HIGH RESOLUTION MODELLING AND DATA ASSIMILATION WITH THE COMMUNITY EARTH SYSTEM MODEL

Justin Small
Fred Castruccio, Steve Yeager
Alicia Karspeck, Gokhan Danabasoglu, Frank Bryan
EASM3 project with Ben Kirtman

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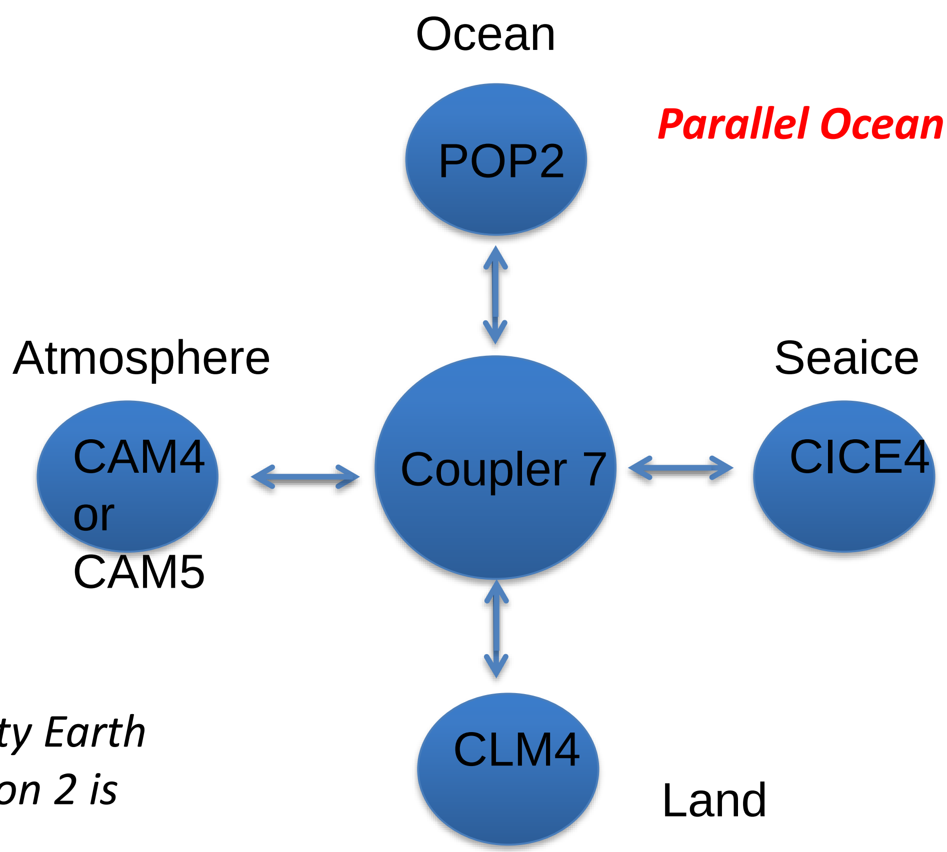
Outline

- Effects of changing model resolution in the Community Earth System Model
  - 1) Atmosphere Resolution 2) Ocean Resolution
- Data assimilation and decadal predictability efforts at NCAR
  - Focussed on high-resolution data assimilation

Community Earth System Model (CESM1)



Parallel Ocean Program

Community Atmosphere Model

Currently Community Earth System Model version 2 is being developed

Many changes to →CAM6, CLM5, CICE5, CIME

Results not included here

Land-ice model and ocean biogeochemistry not used here

Resolution matrix-CESM1

CAM5 Atmosphere Resolution

Ocean Resolution	0.25deg	1deg
0.1deg	**100 years**	**Not performed**
1deg	90 years	166 years

