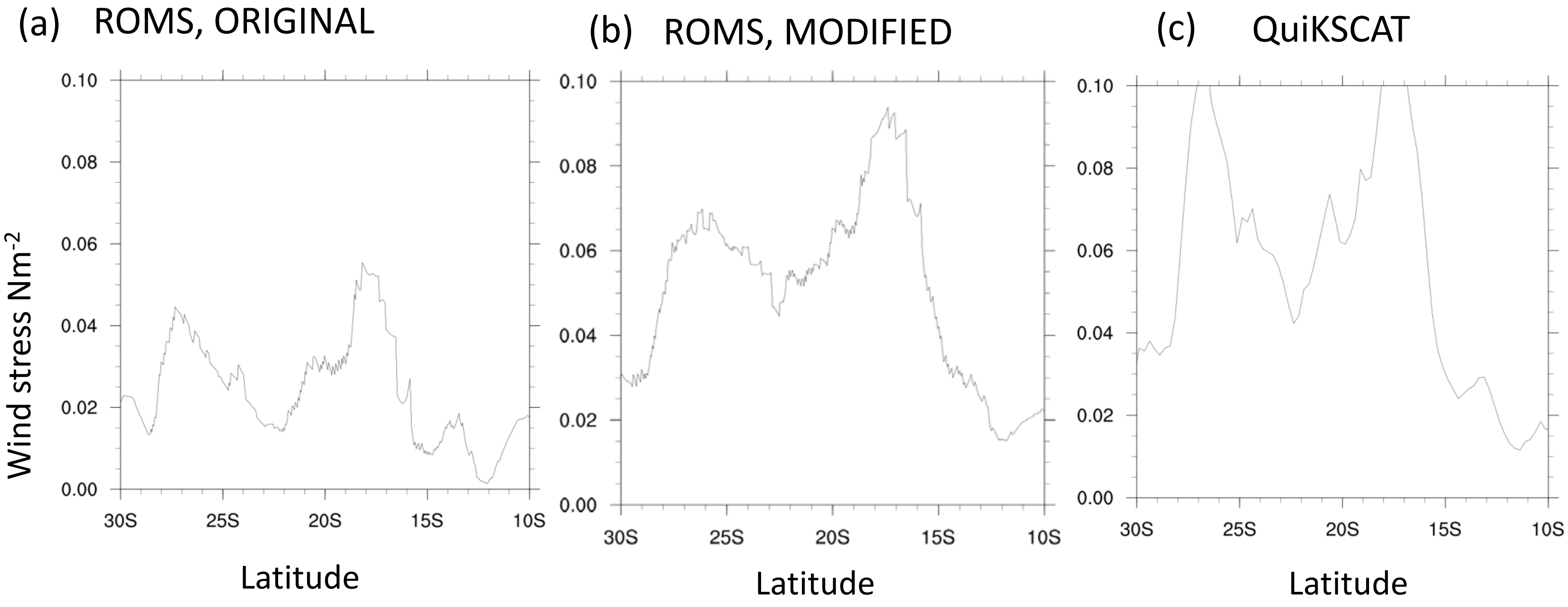


Fig. 10. Wind stress at coastal points as a function of latitude. The stress is the magnitude of time-averaged vector components, at the closest data point to the west Africa coastline. a) in ROMS part of nRCM-0.5. b) corresponding field from nRCM- MOD, C) from QuikSCAT.

Way Forward

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

Way Forward

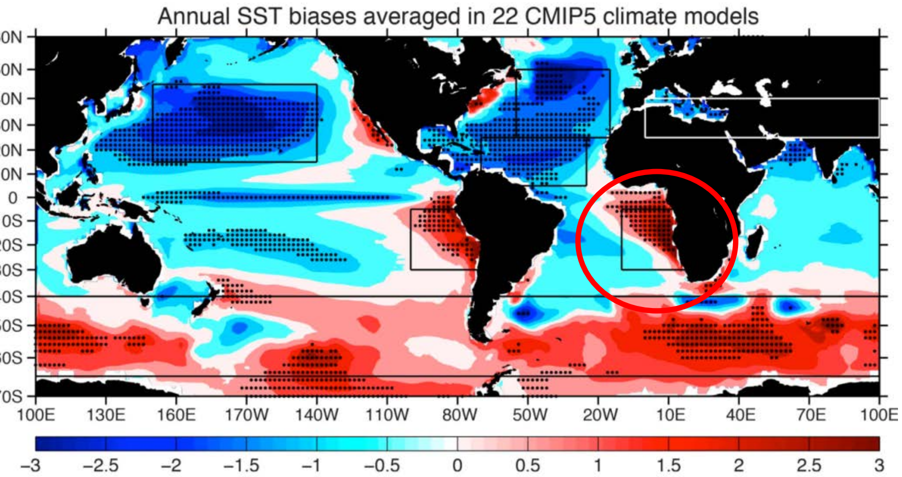
- More shifted wind experiments
- Discuss coastal winds with AMP group
- Analysis of "ASD" suite of runs at varying resolution
  - Does high-res atmosphere, low-res ocean really fix the Peru-Chile and California Current systems (Gent et al. 2010)?

