Eastern boundary upwelling in CORE vs JRA55 ocean-ice simulations

Justin Small
Steve Yeager, Gokhan Danabasoglu, Bill Large, **Who Kim**
NCAR
Hiroyuki Tsujino, JMA

Ocean-ice simulations

- CORE forcing
  - T62, ~1.8deg. winds corrected towards QuikSCAT annual climatology
- JRA55v0.3 forcing
  - 0.5deg winds corrected towards QuikSCAT monthly climatology
- Ocean-POP, 1deg.

Coupled Simulations

- Community Climate System Model (CCSM)4
- Ocean-POP 1deg.
- Atmosphere-CAM 2deg. or 0.5deg.

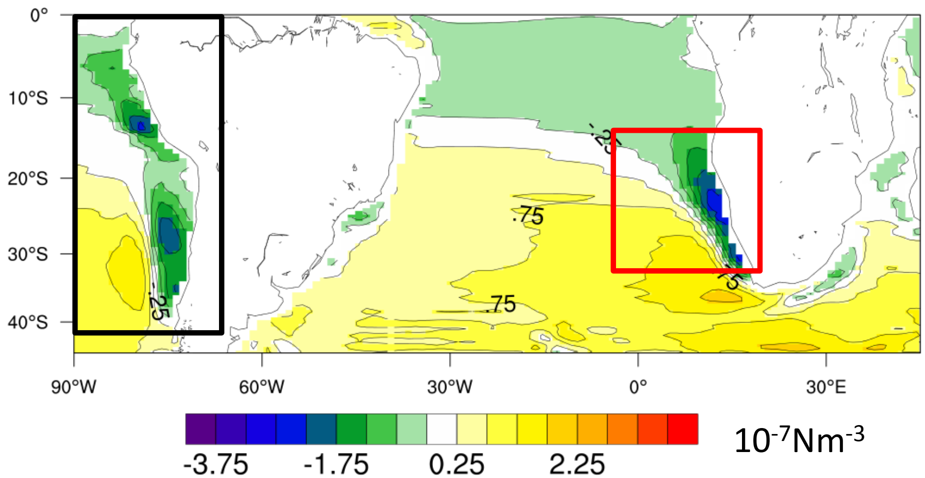
Recap: CCSM4 with 2deg. atmosphere

All plots are for annual mean *Gent et al. 2010, Small et al. 2015*

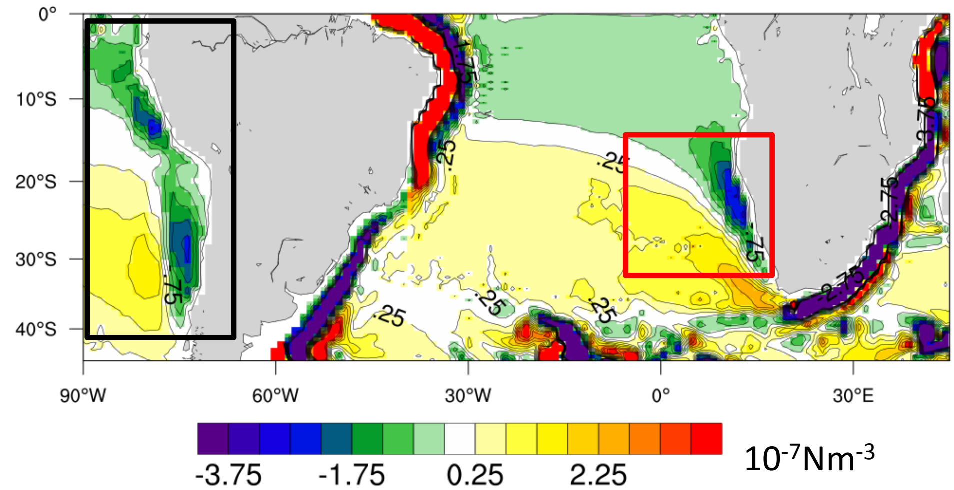
Wind stress curl driven dynamics at eastern boundaries

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

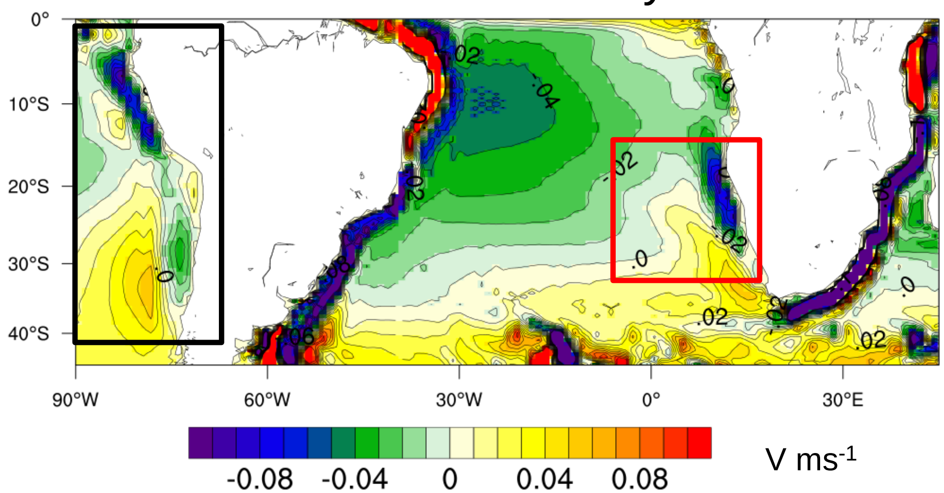
Wind Stress Curl



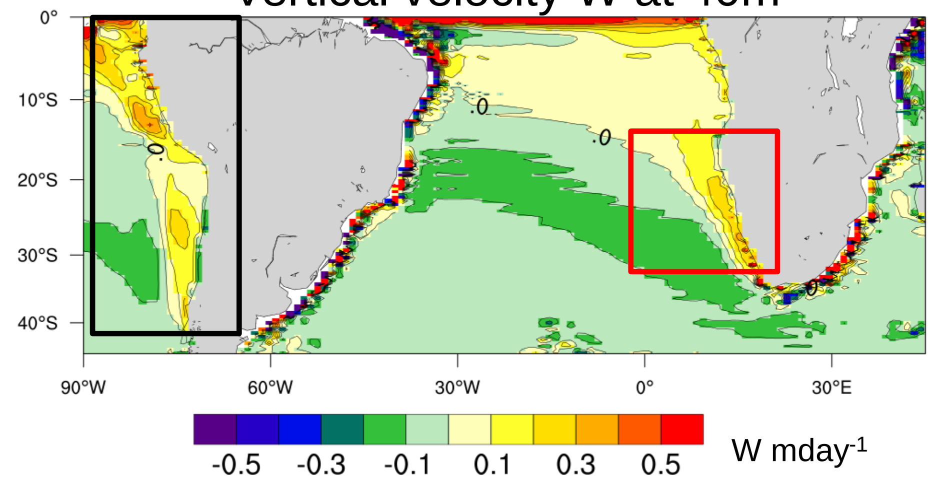
Vertically integrated V



Surface meridional velocity V

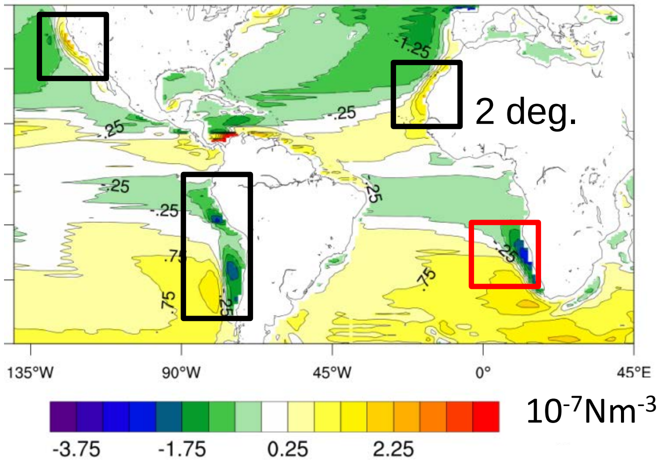


Vertical velocity W at 40m

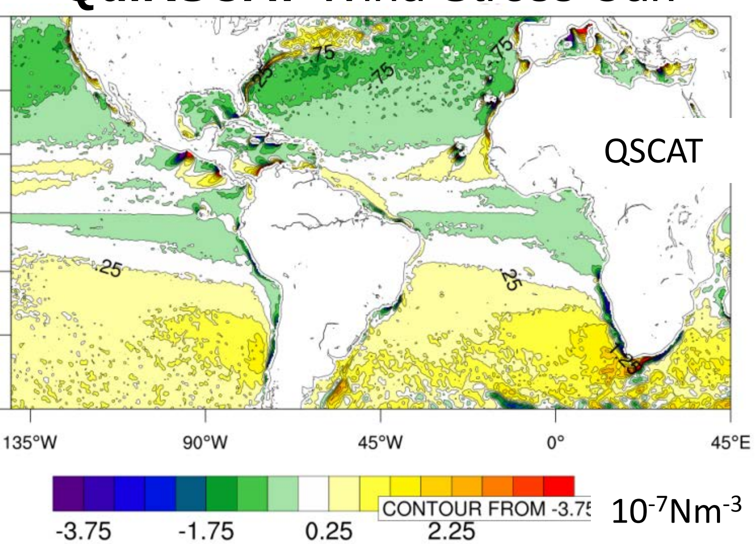


Curse of the broad wind stress curl

CCSM4-2deg. Wind Stress Curl

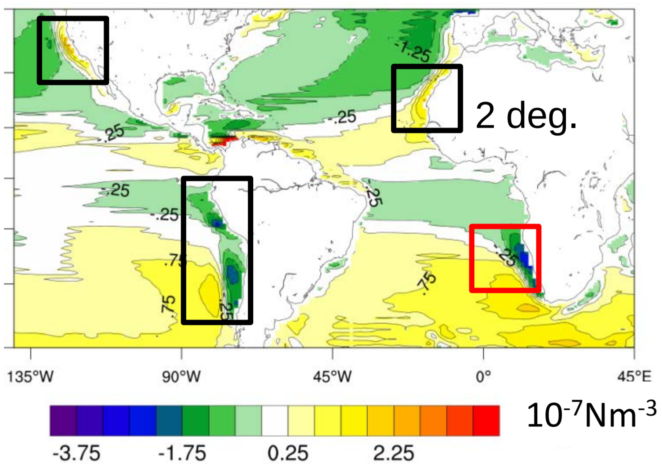


QuiKSCAT Wind Stress Curl

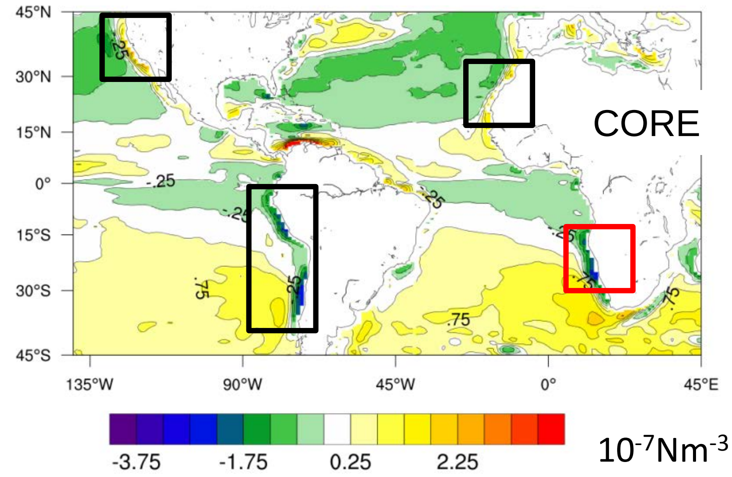


Curse of the broad wind stress curl

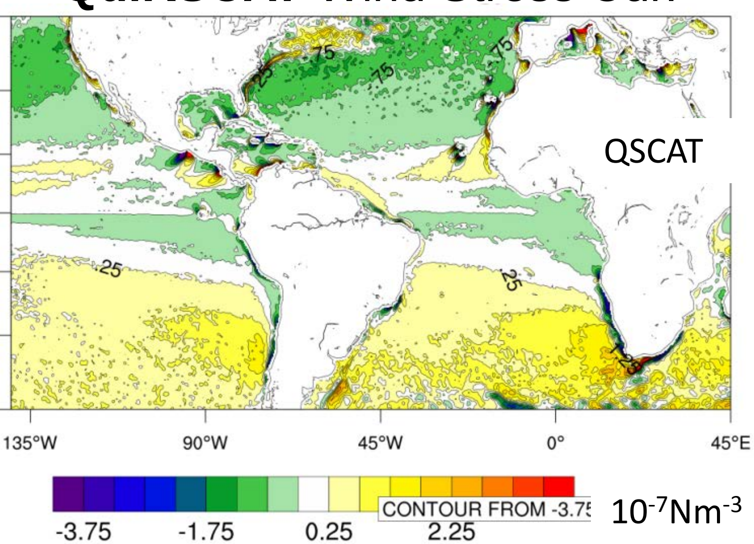
CCSM4-2deg. Wind Stress Curl



CORE Wind Stress Curl



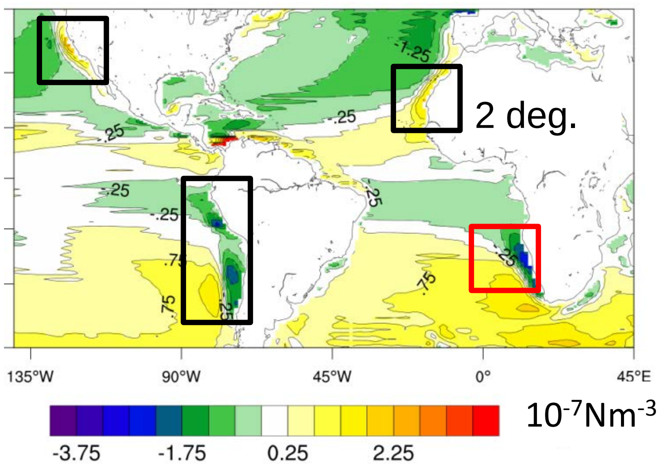
QuiKSCAT Wind Stress Curl



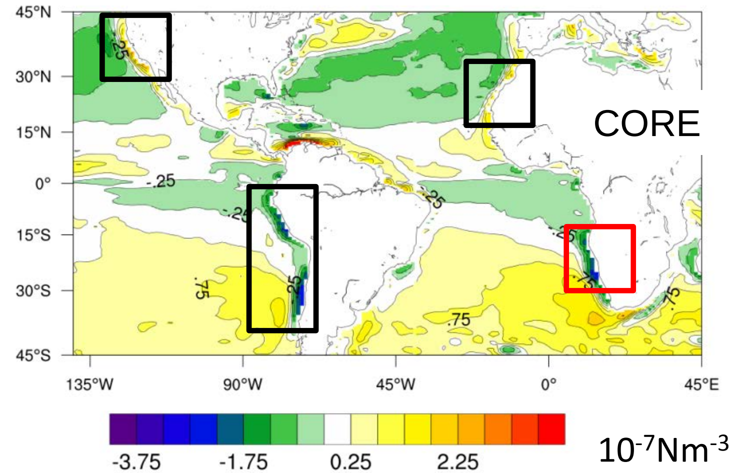
Correction of CORE to QuikSCAT does not fix wind stress gradients. (resolution mismatch)