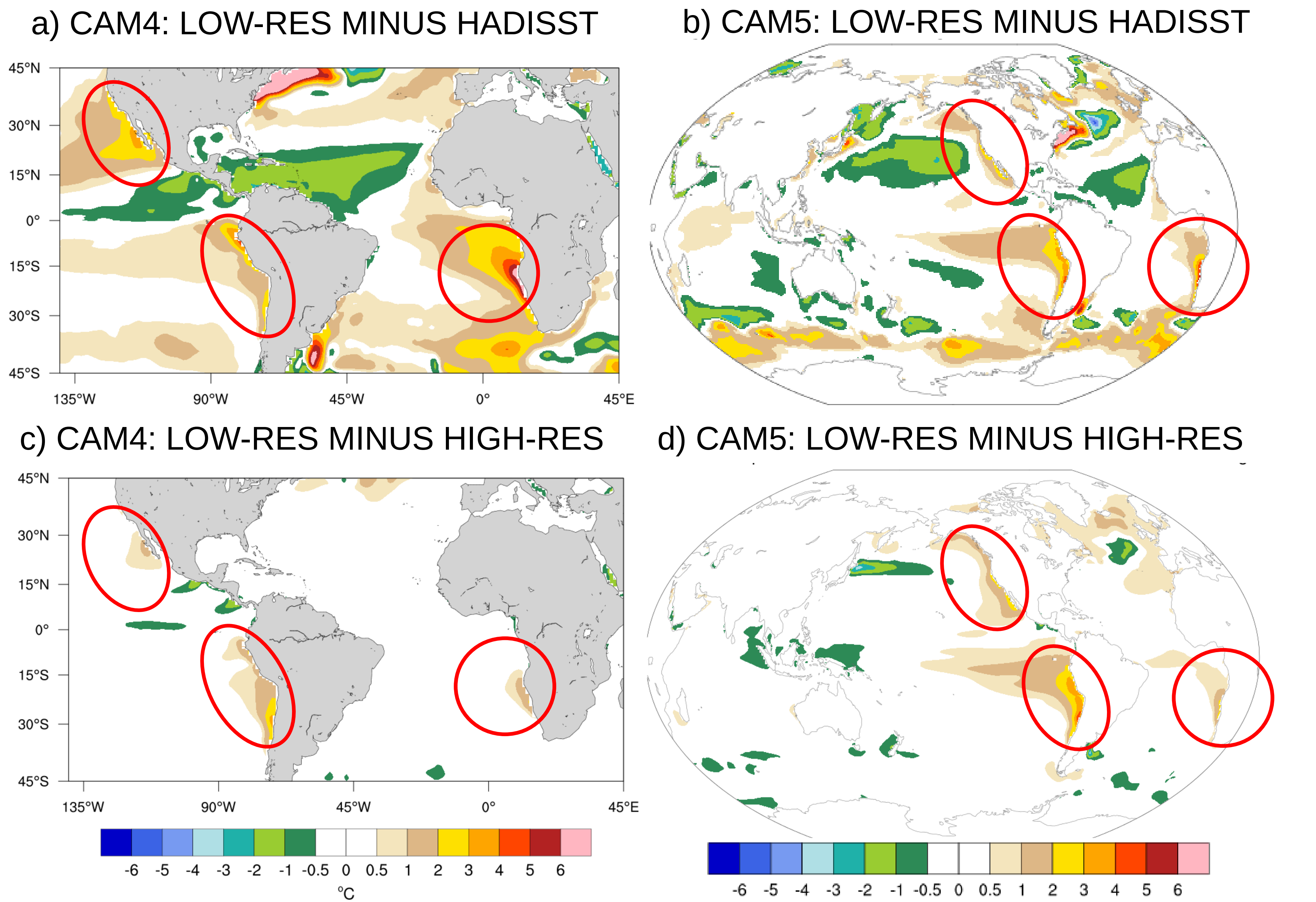
Small et al. 2014, JAMES

Results are also shown for CESM1 with CAM4 with ocean resolution of 1deg. and atmosphere resolutions of 1deg. and 0.5deg.

Gent et al. 2010, Small et al. 2015, JCLI

Effect of changing atmosphere resolution: two examples

- Improvement to SST in eastern boundary regions
  - Driven by more realistic coastal winds, wind stress curl, also coastal low cloud
  - At higher atmosphere resolution, more Equatorward coastal flow and coastal upwelling
  - Upwelling and flow still weak – requires refined ocean resolution? (see later)
- Tropical cyclones are permitted at 0.5deg, 0.25deg.
  - Spatial distribution of tracks very dependent on coupled model SST bias and large-scale flow
  - Intensity distribution still very dependent on physics of model
  - Mesh refinement being used in CAM Spectral Element (Zarzycki et al.)



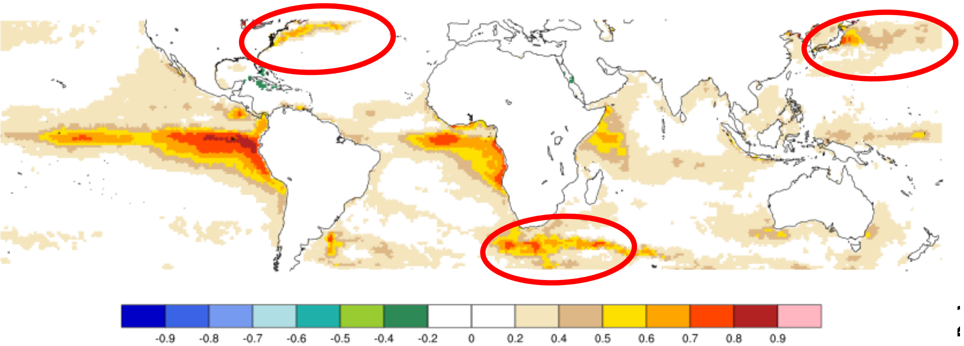
Annual mean SST bias relative to observations and change with atmosphere resolution. Sign convention – matching colors (top and bottom) implies improvement with resolution.

Effect of changing ocean resolution

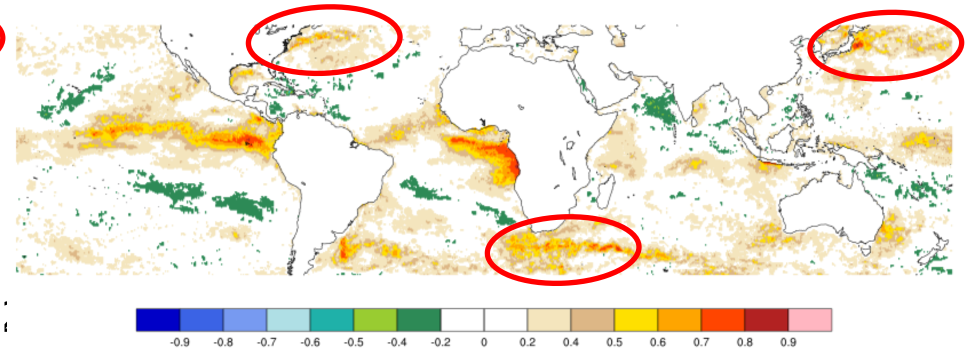
- Improvement to SST in western boundary regions
  - Driven by explicit mesoscale representation, better bathymetry, deep western boundary currents
  - Leads to better location of surface storm track (Small et al. 2014, 2017 inprep)
  - Affects warming of US East coast under climate change? (Saba et al. 2016 (GFDL model), High-resolution CESM)
- Variability of SST drives extratropical ocean-atmosphere heat fluxes
  - Kirtman et al. 2012, Bishop, Bryan and Small 2017, submitted
  - Ocean advection dominates, but at low resolution most extratropical SST variability driven by atmosphere
- Mixed layer biases in southern ocean
  - Shallow bias at low resolution, affects uptake of heat, $C0_2$
  - More realistic spatial distribution, and deeper mixed layers at high resolution
  - Frontal and eddy dynamics appear to play a role, as well as air-sea coupling at fronts

