GFDL's Contributions to CMIP6

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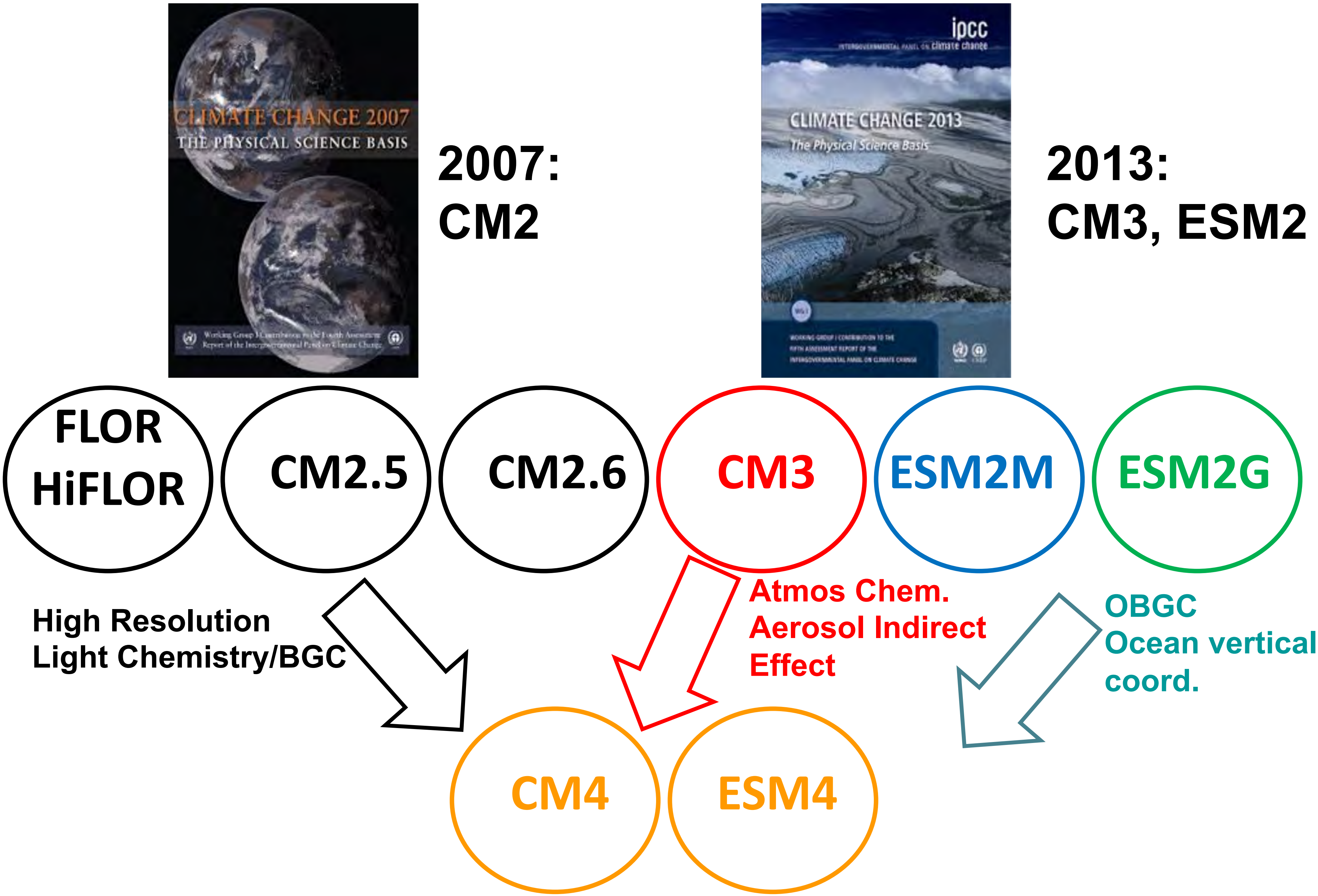
on behalf of the entire GFDL Model Development Team

OCB Ocean Carbon Uptake in CMIP6 Models Synthesis and Intercomparison Workshop
December 8-9, 2018

Origins of GFDL CM4/ESM4 for CMIP6



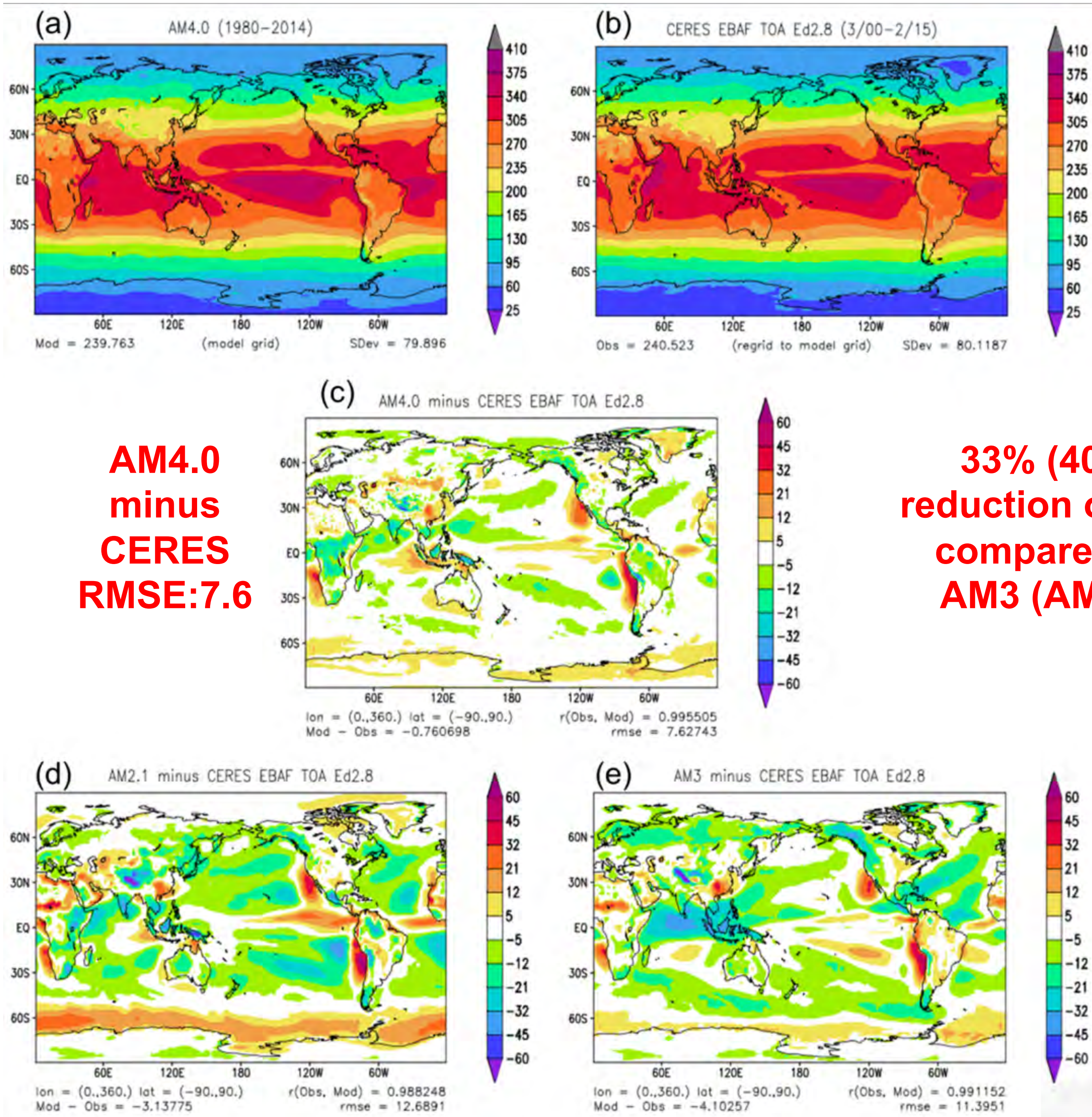
GFDL’s CMIP6 generation models: CM4 and ESM4

	CM4.0	**ESM4.1**
Atm. Dyn.	100 km, 33 levels	100 km, 49 levels
Atm. Chem.	aerosol (21 tracers)	aerosol+chem+ozone (103 tracers)
MOM6 Ocean	$1/4^{o}$, 75 levels	$1/2^{o}$, 75 levels
Ocean BGC	BLINGv2 (6 tracers)	COBALTv2 (33 tracers)
Land	LM4.0	LM4.1 - PPA
Sea Ice	SIS2	SIS2

AM4.0 annual mean TOA net Shortwave radiation (W/m2)

AM4.0

CERES EBAF-ed2.8



AM4.0 minus CERES RMSE:7.6

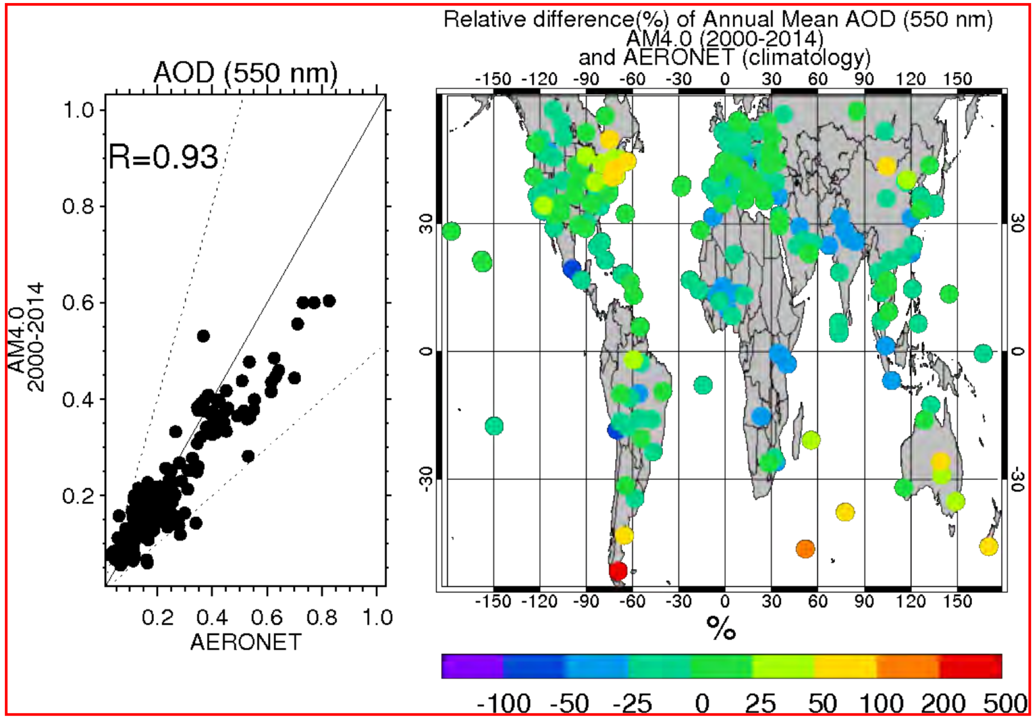
33% (40%) reduction of error compared to AM3 (AM2.1)

AM2.1 minus CERES RMSE:12.7

AM3 minus CERES RMSE:11.4

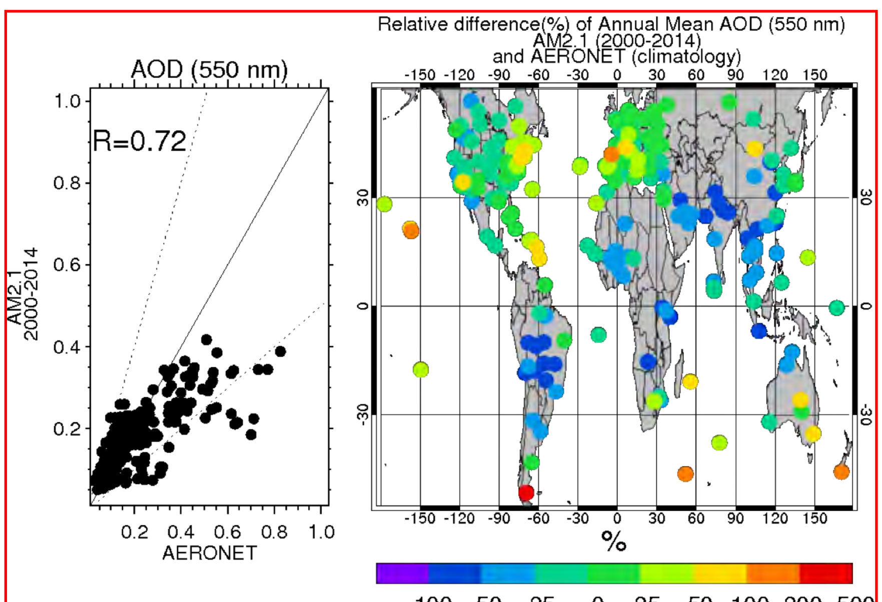
AM4.0 simulated aerosol optical depth compared to AERONET