Curse of the broad wind stress curl

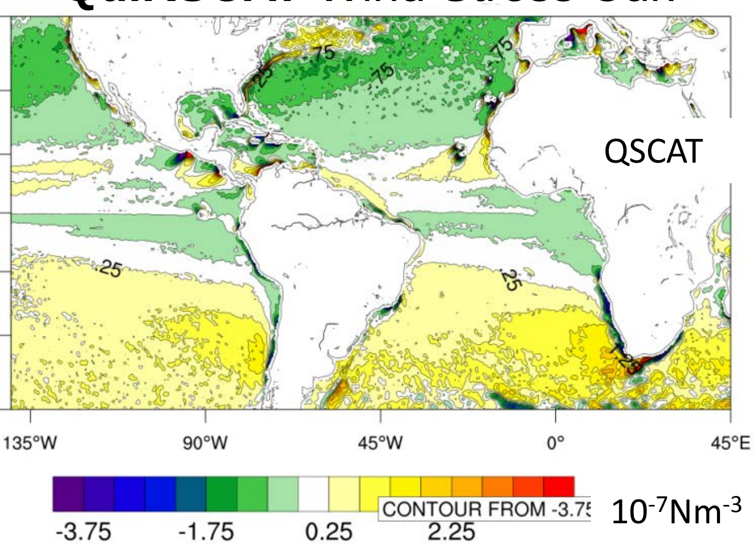
CCSM4-2deg. Wind Stress Curl



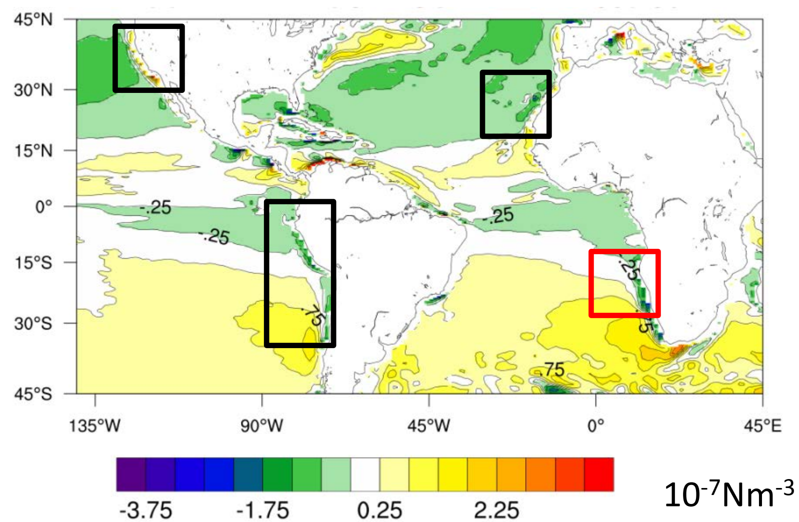
CORE Wind Stress Curl



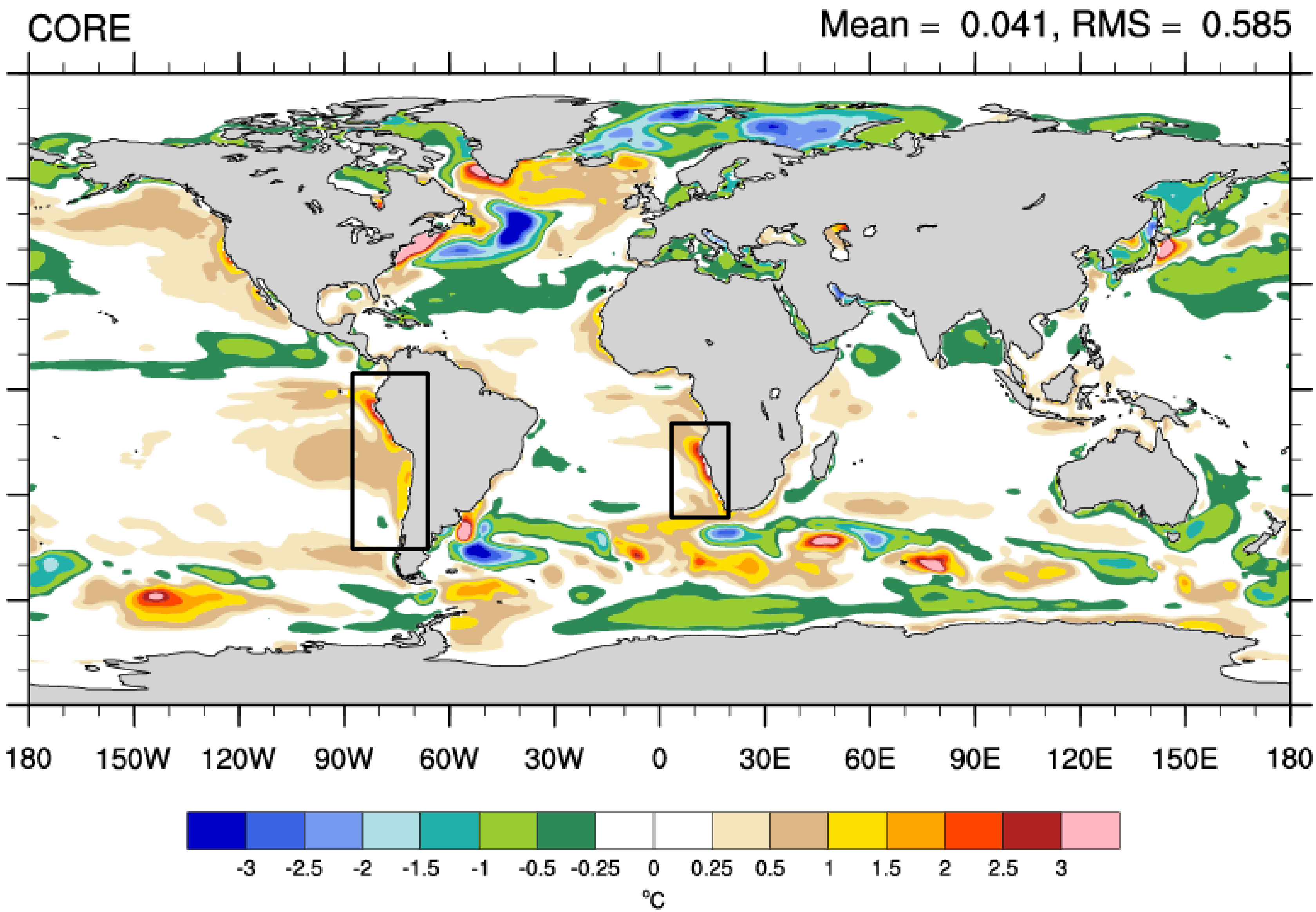
QuiKSCAT Wind Stress Curl



JRA55 Wind Stress Curl

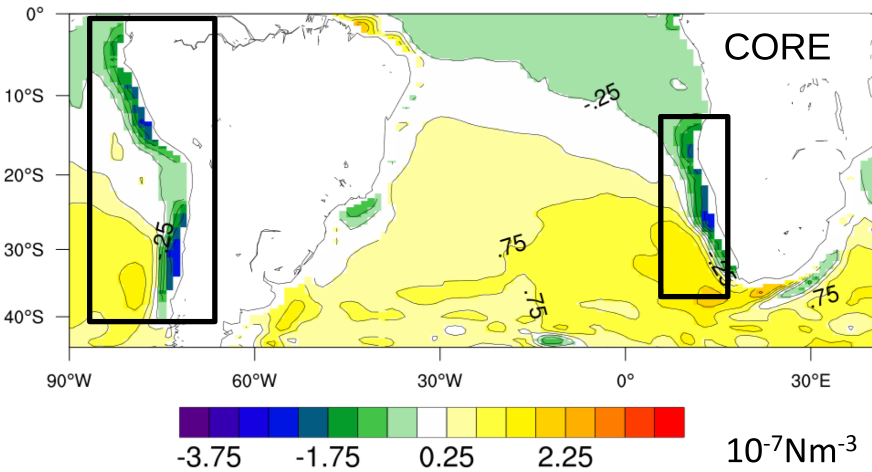


SST bias: CORE forced simulation

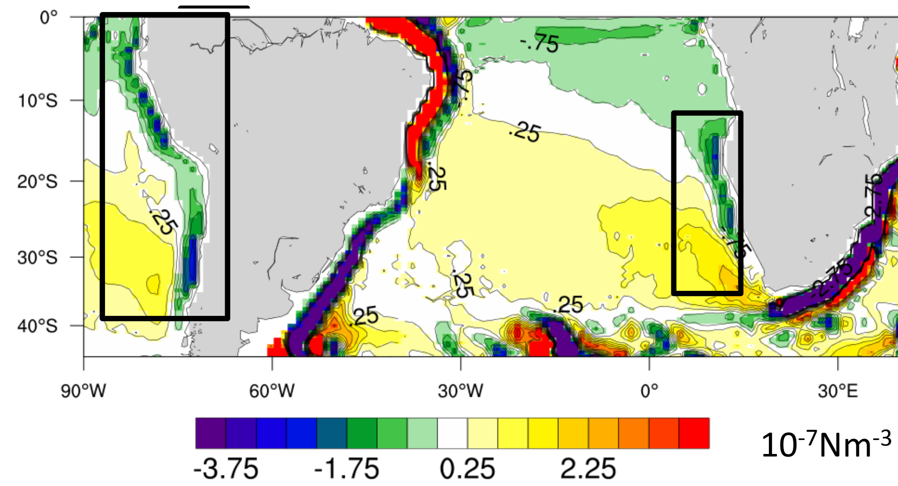


CORE simulations

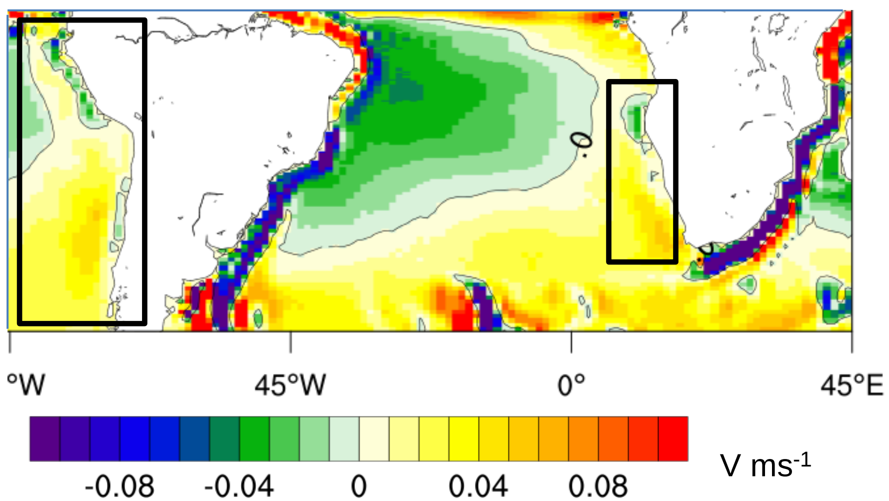
Wind Stress Curl



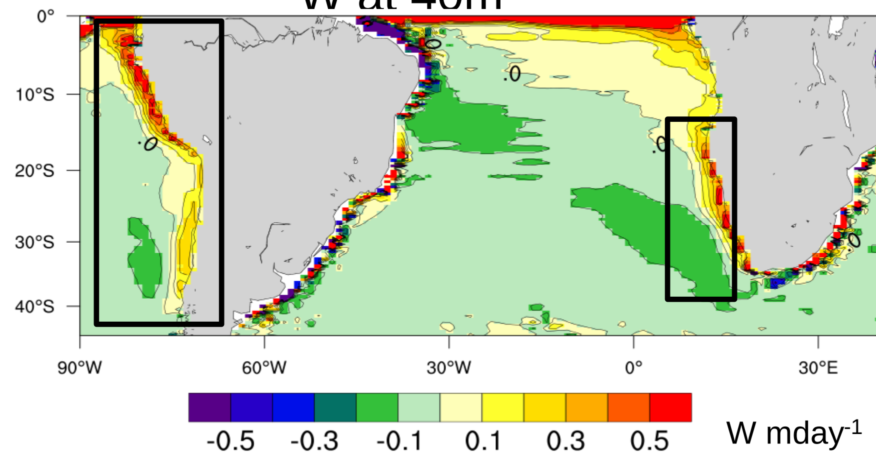
Vertically integrated V



VSURF



W at 40m

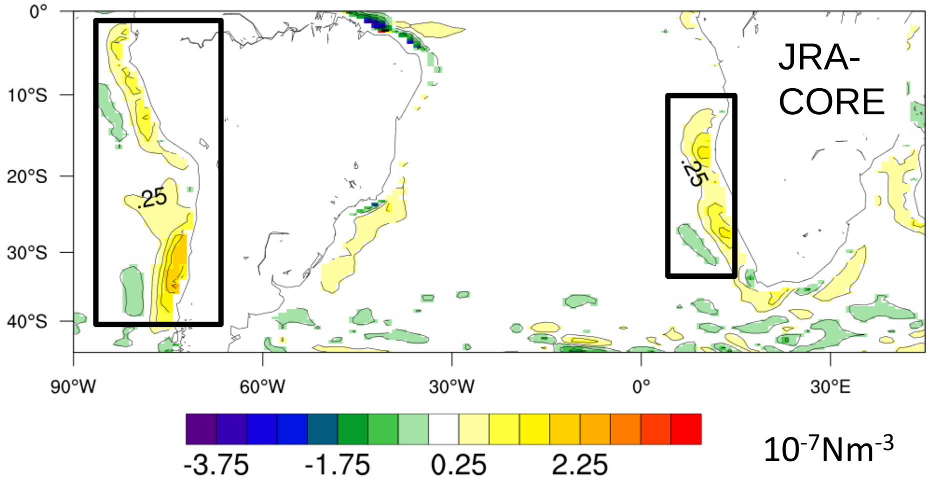


Annual mean. With a ~2deg atmosphere in CORE forced, approximate Sverdrup balance holds in eastern boundaries and sub-tropical gyres. However surface flow is more Equatorward in CORE-forced than in CCSM4 with 2deg atmosphere. Vertical velocity is wind-stress-curl (Ekman-pumping) driven.