Monthly: SST-LHFLX correlations. See Kirtman et al. 2012

OAFLUX

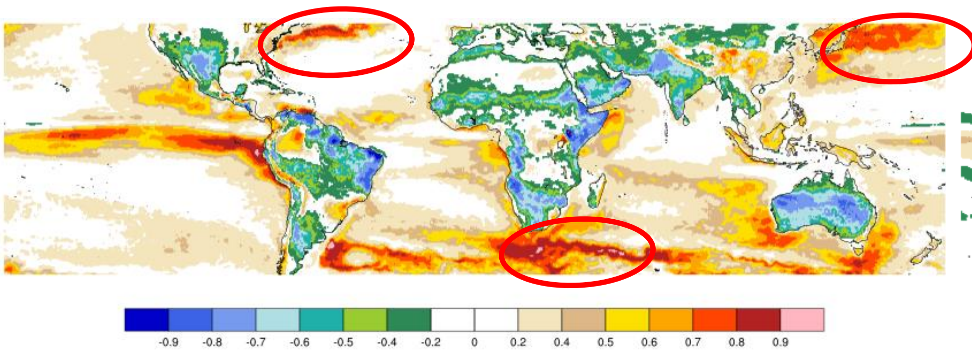


J-OFURO

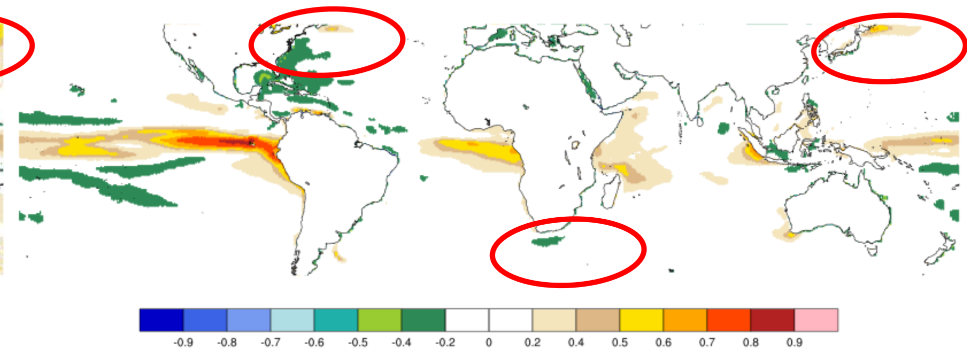


ABOVE: western boundary currents similar. Tropics different – different data lengths?

HIGH RESOLUTION CESM



LOW RESOLUTION CESM



ABOVE: HIGH-RES CESM has much higher correlations in WBCs, compared to obs, & is slightly stronger in a global sense. LOW-RES has very low correlations except in Equatorial region (assuming ENSO is removed properly, these could be partly-resolved Tropical Instability Waves). J-OFURO and OAFLUX similar except in Equatorial region (due to different data lengths?).

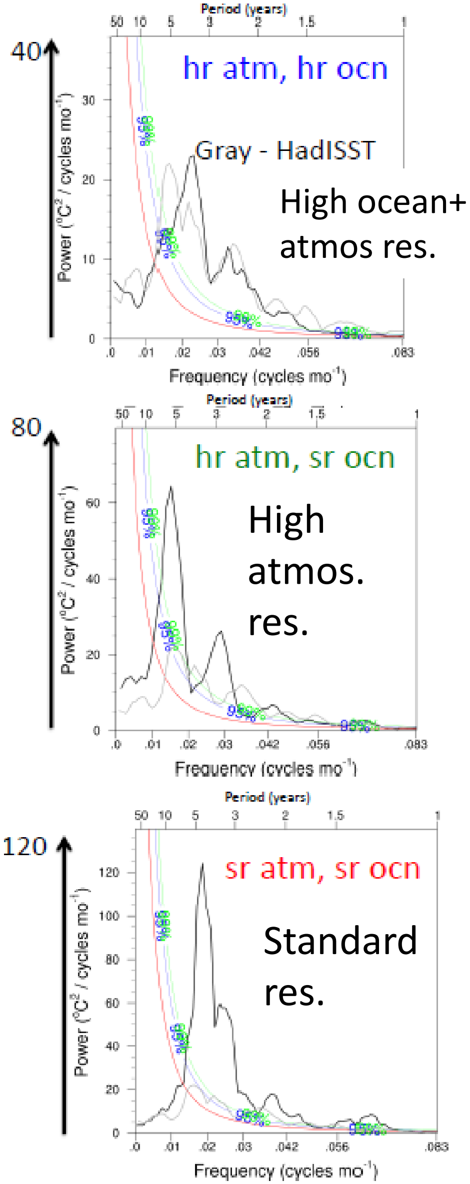
Effect of changing ??? resolution

- Improvement to Nino 3.4 SST variability
  - Low resolution CCSM4, CESM1 has too strong, too peaked SST variability
  - Improvements seen with refined atmosphere resolution and with ocean resolution
  - More realistic zonal gradient of mean SST along Equator at high resolution
  - Also possible role of small scale “stochastic noise” in disrupting too-regular ENSO (Stochastic parameterization, Palmer et al., 2009, Berner et al. 2009, 2015)
- Caveats
  - Simulations are relatively short (~100 years)
  - Changing parameterizations in atmosphere (e.g. convective) can equally affect Nino3.4

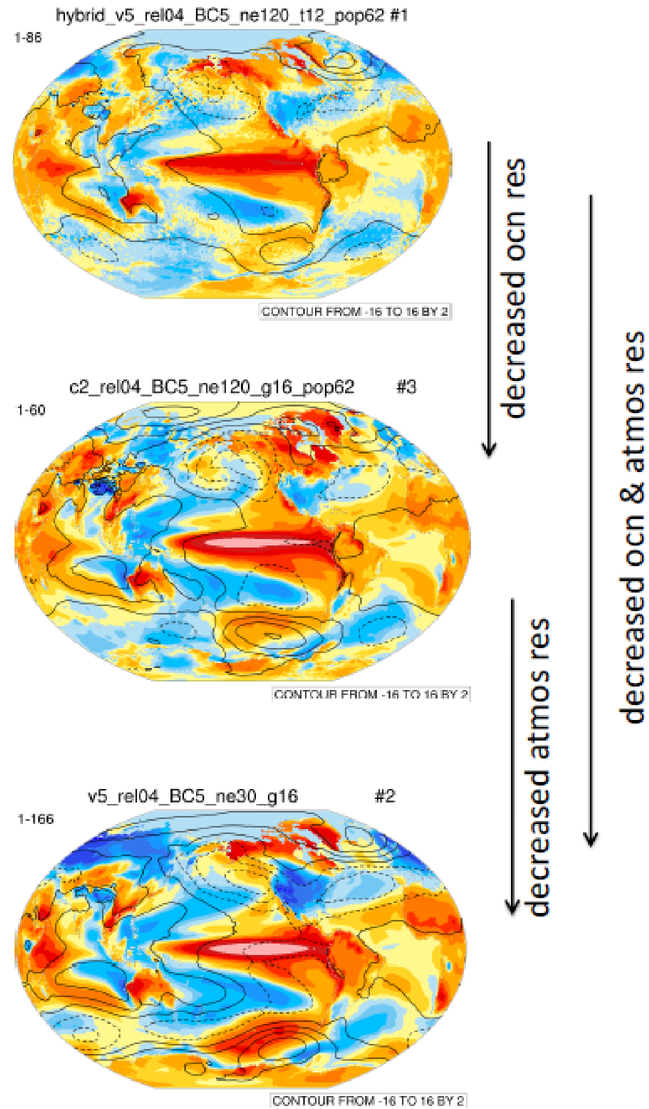
ENSO variability at different CESM resolutions