Acknowledgements

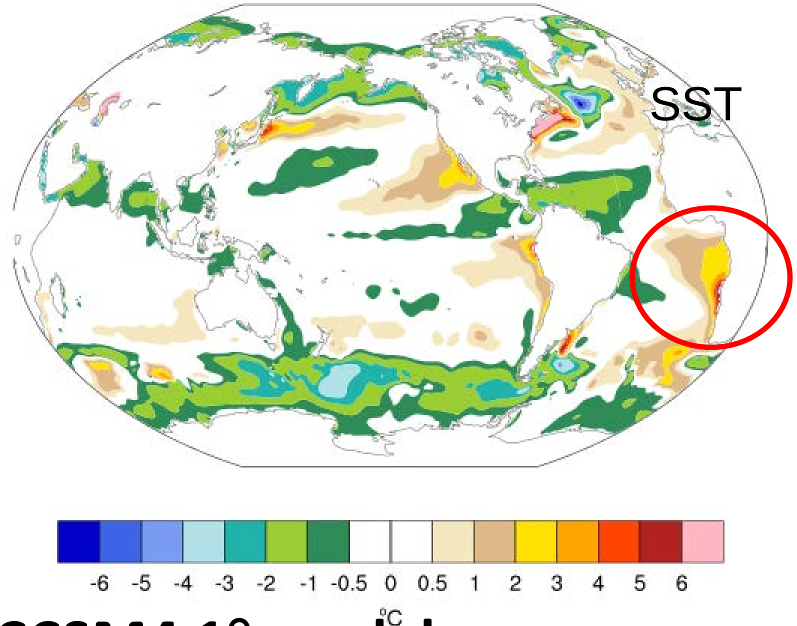
- Discussions with R. Mechoso, M. Jochum, T. Toniazzo, I. Richter, N. Keenlyside, M. Schmidt, P. Chang, F. Desboilles, C. Shields, F. Castruccio, E. Munoz, B. Medeiros, F. Bryan, M. Alexander and P. Gent.
- Recommended papers
  - Fennel, Junker, Schmidt, Morholz 2012. Response of the Benguela upwelling to spatial variations in the wind stress. Cont. Shelf. Res., 45, 65-77.
  - Junker, Tim, 2014. Response of the Benguela upwelling system to changes in the wind forcing. PhD Dissertation, University of Rostock and Leibnitz Institute for Baltic Sea Research, available online.
  - Capet, X. J., P. Marchesiello and J. C. McWilliams, 2004. Upwelling response to coastal wind profiles. Geophys. Res. Lett., 31, L13311, doi: 10.1029/2004GL020123.

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.

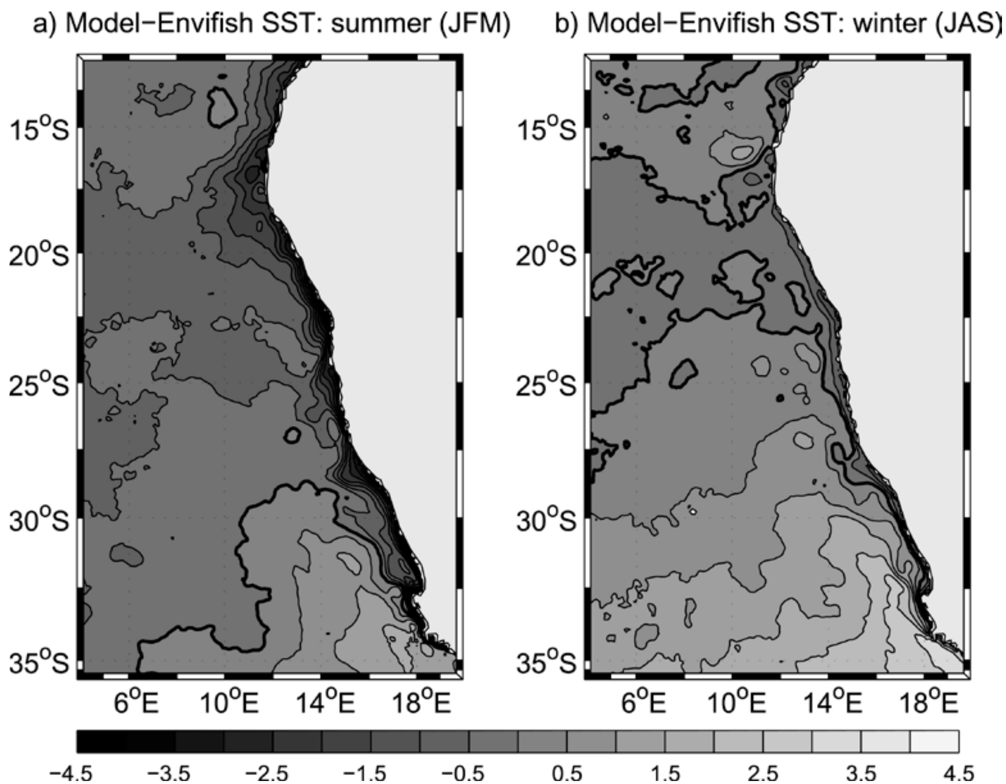


CCSM4 1° model (from Gent et al. 2011). Long term, annual mean SST difference from Hurrell et al. 2008 observations.

