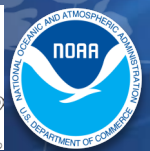
Ocean bias correction in coupled model predictions: ocean tendency adjustment based on data assimilation and machine learning

Feiyu Lu

Collaborators:
GFDL SD-Division, GFDL O-Division, M2LInES

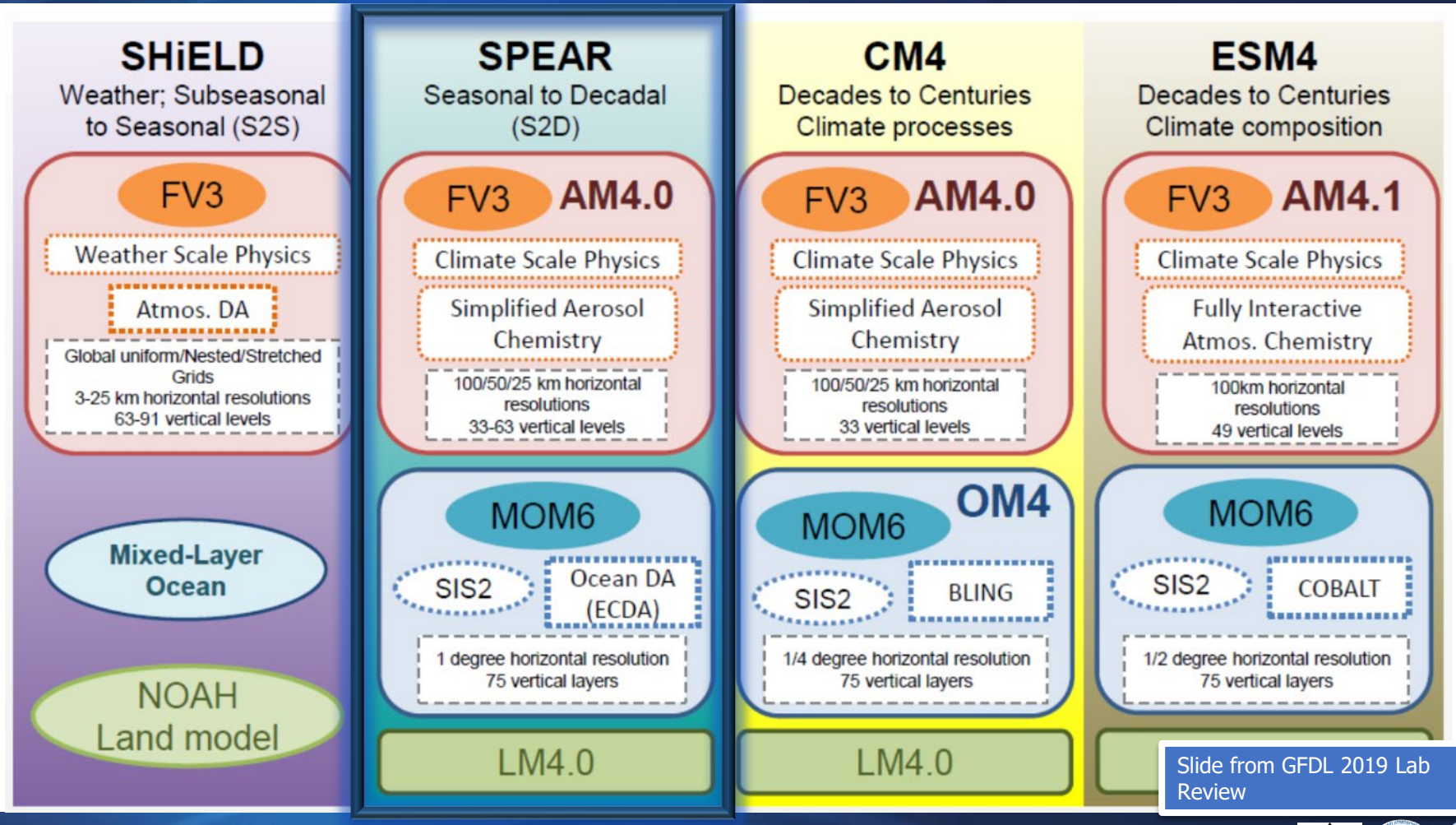



6th WGNE workshop on systematic errors in weather and climate models, Nov 2022

Outline

- Design of SPEAR prediction system
  - Ocean Data Assimilation
  - Coupled model initialization
- Ocean bias correction in seasonal predictions
  - Ocean Tendency Adjustment (OTA)
  - Improvements and pitfalls
- Augment OTA with machine learning

SPEAR Component Models



Slide from GFDL 2019 Lab Review

GFDL SPEAR Activities

- SPEAR large ensemble simulations
  - 30-member ensembles over the period 1921-2100 (Historical + SSP585)
  - https://www.gfdl.noaa.gov/spear_large_ensembles/
- S2S (subseasonal to seasonal) prediction
  - Xiang et al. (2021): S2S Prediction in GFDL SPEAR: MJO diversity and teleconnections
- Decadal predictions
  - Yang et al. (2021): On the Development of GFDL's Decadal Prediction System: Initialization Approaches and Retrospective Forecast Assessment
- Sea ice assimilation and initialization
  - Bushuk et al. (2021): Seasonal prediction and predictability of regional Antarctic sea ice. Journal of Climate)
  - Bushuk et al. (2022): Mechanisms of Regional Arctic Sea ice predictability in two dynamical seasonal forecast systems

How are seasonal predictions initialized?

- Coupled data assimilation system
  - First-guess forecast fields are generated with coupled model, but analysis is done in individual component models (weakly coupled)
  - Examples: GFDL CM2.1 ECDA and CFSv2
- Uncoupled (component) data assimilation systems
  - Both forecast and analysis are done in individual component models with observed/analyzed forcing from other components
  - Examples: ECMWF (SEAS5, Johnson et al. 2019), Met Office (GloSea5, MacLachlan et al. 2015)
  - SEAS5:
    - Historical: ERA-Interim + ORAS5 (forced by ERA-Interim)
    - Real-time: NWP analysis + OCEAN5 (forced by operational analysis/forecast)

SPEAR Seasonal Prediction Initialization

- SPEAR prediction uses uncoupled initialization with a twist
- Ocean: SPEAR_ODA analysis (free atmosphere)
  - Provides OTA increments (climatological ODA increments during Argo period)
  - OTA can be applied to coupled prediction because of the free atmosphere
- Atmosphere/Land/Sea Ice: atmos/SST nudging in same coupled SPEAR models
  - Atmosphere T/U/V/q nudged to 6-hourly CFSR
  - SST nudged to same SST data used by SPEAR_ODA

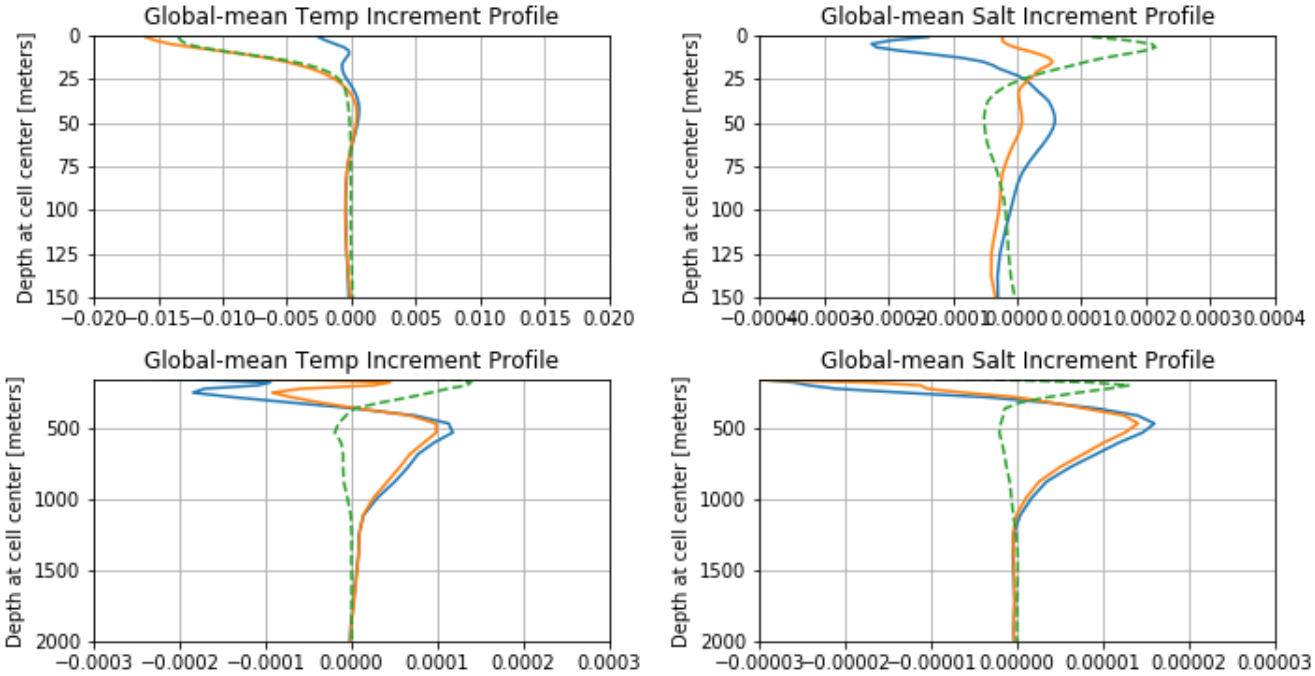
MOM6 Ocean Data Assimilation

- SPEAR_ODA ocean analysis is produced with a free running atmosphere in the coupled SPEAR_LO model.
  - Atmosphere component is only constrained by SST (AMIP-like)