AM4-vs-OBS correlation=0.93

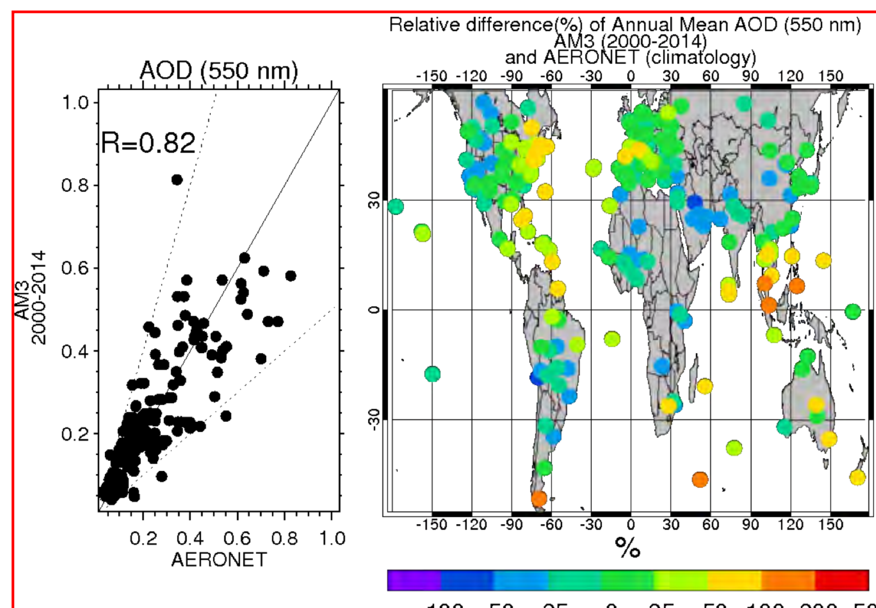


color show percent error compared to AERONET

AM2.1-vs-OBS correlation=0.73



AM3-vs-OBS correlation=0.82



Ocean Modeling with MOM6/SIS2

MOM6 unifies GFDL's ocean modeling efforts - best of MOM5 and GOLD

SIS2 modernizes our sea-ice model physics and dynamics

C-grid discretization (replaces B-grid)

- No "Checkerboard" null mode
- Less smoothing of forcing required

Better representation of topography and narrow channels

- No need for "Cross-land mixing"

MOM6 and SIS2 are basis of OM4 ocean/ice component of CM4

Open development model (MOM6+SIS2)

- All activity visible via *GitHub*

Lagrangian Vertical Dynamics

- Arbitrary Lagrangian-Eulerian method (ALE)
- Tracer advection is not required for gravity wave dynamics
- Able to use a wide range of vertical coordinates

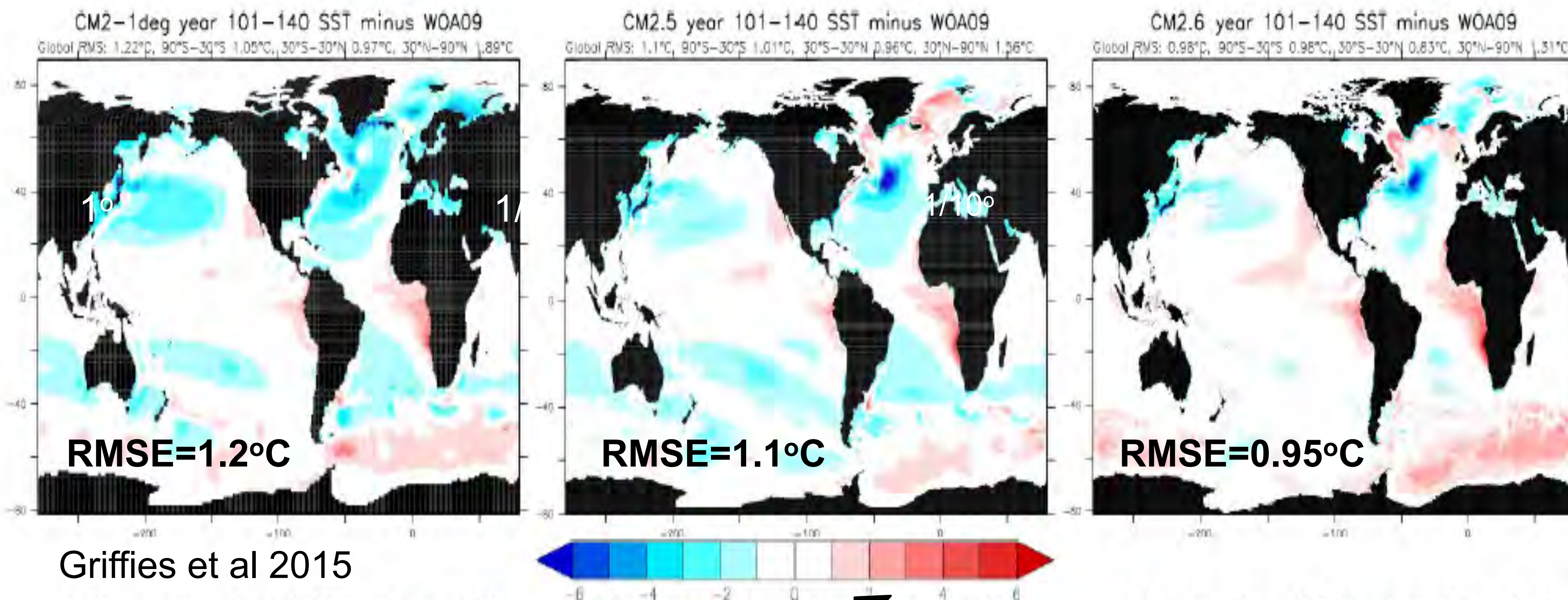
Implicit remapping replaces vertical advection

- No vertical CFL limit on time steps
- Ultra-fine vertical resolution possible

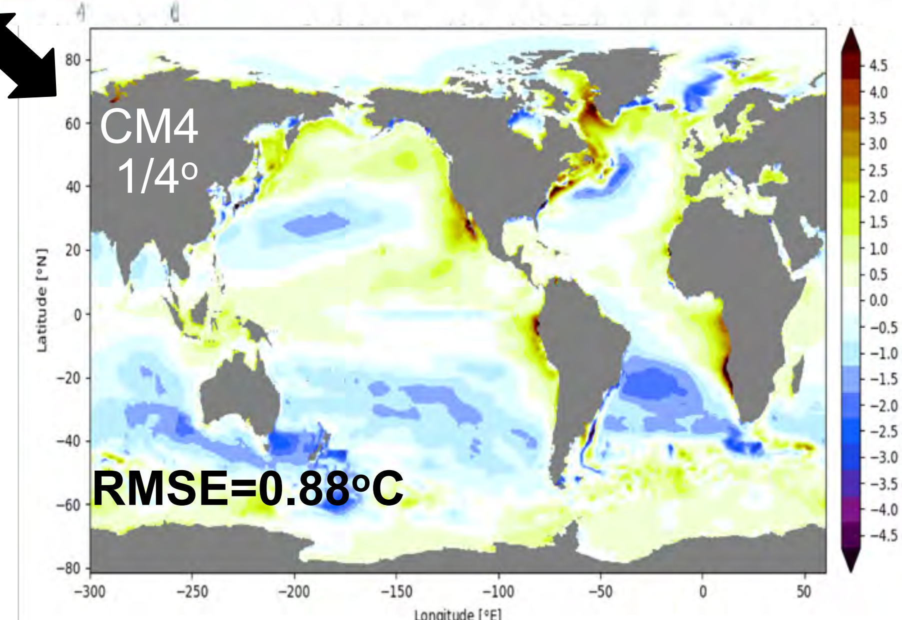
Permits sub-cycled gravity-wave dynamics vs. tracer advection

- Reduces cost to add tracers.

CM4 vs CM2 at various resolutions: SST errors



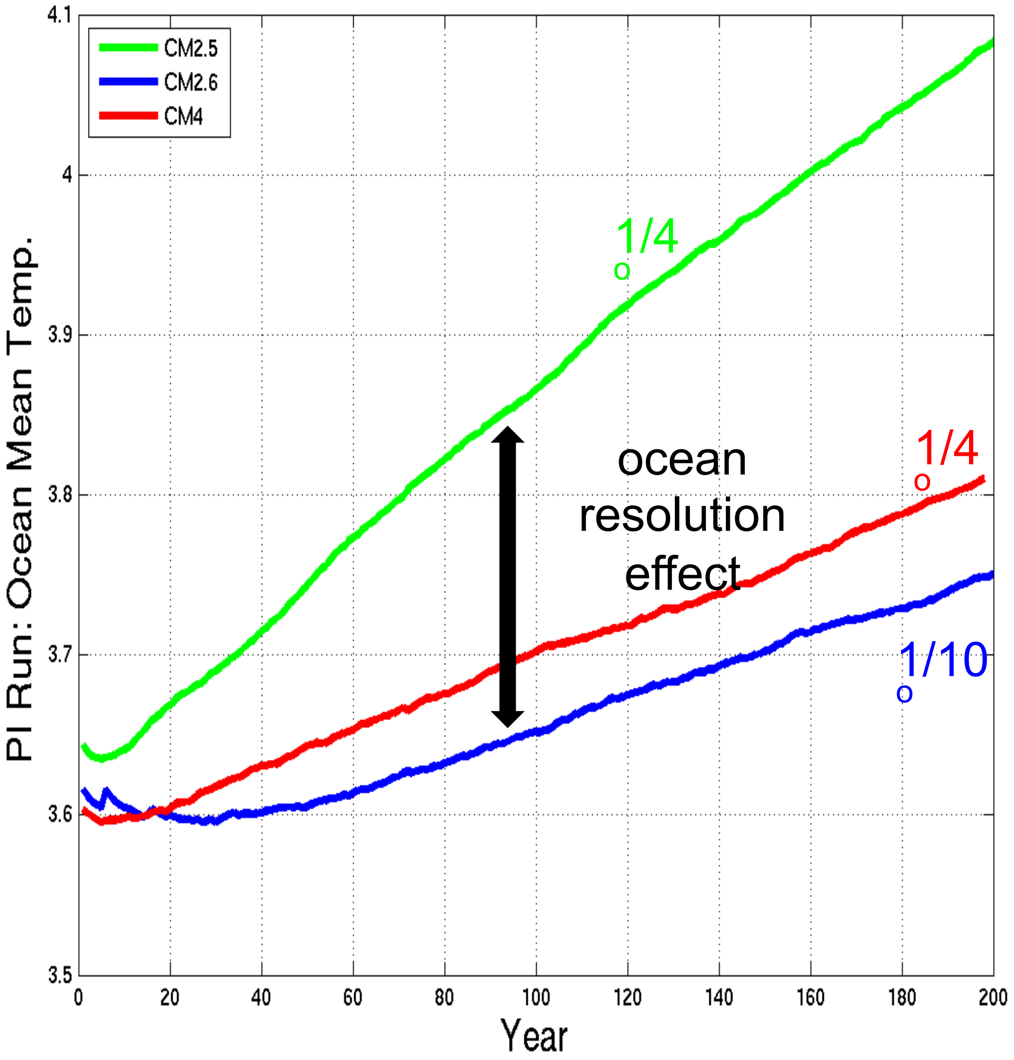
Griffies et al 2015



- CM4's SST errors are similar to CM2.6 (GFDL's previous best simulation)
- We expect these can be improved further with higher ocean resolution as was seen going from CM2.5 to CM2.6 or with an eddy parameterization