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



From Veitch et al. 2010: *J. Phys. Oceanogr.*, **40**, 1942–1964.

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.

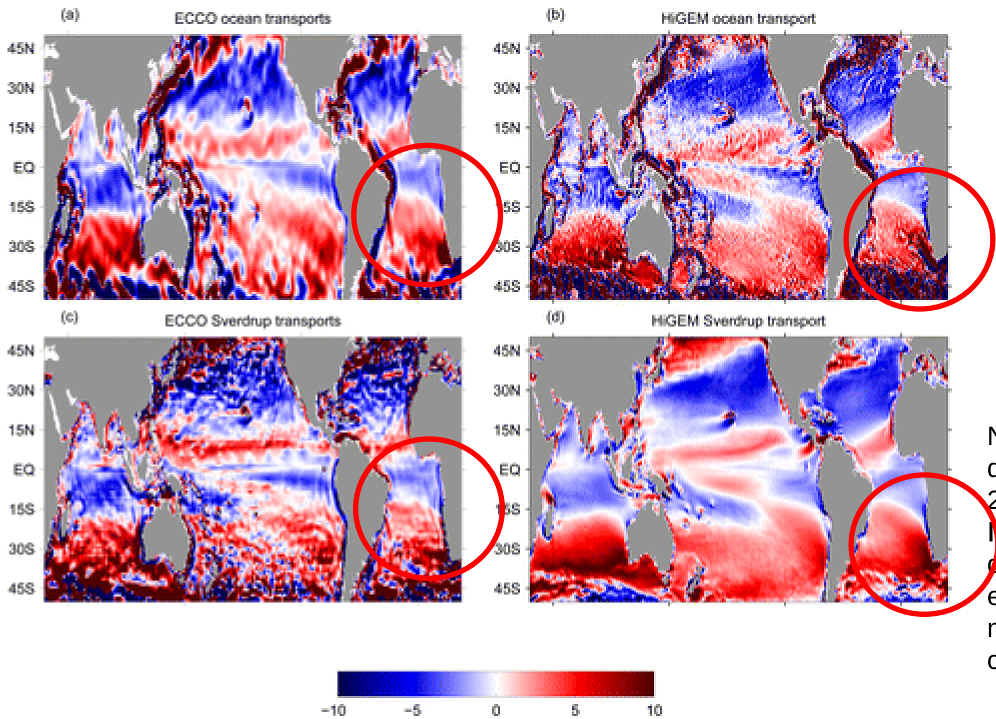
Regional Ocean Modelling System (ROMS): Shchepetkin and McWilliams 2005. *Ocean Modell.*, **9,** 347–404.

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

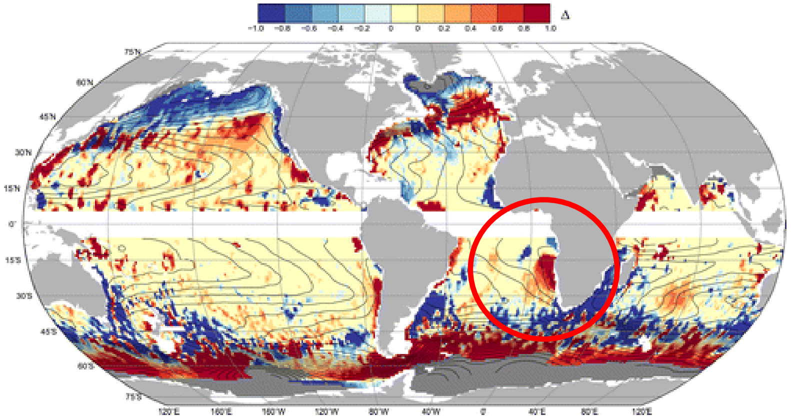
Is Sverdrup balance appropriate here?