Global-mean ODA increments

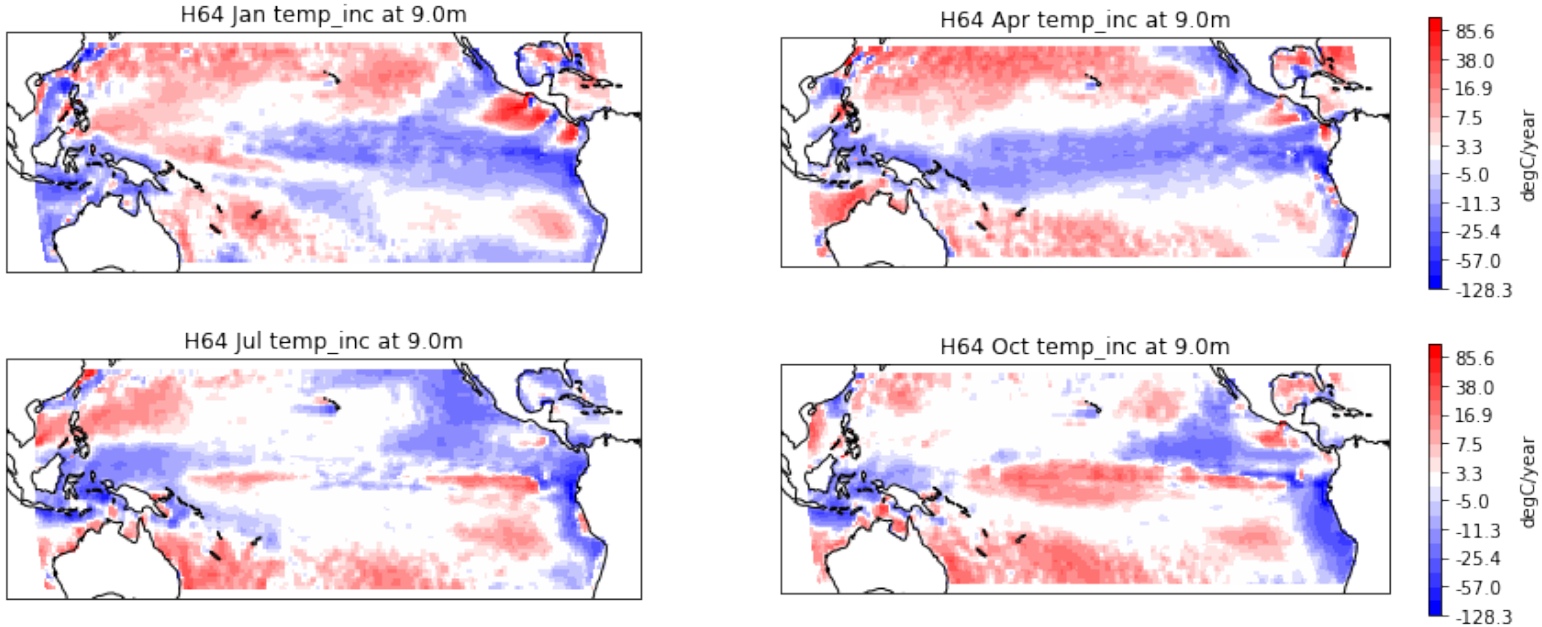
Free atmosphere

Nudged atmosphere



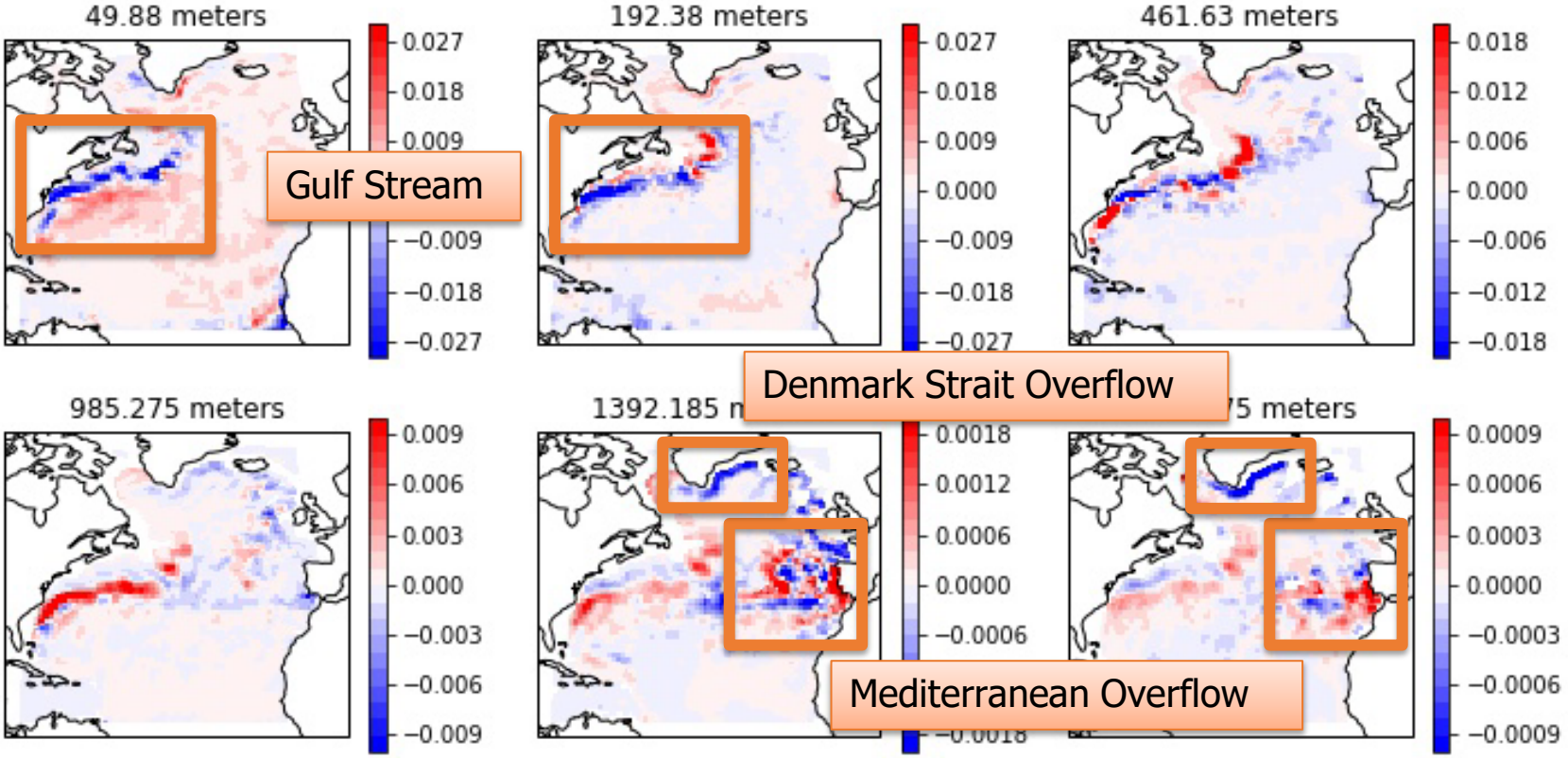
OTA (Ocean Tendency Adjustment)

- Idea: use DA increments for bias correction
- How: apply climatological (annual-cycle) temperature and salinity increments from 2007-2018 based on ARGO and SST to forecast model
- What's new: **OTA can be applied to coupled model forecast or control simulations**