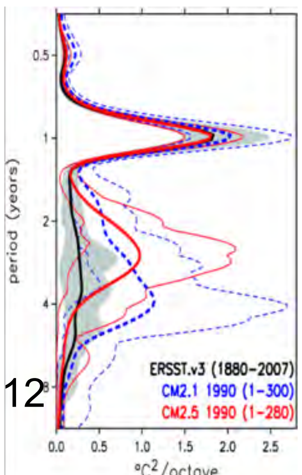
CM4 vs CM2.5/CM2.6: ocean temperature drift

- CM4's spurious heat uptake under pre-industrial forcing is similar to CM2.6
- CM2.5/CM2.6 comparison shows that CM4's eddy permitting resolution is a source of spurious heat uptake
- Heat uptake could be remedied by higher ocean resolution or an eddy parameterization



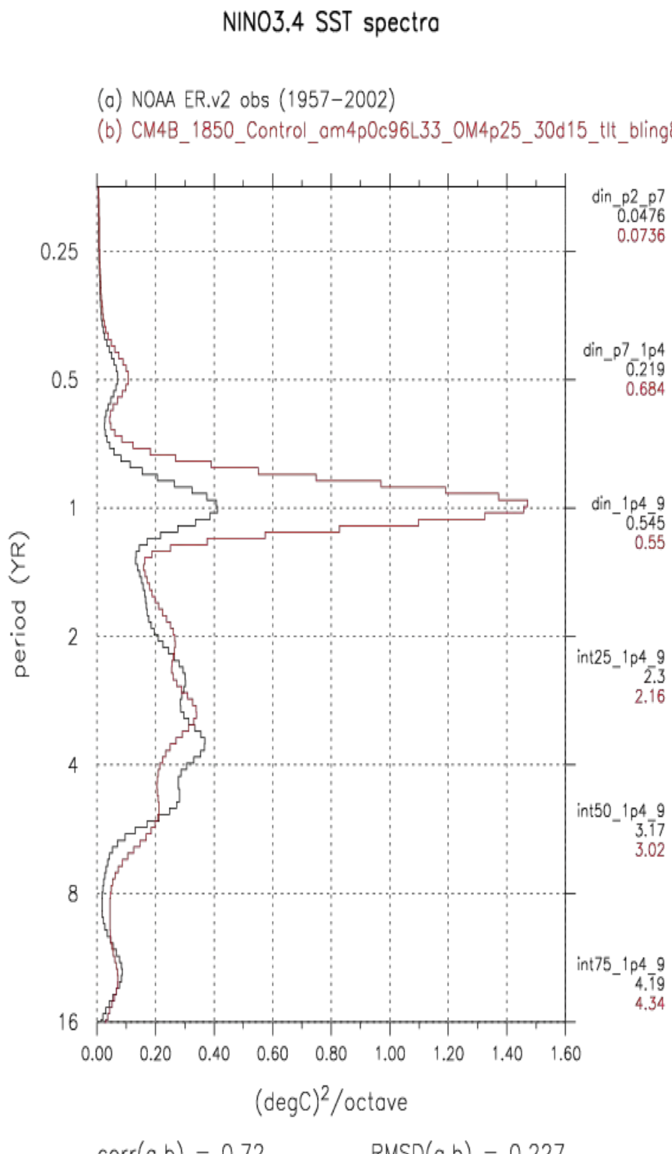
CM4 El Niño Southern Oscillation and Teleconnection

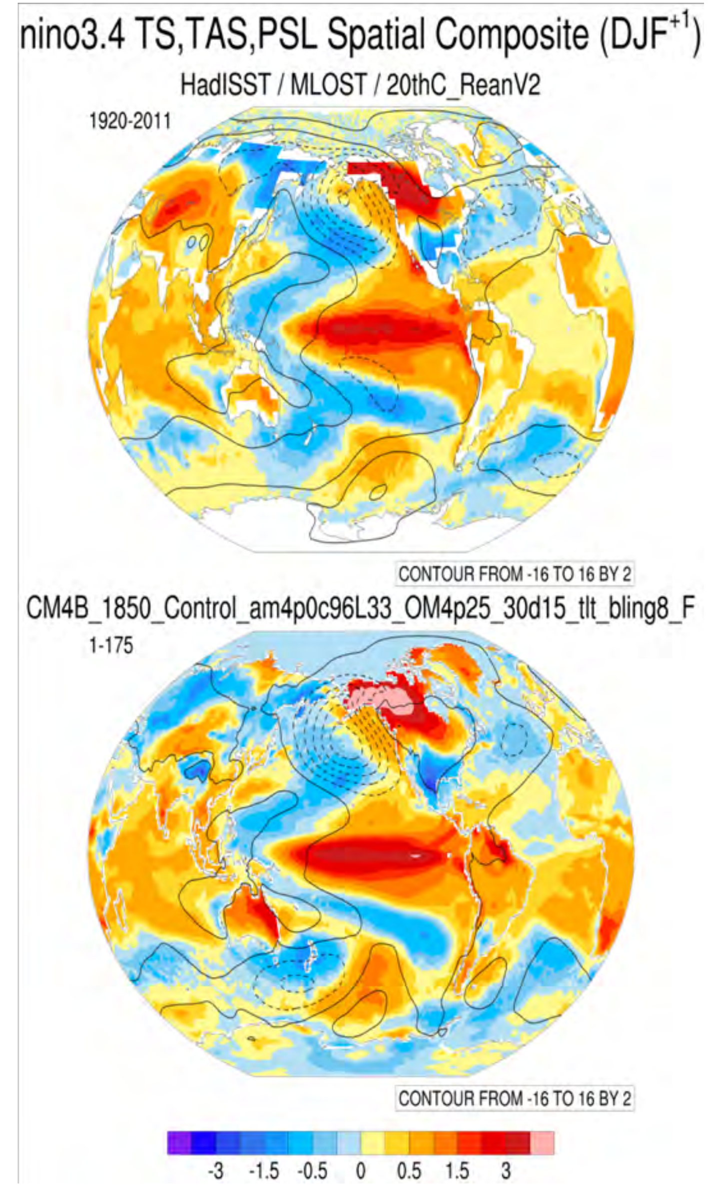
- ENSO magnitude is more realistic than previous GFDL models which tended to be too large