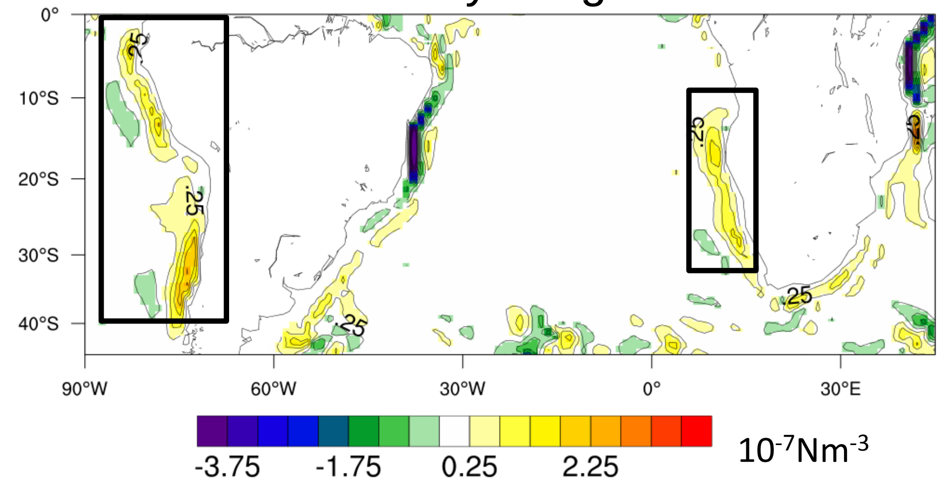
Sensitivity to atmosphere resolution

Difference, JRA-forced minus CORE-forced

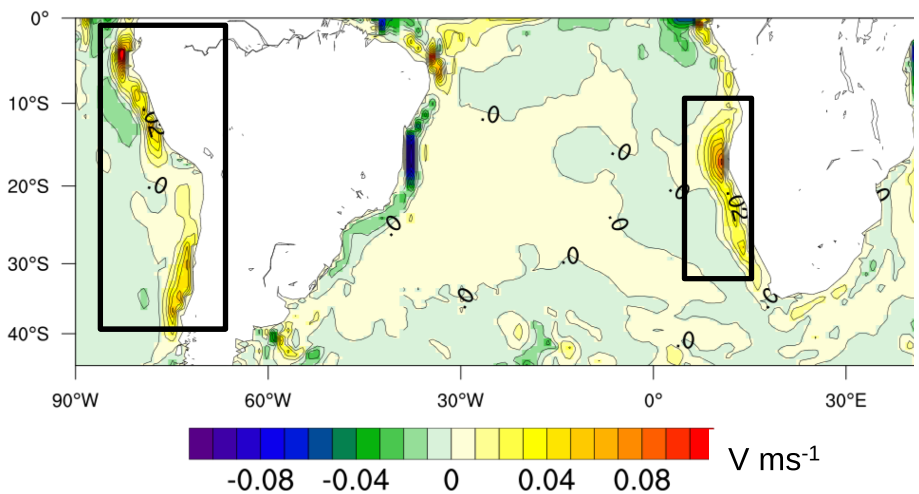
Wind Stress Curl



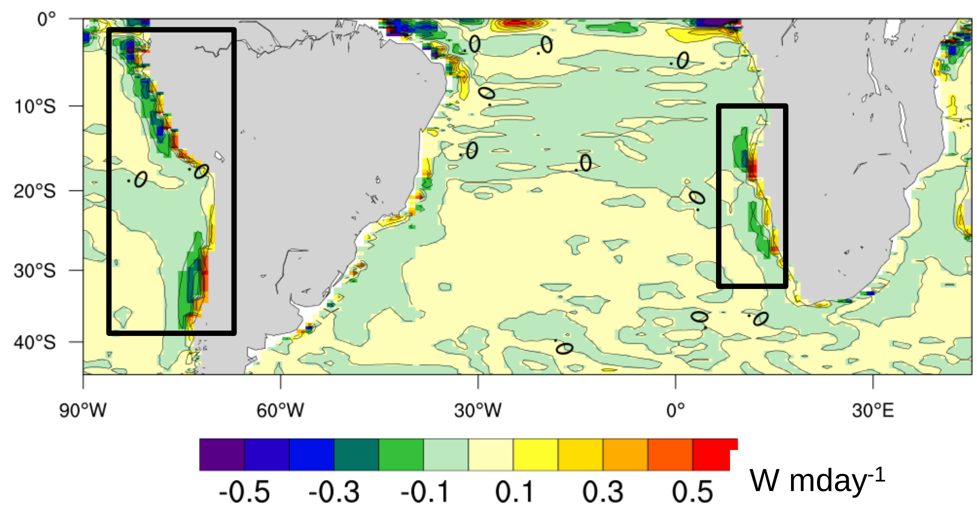
Vertically integrated V



Surface V

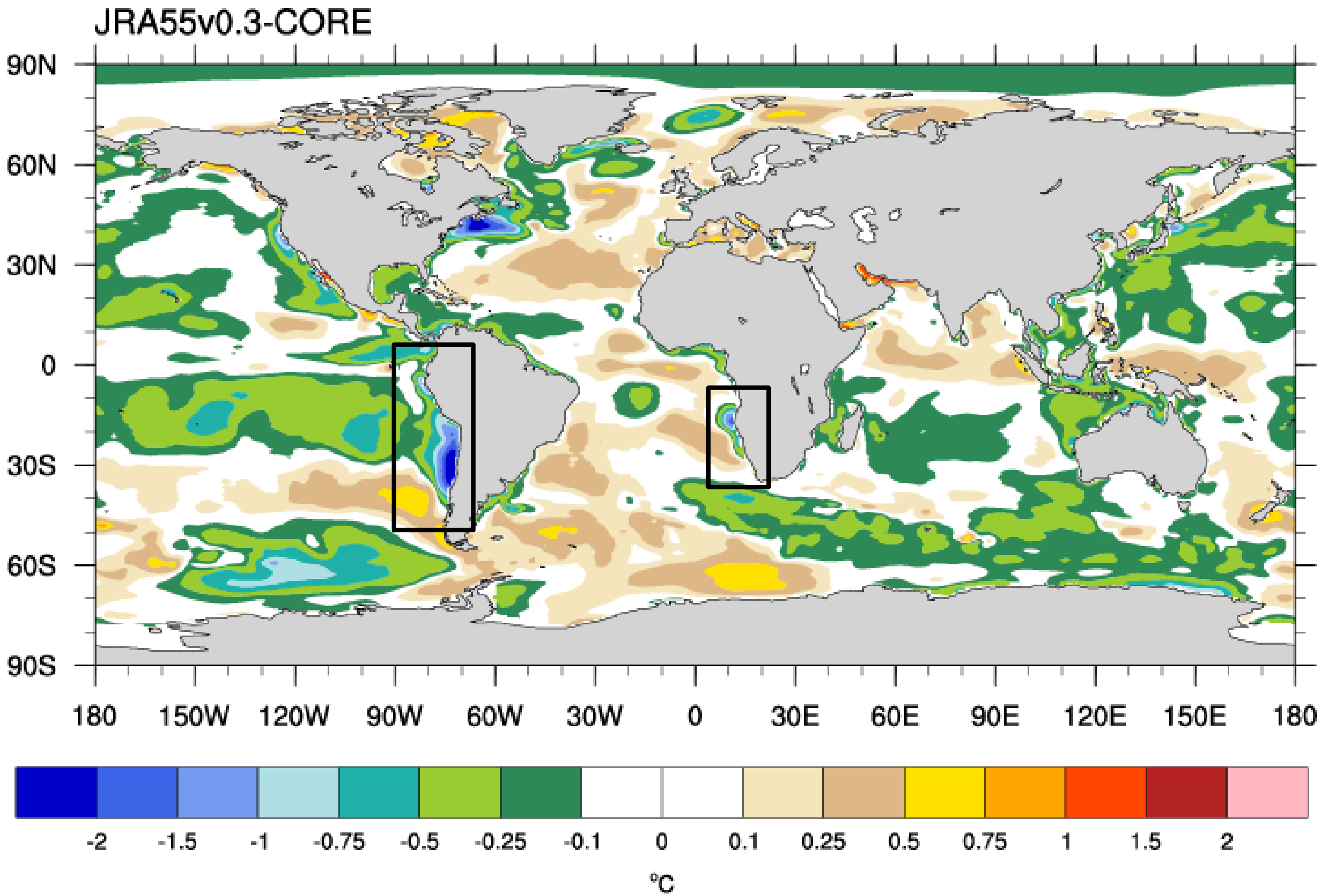


W at 40m



With higher atmosphere resolution, there is more Equatorward flow, due to narrowing & weakening of Wind stress curl. Vertical velocity is less WSC-driven and more coastal wind driven.

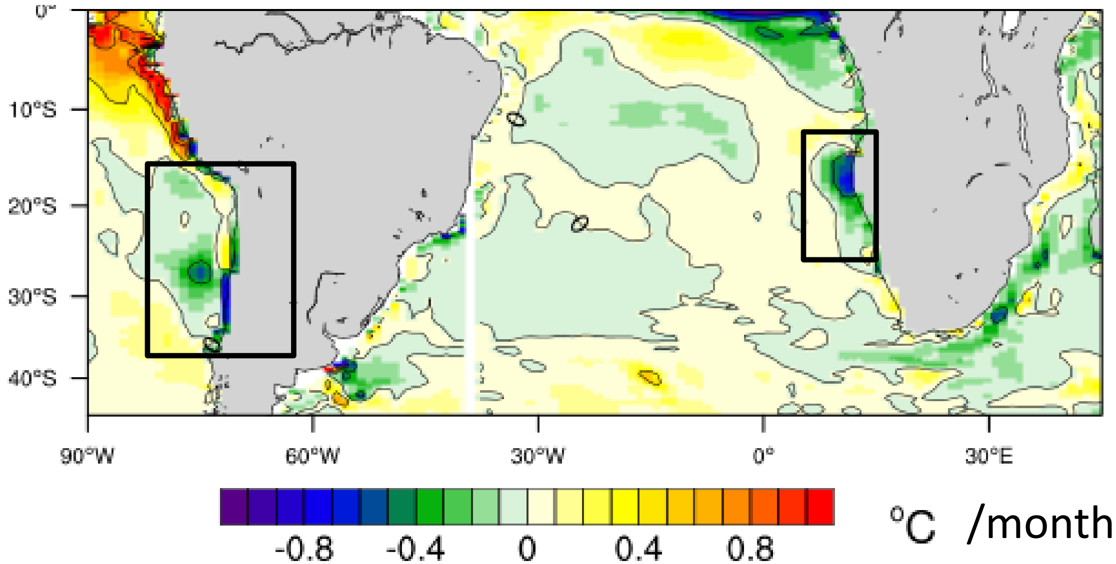
JRA55-CORE forced: SST difference



Caveat: upper ocean heat budget required to attribute change in SST to ocean advection vs air-sea fluxes or ocean mixing etc.,

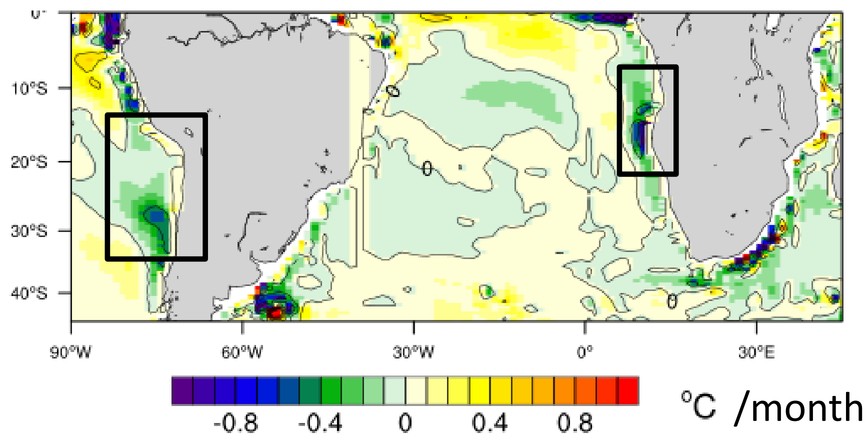
Upper ocean heat budget (1)

FULL 3D OCEAN HEAT FLUX CONVERGENCE: JRA - CORE

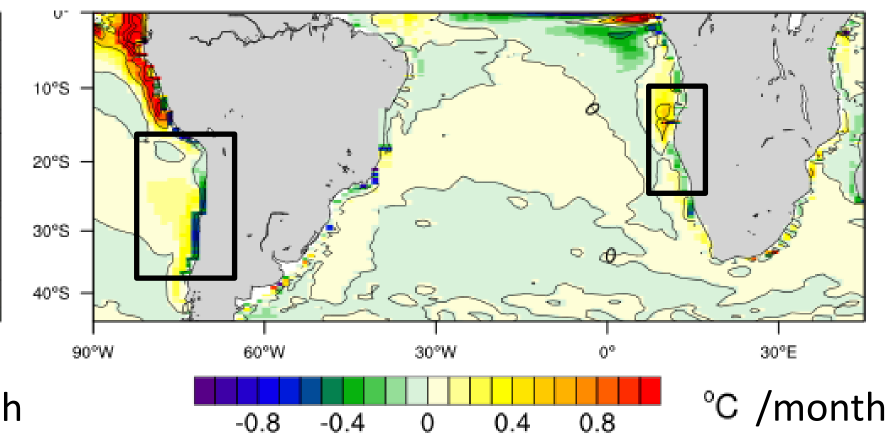


Upper 50m heat budget for evolution from initial state to start of year 10. Difference of JRA-forced minus CORE-forced.

MONTHLY HORIZONTAL ADVECTION: JRA - CORE



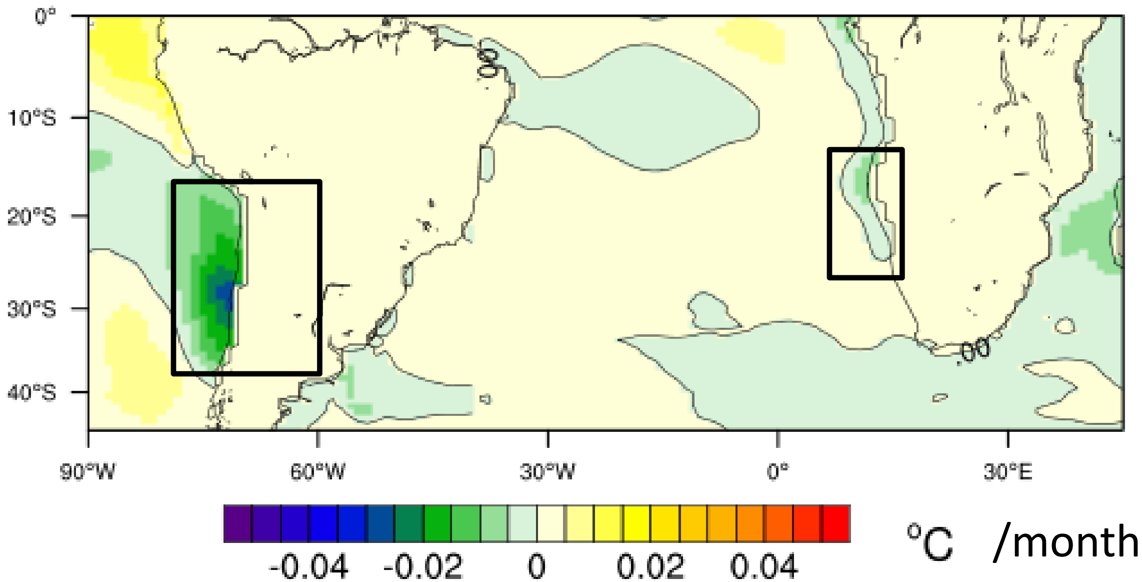
MONTHLY VERTICAL ADVECTION: JRA - CORE



CHILE UPWELLING – HORIZONTAL & VERTICAL. BENGUELA-HORIZONTAL.

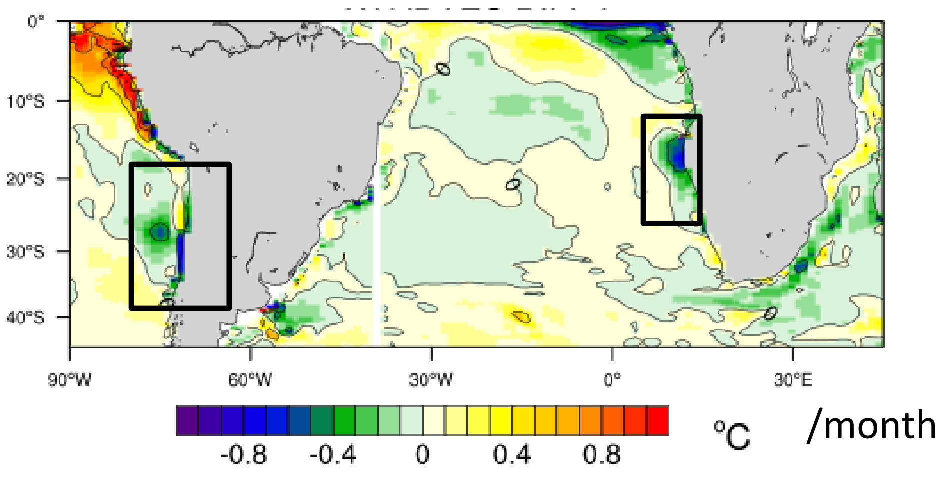
Upper ocean heat budget (2)

TEMPERATURE TENDENCY: JRA - CORE

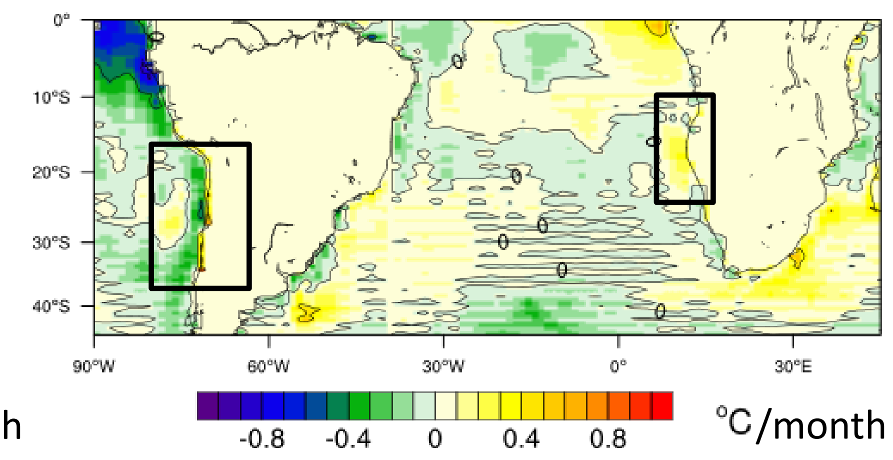


Upper 50m heat budget for evolution from initial state to start of year 10. Difference of JRA-forced minus CORE-forced.