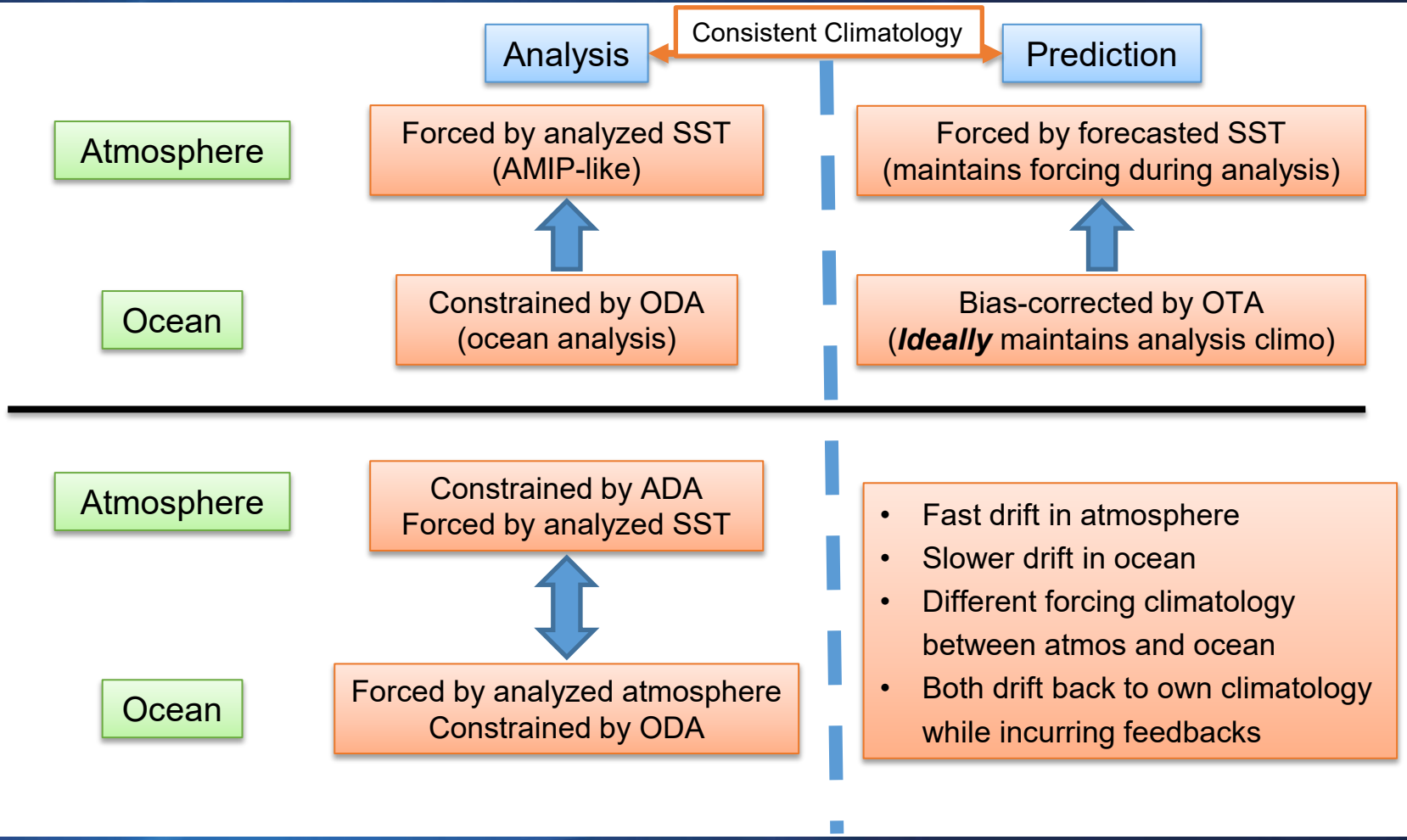


What are the increments like?

Temperature increments in North Atlantic



Consistency from analysis to prediction

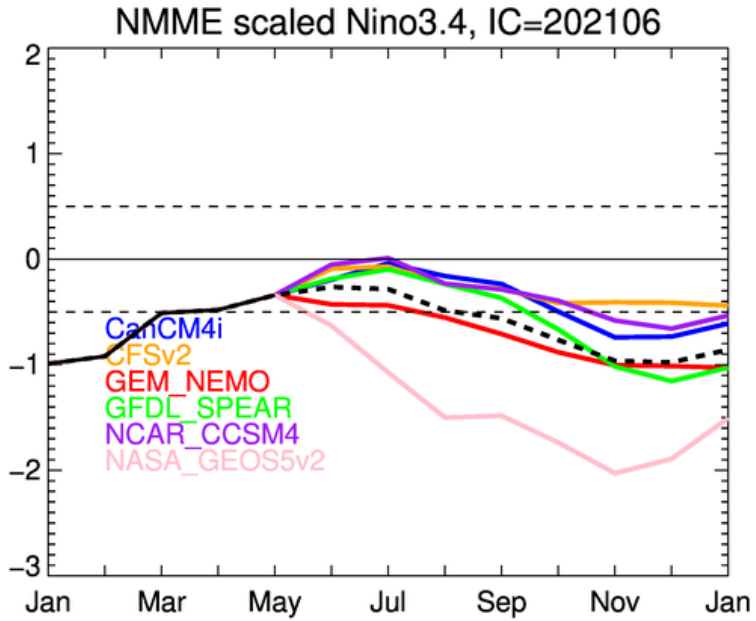


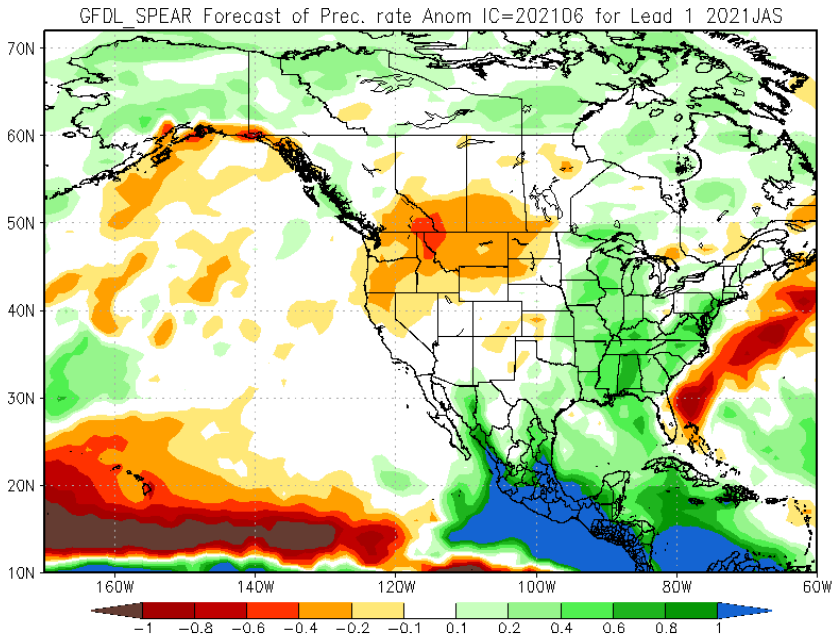
Why add atmosphere nudging then?

- Sea ice
  - Sea ice thickness is critical for sea ice extent prediction
  - Without sea ice thickness or subsurface in-situ observations, atmosphere forcing is important to constrain sea ice thickness
- Land
  - Memory for subseasonal-to-seasonal prediction, e.g. hydrology over land
- Stratosphere
  - Potential seasonal predictability from stratosphere, e.g. sudden warming
- Complications
  - Inconsistency of forcing on the ocean for initial weeks of forecast
  - Ocean and sea ice compatibility (used same SST for ODA and nudging)

Seasonal forecasts

- Real-time SPEAR seasonal forecast joined NMME in 2021
  - 30-member SPEAR_MED (50-km atmosphere/land, 1-deg ocean/sea ice)





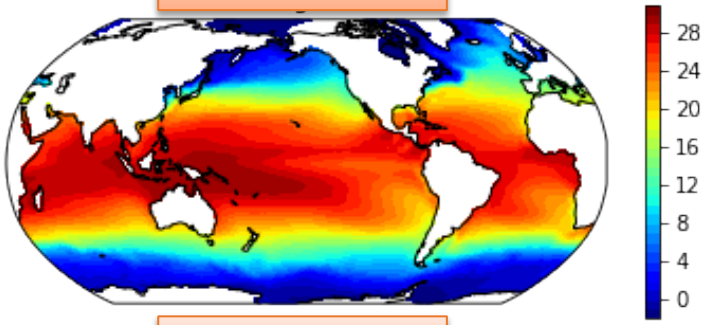
Model Bias and Prediction Skill

- OTA provides a unique tool to test the impact of model bias on predictions
- SPEAR_LO (100-km atmos/land, 1-deg ocean/sea ice) for development
- SPEAR seasonal reforecasts (15 members, 4/year, 1992-2018):
  - **RF_MED**: NMME configurations
  - **RF_LO_1**: same as RF_MED, but with SPEAR_LO model
  - **RF_LO_2**: RF_LO_1 without OTA
- SPEAR climate ensemble simulations:
  - **SPEAR_LO**: PI control (5000 years+), 1851-2100 (30 members)
  - **SPEAR_LO_OTA**: PI control (500 years), 1851-2100 (5 members)