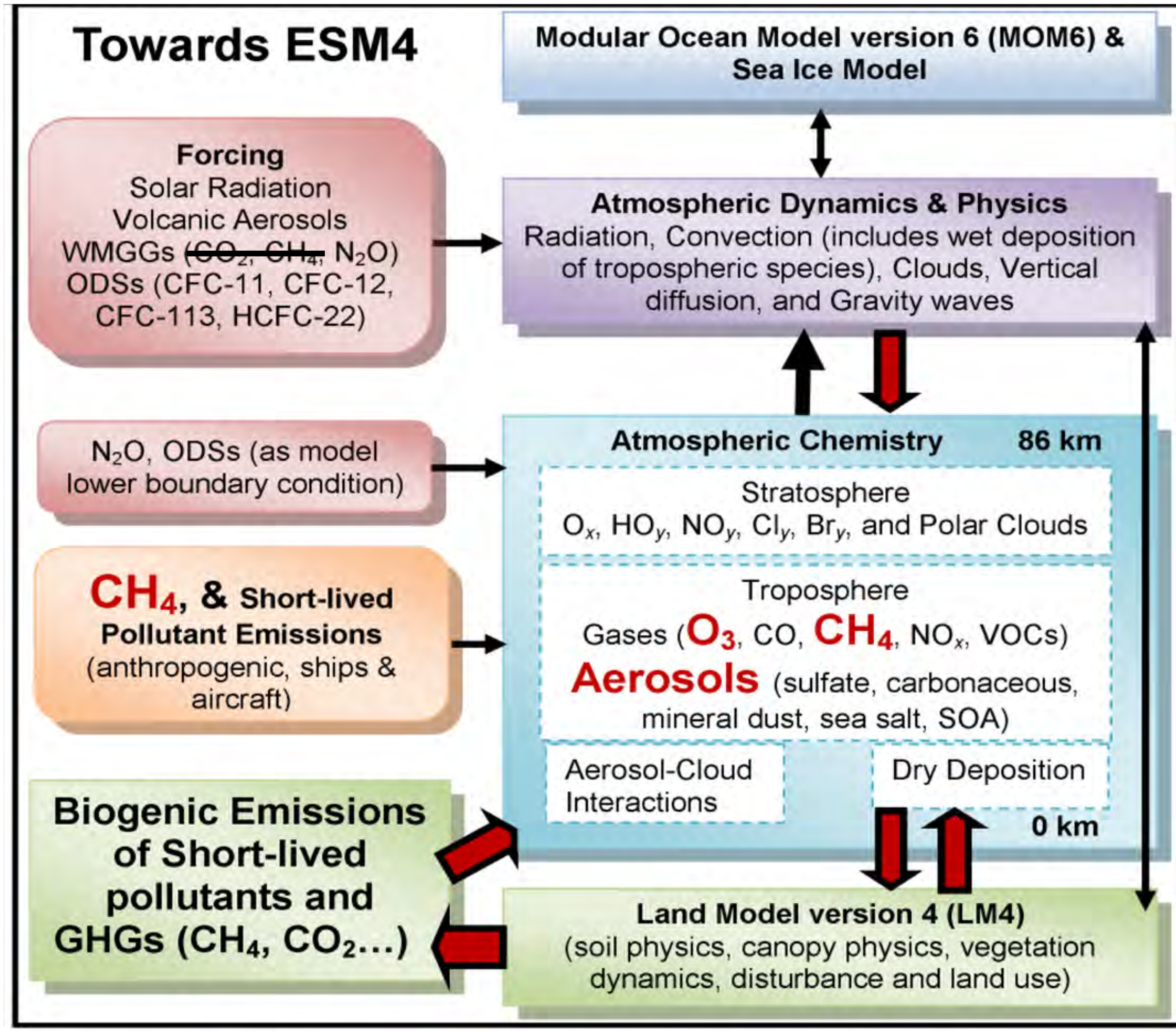
Delworth et al 2012

- ENSO teleconnections look good

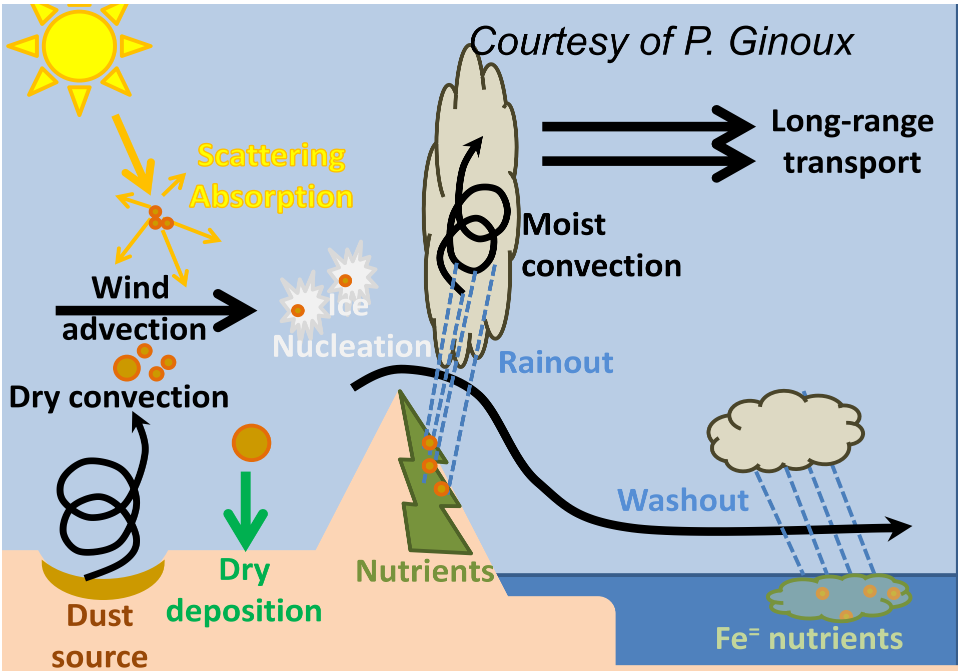




ESM4: Atmospheric Chemistry in the Earth System

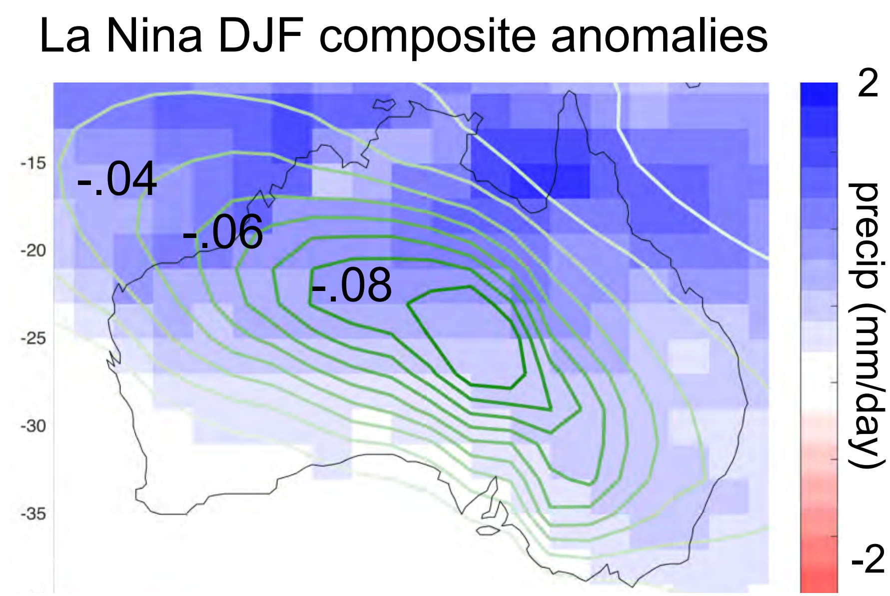


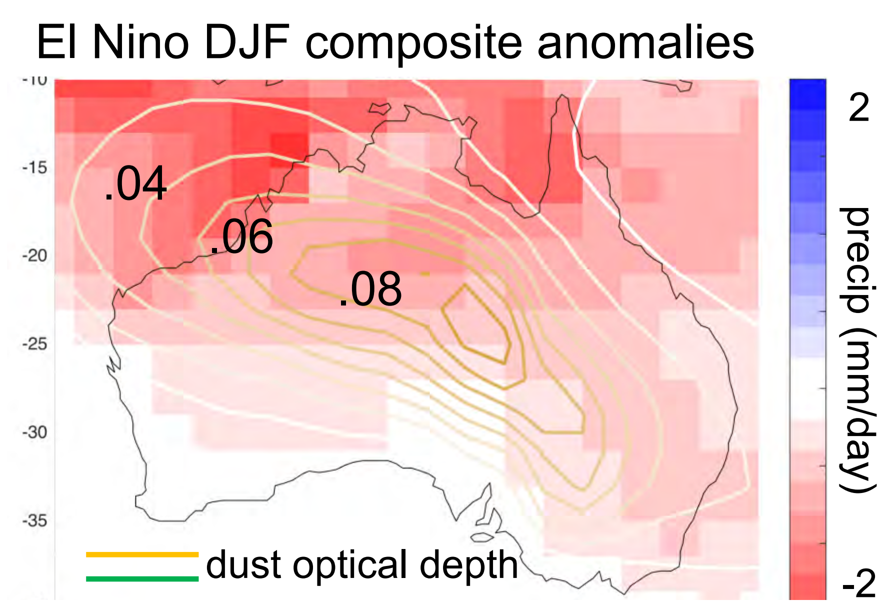
Dust-ecosystems-climate interactions



- “Dusty” CM3 connects Australian dust
- emissions with ENSO
- ENSO creates precip anomalies =>dust anomalies.
- Dust optical depth anomalies are 30% up from seasonal mean
- Precip anomalies are 50% of seasonal mean

Evans, Ginoux et al., 2016, GRL

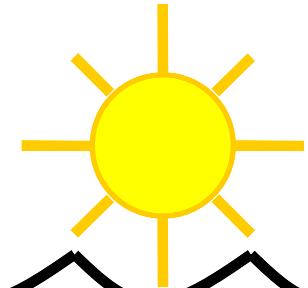


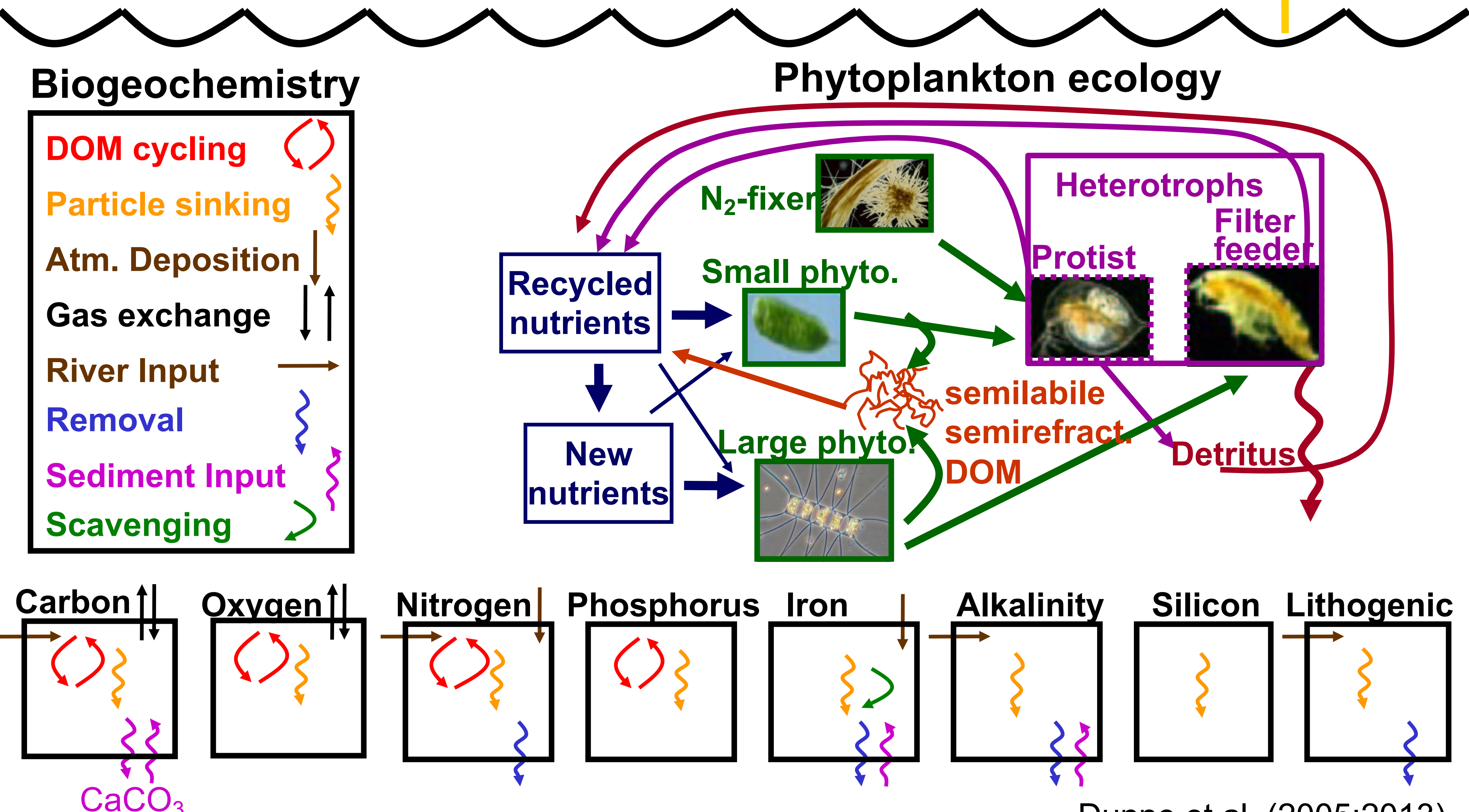


Tracers of Phytoplankton with Allometric Zooplankton (TOPAZ) in ESM2 for CMIP5

Diatoms and Other Large Phytoplankton
Flexible N:P:Si:Fe:Chl
Aragonite and Calcite

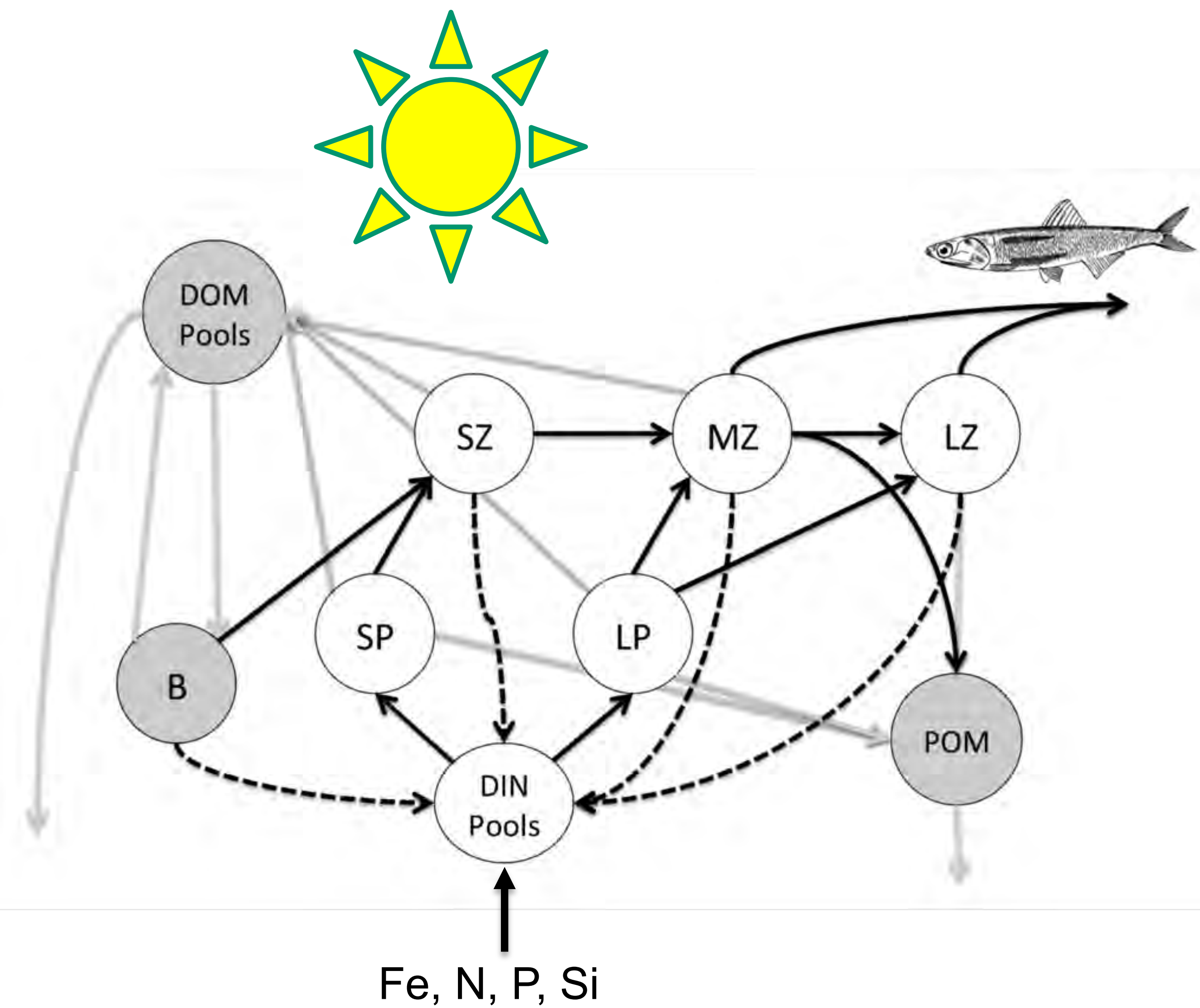
30 Tracers





Dunne et al. (2005;2013)