Thomas et al. 2014. Spatial and temporal scales of Sverdrup balance (JPO)

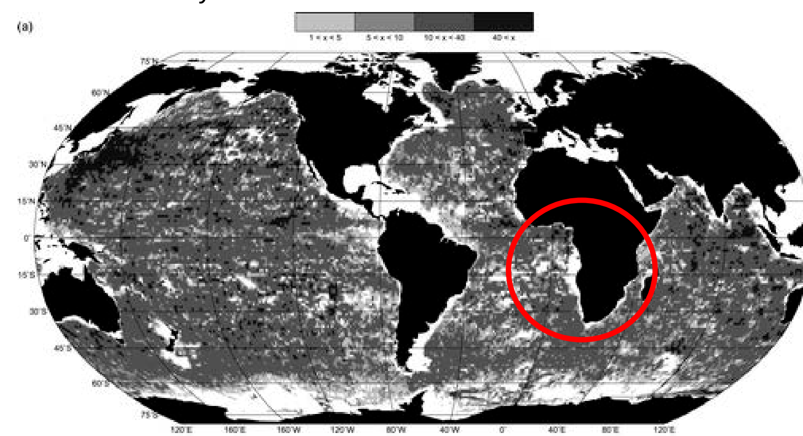


Vorticity terms (m^2 s^{-1}) in the 15-yr time-averaged Sverdrup balance in (left) ECCO–GODAE
and (right) HiGEM: (a),(b) *V* (using integration depths of 1400 and 1000 m, respectively),
(c),(d) , and (e),(f) the Sverdrup error, .
The yellow border in (e) and (f) indicates the edge of the masked regions not included in the determination of any integrated quantities.

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



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 σ_θ 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.



(a) Spatial distribution of all profile data shown as the number of profiles *x* in each 1° × 1° box

Is Sverdrup balance appropriate here?

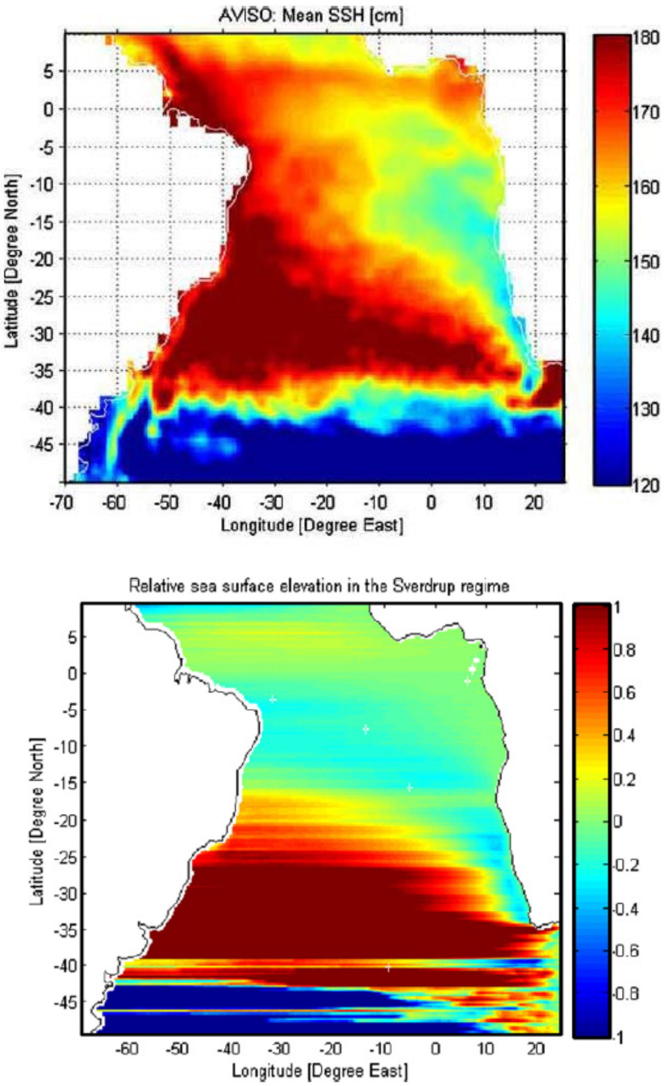
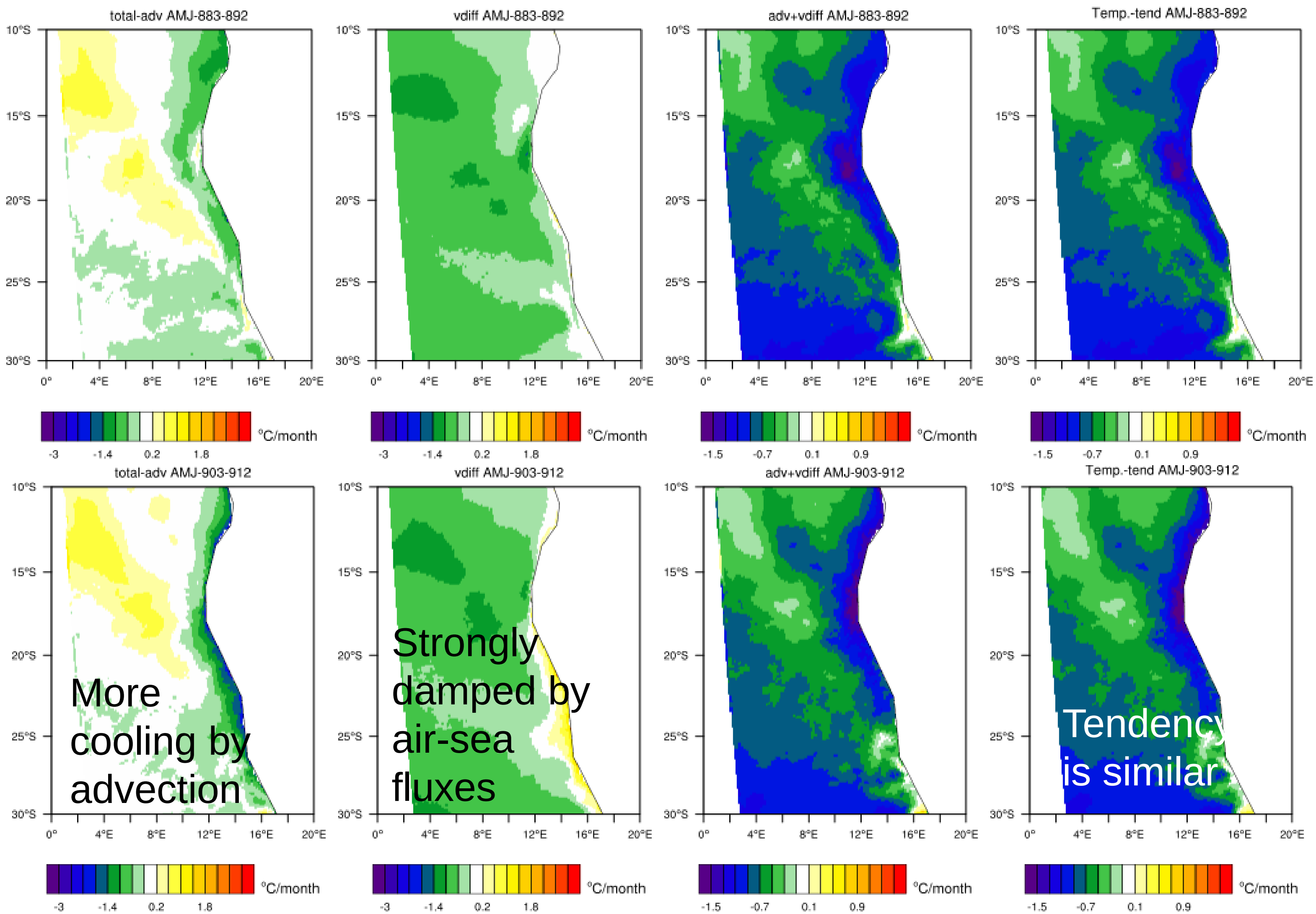