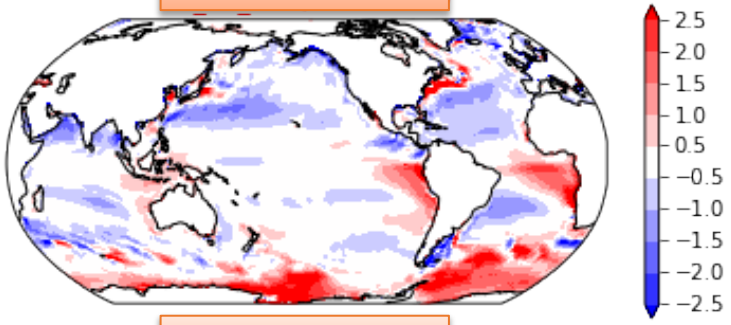
Model SST Prediction Drift

January SST prediction bias from **July** forecasts

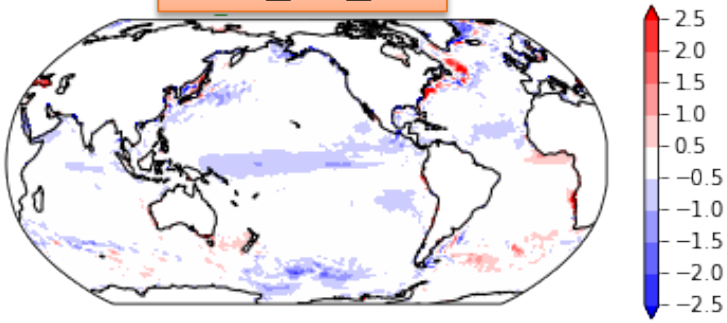
OI SST



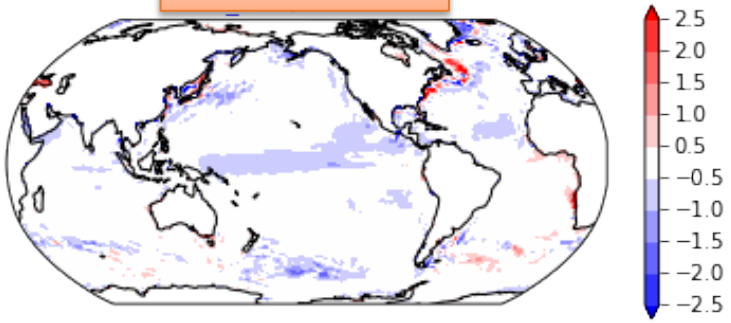
RF_LO_2



RF_LO_1

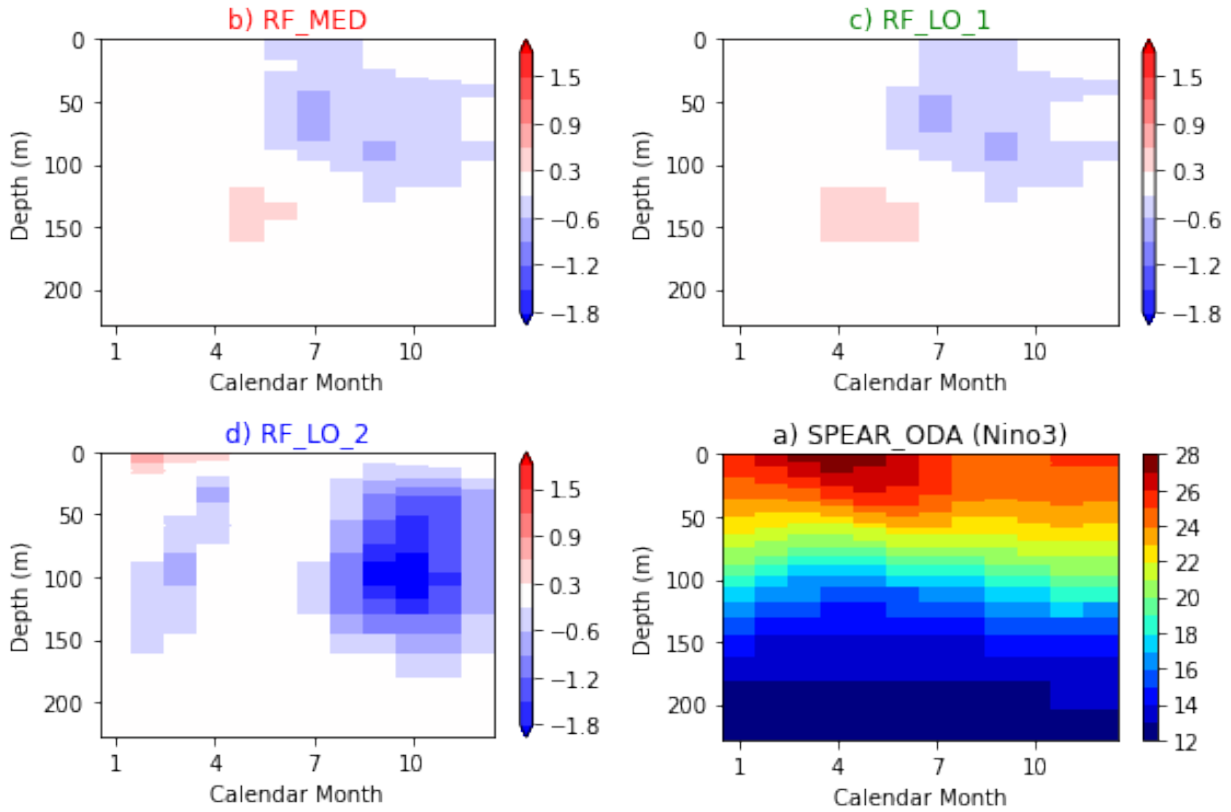


RF_MED

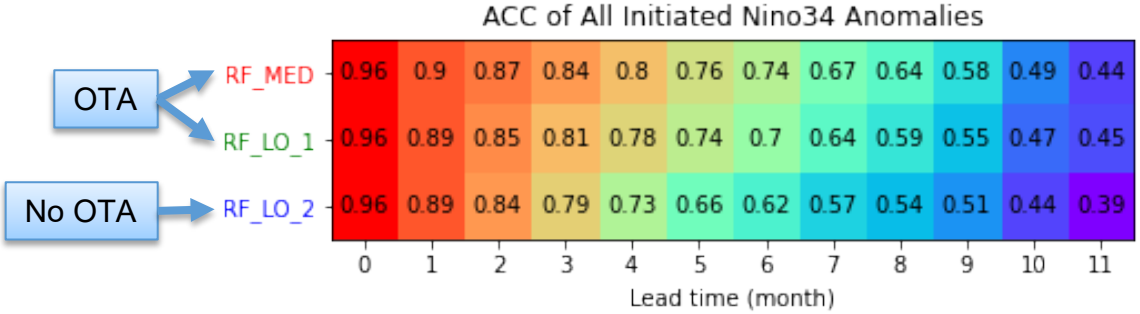


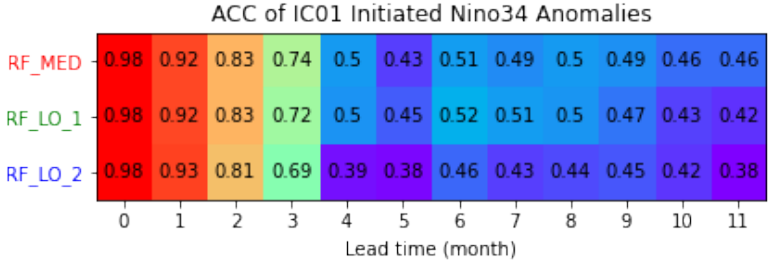
Climatological Ocean T Prediction Drift

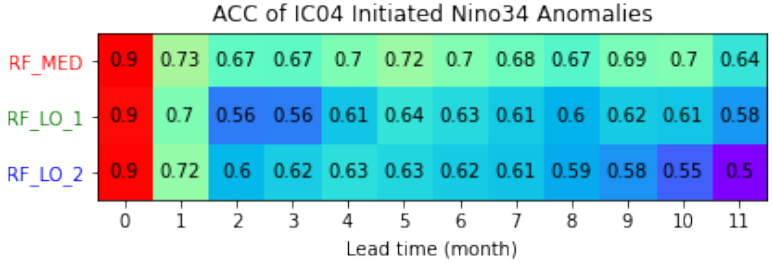
Ocean temperature (Nino3 region) drift from January-initiated reforecasts