ENSO Variability

Nino 3.4 Power Spectra

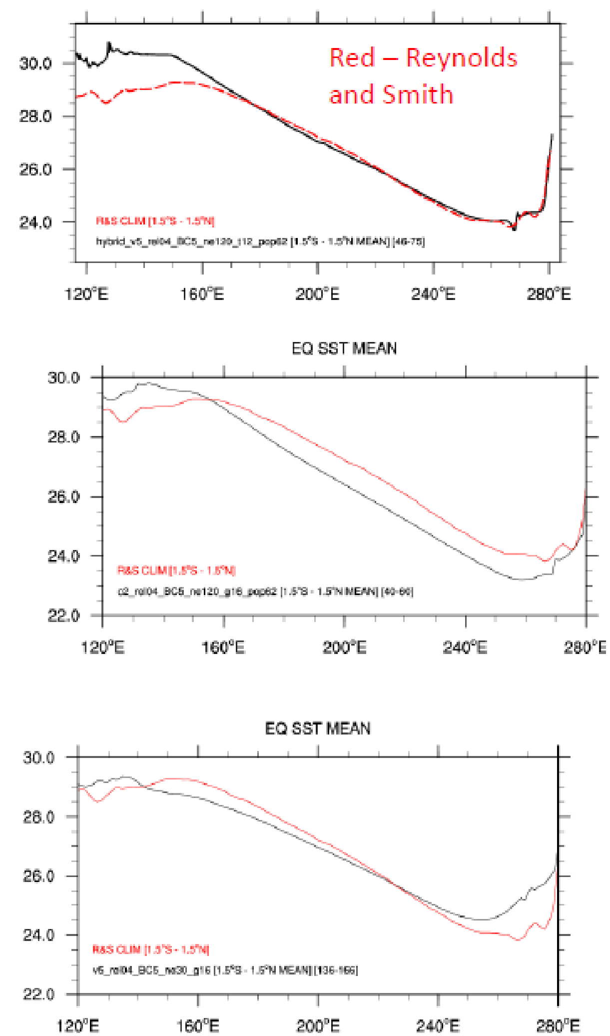


DJF Comp. SST, T_{air}, SLP



Equatorial Pacific SST

Annual Mean

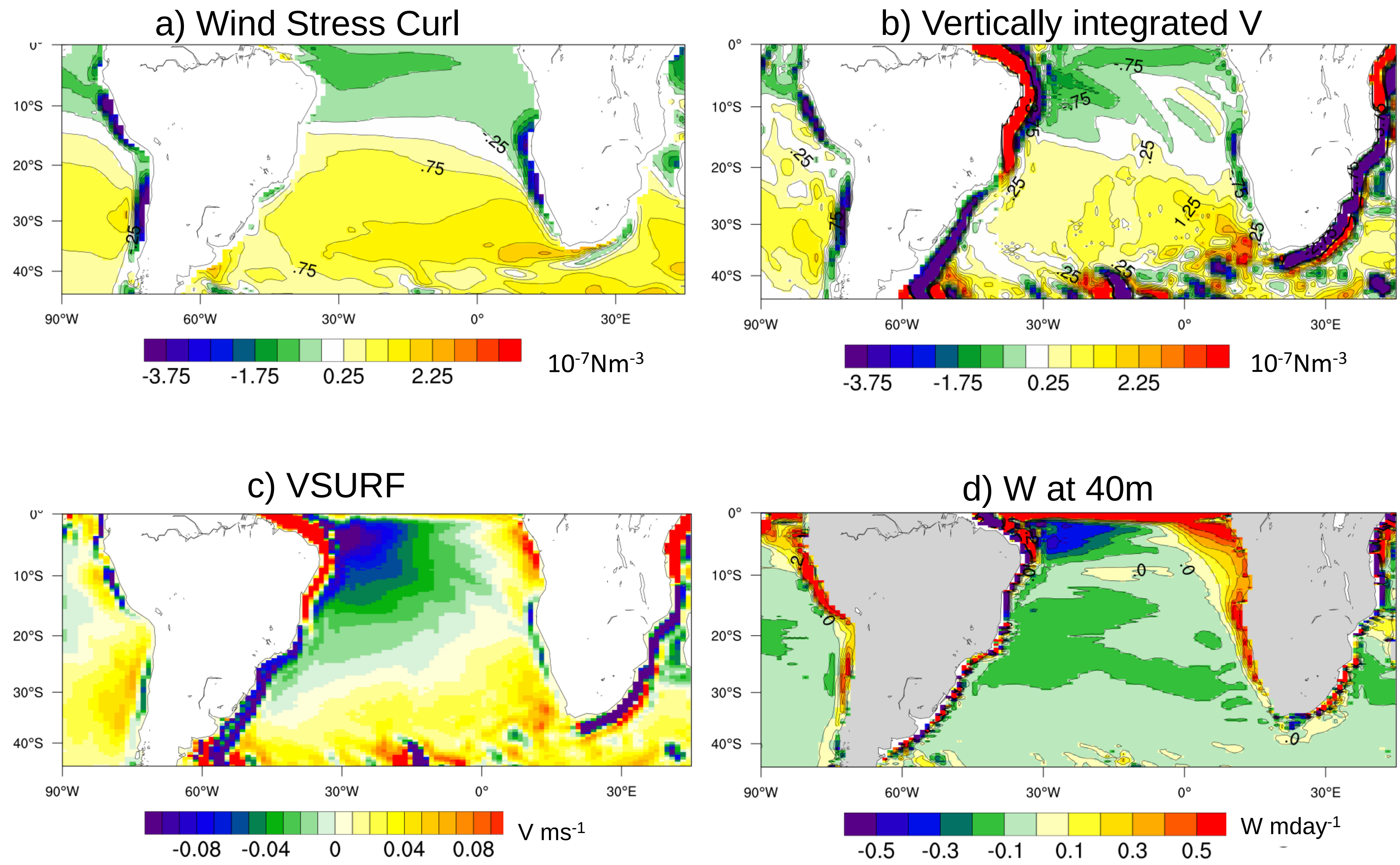


HIGH RESOLUTION OCEAN DATA ASSIMILATION

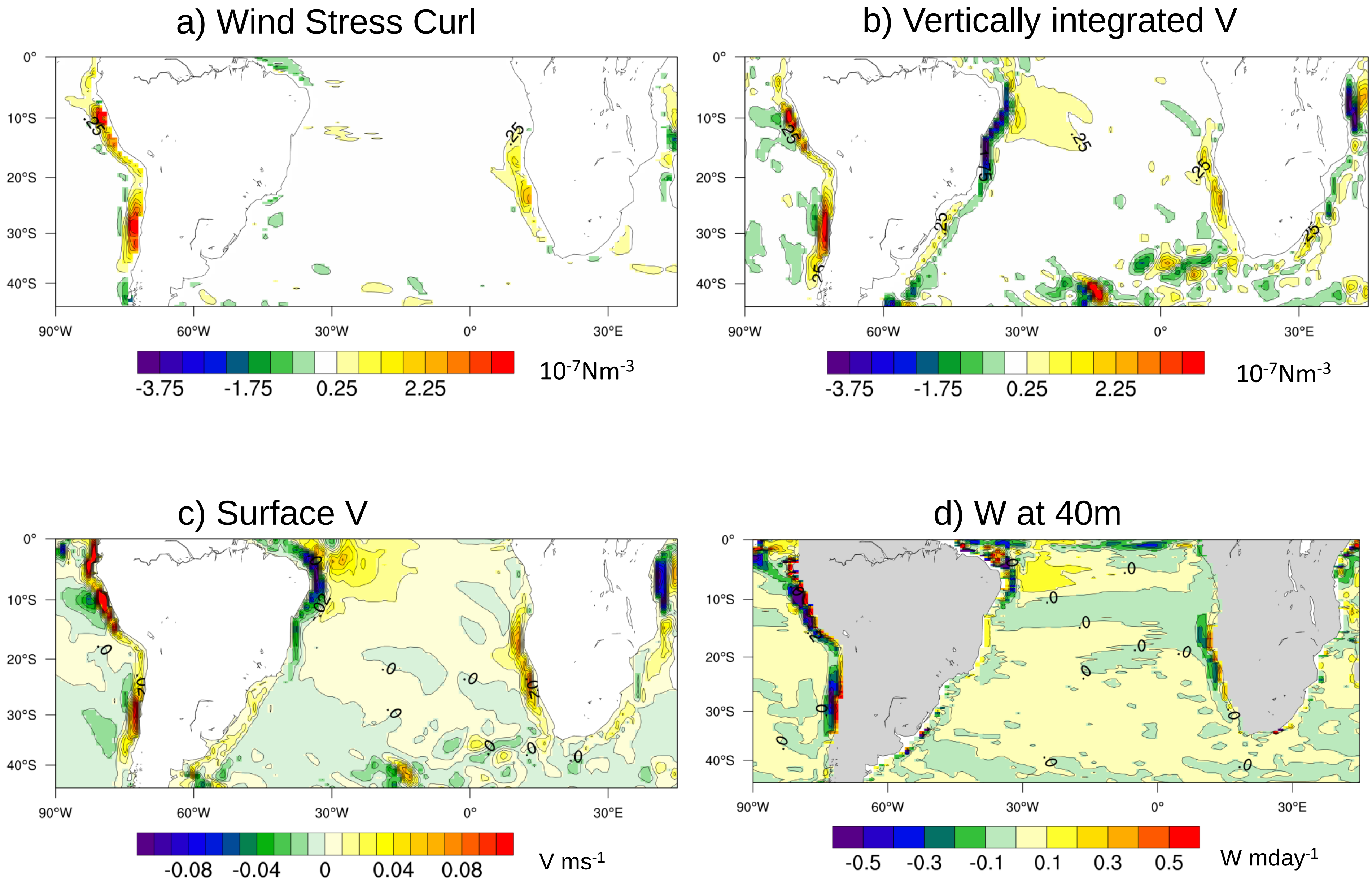
- EaSM-3: The Role of Ocean Eddies in Decadal Prediction
  PI Benjamin Kirtman (UMiami), PI Alicia Karspeck (NCAR)
- POP2 1^{o} model currently has ensemble data assimilation capabilities through the Data Assimilation Research Testbed (DART) software system. (Ensemble Kalman Filter –EnKF)
  - Anderson et al 2009, BAMS
  - Karspeck et al. 2013 JCLI – ocean component
- For 0.1^{o} POP2 a new Remote Memory Access (RMA) version of DART has been developed to work with large state-space models
  - DA update step takes ~20 minutes on ~3K cores
- However, the limiting factor is running ensembles of the 0.1deg model