Fig. 27. Sea level elevation [m] with respect to the eastern boundary derived from the measured wind stress field assuming a Sverdrup balance.

Lass and Mohrholz 2008. On the interaction of the subtropical gyre and the subtropical cell on the shelf of the SE Atlantic. J. Mar. Sys.

Upper ocean Heat budget



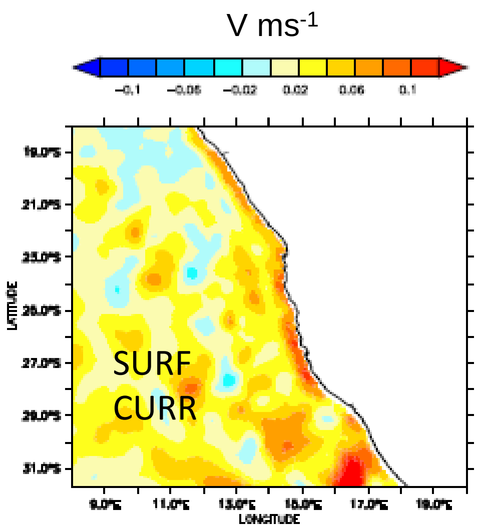
Original case, ROMS in CCSM4

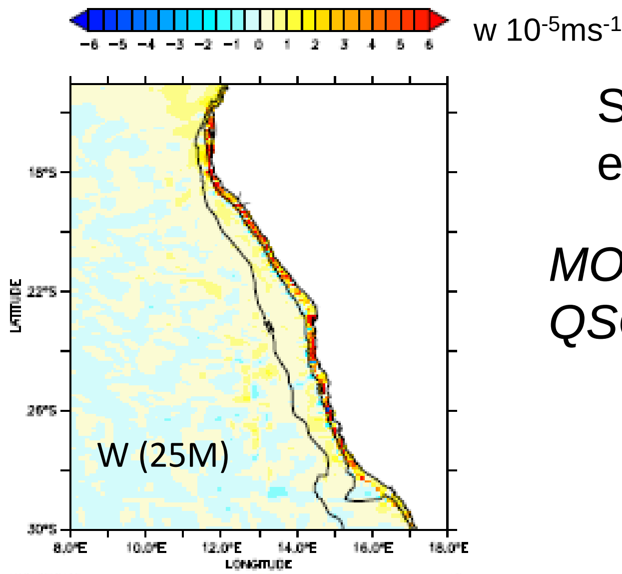
"Shifted wind" case, ROMS in CCSM4

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

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

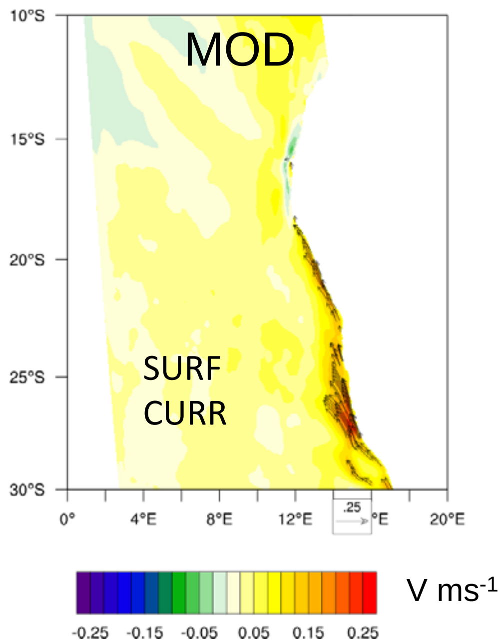
Comparison with forced ocean runs

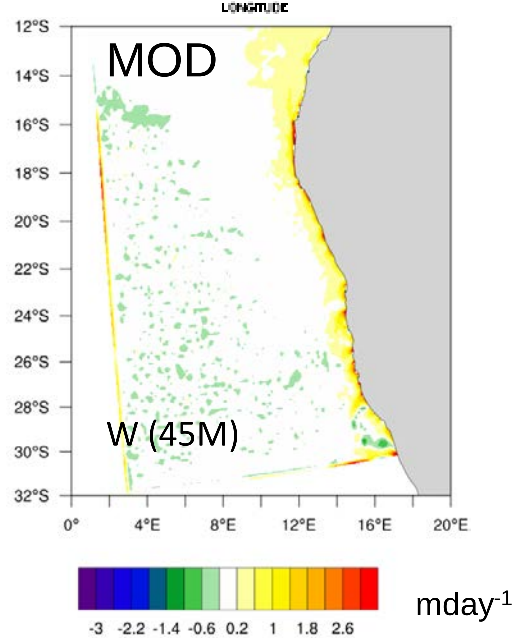




Schmidt, Fennel, Junker et al

MOM4 regional model forced by QSCAT winds, NCEP states.