OCEAN HEAT FLUX CONVERGENCE: JRA - CORE

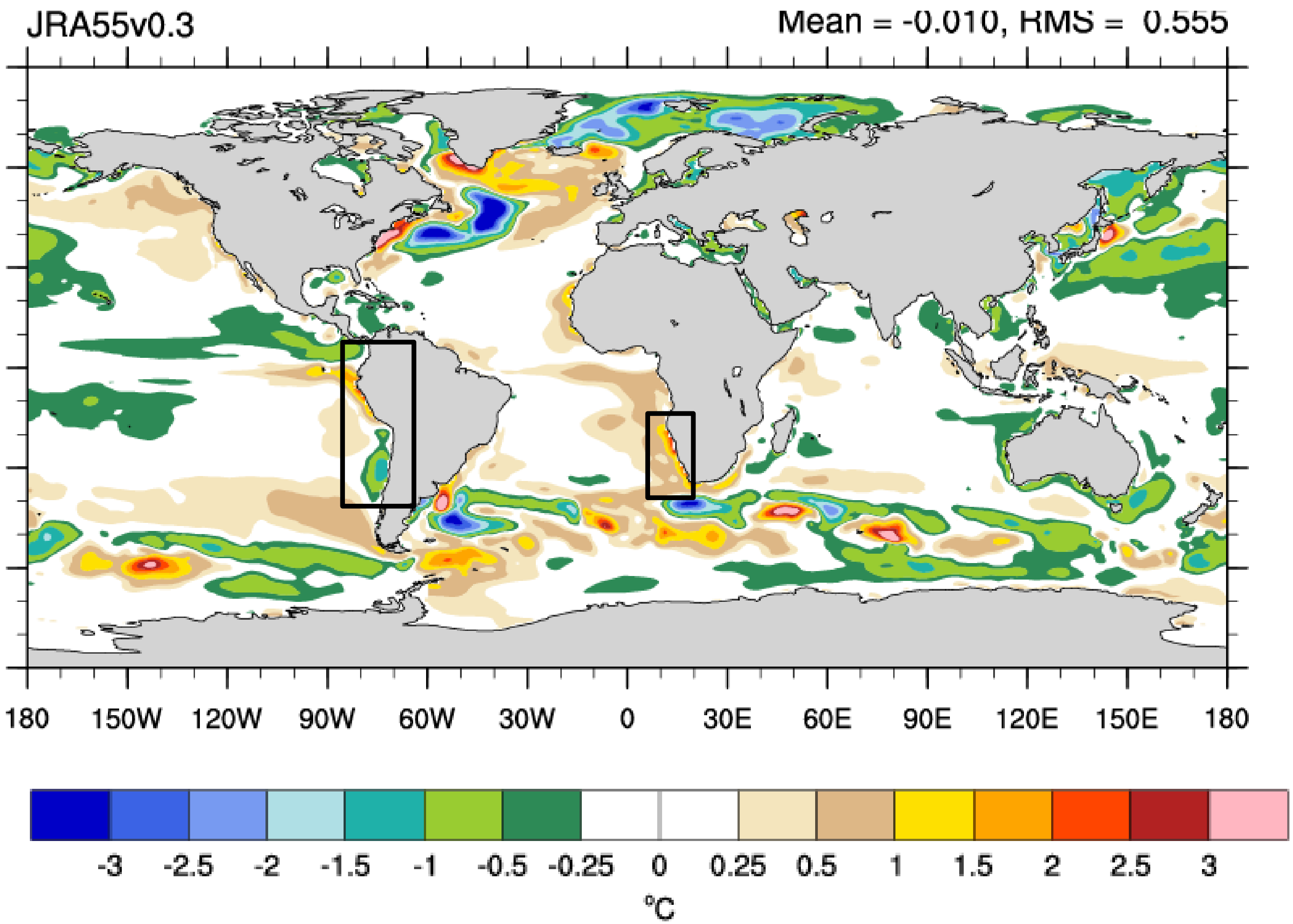


SURFACE HEATING : JRA - CORE



CHILE UPWELLING – ADVECTION+SURFACE HEATING. BENGUELA-ADVECTION.

SST bias: JRA-55 forced simulation



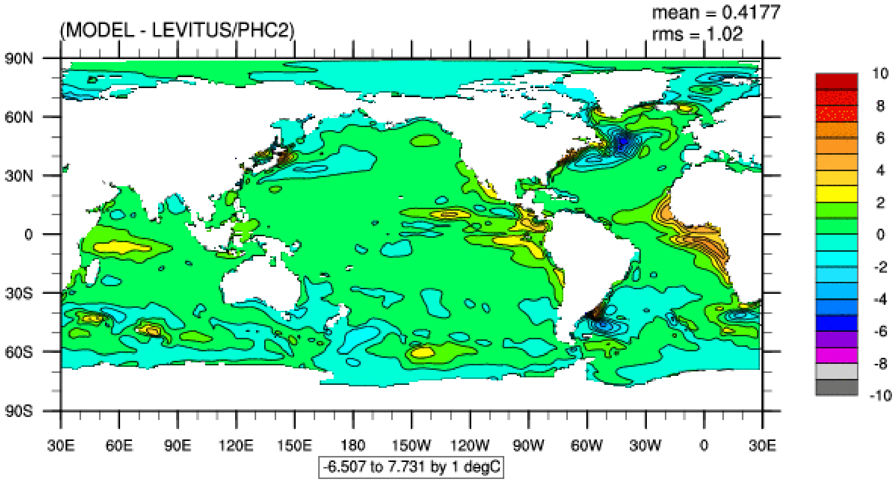
Coastal currents and upwelling still too weak compared to:
estimates from observations, and to
simulations with high resolution ocean and good forcing

Conclusions

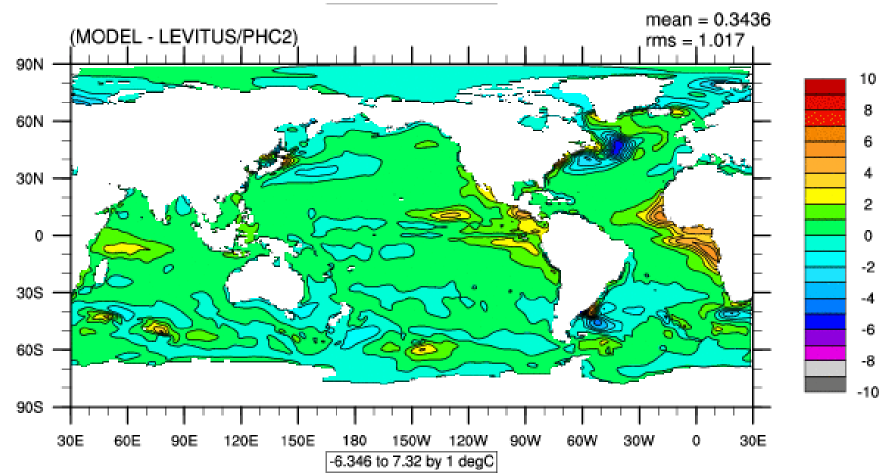
- CORE- wind stress curl too broad
  - Ekman pumping & Sverdrup balance
- JRA55 – wind stress curl more realistic
  - More coastal upwelling and Equatorward jet
- Heat budget (JRA minus CORE) showed:
  - Benguela SST improved – horizontal advection
  - Chile improved – advection + surface cooling (relative)
- Jra-55 forced still has errors in Benguela, Peru
  - and subsurface errors!!!
- Way forward-
  - High-res POP (*beware curse of excessive wind stress curl*)
  - JRA-forced is nice candidate for ocean-BGC simulations
  - Benguela may require even higher atmosphere resolution for forcing (Ping Chang et al.)

This is all good, however…

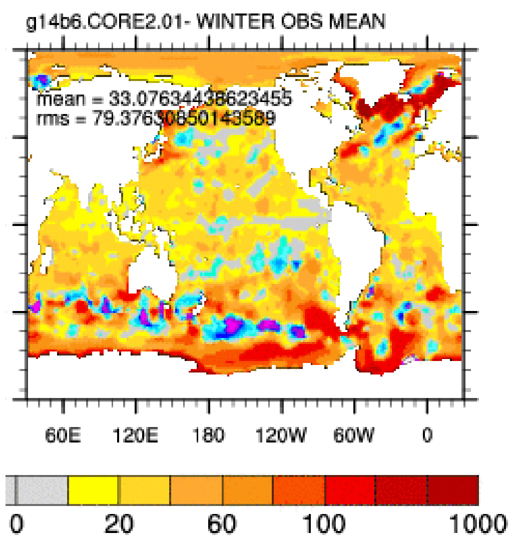
45m temperature bias of CORE-forced



45m temperature bias of JRA55-forced

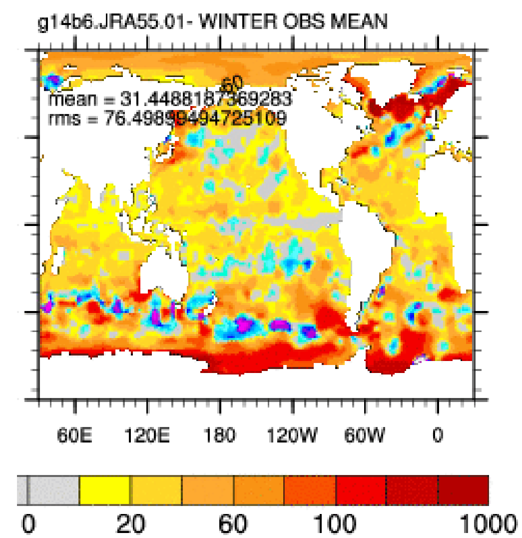


Mixed-layer-depth bias of CORE-forced

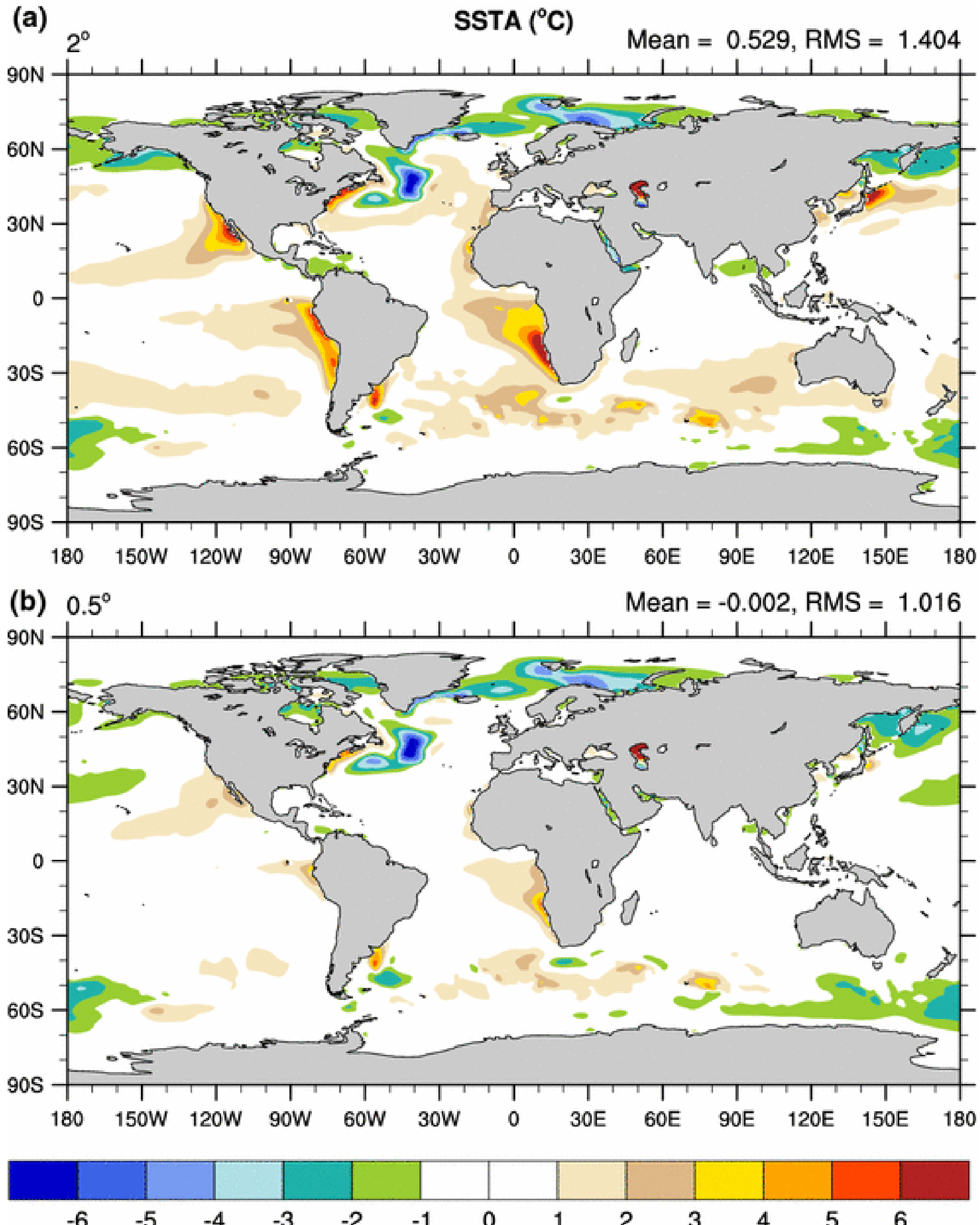


Significant bias of 50m temperature remains in eastern Atlantic in both runs, and too deep mixed layers .