- Ensemble Optimal Interpolation (EnOI) (Oke et al. 2002, 2005) is used instead of EnKF
  - Does not require ensembles
- Preliminary simulations are progressing…

Extra slides

- 1. Examples of processes
- 2. More detail on data assimilation



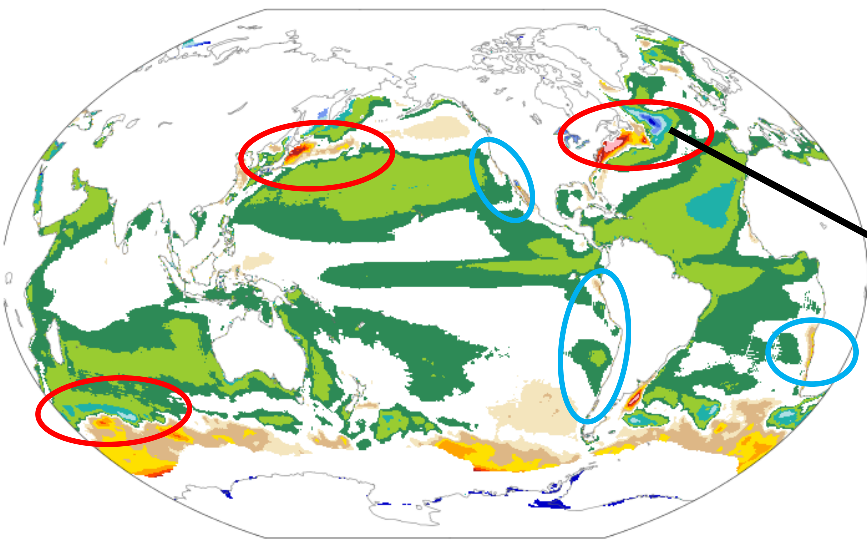
Eastern boundary upwelling. CCSM4 with a 1°. Atmosphere, JJA. Top Right panel: Depth-integrated meridional current to 500m multiplied by $\beta\rho_0$ where β is the meridional gradient of Coriolis force, ρ_0 is a reference ocean density. Under Sverdup balance this should equal the curl of the wind stress shown in left panel. Bottom left: surface velocity. Bottom right: vertical velocity at 40m. Note poleward flow along much of the eastern boundary coastline corresponding to the broad negative wind stress curl, and Ekman-pumping driven upwelling.