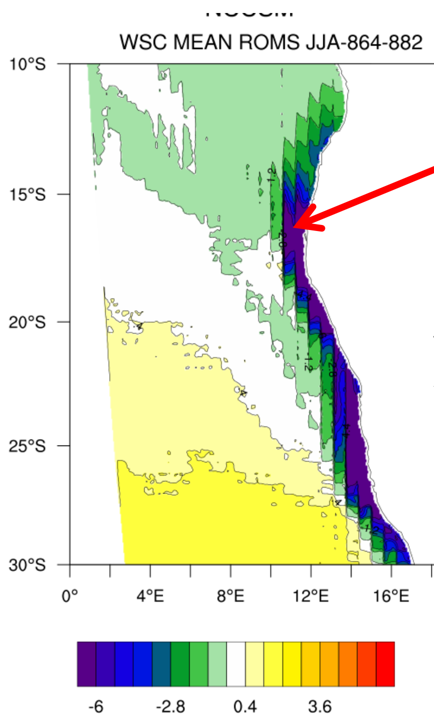




Nrcm Run with shifted winds

“Shifted wind” experiments

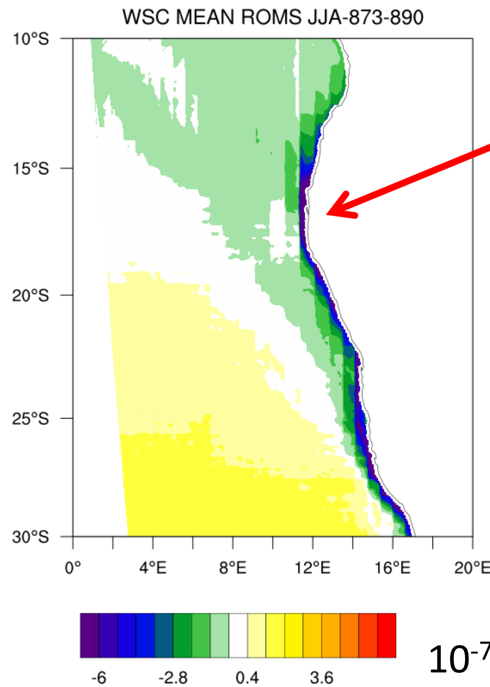
(a) ROMS, ORIGINAL



Strong and wide WSC

$10^{-7}Nm^{-3}$

(b) ROMS, MODIFIED

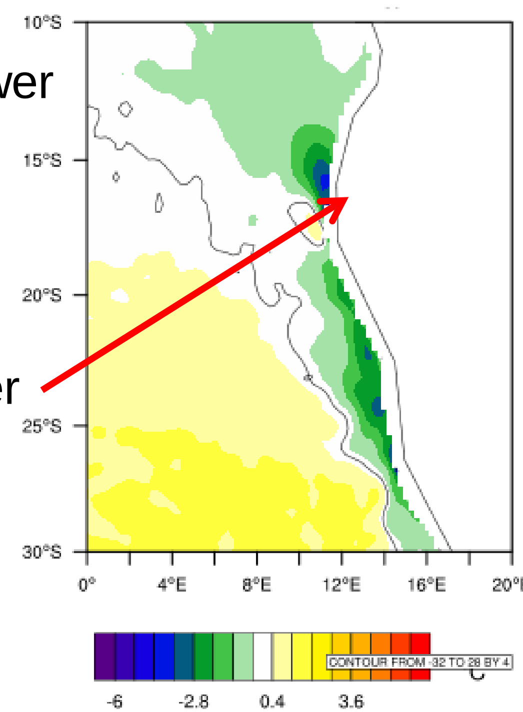


$10^{-7}Nm^{-3}$

Narrower WSC band

(c) QuiKSCAT

Weaker WSC



$10^{-7}Nm^{-3}$

Wind stress curl in JJA