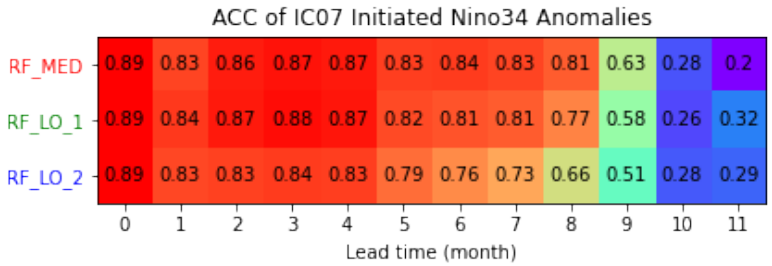


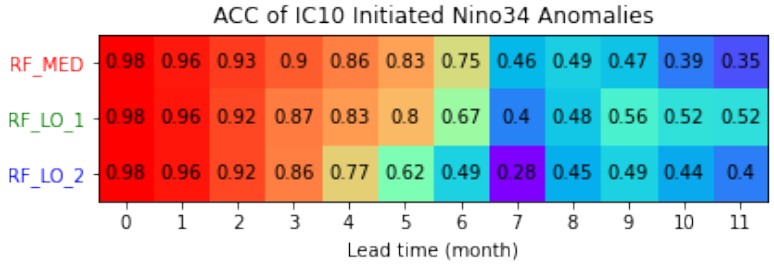
Ensemble-mean Nino3.4 Skills









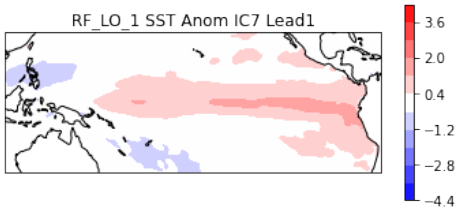


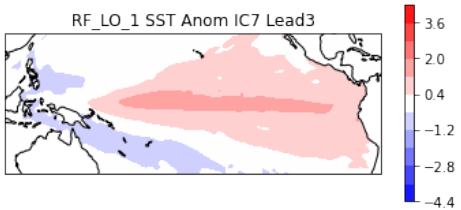
El Niño Composite SST Anomalies

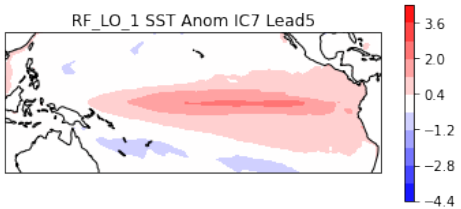
July-initiated forecasts for El Niño years (1994, 1997, 2002, 2006, 2009, 2015)