Mixed-layer depth bias of JRA55-forced



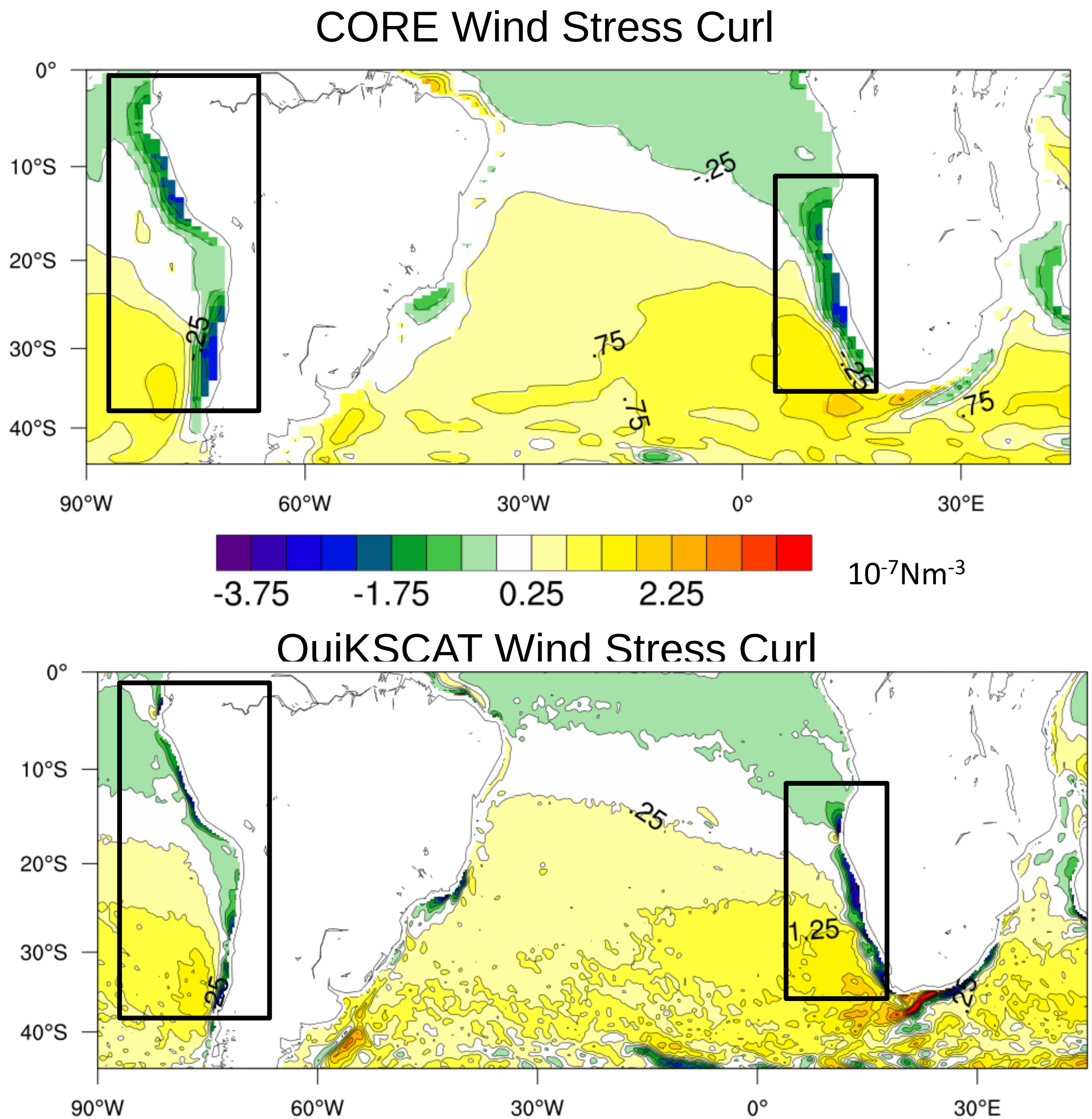
SST bias: coupled runs



CCSM3.5 finite volume atmosphere (Gent et al. 2010)

CORE: Curse of the broad wind stress curl

Annual mean WSC



Correction of CORE to QuikSCAT does not fix wind stress gradients. (resolution mismatch)

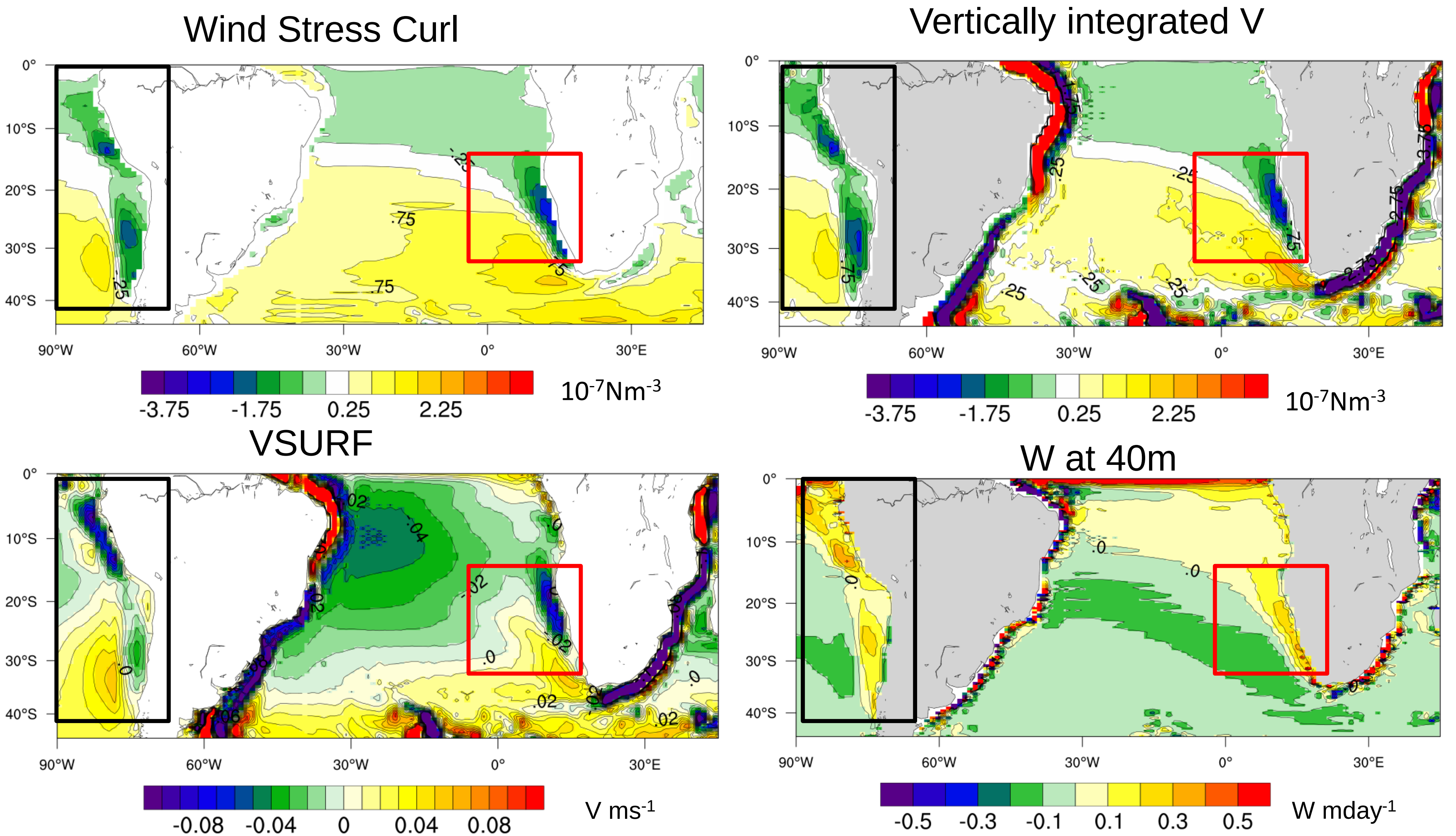


Fig.1. Eastern boundaries in a global climate model with a coarse, 2deg. Atmosphere, annual mean. Top Right: Depth-integrated meridional current to 500m multiplied by $\beta\rho_0$ where β is the meridional gradient of Coriolis force, ρ_0 is a reference ocean density. Under Sverdup balance this should equal the curl of the wind stress shown in top left. Bottom left: surface meridional velocity. Bottom right: vertical velocity at 40m depth. With a 2deg atmosphere in CCSM4, approximate Sverdrup balance holds in eastern boundaries and sub-tropical gyres. General poleward flow at eastern boundaries tends to produce a warm SST error by flux of heat poleward. Likewise, vertical velocity is wind-stress-curl (Ekman-pumping) driven. This figure is produced from data discussed in Small et al. (2015).

Consequences of weak coastal winds

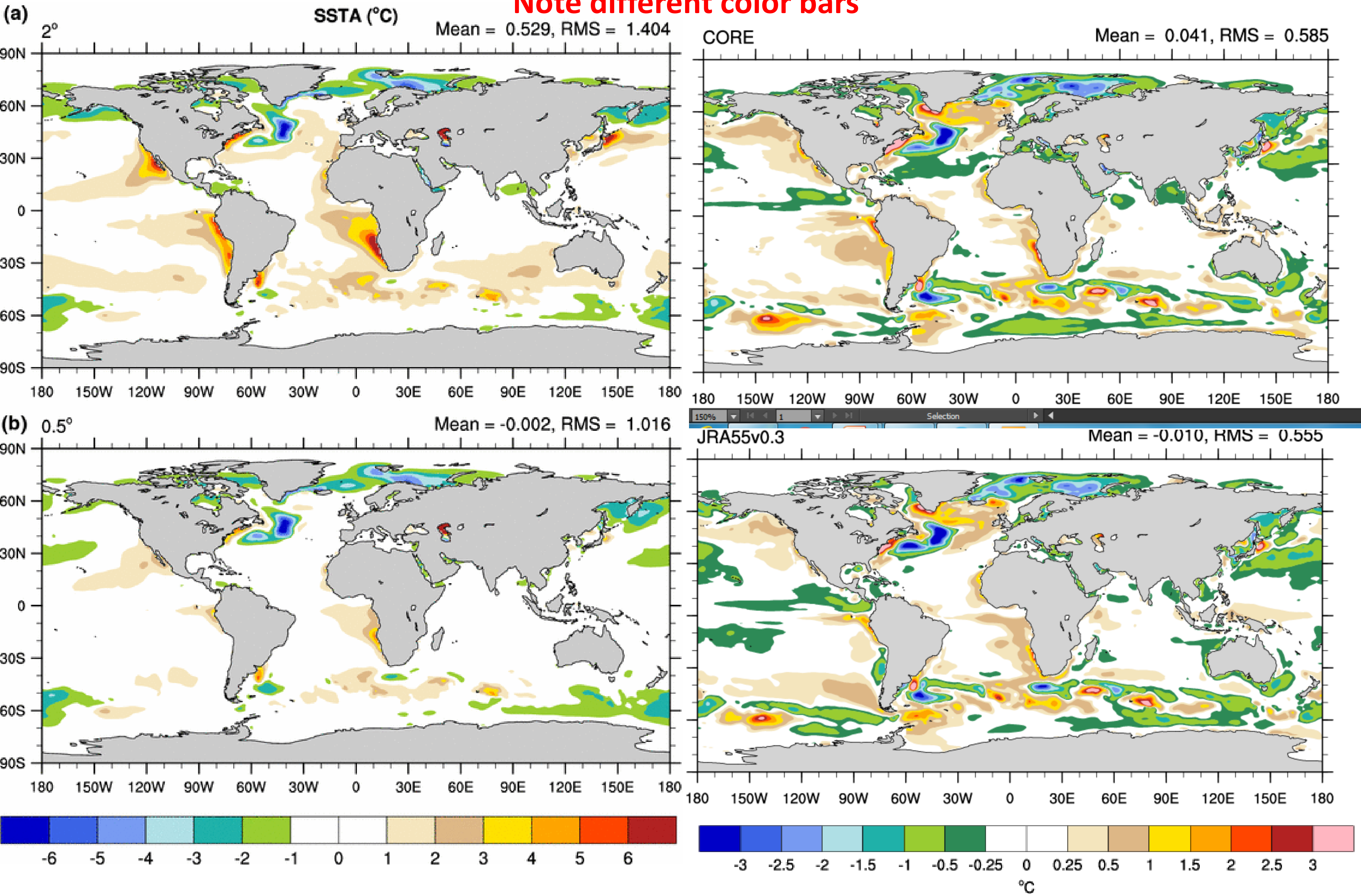
- Weak coastal upwelling
  - Ekman offshore transport weak
- Weak or no Equatorward "coastal jet"
  - Yoshida 1955, Charney 1955, **Fennel et al. 2012, Junker 2014**
- Strong wind stress curl
- Ekman pumping driven upwelling
  - Picket and Paduan 2003, Junker 2014
- Countercurrents by Sverdrup balance

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

→ Southward transport if curl is negative

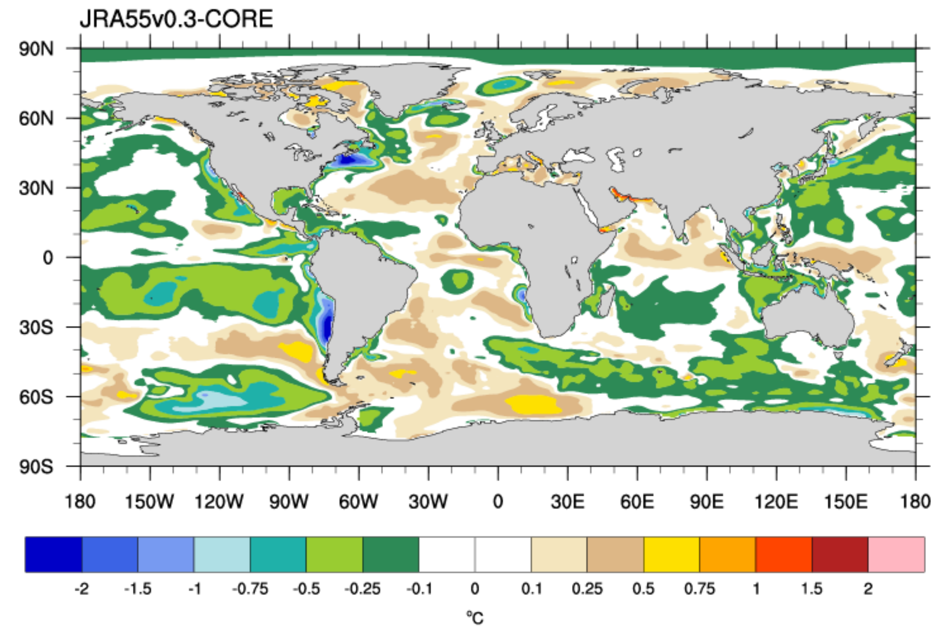
SST bias: coupled vs forced ocean runs

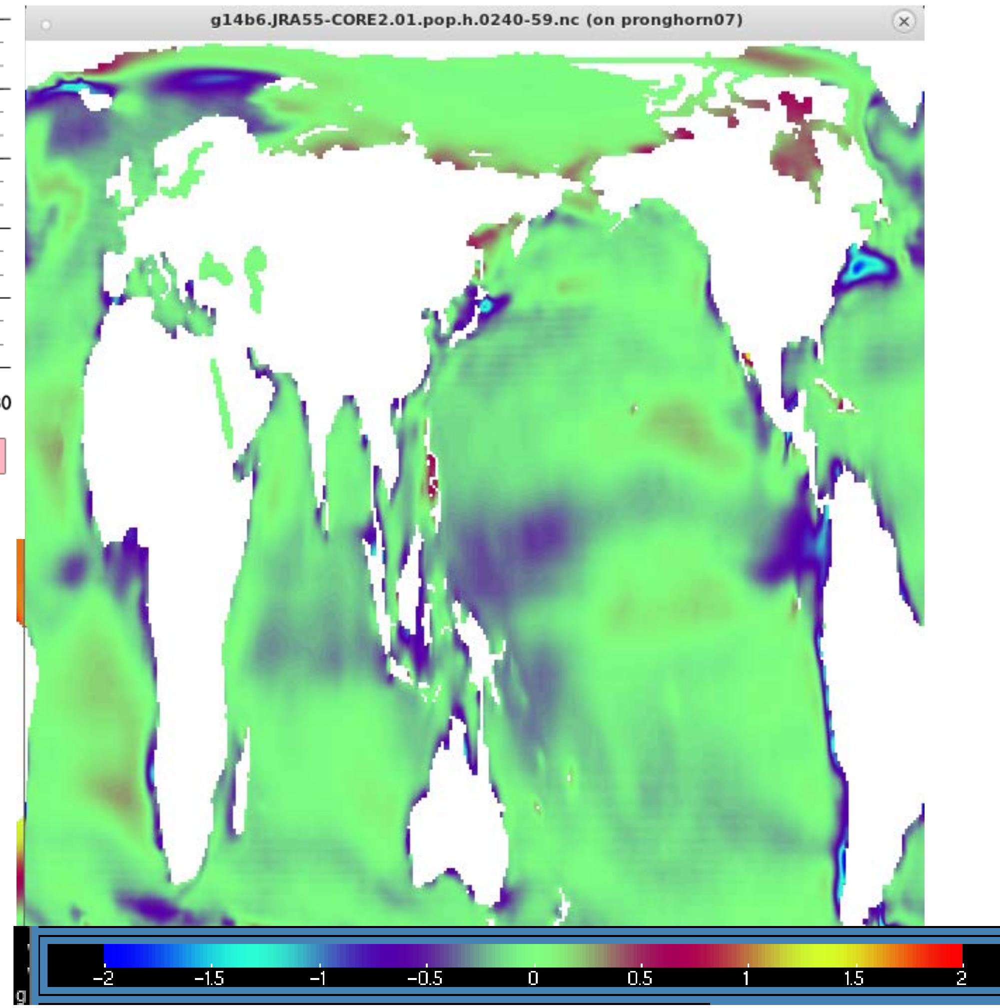
Note different color bars



Top level temperature

JRA55v0.2-forced minus CORE-forced.