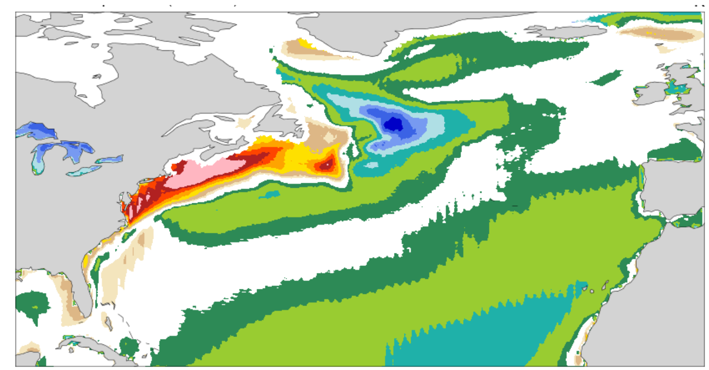
Eastern boundary upwelling. As previous slide, but now showing the difference between CCSM4 with 0.5° atmosphere minus that with 1° atmosphere. Note that flow is more Equatorward at eastern boundary coasts, with more upwelling at the coast (thin strip of red in panel d) and less offshore upwelling.

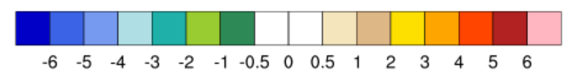
EFFECT OF CHANGING OCEAN RESOLUTION IN A COUPLED MODEL: SST

LOW-RES MINUS REYNOLDS 2007 SST

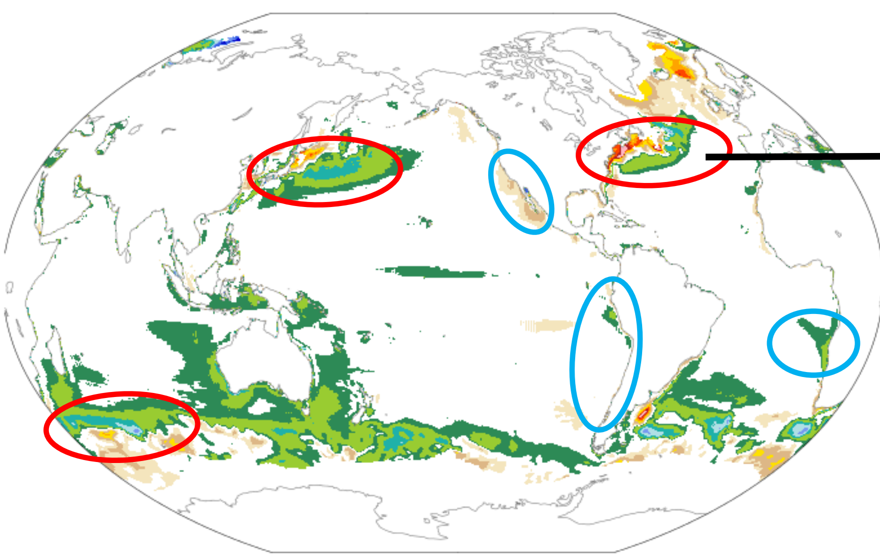


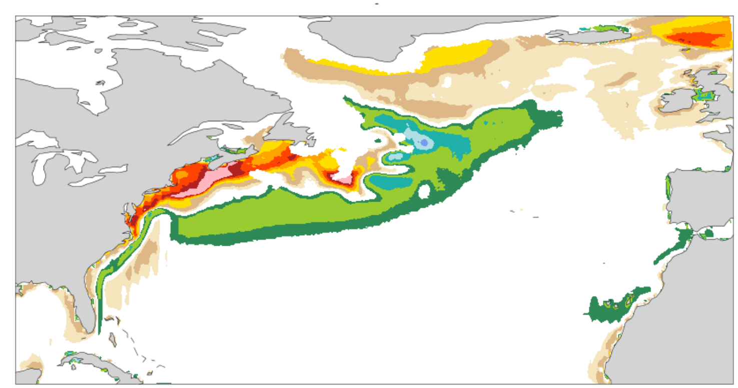
Sign convention – matching colors (top and bottom) implies improvement with resolution. Ocean frontal zones (red rings) are improved.

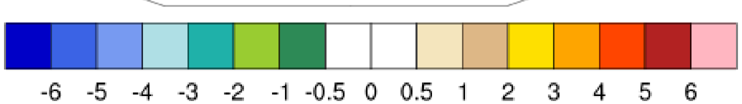




LOW-RES OCEAN MINUS HIGH-RES



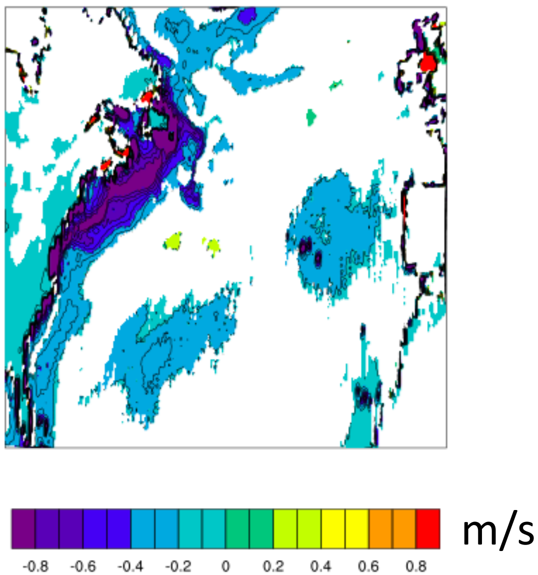




Why do the upwelling zones (blue rings) not improve with ocean resolution (except off California)? Wind stress curl is too strong near coast (Small et al. 2015, JCLI)

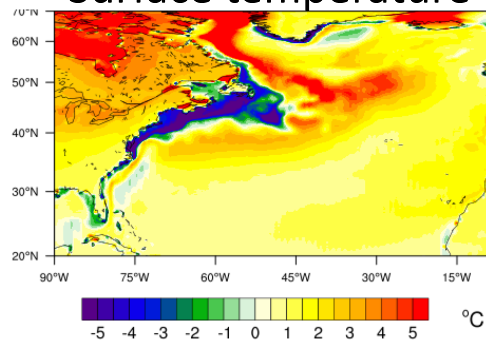
Storm track change with ocean resolution