Composite SST anomalies for August, October and December

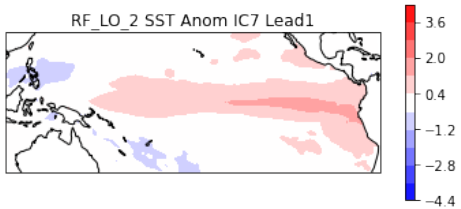
RF_LO_1

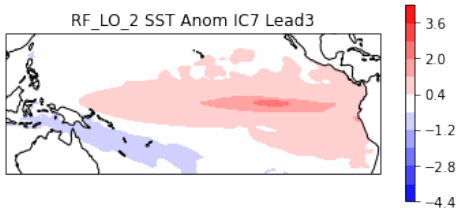


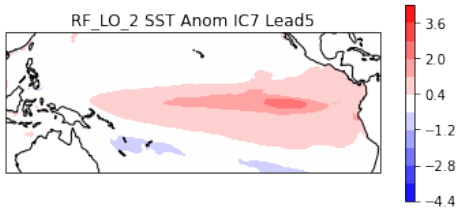




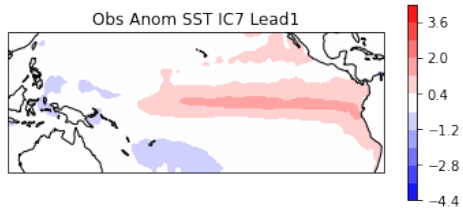
RF_LO_2

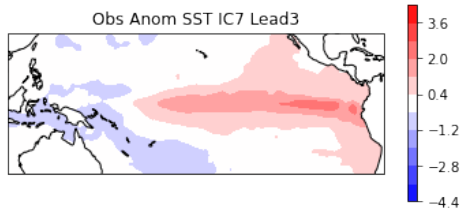


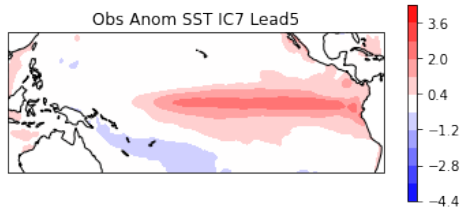




OI SST

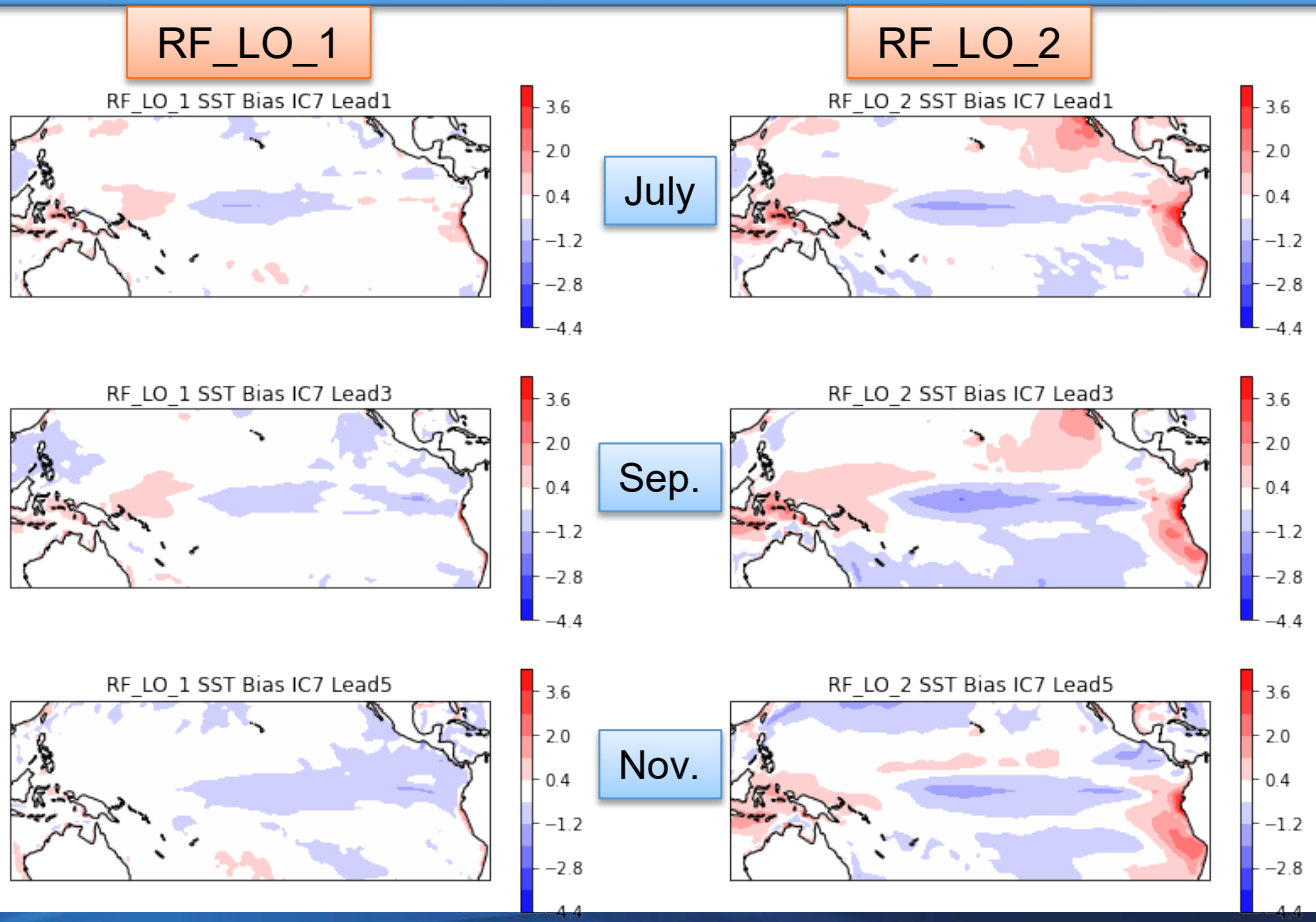






SST prediction bias

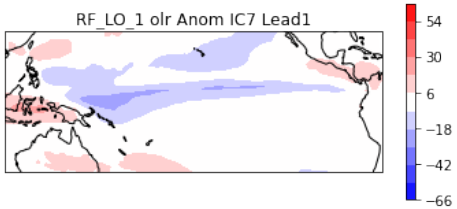
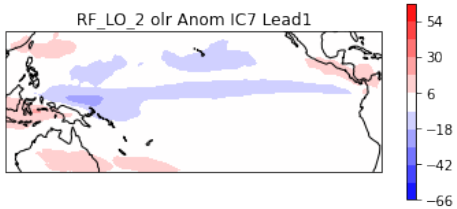
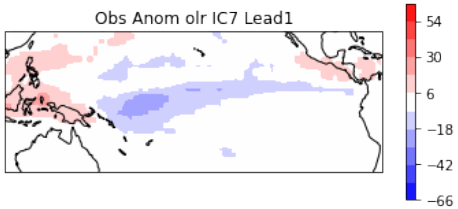
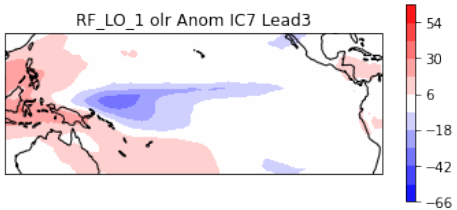
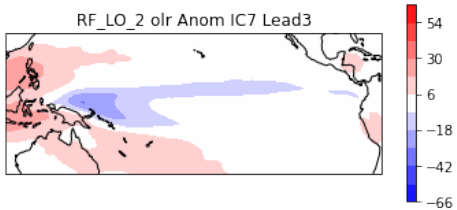
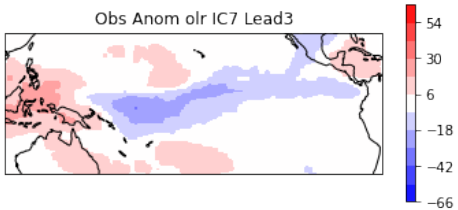
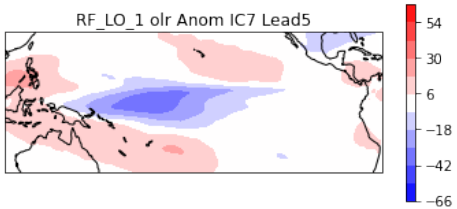
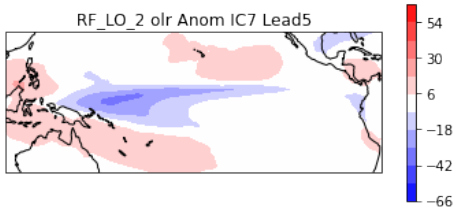
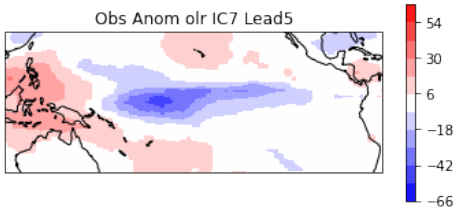
July-initiated forecasts for El Niño years (1994, 1997, 2002, 2006, 2009, 2015)



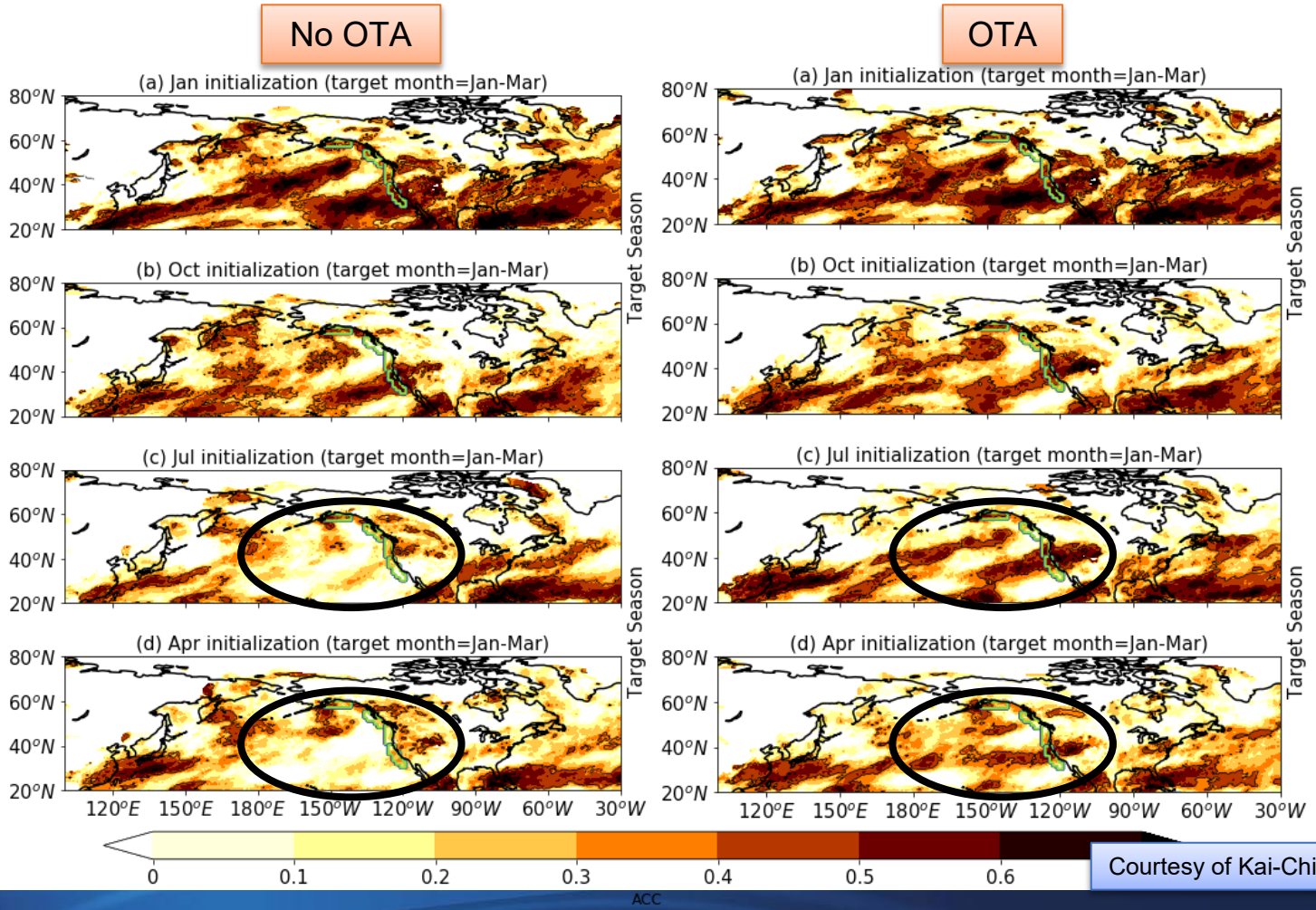
OLR prediction anomalies

July-initiated forecasts for El Niño years (1994, 1997, 2002, 2006, 2009, 2015)

Composite OLR anomalies for August, October and December

RF_LO_1	RF_LO_2	Obs
		
		
		

Seasonal Prediction of Atmospheric River



Courtesy of Kai-Chih Tseng

AR Climatology & OTA

The bias in AR frequency averaged over all forecast lead times

OTA reduces AR forecast bias over the oceans and eastern Canada

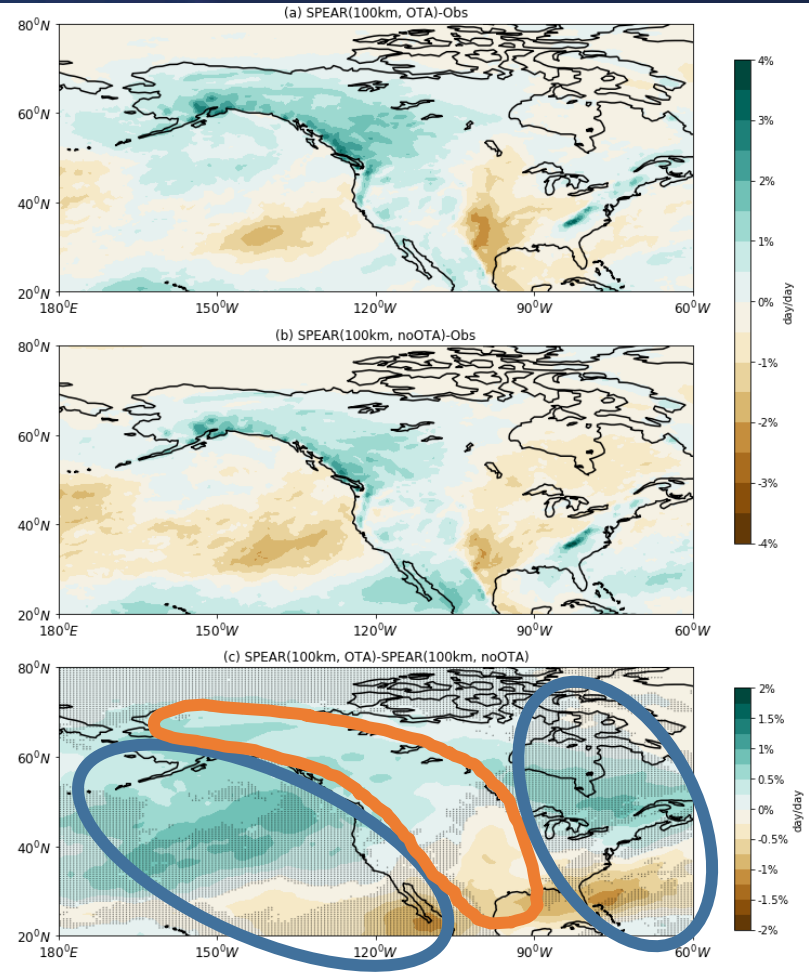
OTA increases AR forecast bias over Alaska, western Canada and US by revealing **compensating biases** between