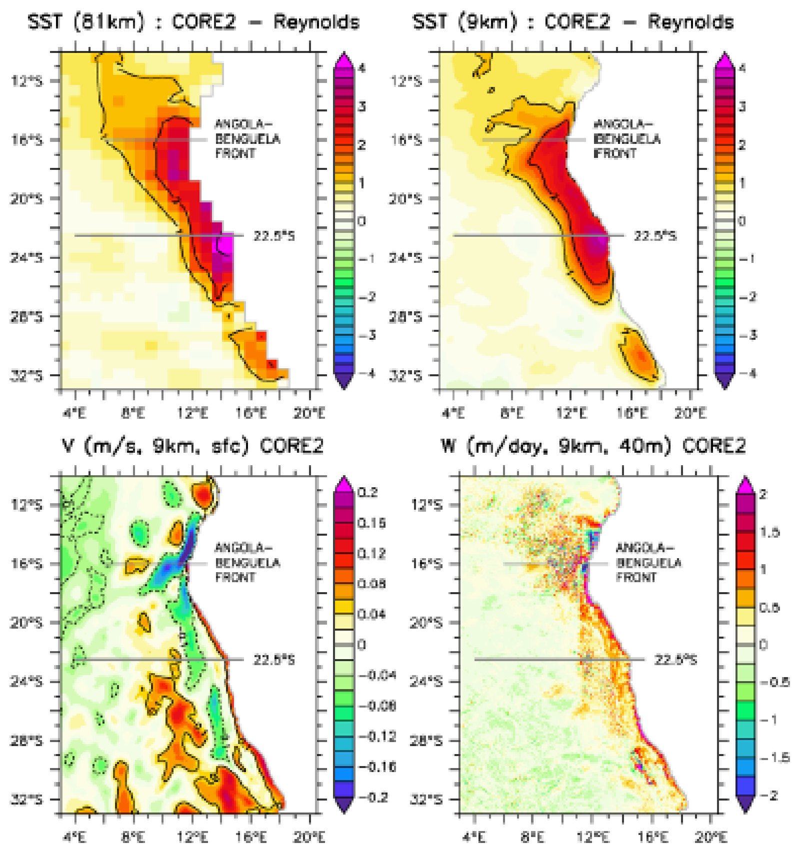
Units are deg.C – see color-bar at top. Note cooler temperature around upwelling coasts (and other regions) in JRA55 forced.

Ocean Resolution

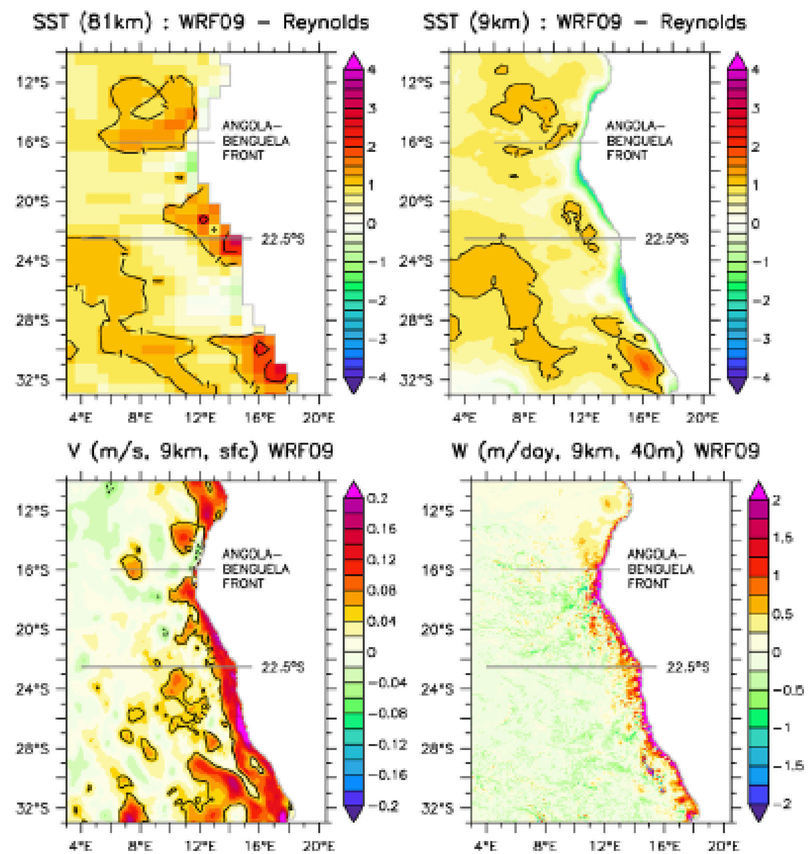
- This is tricky !
- Beware of "curse of the **excessive** wind stress curl"
- Need good atmosphere model and careful interpolation of winds onto ocean near coast.

Simulations with WRF and ROMS (Ping Chang, C. Patricola, J. Kurian)

ROMS is run at 81km or 9km in the Benguela. Forcing is either CORE2 or 9km WRF, with forcing interpolated onto ocean grid.

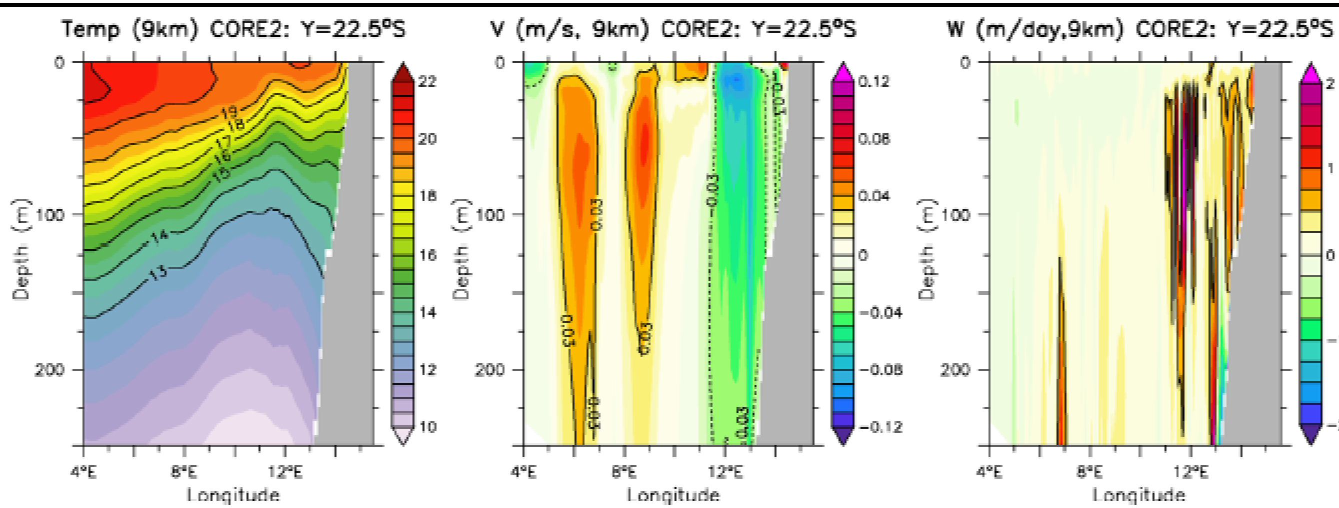


ROMS forced with CORE II. SST bias at different ocean resolution (top): surface V and W at 40m in 9km run (bottom)

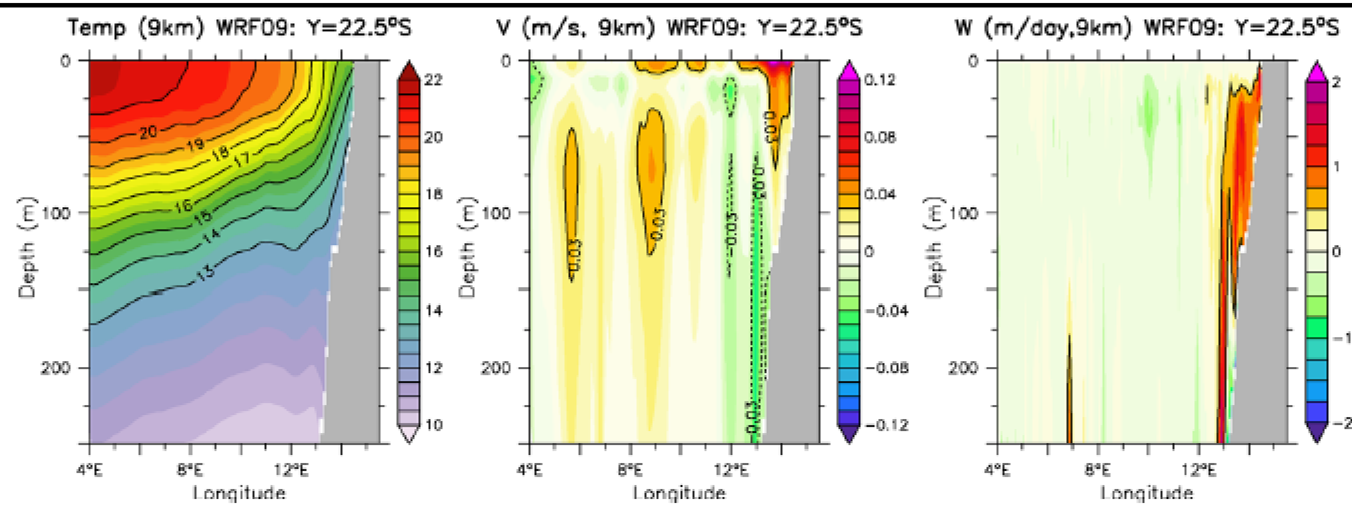


ROMS forced with WRF. SST bias at different ocean resolution (top): surface V and W at 40m in 9km run (bottom)

Simulations with WRF and ROMS (Ping Chang, C. Patricola, J. Kurian)



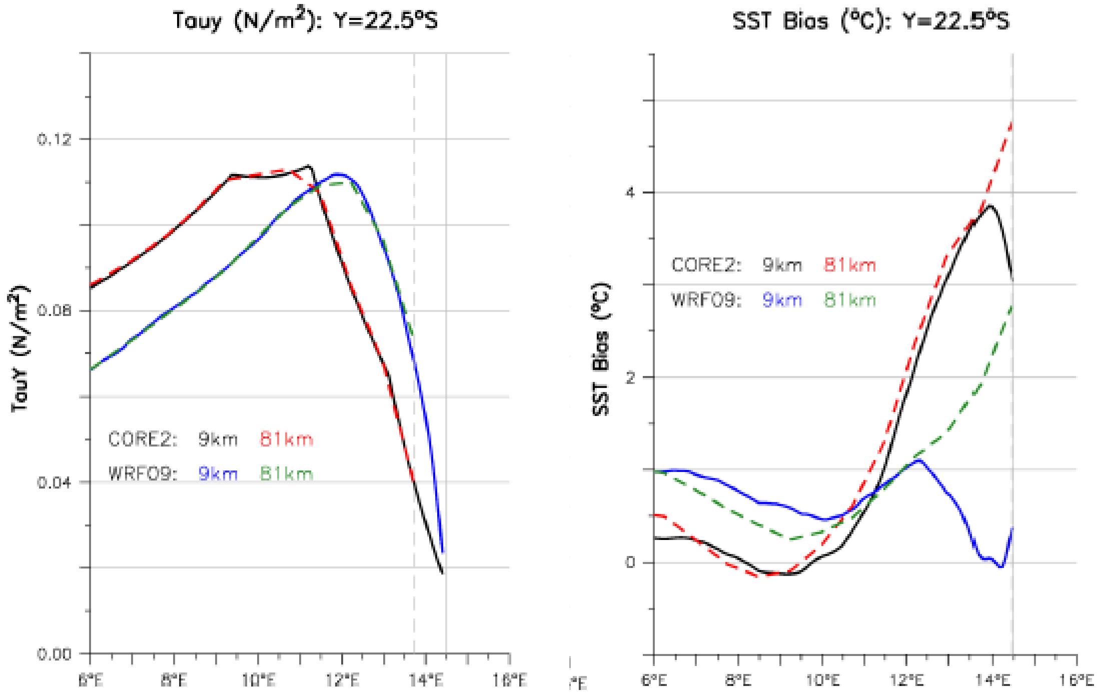
CORE-forced: Vertical sections at 22.5deg.S, T: V: W



WRF-forced: Vertical sections at 22.5deg.S, T: V: W

Consistent with results of Small et al (2015, JCLIM) where we had to manually adjust CAM winds to get good WSC.

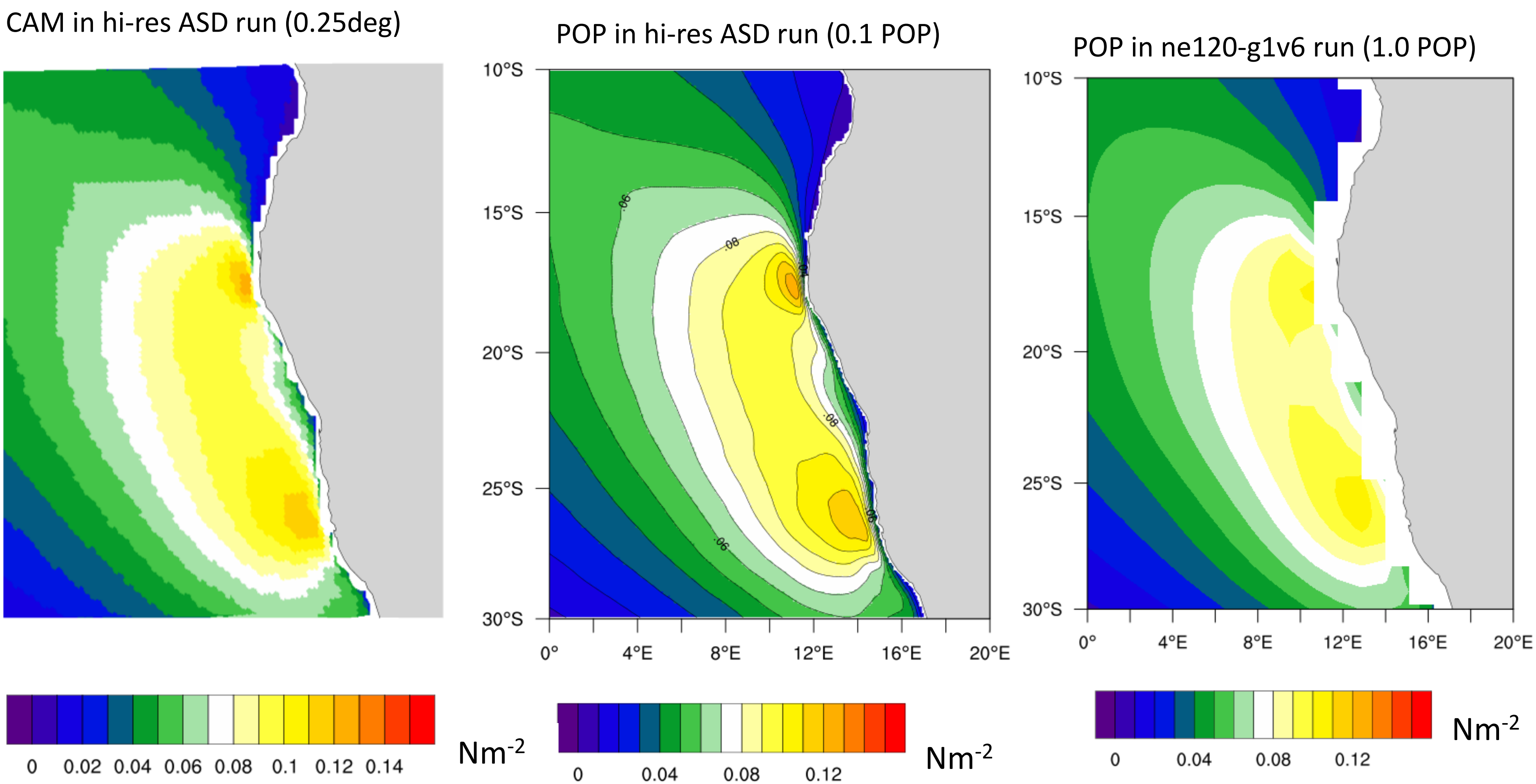
Simulations with WRF and ROMS (Ping Chang, C. Patricola, J. Kurian)



Ping Chang et al have concluded that an atmosphere resolution of ~10km or less is needed to capture correct wind reduction near coast (compared to QuikSCAT).

