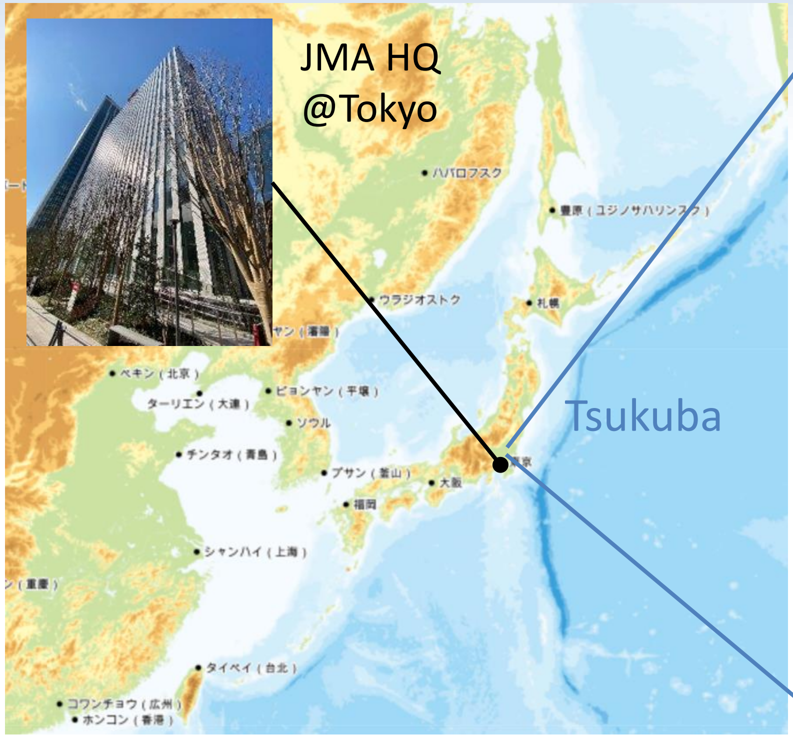
Ocean Initialization of the Coupled Prediction System Version 3 (CPS3) for Seasonal Forecasts

YOSHIDA Takuma[1,2], SUGIMOTO Hiroyuki[3,1,2], KUBO Yutaro[1,2], HIRAHARA Shoji[2], TAKAKURA Toshinari[1,2], KOMORI Takuya[1,2], CHIBA Jotaro[1], KANEHAMA Takafumi[1,2], SEKIGUCHI Ryohei[1], OCHI Kenta[4,1], FUJII Yosuke[2,1], ADACHI Yukimasa[2,1], and ISHIKAWA Ichiro[2]

1) Numerical Prediction Development Center, Japan Meteorological Agency
2) Meteorological Research Institute, Japan Meteorological Agency
3) Climate Prediction Division, Japan Meteorological Agency
4) European Centre for Medium-Range Weather Forecasts

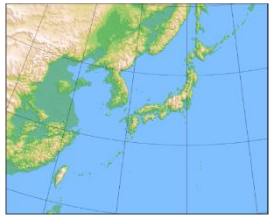
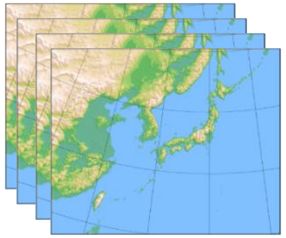
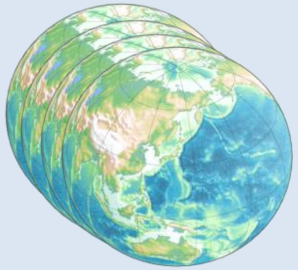
About NPDC, JMA (est. Oct. 2020)



Numerical Prediction Development Center (NPDC) and Meteorological Research Institute (MRI) on the same campus