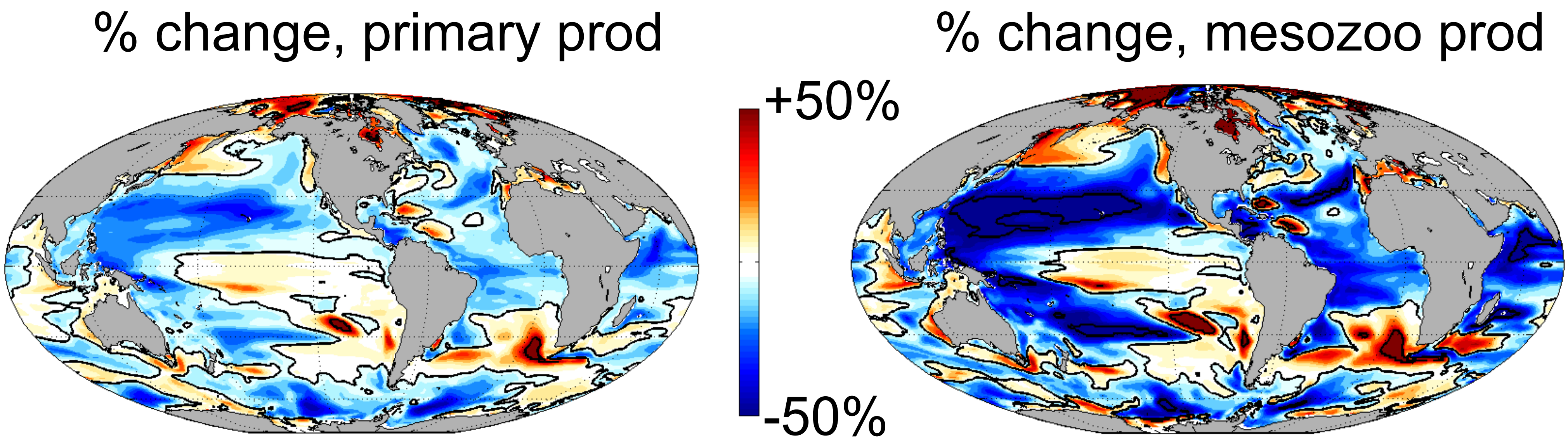
Carbon Ocean Biogeochemistry and Lower Trophics (COBALT): A multi-stressor plankton food web model in ESM4 for CMIP6



- More effective nutrient scavenging for small P, but more susceptible to grazing
- Longer food chain from small P to fish
- Zooplankton must compete with other loss processes for primary production
- Not all of what zooplankton eat makes it to the next trophic level
- Calibrated to diverse observation-based energy flow estimates

Stock et al., 2014, PinO, 120, 1-28

Amplification of ocean productivity changes



- Projected percent changes in mesozooplankton productivity are 2X primary productivity changes
- Large regional changes
- Quantitative attribution to the same planktonic food web characteristics that drive spatial gradients

Stock, C. A., J. P. Dunne, and J. G. John, 2014: Drivers of trophic amplification of ocean productivity trends in a changing climate. Biogeosciences, 11(24), DOI:10.5194/bg-11-7125-2014.

GFDL Earth System Model Summary for CMIP6 (ESM4.1)

Includes:

- New Interactive atmospheric chemistry including improved Nitrogen, SO_4, and BVOC
  - New Sea salt emissions as a stronger function of temperature
  - Reduced N cycle including interactive SO4 and ocean-atmosphere NH3 emissions
  - Revised atmospheric dry deposition for consistency across tracers
  - New BVOC including isoprene and terpene
- Interactive Dust with dynamic vegetation
- COBALT Ocean biogeochemistry module for explicit treatment of zooplankton biodiversity
  - Revised physiology and remineralization
  - Interactive dust/Iron and NH4
  - Iceberg Iron (Laufkotter, Stock)

Some Early Looks at CM4 and ESM4 results

…or…

Beware the Superpolyna

Real World Polynas

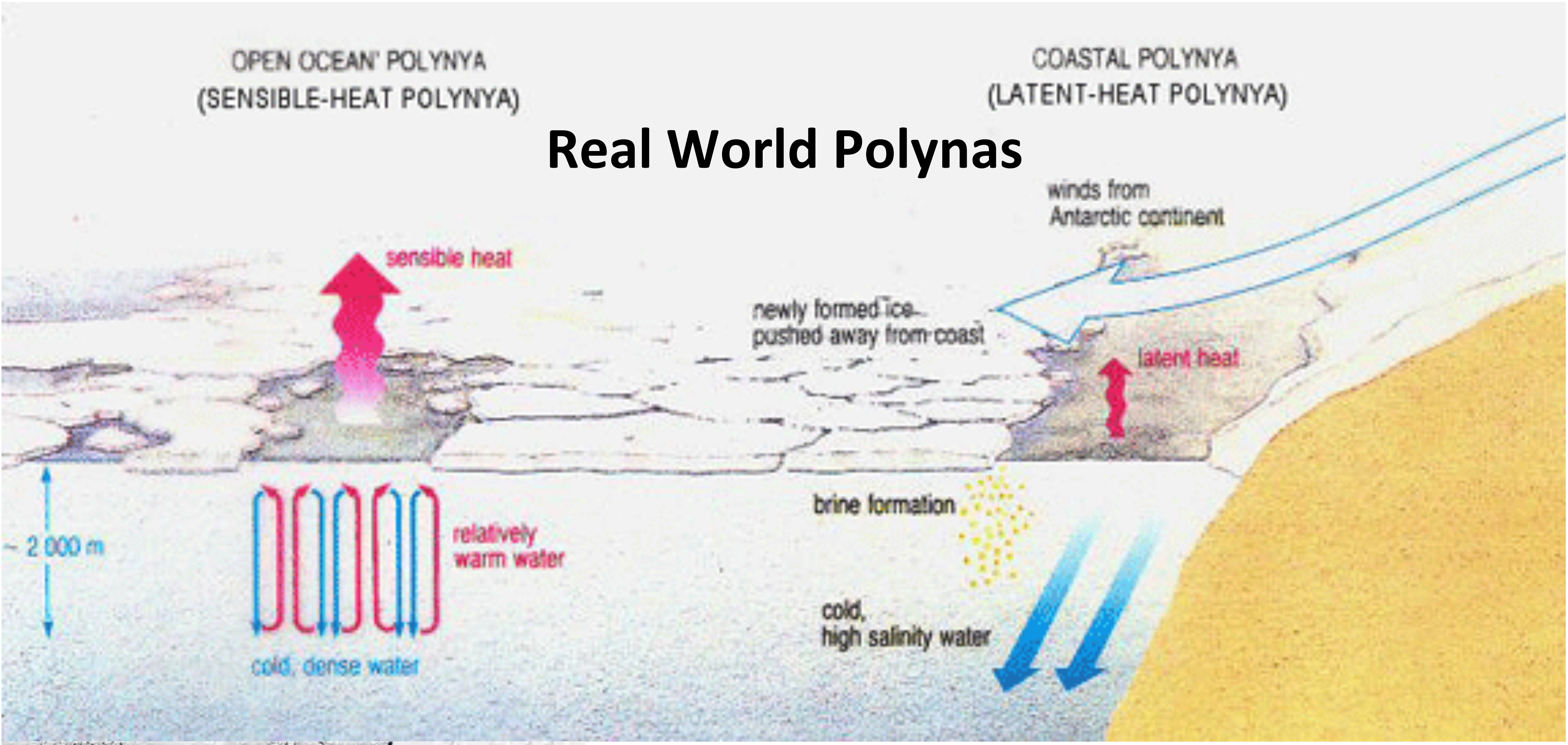
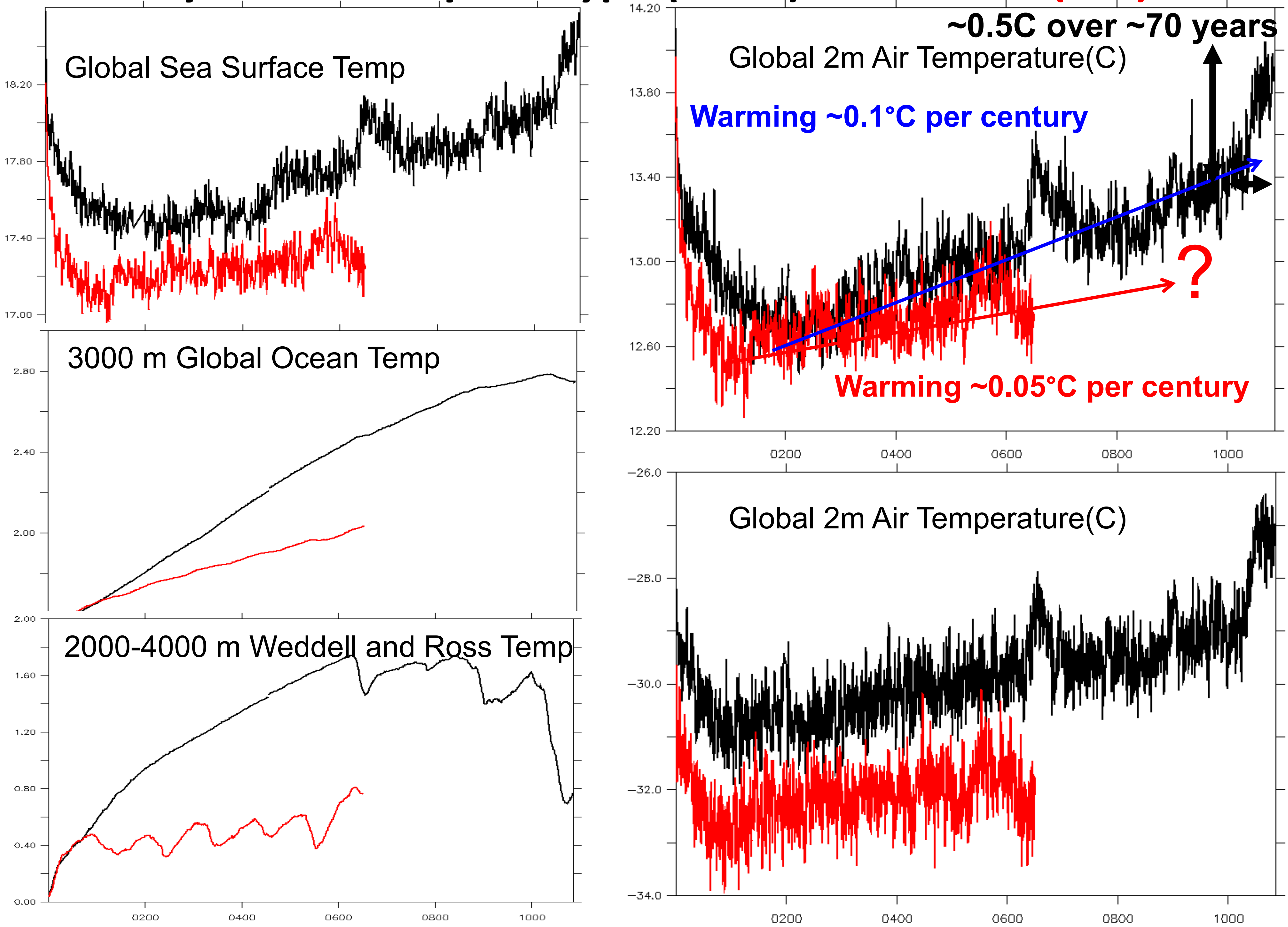