Wind stress curl structure is modified – much narrower but still strong in the modified experiment.

Vertical sections

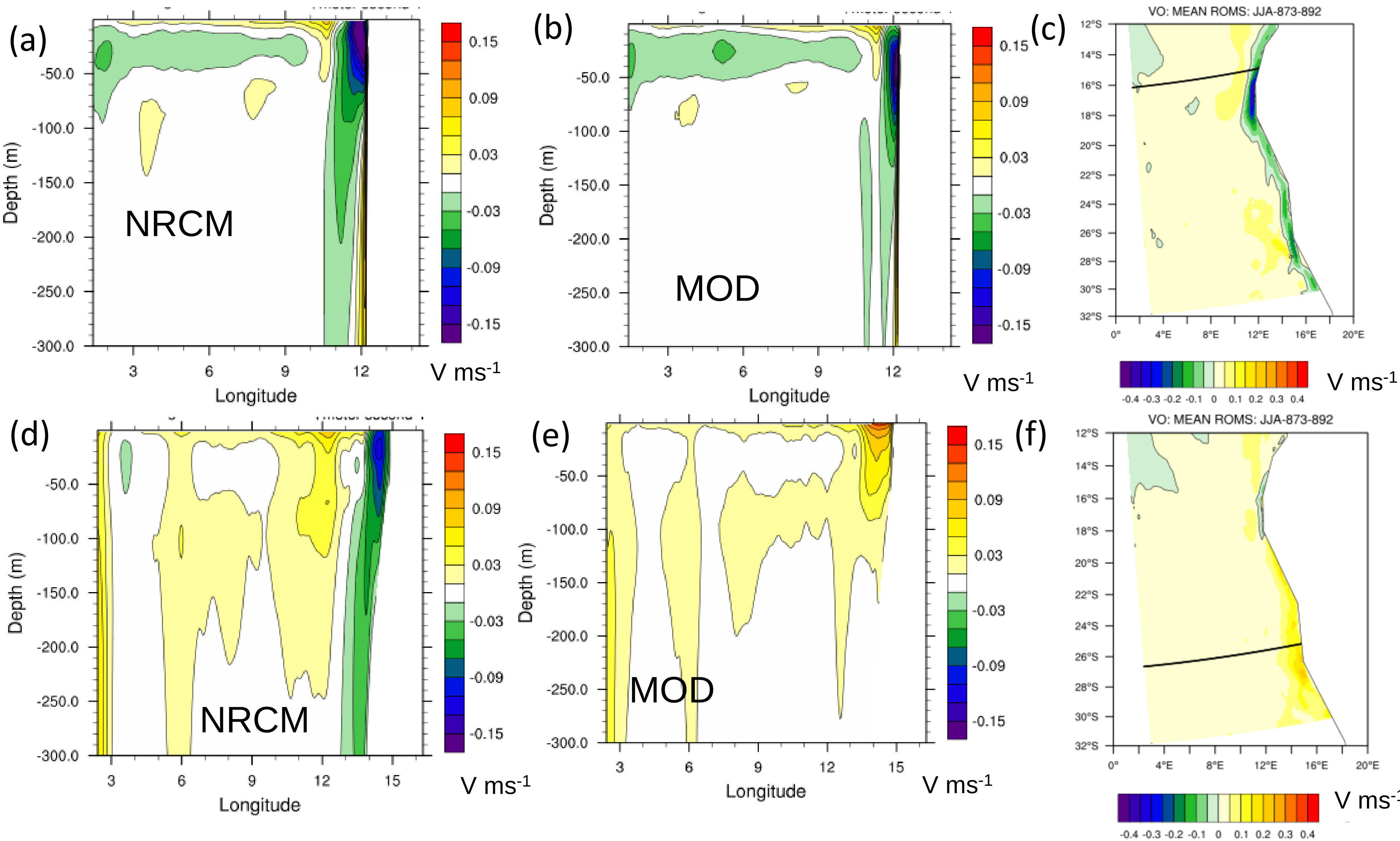


Fig. 12. Meridional velocity sections vs longitude and depth. a), b) are along the line shown in c). d,e) are along the line shown in f). Left panels: from nRCM-0.5. Middle panels: from nRCM-mod. Shading in right panels shows the surface velocity from c) nRCM-0.5 and f) nRCM-MOD.