Operational NWP models at JMA

as of July 2022

	Local Forecast Model (LFM)	Meso-scale Model (MSM)	Meso-scale EPS (MEPS)	Global Spectral Model (GSM)	Global EPS (GEPS)	Seasonal EPS (JMA/MRI-CPS3)
Domain						
Horizontal resolution	2 km	5 km	5 km	approx. 20 km	approx. 27 km（up to 18 days） approx. 40 km（up to 34 days）	Atmosphere: approx. 55 km Ocean: approx. 25 km
Forecast length (initial hours)	10 hours (every hour)	78 hours (00,12 UTC) 39 hours (03,06,09, 15,18,21 UTC)	39 hours (00,06,12,18 UTC)	264 hours (00,12 UTC) 132 hours (06,18 UTC)	5.5 days (06,18 UTC) 11 days (00 UTC) 18 days (12 UTC) 34 days (12 UTC on Tue. and Wed.)	7 months (00 UTC)
Ensemble size (per init)	1	1	21	1	51 (up to 18 days) 25 (up to 34 days, 50 with LAF)	5 (51 with LAF)
Main Products	Aviation Weather Forecasts and Warnings, Weather Warnings/Advisories, Precipitation Forecasts	Weather Warnings/Advisories, Precipitation Forecasts, Aviation Weather Forecasts and Warnings, Three-hourly Forecasts, Daily Forecasts	Weather Warnings/Advisories, Aviation Weather Forecasts and Warnings, Three-hourly Forecasts, Daily Forecasts	Typhoon Forecasts, Three-hourly Forecasts, Daily Forecasts, Aviation Weather Forecasts and Warnings	Typhoon Forecasts, One-week Forecasts, Early Warning Information on Extreme Weather, Two-week Temperature Forecasts, One-month Forecasts	Three-month Forecasts, Warm/Cold Season Forecasts, El Niño Outlook
Initial conditions	Hybrid 3D-Var	Atmosphere: 4D-Var Ocean: HIMSST+ Climatological Profile	Meso-scale Analysis + SV	Hybrid 4D-Var	Global Analysis + SV + LETKF	Atmosphere: Global Analysis＋BGM Ocean: MOVE-G3 + perturbations calculated using 4DVAR minimization history
Sea Surface Temperatures conditions	Fixed (HIMSST)	Fixed (HIMSST) + 1D ocean mixed layer model	Fixed (HIMSST) + 1D ocean mixed layer model	Anomaly-fixed SST (MGDSST）	Anomaly-fixed SST and ensemble-mean SST by CPS3 after 6 days (two-tier method)	Predicted SST in the fully coupled model (one-tier method)

Coupled Prediction System (CPS) Specifications

		CPS2 (June 2015)	CPS3 (February 2022)
Atmospheric model	Model version	GSM1011C	GSM2003C
	Horiz. resolution	TL159 (~110 km)	TL319 (~55 km)
	Vertical levels	60 levels	100 levels
Ocean model	Model version	MRI.COM v3.2	MRI.COM v4.6
	Horiz. resolution	1° (longitude) × 0.3-0.5° (latitude)	0.25°
	Vertical levels	52 levels with a bottom boundary layer	60 levels
Initial conditions	Atmosphere	JRA-55	Global Analysis (GA)
	Ocean/Sea ice	MOVE-G2	MOVE-G3 *(detailed next)*
Ensemble generation	Size and Frequency	13 members per 5 days	5 members per day
	Perturbation	Stochastic physics in the atmosphere Breeding for the atmosphere	Stochastic physics in the atmosphere Breeding for the atmosphere New ocean perturbations *(detailed later)*

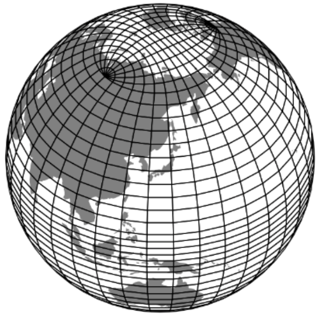
MRI.COM: Meteorological Research Institute Community Ocean Model.