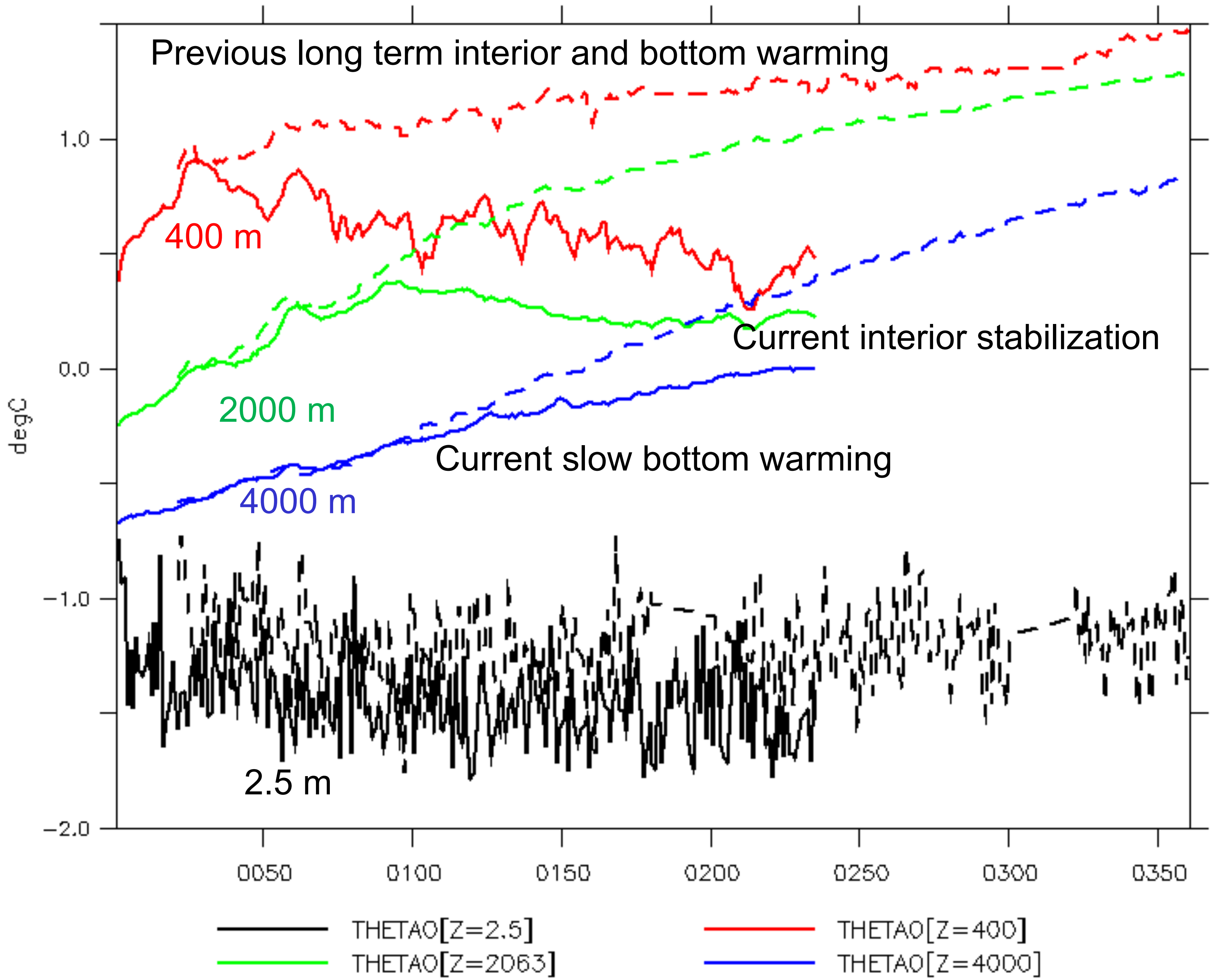
Diagram of sensible-heat (open-ocean) and latent-heat (coastal) polynya formation. Image modified from *Ocean Circulation, 2nd Edition* by Open University, Butterworth-Heinemann Publishers, page 219.

Satellite view of polynyas (dark areas) near Oates Coast, Antarctica (solid white area at right of photo).
—*Image courtesy of NASA.*

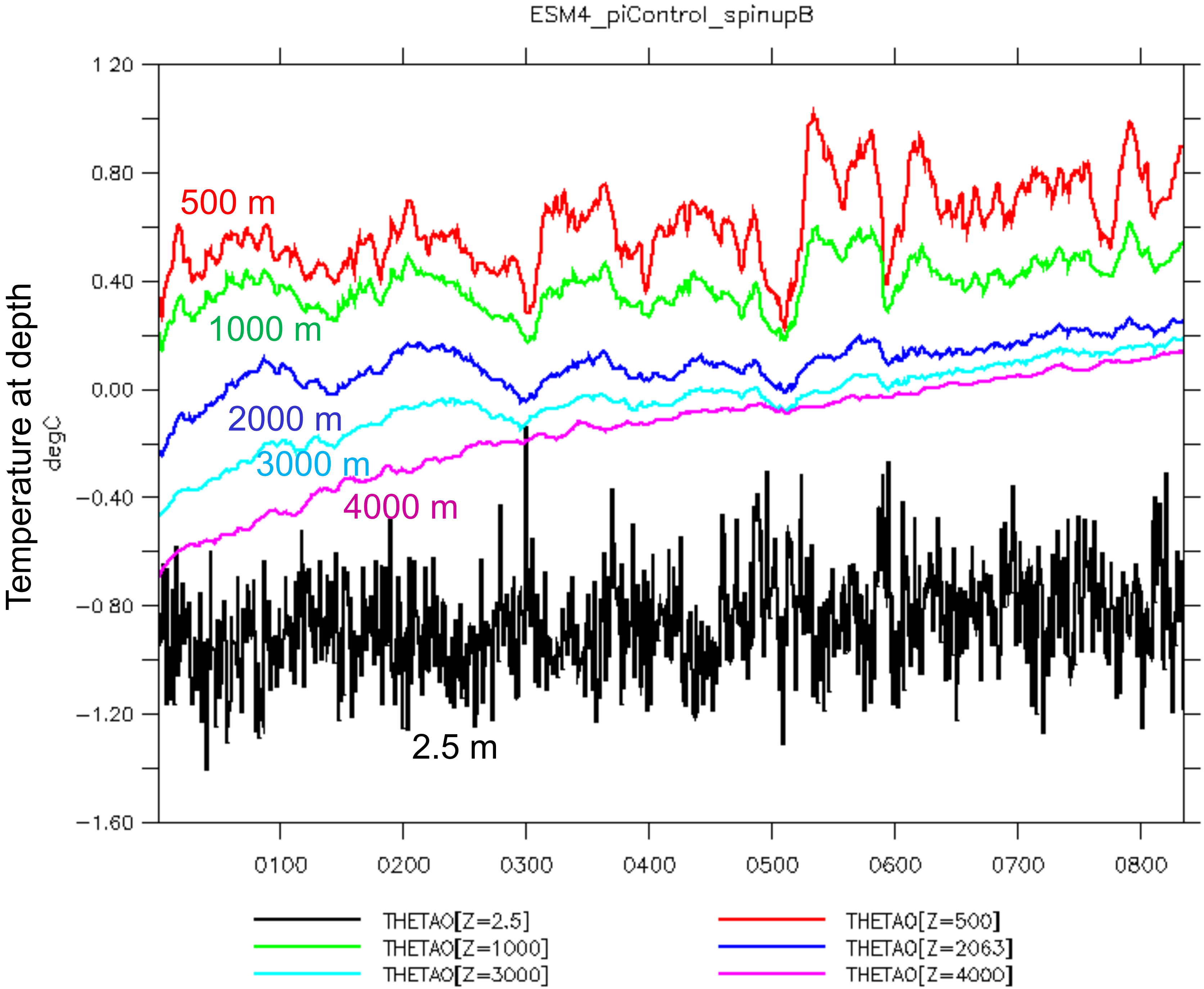
Polynas in CM4 prototype (black) and CM4.0 (red)



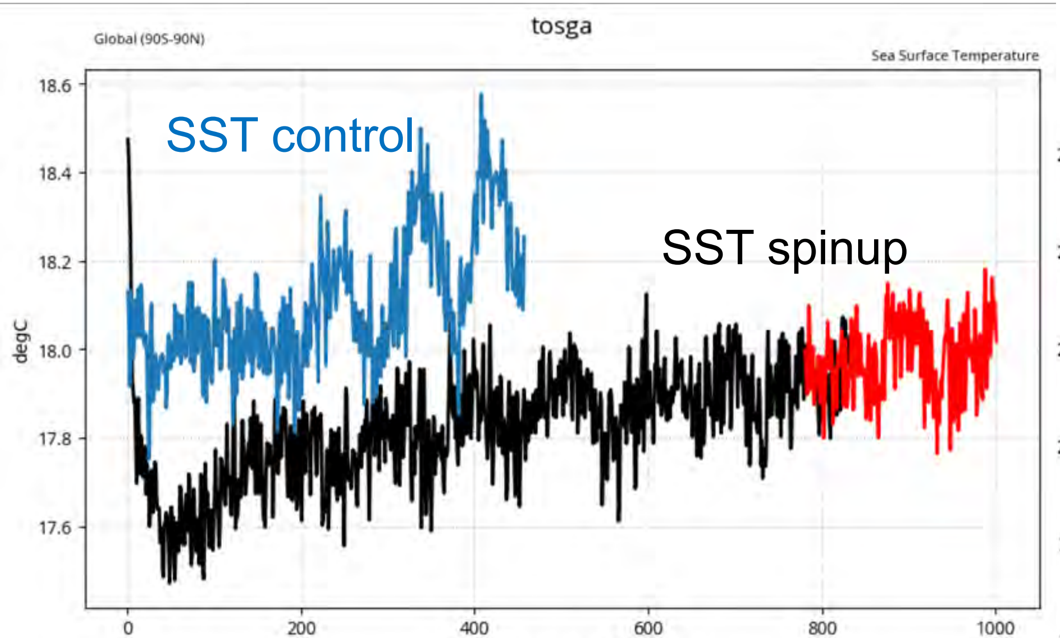
CM4 Weddell Sea Temp *(dash Plan A; solid Plan C)*