When forced by 9km WRF, an ocean model at 81km can fix much of the SST bias but the most realistic upwelling, currents and SST is obtained with mesoscale-resolving 9km ROMS.

Curse of the excessive wind stress curl



Meridional wind stress in JJA off benguela

Note that interpolating to a fine resolution ocean grid (middle) introduces extra wind drop-off near coast whereas interpolating to a coarse ocean grid (right) smooths-out the drop-off. Original atmosphere wind stress at left. Note also that the atmosphere model already has too much curl compared to QuikSCAT (not shown).

Possible way forward for high resolution ocean simulations with JRA55

- When interpolating winds or fluxes to ocean grid, do not include atmosphere cells over land
  - Simplest: Nearest neighbour
  - Smoothing/extrapolation of atmosphere values over ocean towards land(Kara et al. 2007, Nadia Pinardi 1980s)
  - See also Steve Griffies' talk
- Compare resulting WSC with QuikSCAT
- If WSC is not too strong, we might expect good upwelling/currents
- If WSC is too strong and/or too wide, don't rely on ocean solution

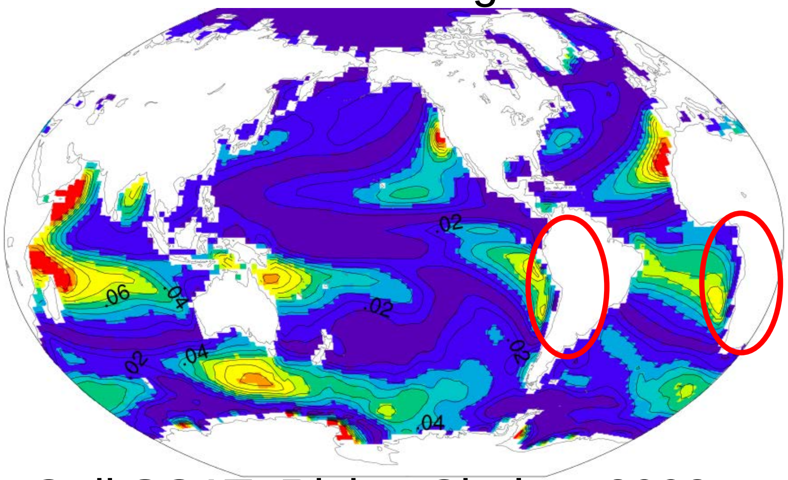
Further information: See Small et al 2015, JCLIM, P. Chang et al 2016 in preparation, also posters on Oct. 2015 CPT Workshop website

Atmosphere Resolution

- Beware of "curse of the **broad** wind stress curl"

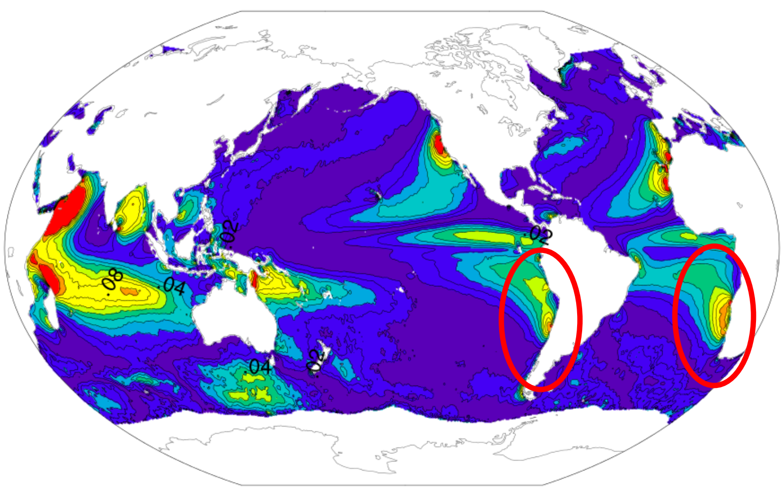
Wind stress & atmosphere resolution

CCSM4-2deg



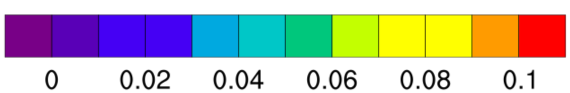
With a 2deg atmosphere model, wind stress is too weak adjacent to eastern boundaries

QuikSCAT Risien Chelton 2008



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

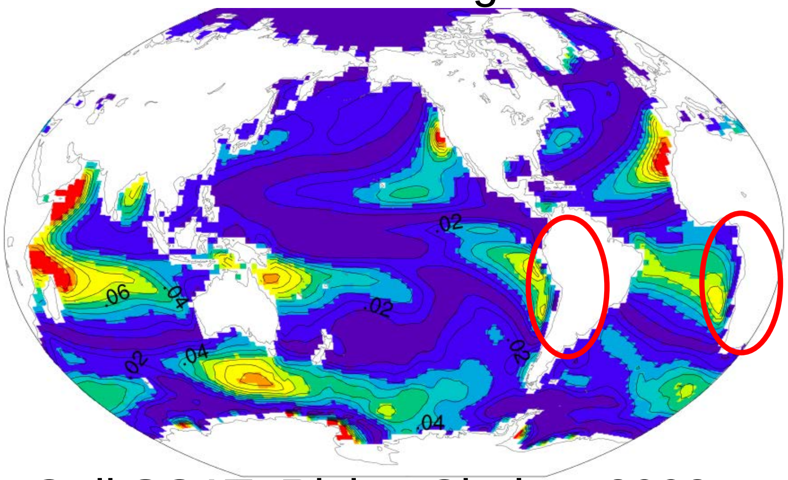
Only CAM cells over pure ocean shown (no land cells)



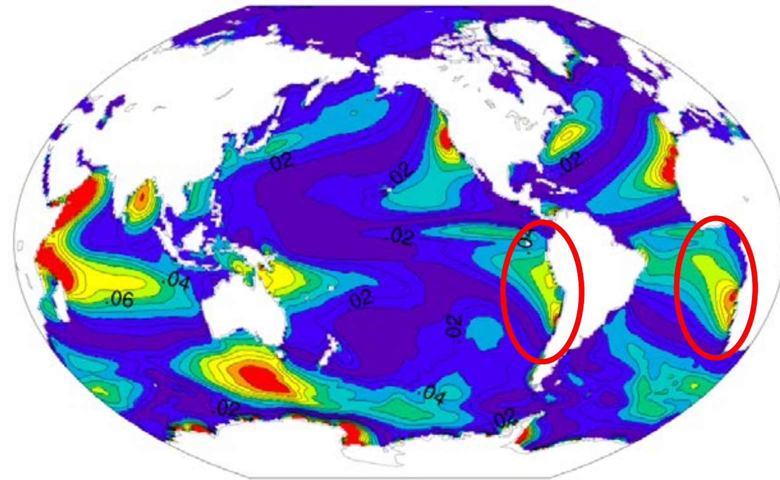
Nm^{-2}

Wind stress & atmosphere resolution

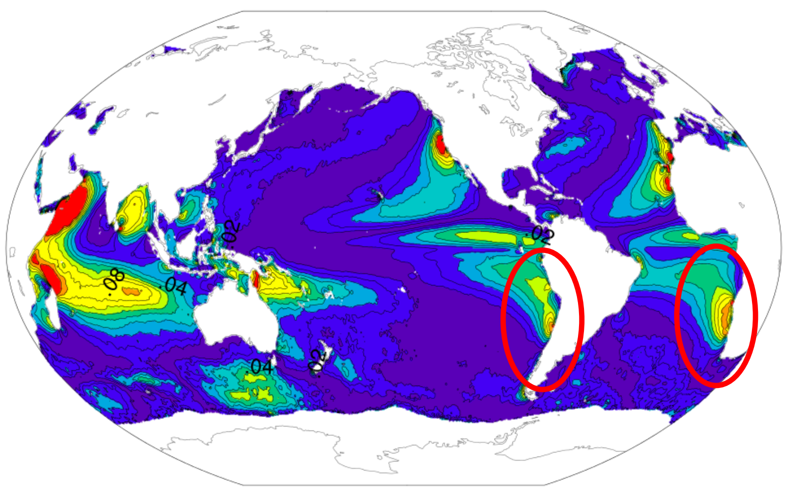
CCSM4-2deg



CCSM4-0.5deg



QuikSCAT Risien Chelton 2008

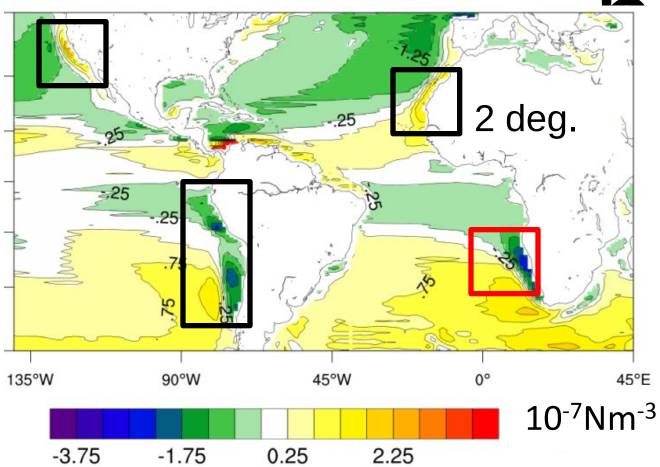


Notable improvement when going to a 0.5deg atmosphere.
Ocean resolution unchanged at 1deg.

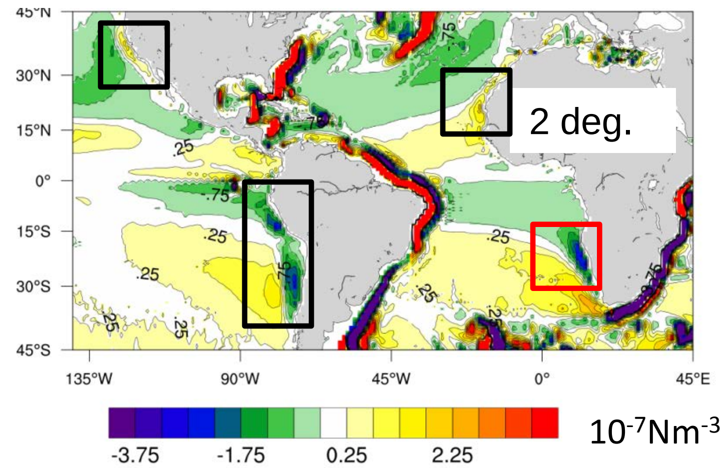
Absolute value of meridional wind stress TAUY, in June-July-August (JJA)