Ocean data assimilation (MOVE) Specifications

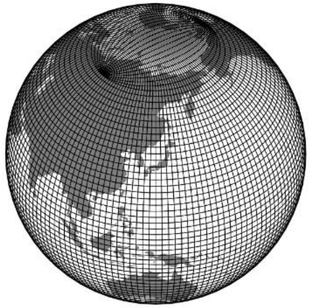
	MOVE-G2	MOVE-G3	
		G3A (4DVAR analysis)	G3F (initialization of fcst.)
Horizontal resolution	1.0° (lon) × 0.3-0.5° (lat)	1.0° (lon) × 0.3-0.5° (lat)	0.25°
Vertical layers	52 + Bottom Boundary Layer	60 + Bottom Boundary Layer	60
Temperature/Salinity analysis	3DVAR-FGAT+IAU	4DVAR+IAU	IAU to G3A Analysis *(detailed next)*
Sea Ice Concentration analysis	-	3DVAR+IAU	3DVAR+IAU
Assimilated Observations	In-situ T/S COBE-SST (L4) CMEMS SLA (L3)	In-situ T/S MGDSST (JMA-GHRSST, L4) CMEMS SLA (L3) Sea Ice Conc. (L4)	Sea Ice Conc. (L4)
Atmospheric forcings	JRA-55	JRA-3Q (delayed) and Global Analysis (early)	
Analysis window	10 days	10 days	5 days
Observation window (= Analysis interval)	10 days	5 days	

MOVE: Multivariate Ocean Variational Estimate. IAU: incremental analysis updates.