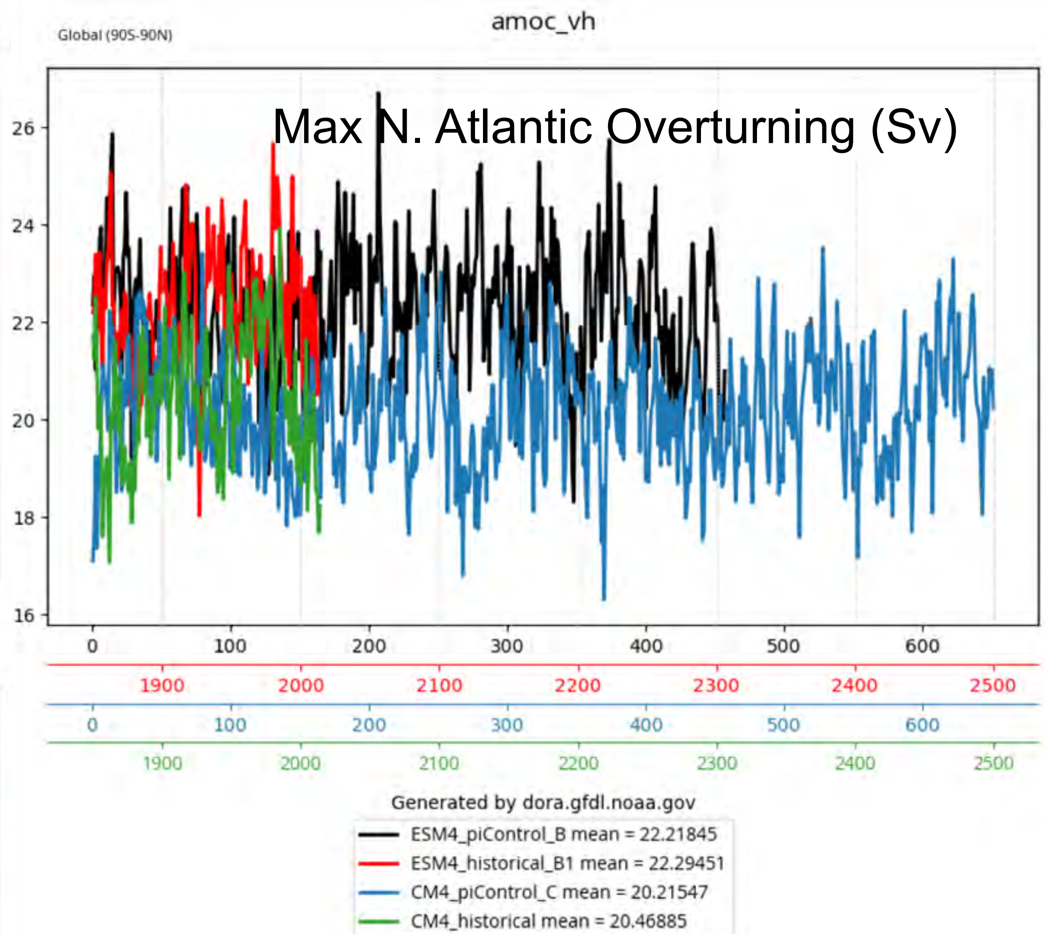


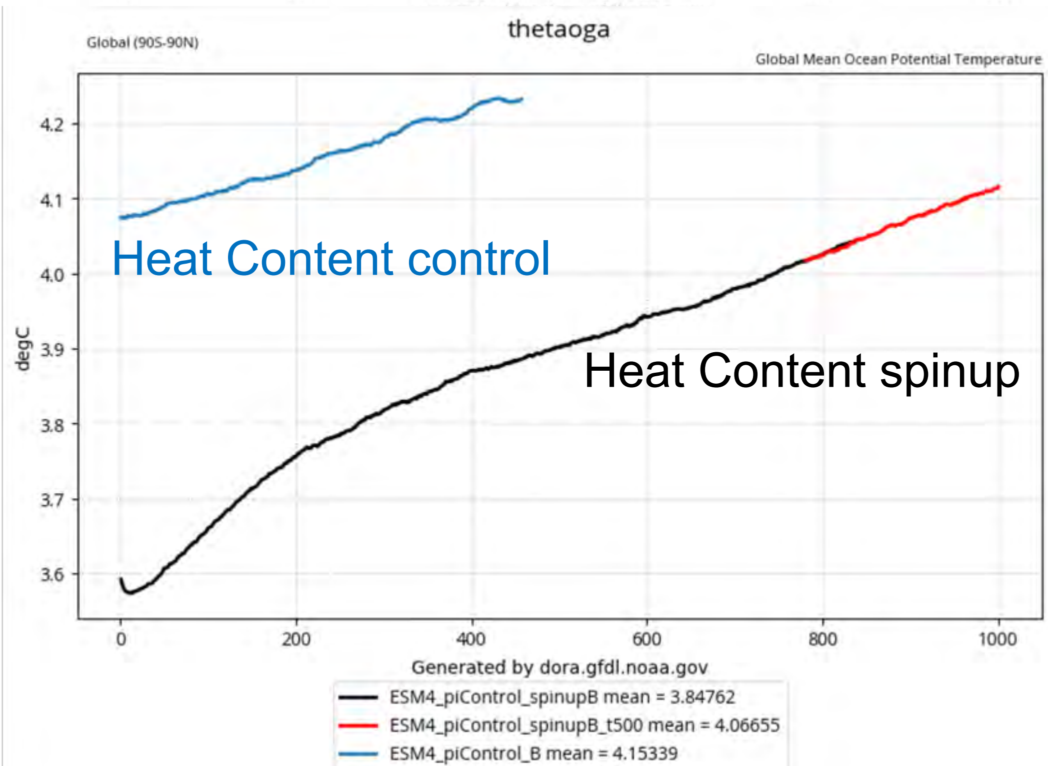
Lingering Concern for ESM4.1during the spinup