RECAP: 2deg. Atmosphere: Eastern bounda

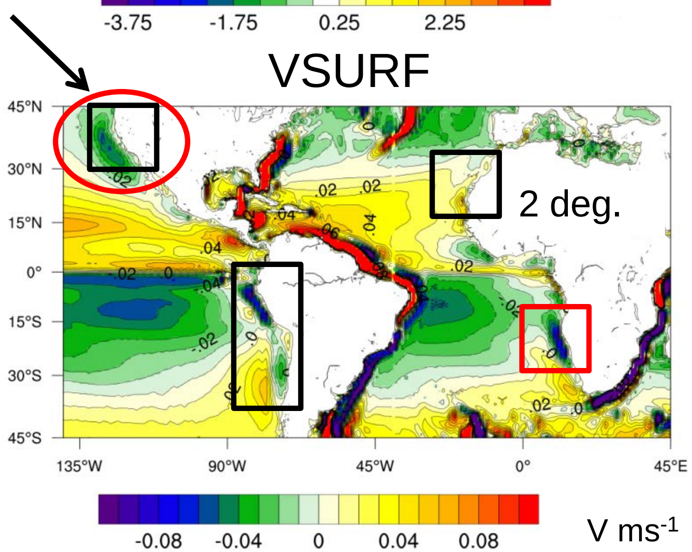
Wind Stress Curl



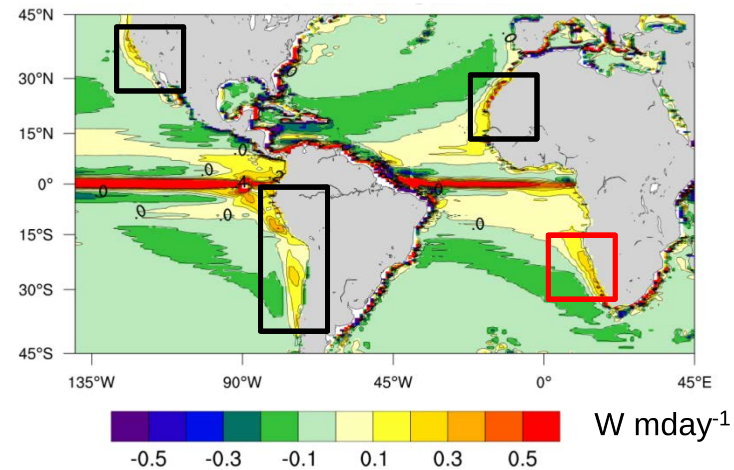
Vertically integrated V



VSURF



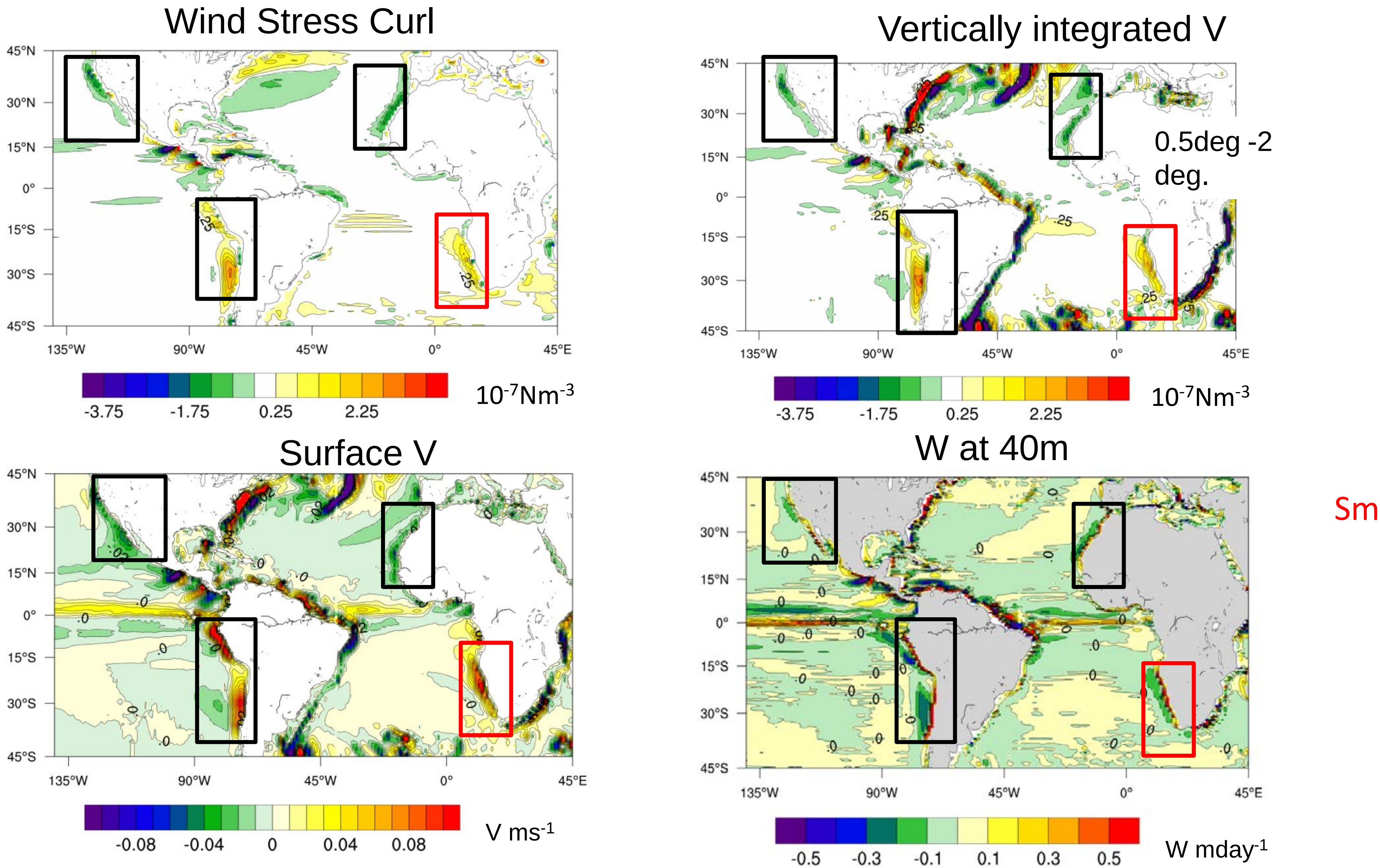
W at 40m



Annual mean. With a 2deg atmosphere in CCSM4, approximate Sverdrup balance holds in eastern boundaries and sub-tropical gyres. General poleward flow at eastern boundaries tends to produce a warm SST error by flux of heat poleward. Only California Current has Equatorward surface flow. Likewise, vertical velocity is wind-stress-curl (Ekman-pumping) driven.

Small et al. 2015

Sensitivity to atmosphere resolution

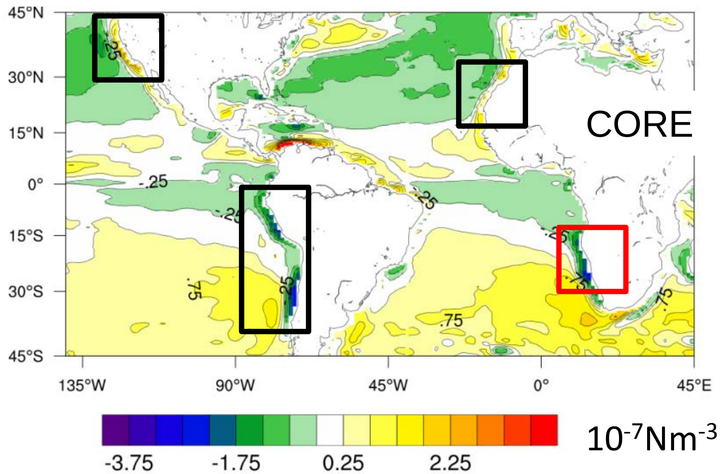


Difference, 0.5deg atmosphere minus 2deg atmosphere

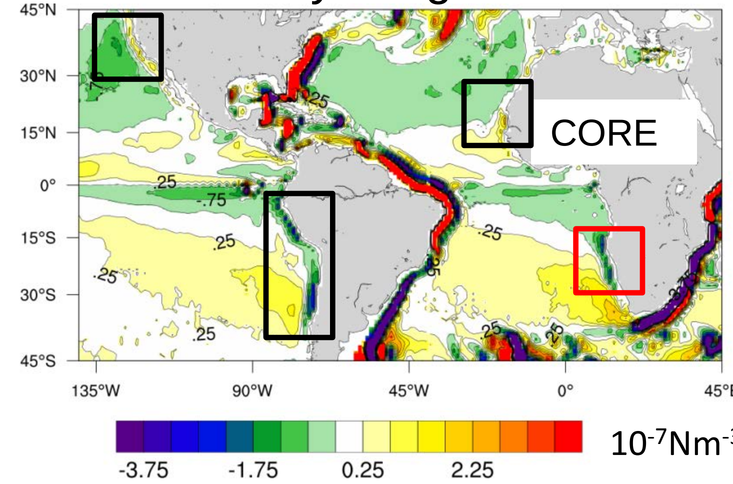
With higher atmosphere resolution, there is more Equatorward flow, due to narrowing & weakening of Wind stress curl. Vertical velocity is less WSC-driven and more coastal wind driven.

CORE: Eastern boundary

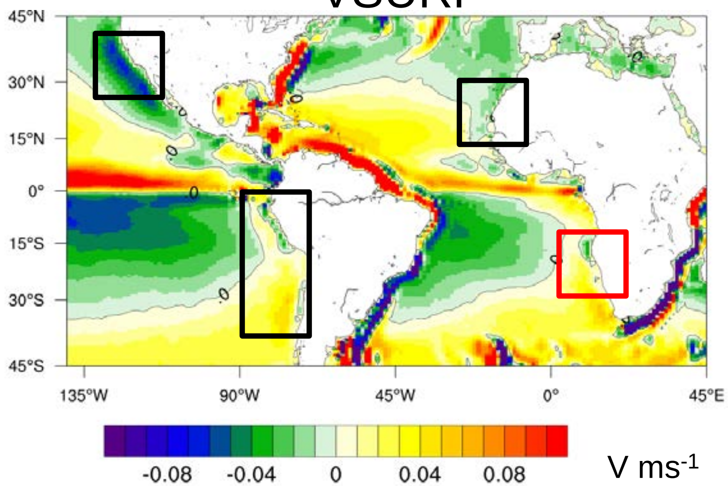
Wind Stress Curl



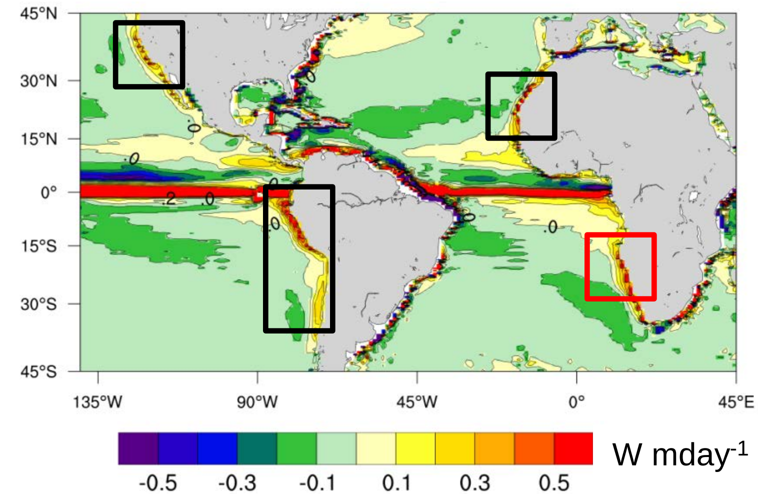
Vertically integrated V



VSURF

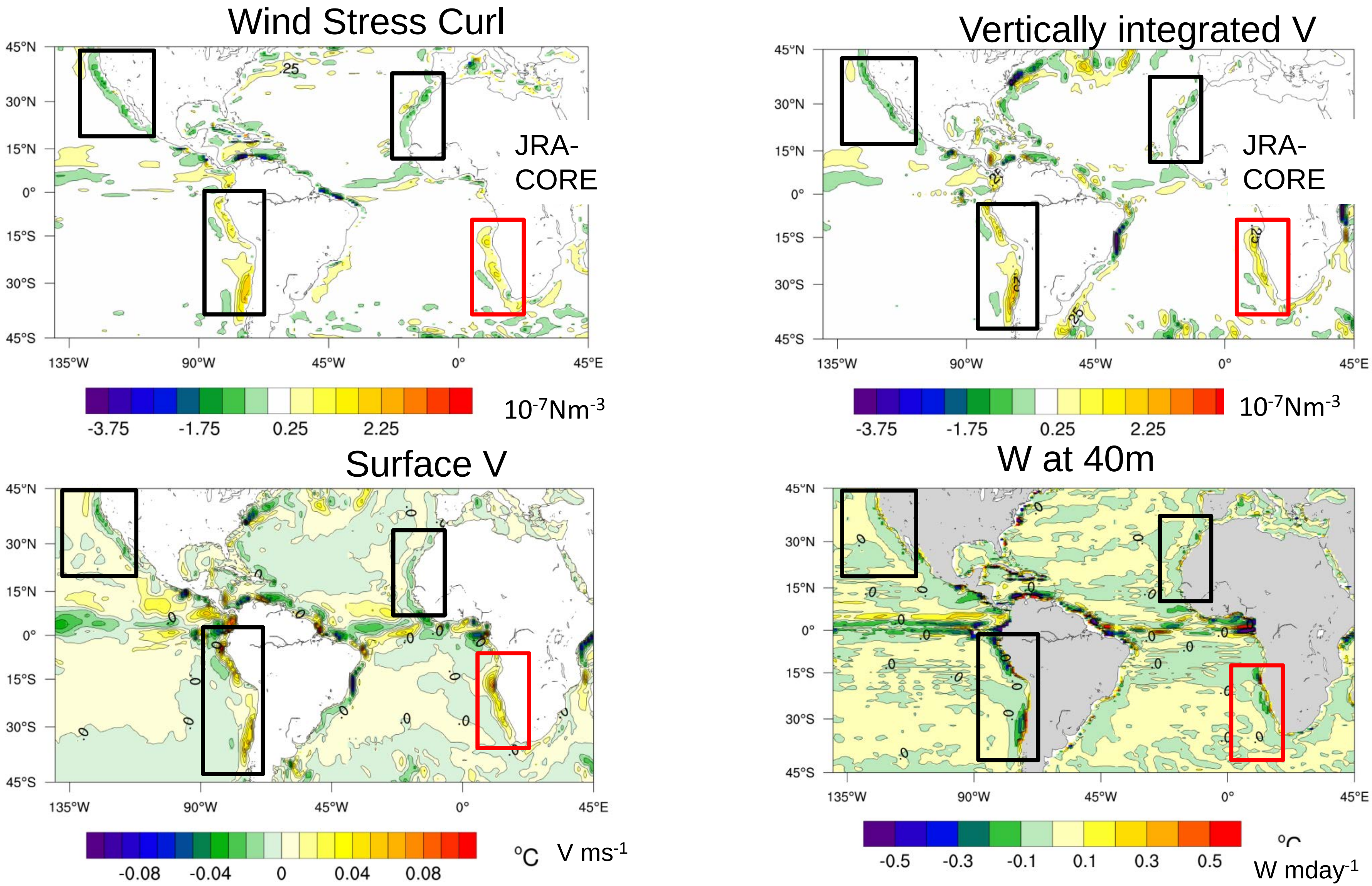


W at 40m



Annual mean. With a ~2deg atmosphere in CORE forced, approximate Sverdrup balance holds in eastern boundaries and sub-tropical gyres. However surface flow is more Equatorward in CORE-forced than in CCSM4 with 2deg atmosphere. Vertical velocity is wind-stress-curl (Ekman-pumping) driven.

Sensitivity to atmosphere resolution

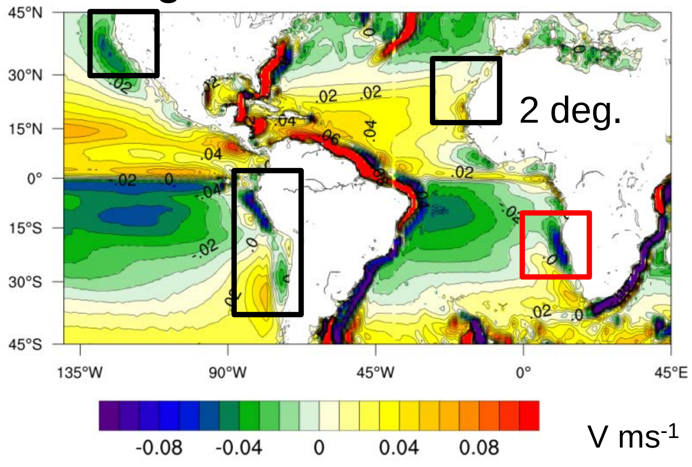


Difference, JRA-forced minus CORE-forced

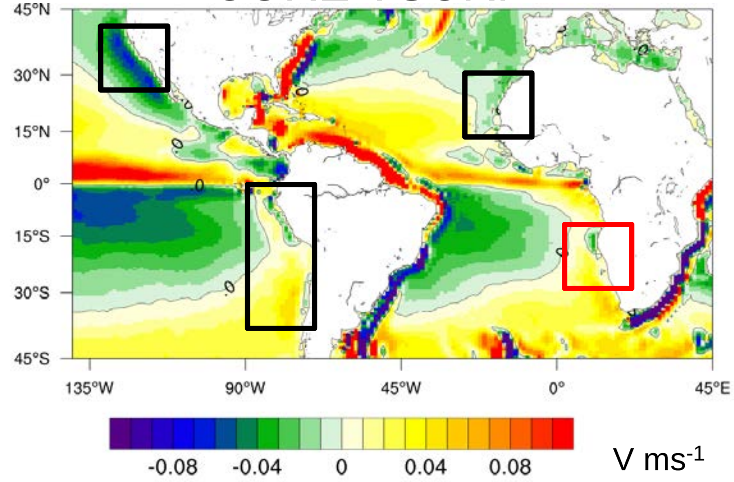
With higher atmosphere resolution, there is more Equatorward flow, due to narrowing & weakening of Wind stress curl. Vertical velocity is less WSC-driven and more coastal wind driven.

Surface velocity

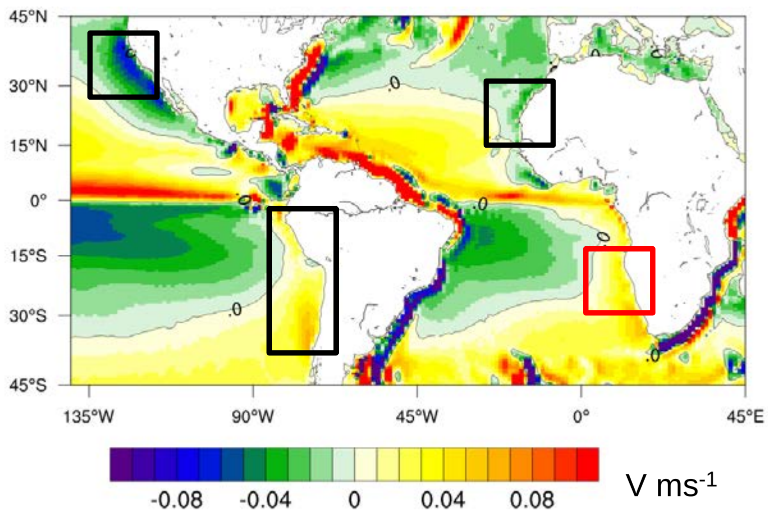
2deg. CAM VSURF



CORE VSURF



JRA55 VSURF



JRA55 surface velocity is almost totally Equatorward – similar to CCSM4 with 0.5deg CAM.

CORE-forced surface velocity is more Equatorward (better) than CCSM4 with 2deg. CAM. Possibly due to correction of absolute wind to QuikSCAT.