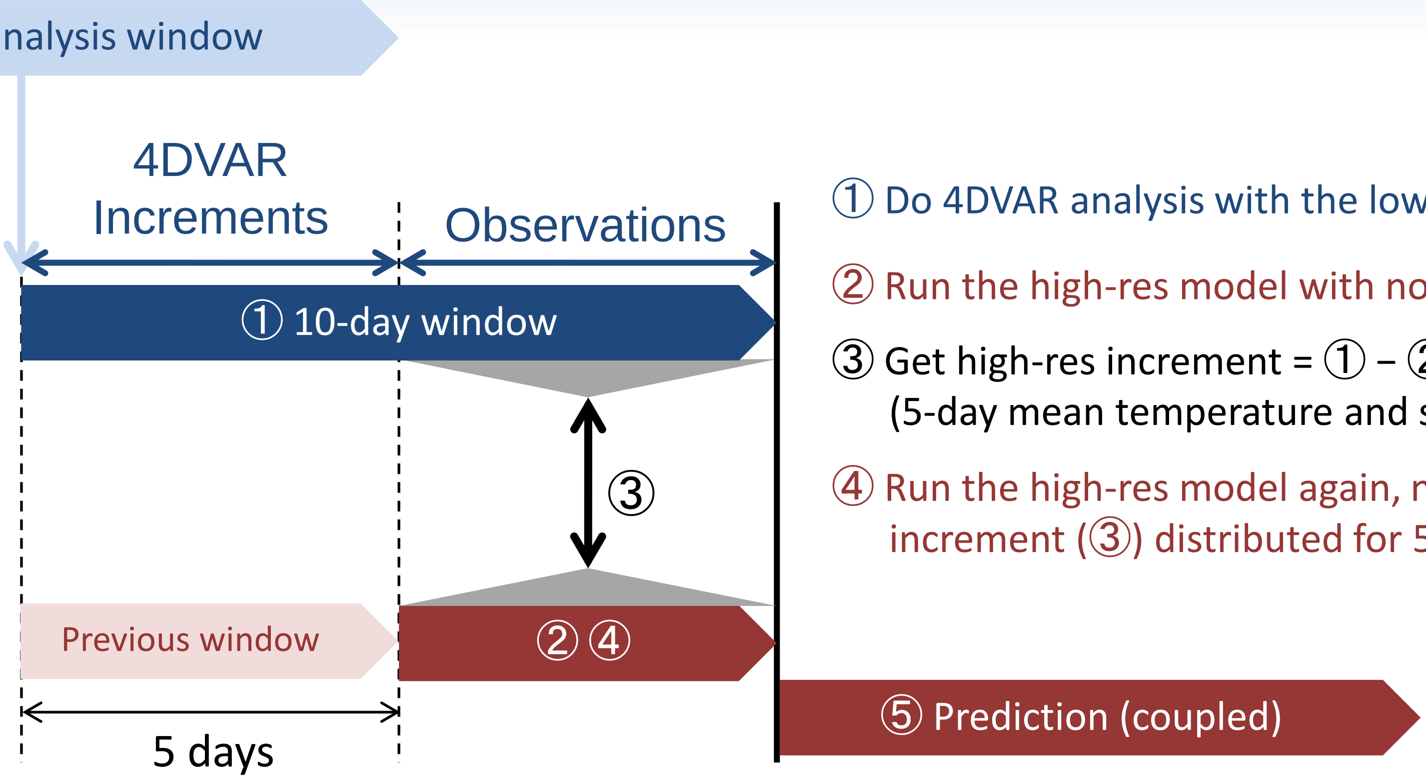
4DVAR and Downscaling with IAU



G3A
4DVAR analysis
1×0.3-0.5 deg.



G3F
Initialization of fcst.
0.25×0.25 deg.



① Do 4DVAR analysis with the low-res model

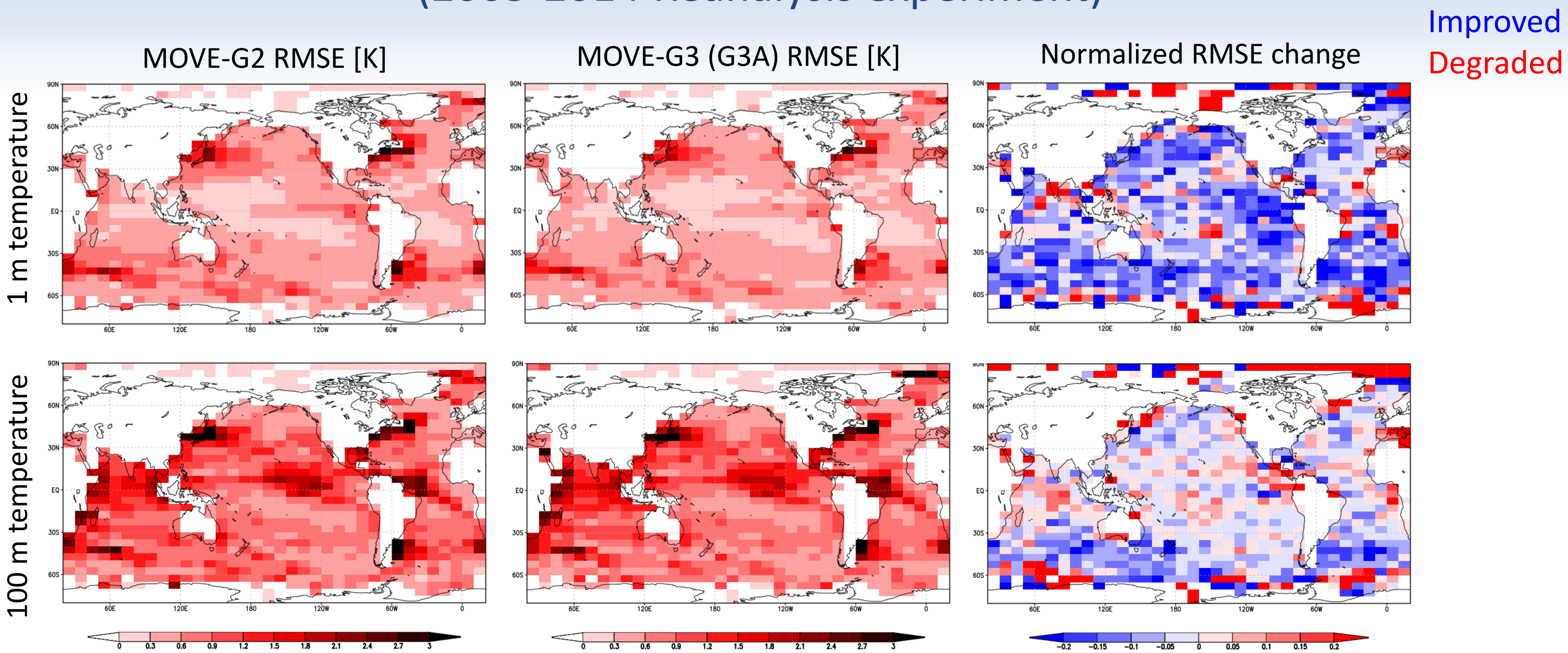
② Run the high-res model with no obs info