V10 storm track

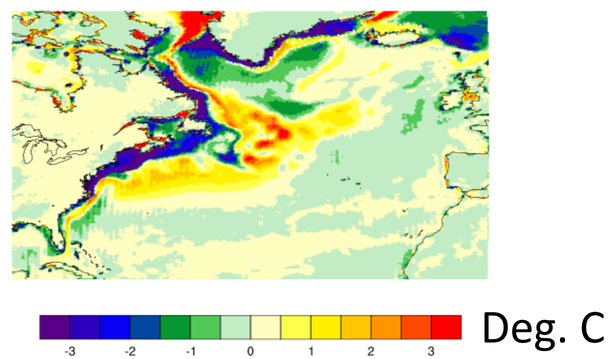


Changes in storm track (top left) and various forcing factors between CESM with high resolution ocean and with low resolution ocean. Storm track is reduced off coast due to reduction in mean SST in high-res.

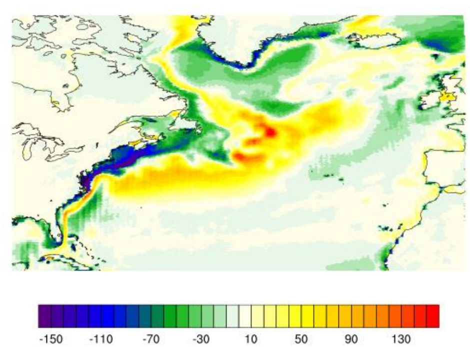
Surface temperature



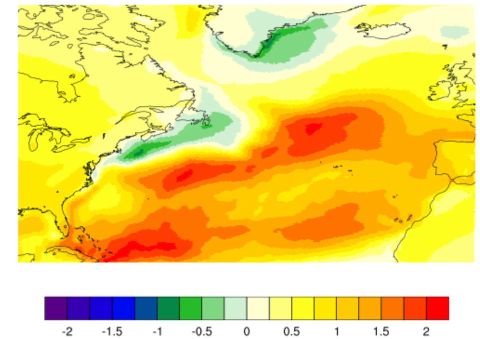
TS-TA



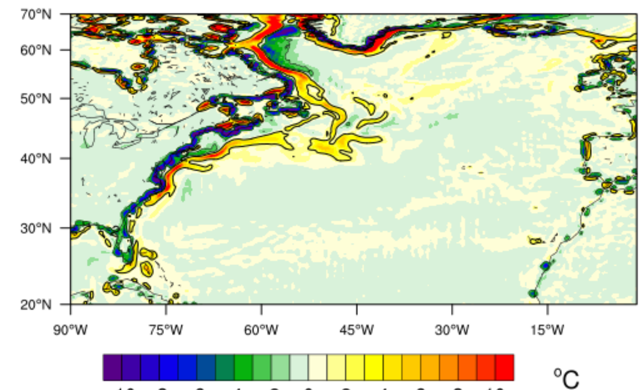
Latent heat flux difference, W/m2



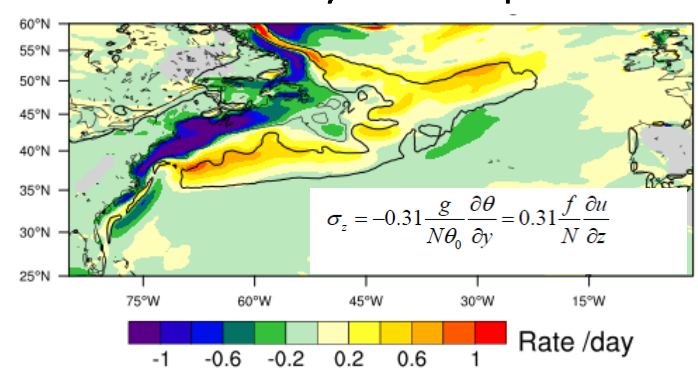
Precipitable water, mm



Surface temp. gradient per 100km

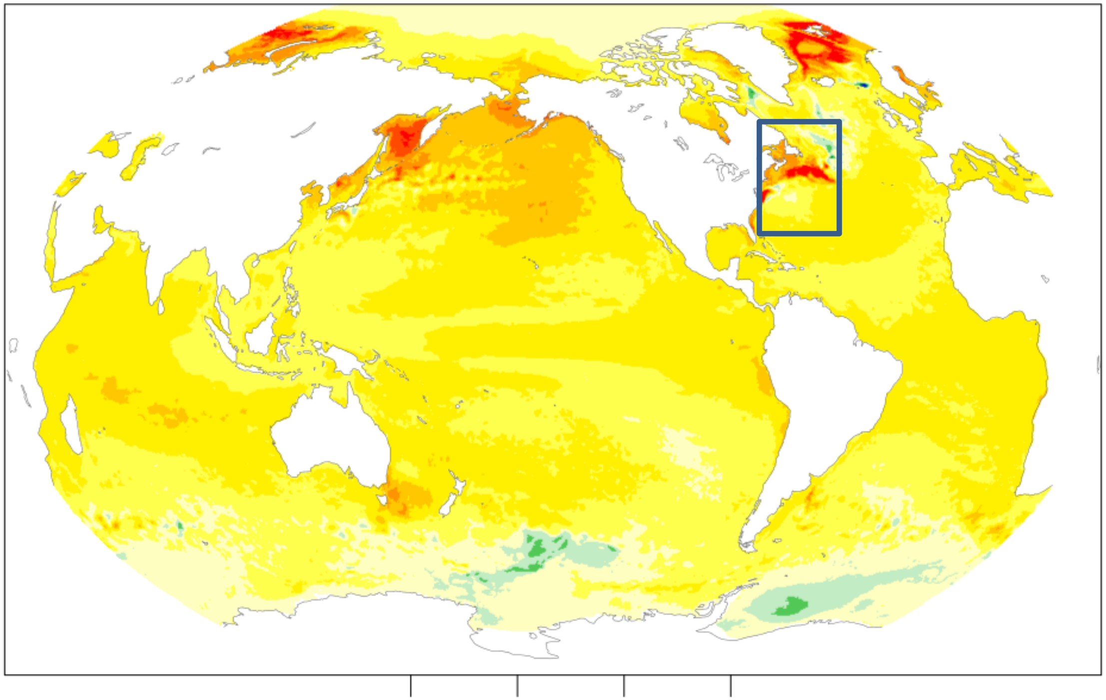


Baroclinicity at 950hpa

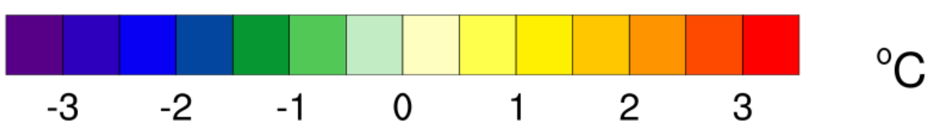


SST change, in first half of 21st C

CESM1-high resolution RCP8.5

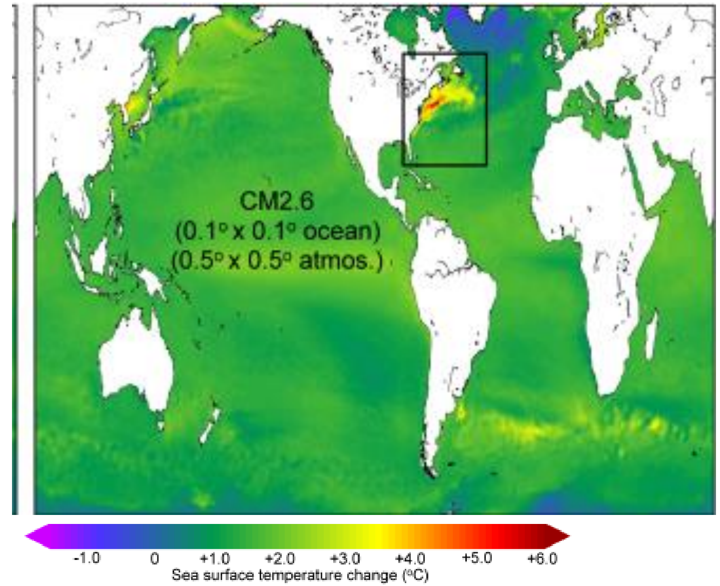


2006-2015 to 2041-2050 SST change



High-res CESM is 0.25deg atmosphere, 0.1 deg ocean.

Compare with CM2.6: 1%CO_2



Top right panel from **Enhanced warming of the Northwest Atlantic Ocean under climate change**
Vincent S. Saba et al. 2016, JGR.

CM2.6 is 0.5deg atmosphere, 0.1deg ocean.

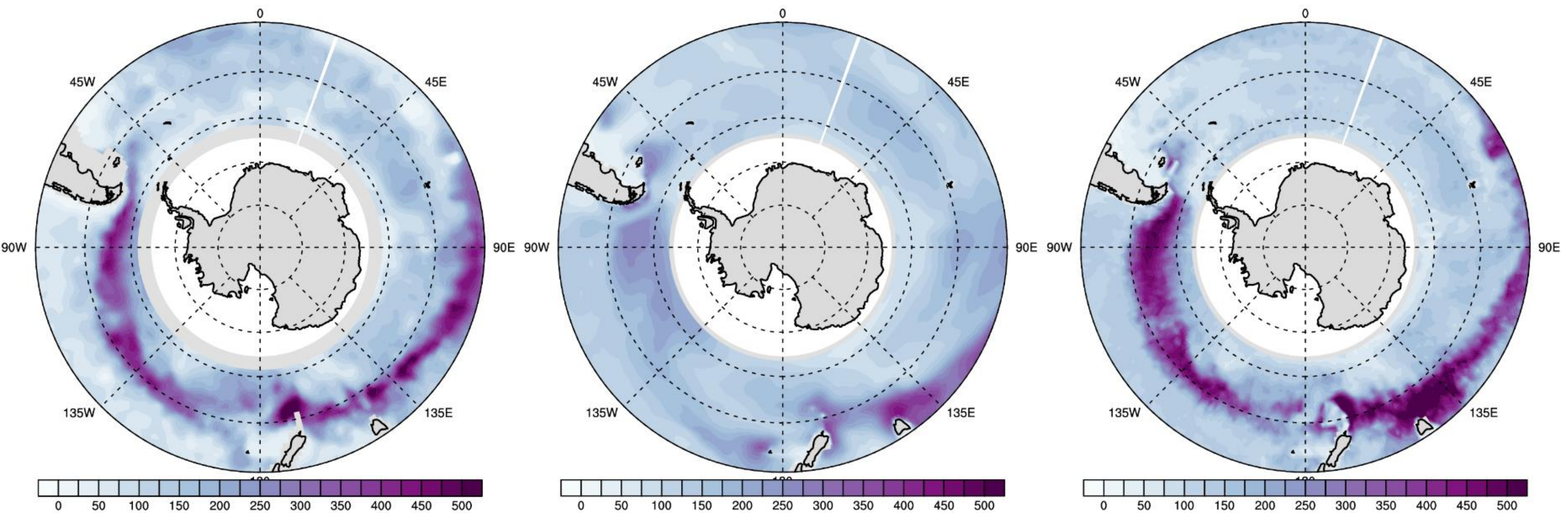
Qualitative agreement comparing the high resolution CESM RCP8.5 to the GFDL CM 1%per/yr simulations. North-east USA coast is a hotspot of warming.

Southern Ocean winter: mixed layer depths

ARGO

LOW-RES FORCED OCEAN RUN

HIGH-RES FORCED OCEAN RUN



Much deeper mixed layers with high-resolution ocean, and more realistic spatial distribution compared to ARGO. Similar picture emerges in coupled simulations.

Design challenges for global high resolution ensemble data assimilation

Time and computing resources remain a big challenge:

- DA update step takes ~20 minutes on ~3K cores
- However, the limiting factor is not the DA step…

  The DA step is only 5% of the cost of the assimilation with a 50 member ensemble. The vast majority of the cost is running ensembles of the $1/10^{o}$ model.

- We need an alternative strategy

  $\Rightarrow$ Ensemble Optimal Interpolation (EnOI) (Oke et al. 2002, 2005)

Assimilation of along-track SLA

Initial phases of testing the infrastructure, optimizing the system performance and preparing the necessary observational data streams for eddy-resolving data assimilation are complete.

- Data processing streams and forward operators
- Scripting and workflow for DART RMA-CESM2 EnOI
- Short prototype runs to test the new POP 1/10^{o} EnOI