- **Low AR frequency from Pacific**
- **Easier AR penetration inland due to coarse-resolution topography**

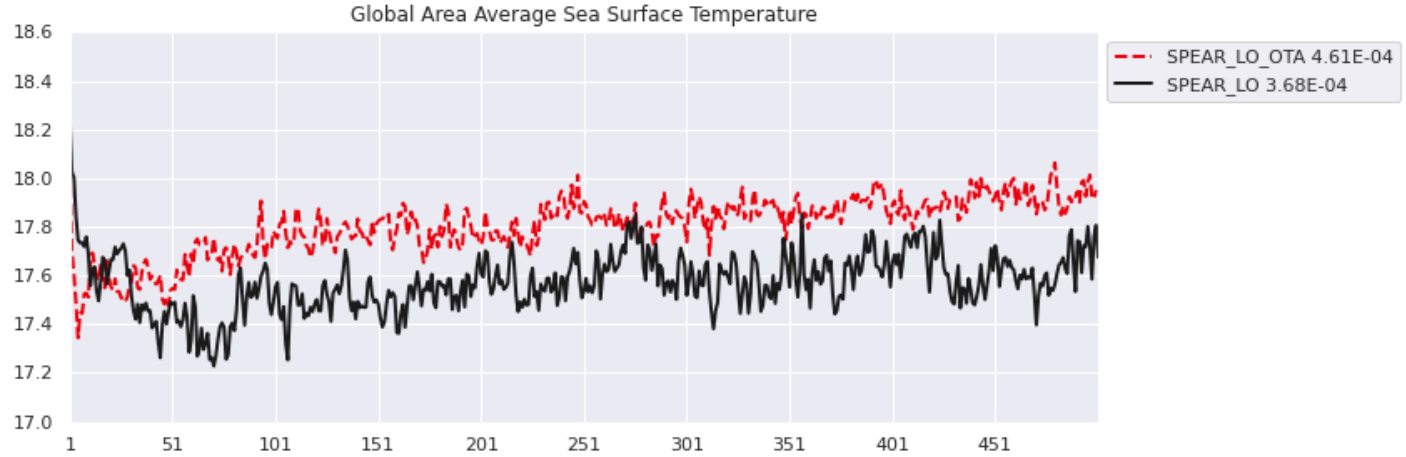
OTA

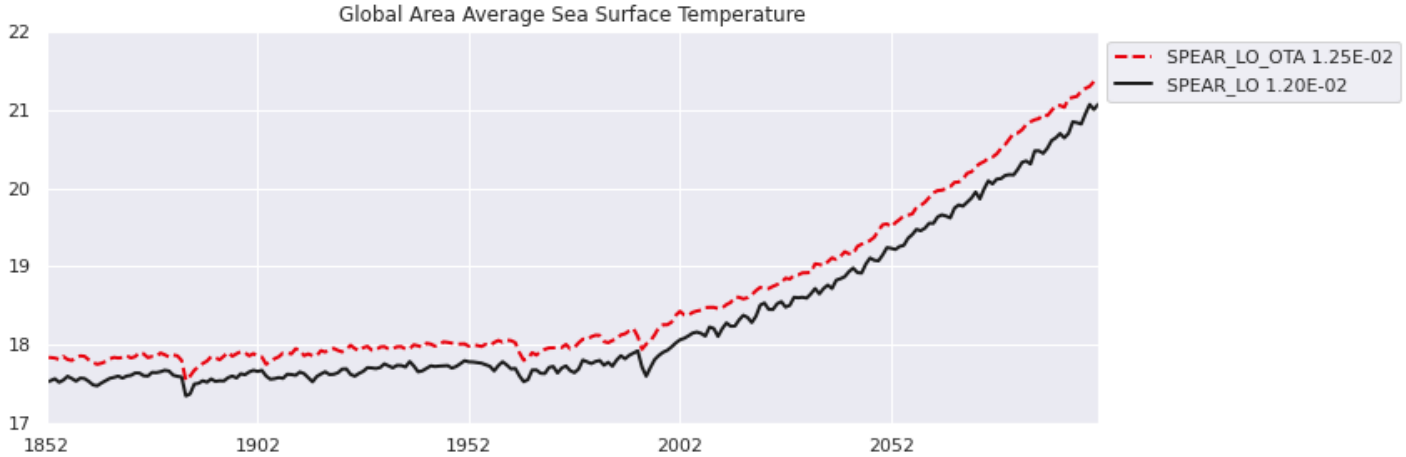
No OTA

OTA – No OTA



SPEAR OTA Climate Simulations



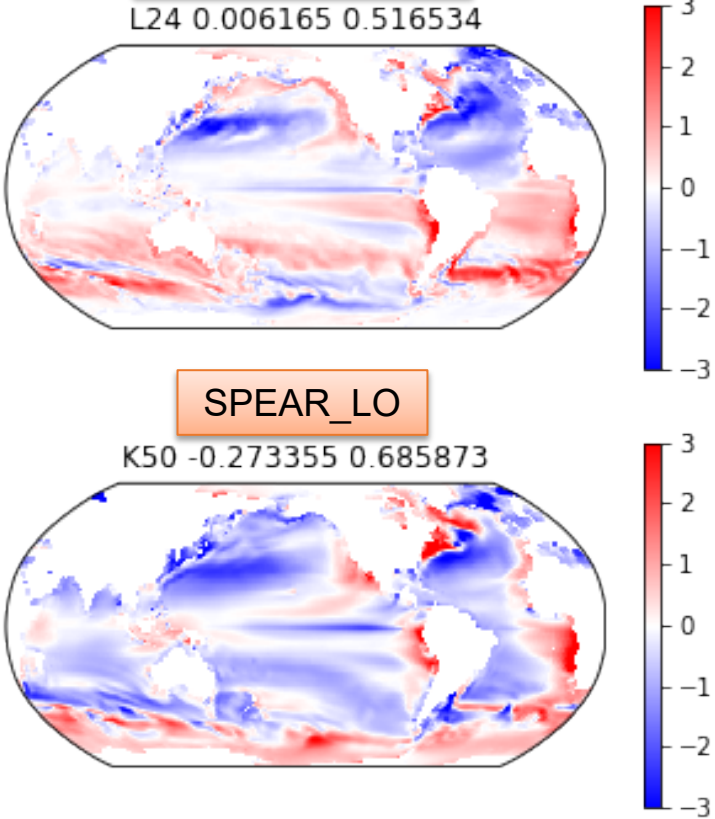


SPEAR OTA Climate Simulations

1921-2020 SST Climatology

SPEAR_LO_OTA

L24 0.006165 0.516534



SPEAR_LO

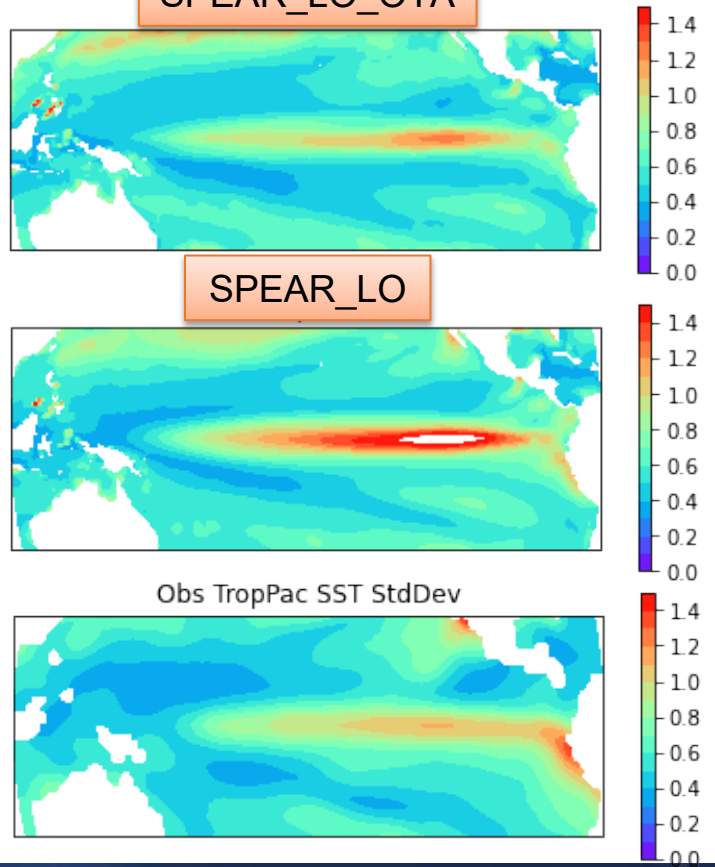
K50 -0.273355 0.685873

1921-2020 Tropical SST Anomaly StdDev

SPEAR_LO_OTA

SPEAR_LO

Obs TropPac SST StdDev

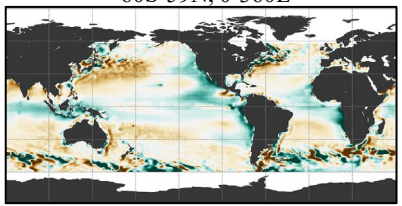


OTA and Machine Learning (M2LInES)