③ Get high-res increment = ① – ②
(5-day mean temperature and salinity)

④ Run the high-res model again, now adding the increment (③) distributed for 5 days (IAU)

Experiments with a prototype system showed this setup outperforms straightforward 3DVAR with the 0.25-deg. model (with acceptable additional cost)

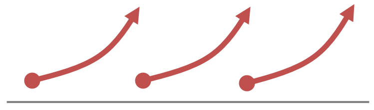
Error to independent (non-assimilated) Argo
(2005-2014 Reanalysis experiment)



*Verified with 20% of Argo withheld from assimilation

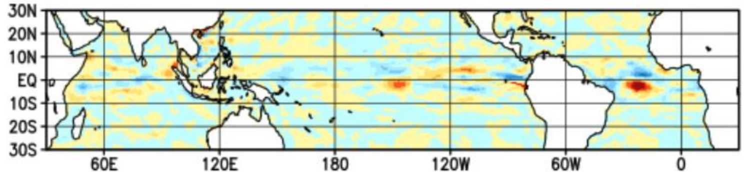
Initial Ocean Perturbation (method)

CPS2



Breeding of growing modes in atmosphere

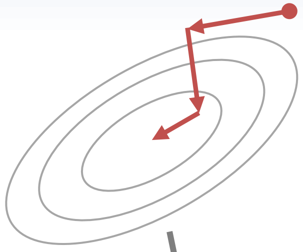
(Perturbed forcing during ocean analysis window)



Perturbed ocean analyses

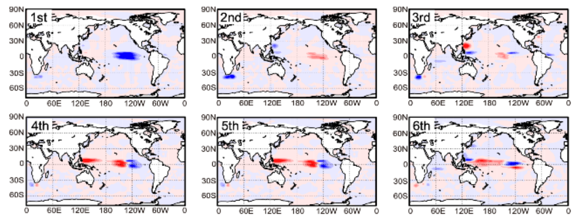
⇒ Too small ocean perturbations, especially where ocean itself should be active

CPS3



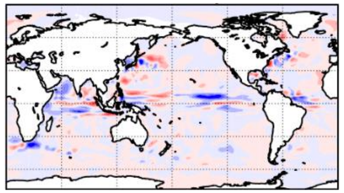
History of control variable vectors and cost gradient vectors during quasi-Newton minimization of 4DVAR

✓ No additional TL/Adj. integrations



Approx. eigenvectors of analysis error covariance matrix (Niwa and Fujii, 2020; Fujii et al., 2022)

(Mixed and scaled)