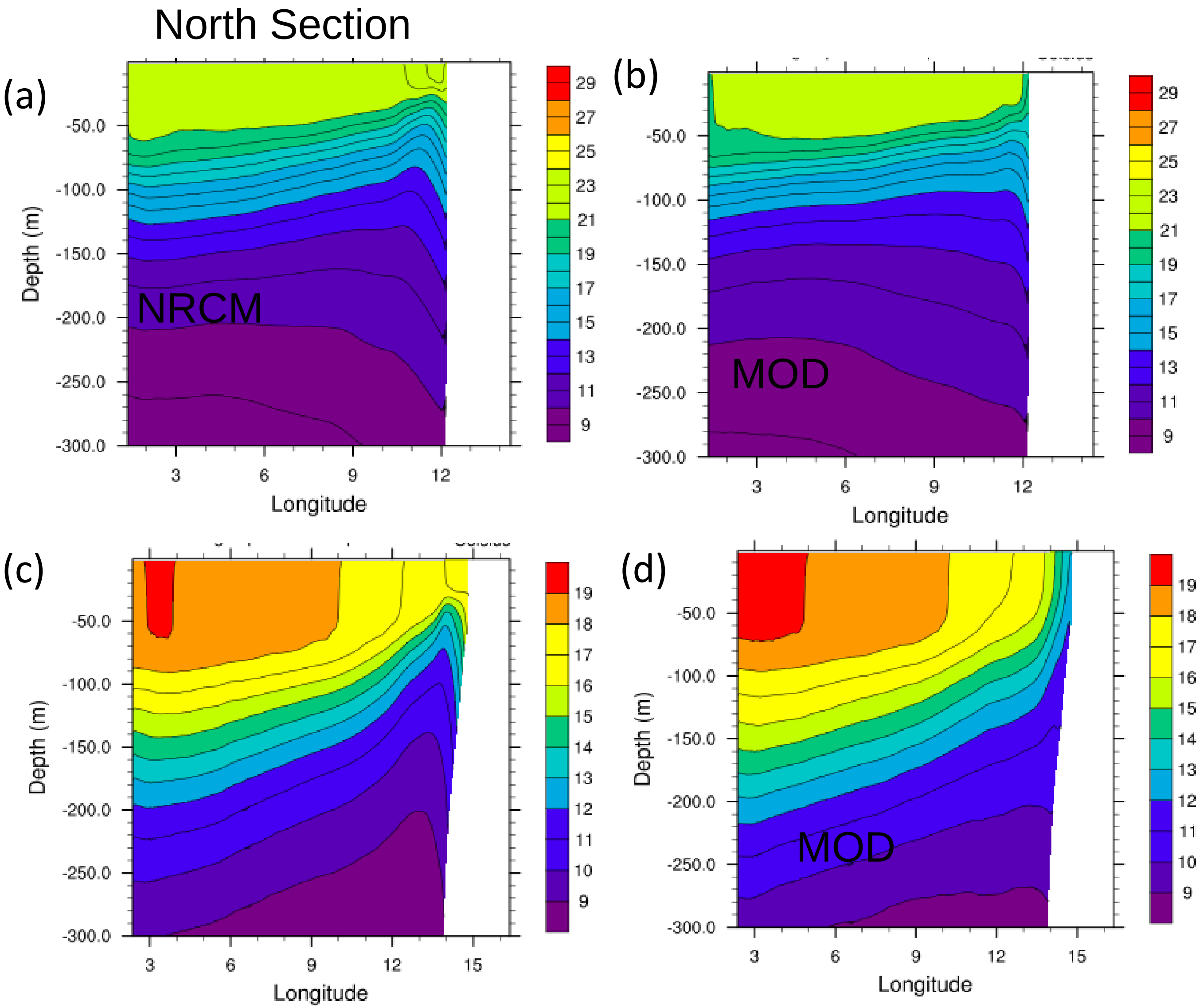


Fig. 13. Potential temperature sections (°C) vs longitude and depth. a), b) are along the northern line shown in Fig. 12c). b,ed) are along the southern line shown in Fig. 12f). Left panels: from nRCM-0.5. Middle panels: from nRCM-MOD. Note change of temperature color range from upper row to lower row.

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