- Issues about current OTA implementation
  - Insufficient Argo coverage spatially/temporally
  - Stationary increments
  - Mixture of all bias sources
- Enhance OTA with machine learning
  - OTA increments (lat,lon,time of year) -> (ocean state variables, surface fluxes)
- Goals of ML-OTA
  - Improved coupled model prediction and projection
  - Connection with ML/AI efforts that learn ocean parameterization from high-res simulations

- ✓ **Goal:** Learn state-dependent local model (or a parameterization) of systematic ocean data assimilation increments.
- ✓ **Output:** daily climatology of temperature increments
- ✓ **Inputs:** daily [T], [T_z], [T_zU_z], [T_zV_z], [$T_zU_zV_z$]

60S-59N, 0-360E



- ✓ near-global domain
- ✓ sub-sampled to 3^o horizontally
- ✓ coarsened to 19 levels in vertical
- ✓ sub-sampled every 3rd day

- ✓ Using **GFDL SPEAR DA system** which assimilates SST, ARGO observations
- ✓ 2004-2021

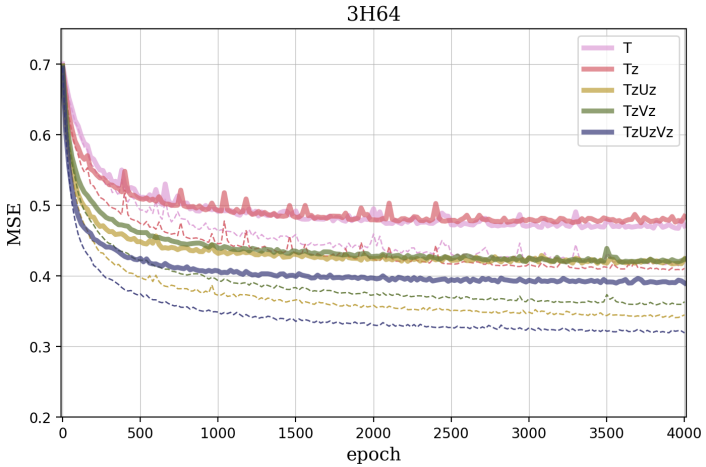
Train | Test
2010-2019 | 2020-21

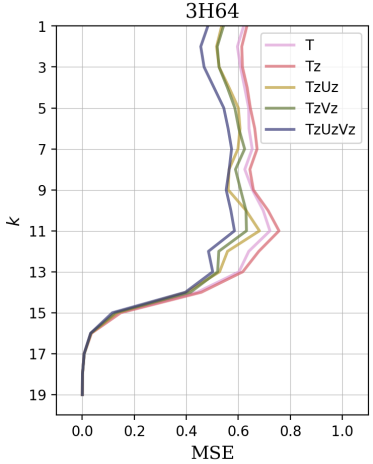
Courtesy of Tarun Verma

Learning Curves

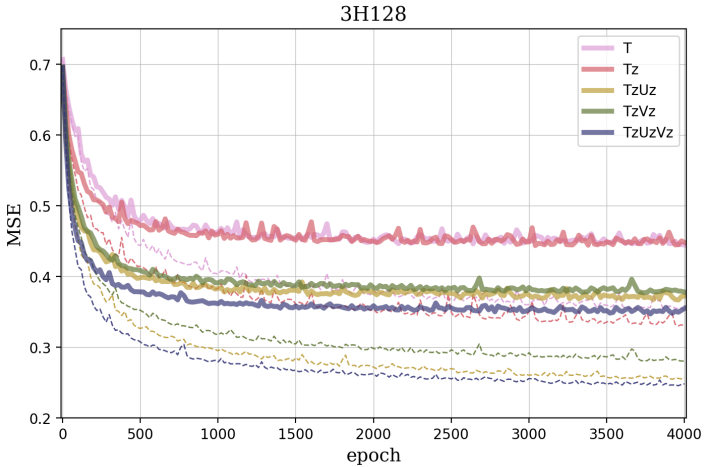
Test Vertical MSE (epoch = 4000)

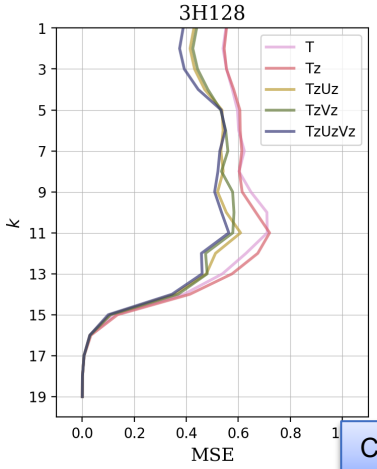
3H64





3H128

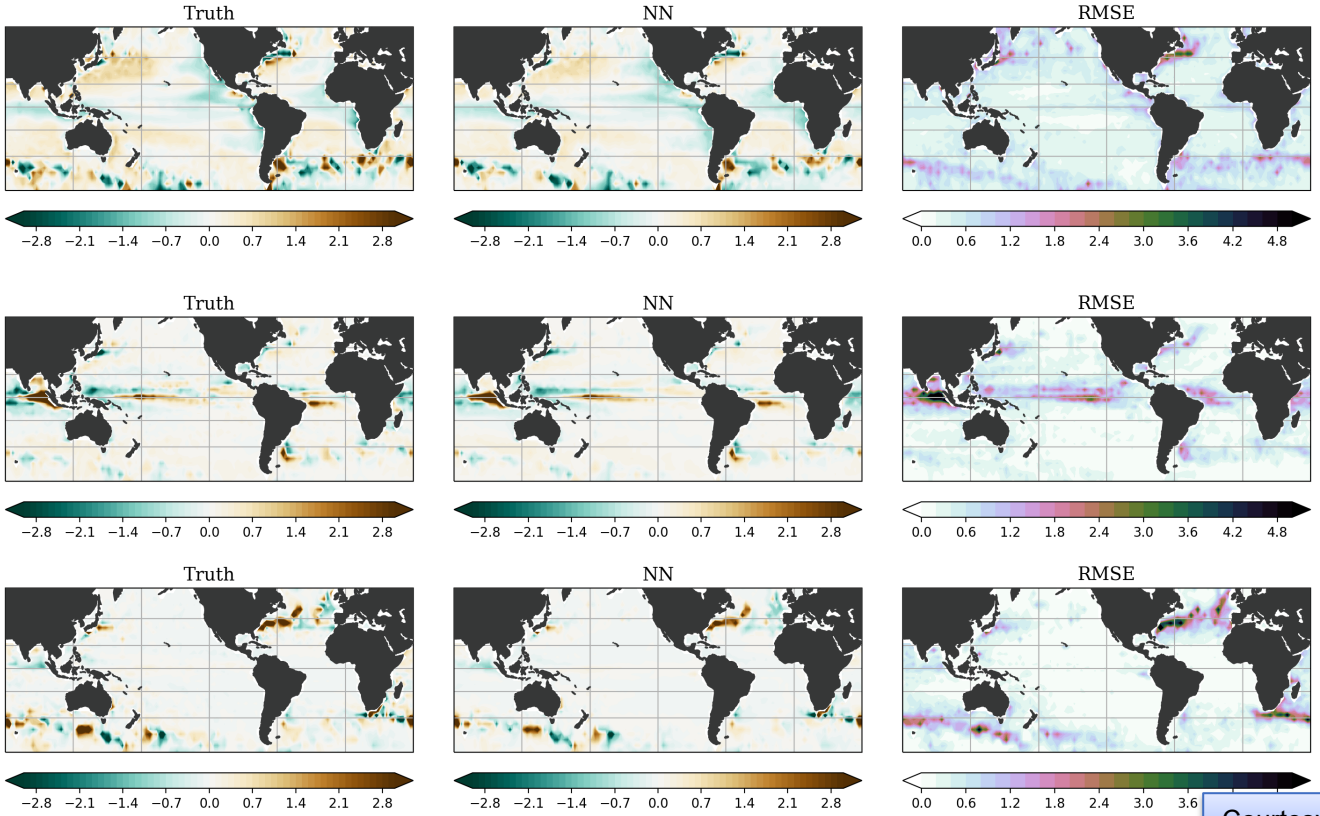




Courtesy of Tarun Verma

2020-21 Predictions (normalized)

using 3h128_$T_zU_zV_z$ (with L2; epoch=4000)



Courtesy of Tarun Verma

Thank you for your attention!
Questions?