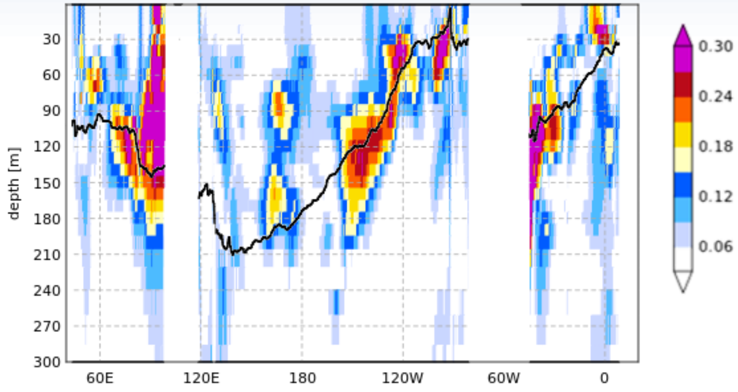
Initial perturbations

✓ We generate 4 perturbed + 1 unperturbed members per day

Ensemble spread

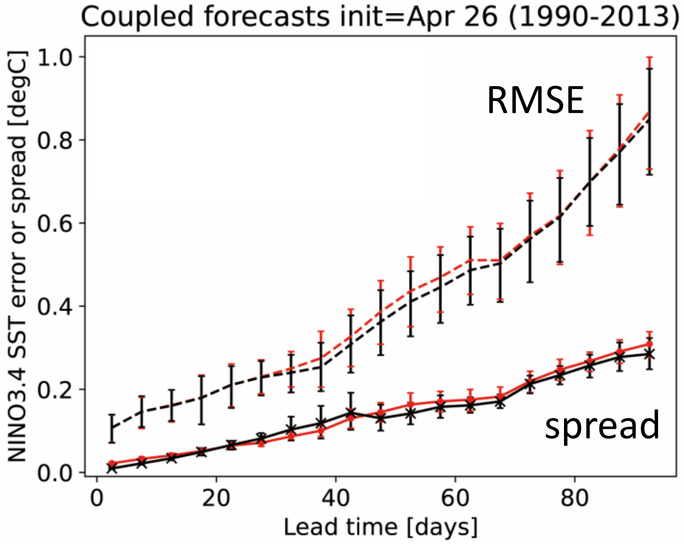
CPS2

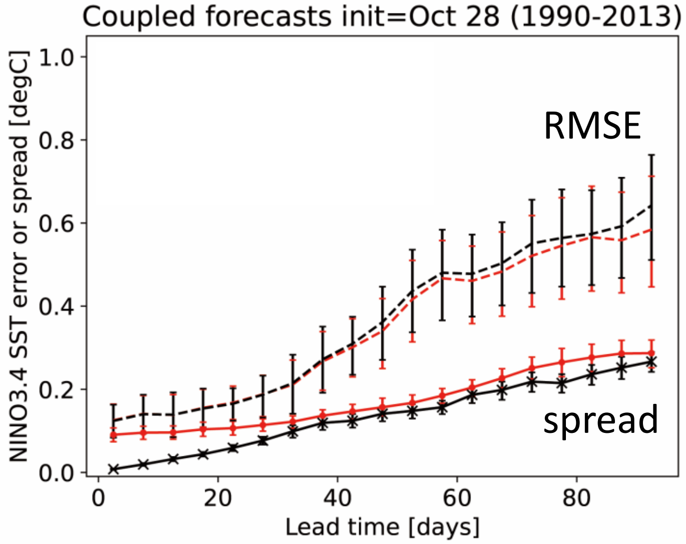
CPS3



← Initial ensemble spread for equatorial water temperature [℃] on May 31, 2012.
The black lines indicate the 20℃ isotherm.