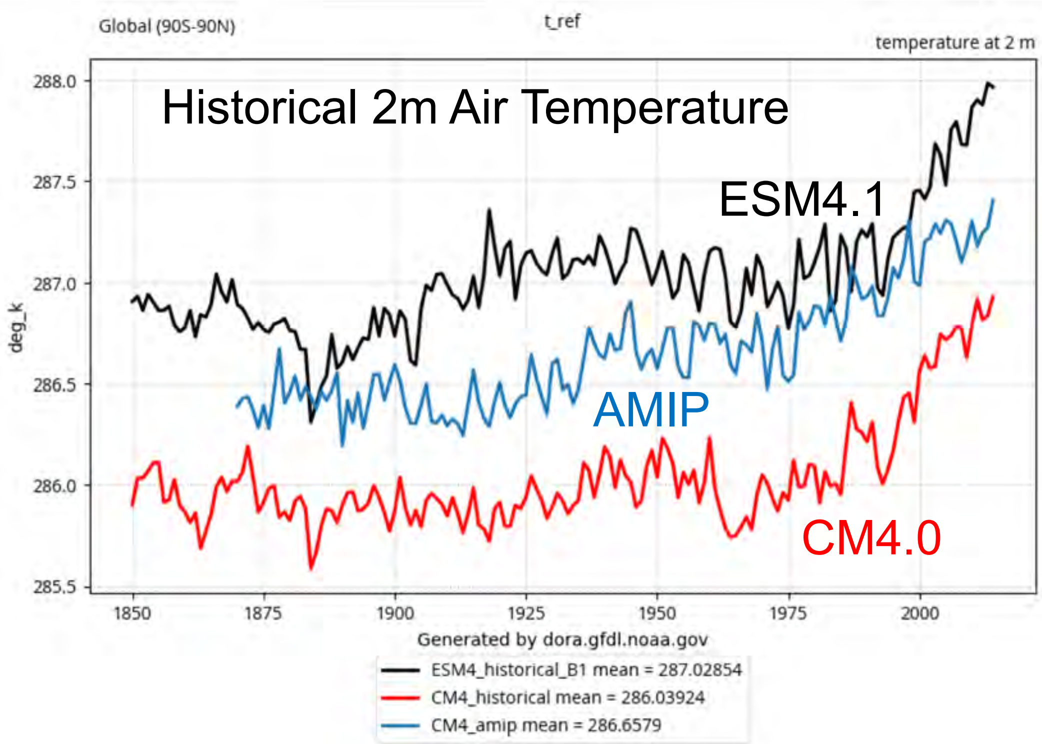


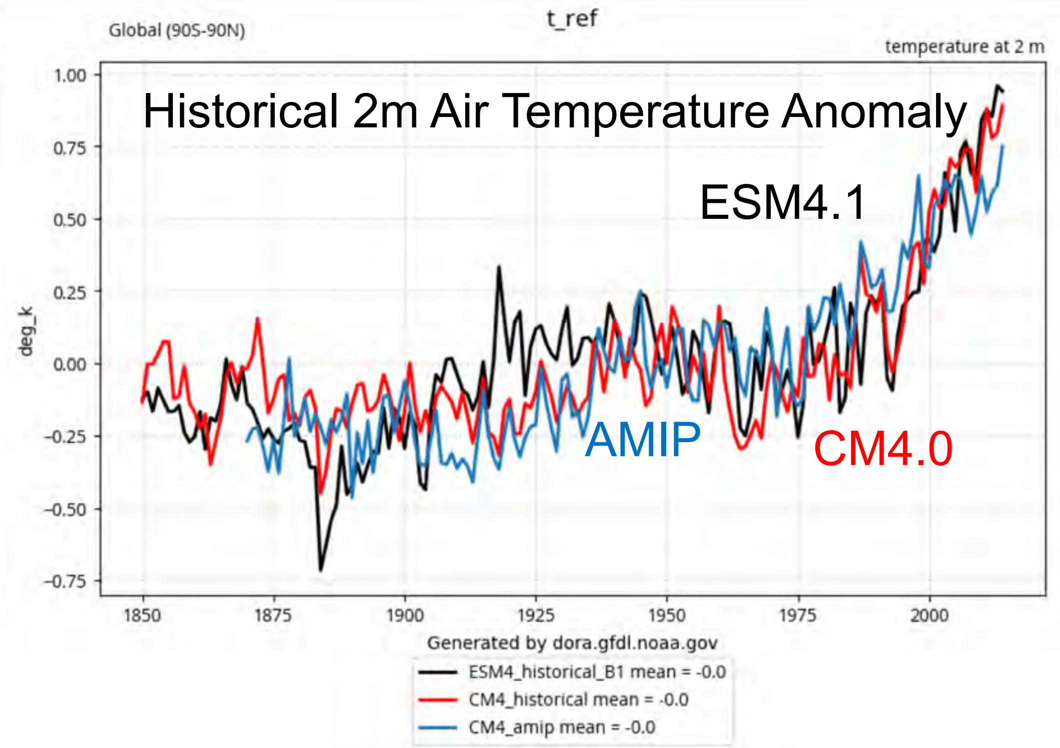
ESM4.1 Spinup

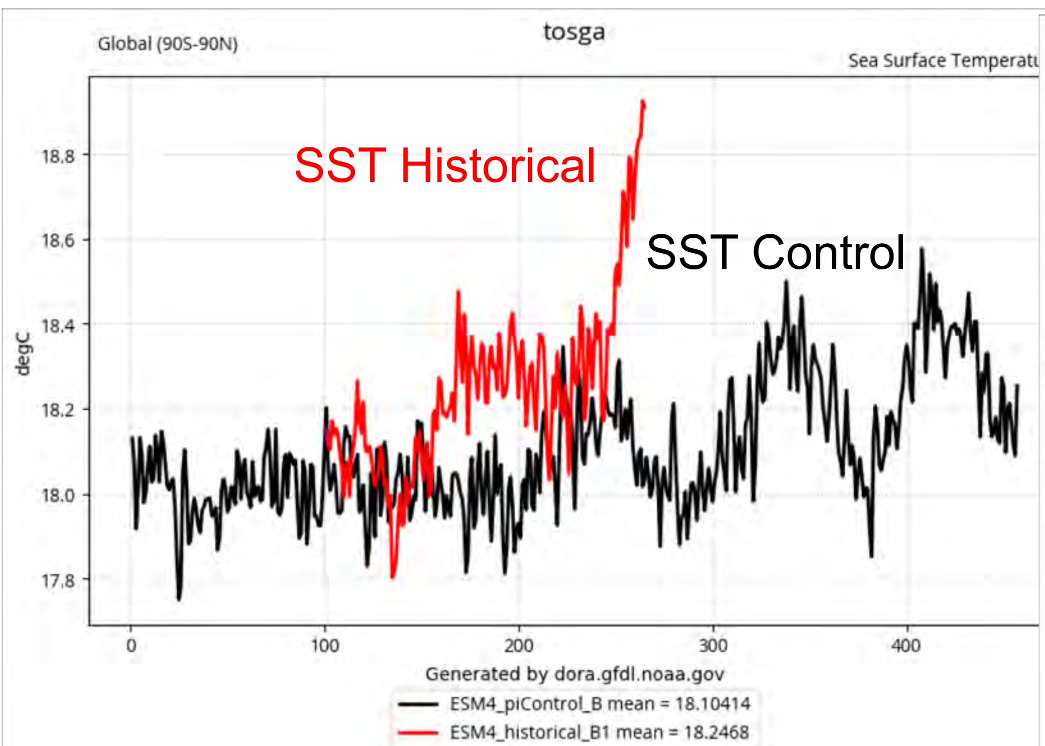


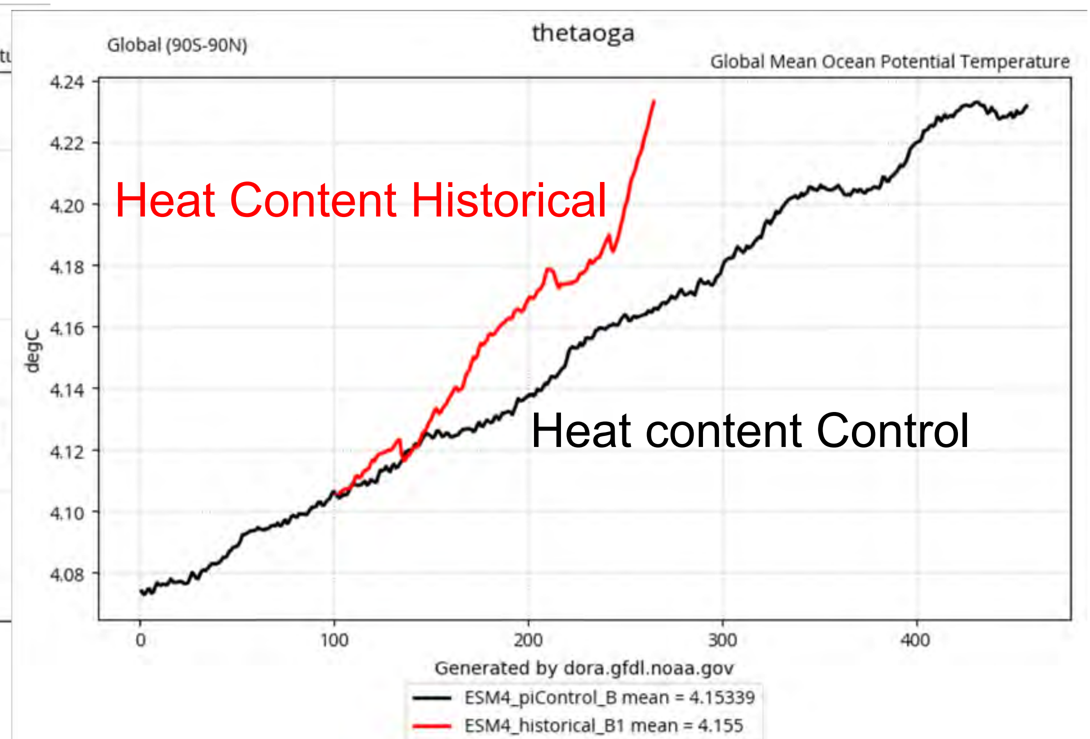




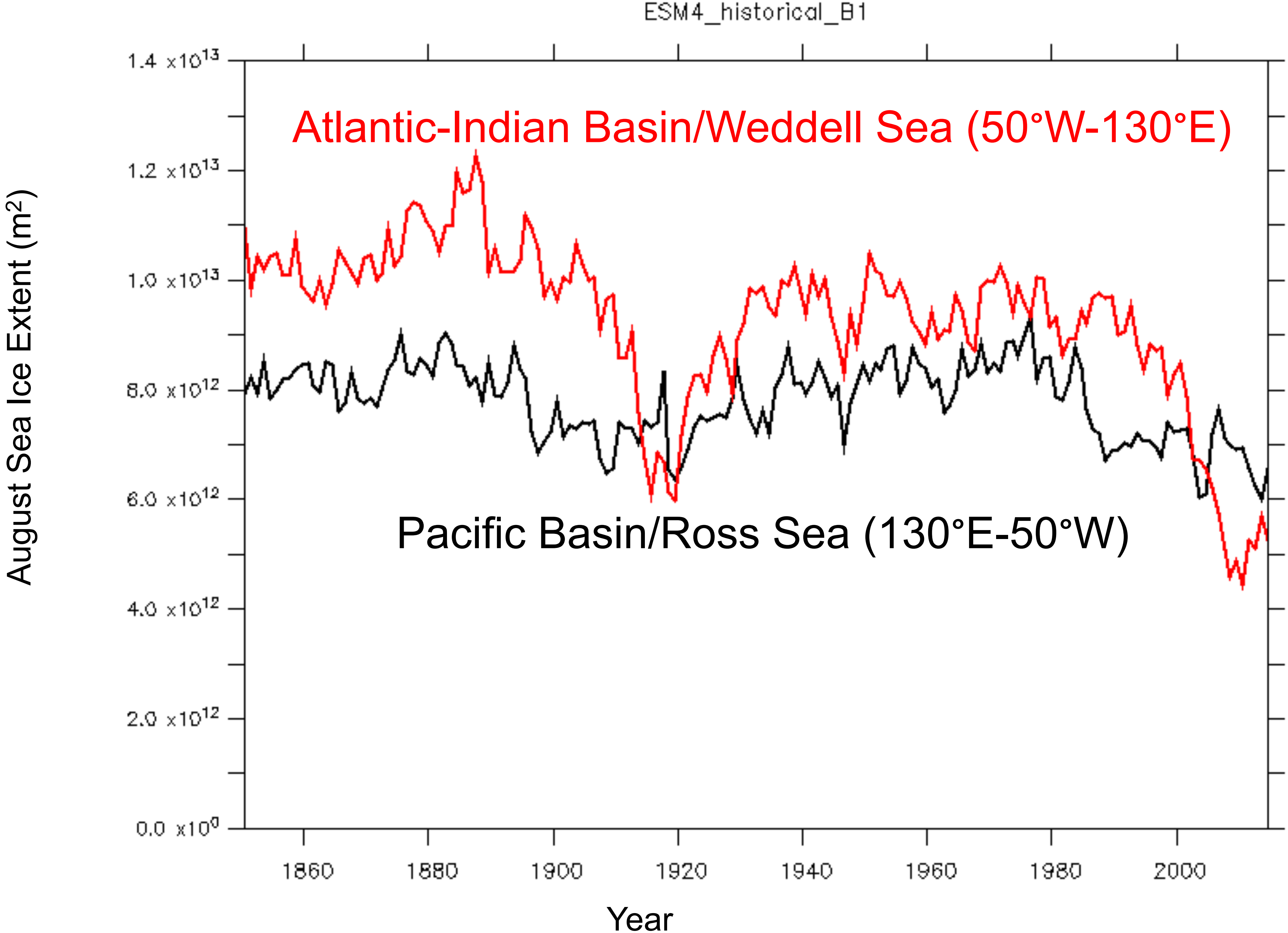

Global (90S-90N)
t_ref
temperature at 2 m
Historical 2m Air Temperature
ESM4.1
AMIP
CM4.0
deg_k
Generated by dora.gfdl.noaa.gov
ESM4_historical_B1 mean = 287.02854
CM4_historical mean = 286.03924
CM4_amip mean = 286.6579

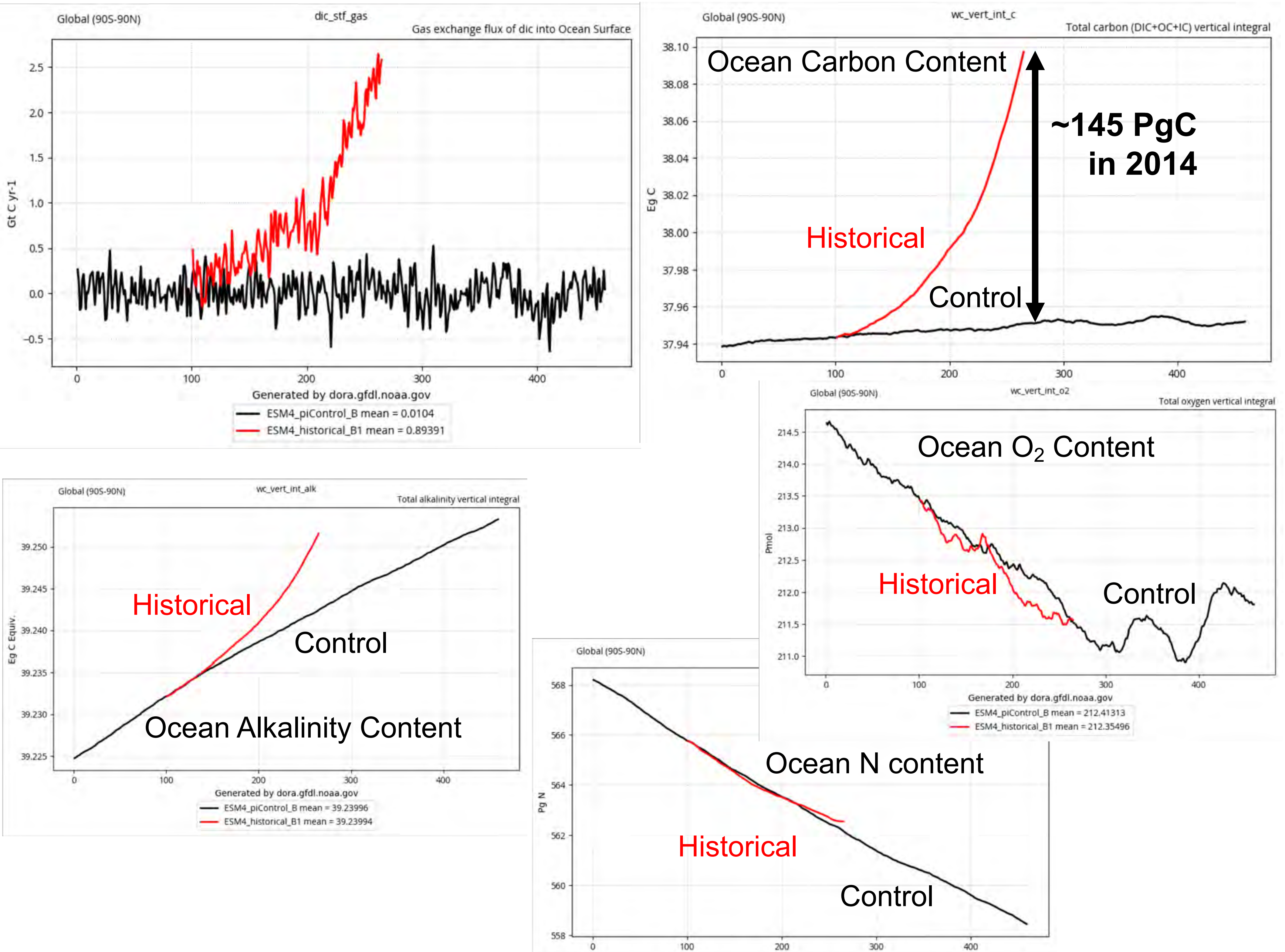

Global (90S-90N)
t_ref
temperature at 2 m
Historical 2m Air Temperature Anomaly
ESM4.1
AMIP
CM4.0
deg_k
Generated by dora.gfdl.noaa.gov
ESM4_historical_B1 mean = -0.0
CM4_historical mean = -0.0
CM4_amip mean = -0.0


Global (90S-90N)
tosga
Sea Surface Temperatu
SST Historical
SST Control
degC
Generated by dora.gfdl.noaa.gov
ESM4_piControl_B mean = 18.10414
ESM4_historical_B1 mean = 18.2468


Global (90S-90N)
thetaoga
Global Mean Ocean Potential Temperature
Heat Content Historical
Heat content Control
degC
Generated by dora.gfdl.noaa.gov
ESM4_piControl_B mean = 4.15339
ESM4_historical_B1 mean = 4.155

Let the Buyer Beware – super Polyna in Historical annual maximum sea ice extent




Global (90S-90N)
dic_stf_gas
Gas exchange flux of dic into Ocean Surface
Gt C yr-1
Generated by dora.gfdl.noaa.gov
ESM4_piControl_B mean = 0.0104
ESM4_historical_B1 mean = 0.89391
Global (90S-90N)
wc_vert_int_c
Total carbon (DIC+OC+IC) vertical integral
Eg C
Ocean Carbon Content
~145 PgC
in 2014
Historical
Control
Global (90S-90N)
wc_vert_int_o2
Total oxygen vertical integral
Pmol
Ocean O_2 Content
Historical
Control
Generated by dora.gfdl.noaa.gov
ESM4_piControl_B mean = 212.41313
ESM4_historical_B1 mean = 212.35496
Global (90S-90N)
wc_vert_int_alk
Total alkalinity vertical integral
Eg C Equiv.
Historical
Control
Ocean Alkalinity Content
Generated by dora.gfdl.noaa.gov
ESM4_piControl_B mean = 39.23996
ESM4_historical_B1 mean = 39.23994
Global (90S-90N)
Pg N
Ocean N content
Historical
Control

GFDL Physical Climate update Summary for CMIP6

- AM4 includes improved resolution (100km, 33/49 layers), moist convection, mountain gravity wave drag, etc., and predicts aerosols from emissions with either full (ESM4) or light (CM4) chemistry.
- OM4 includes C-grid hybrid coordinate ocean with scale-depended physics and other numerical improvments
- CM4/ESM4 combine strengths of GFDL's CMIP5 models into two, related models based on the same code with differing emphasis on resolution and complexity.
- CM4's simulates very good surface climatology and ENSO variability.
- CM4 has drift but the drift is reduced relative to a previous GFDL model of comparable resolution.
- CM4 produces historical simulations of global temperature broadly consistent with observations.

GFDL Earth System Update Summary for CMIP6

- New Interactive atmospheric chemistry from CM3 including improved Nitrogen, SO_4, and BVOC interactions
- Interactive Dust/iron and NH_3
- COBALT Ocean biogeochemistry for explicit treatment of zooplankton biodiversity and other improvements… full fidelity assessment awaits
- Beware Heat Content Drift – It's about half the historical signal.
- Beware the Superpolyna! Become disturbingly strong after 1100 years. We will need to run a historical before the polyna begin and conduct many ensemble members to damp out polyna variability
- Beware unequilibrated elemental cycles! – Air Sea CO_2 Flux is well in equilibrium, but open oxygen, nitrogen and alkalinity cycles are still adrift larger than the forced signal.
- Scenario simulations beginning soon… hopeing for data availability by June, 2019