NINO 3.4 SST RMSE and Spread [℃] →
with (red) and without (black)
initial ocean perturbations
in CPS3 hindcast experiments





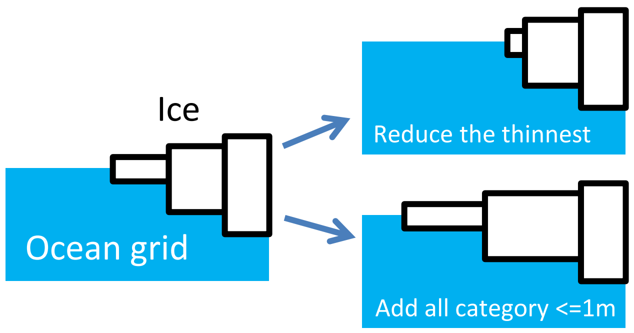
Assimilation of Sea Ice Concentration (method)

Independently for G3A and G3F:

1. Get a background SIC field
2. Combine background and obs-based (L4) SICs via 3DVAR
3. Forward model is integrated with the analyzed SIC increment added with the IAU method (along with T/S increment)

During IAU we apply a few heuristic rules.

- If SIC increment < 0, we reduce the thinnest sea ice existing
- If SIC increment > 0, all the sea ice thickness categories get additional sea ice area proportionally (i.e., % change in local volume = % change in local SIC)
  - ➢ However, if a part of existing ice is thicker than 1m, we add 1m-thick ice instead of that category.



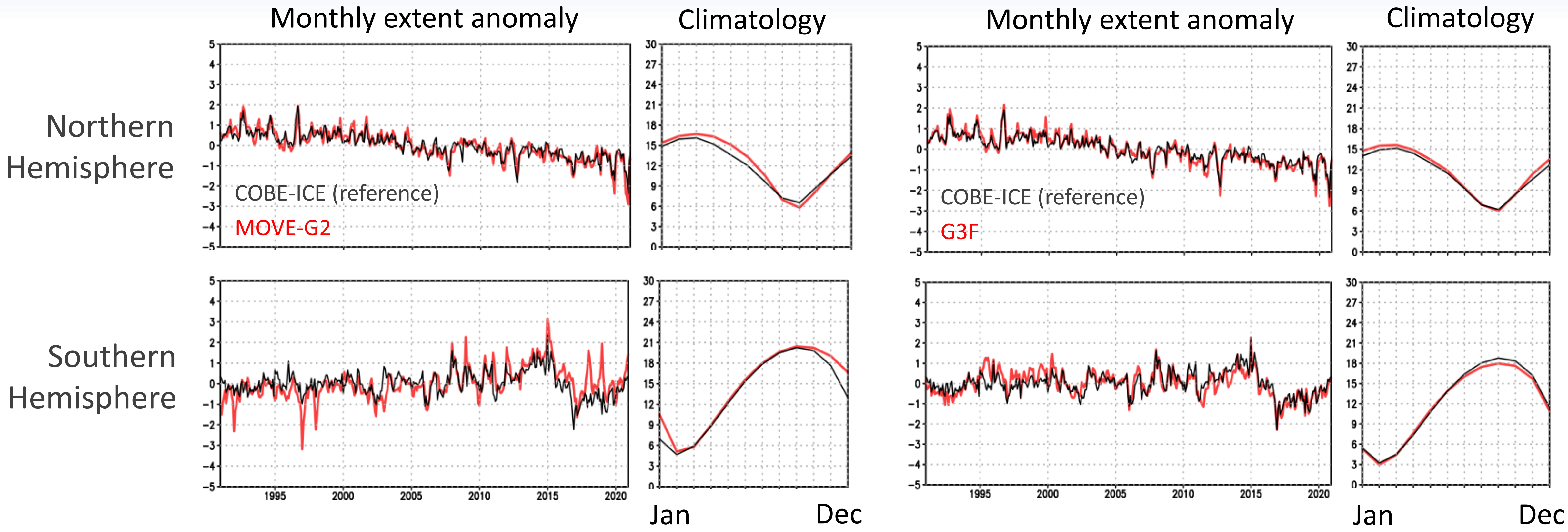
*We use 5-category model

- We also adjust SST, and air temperature and humidity forcings throughout the assimilation window (Toyoda et al., 2016; G3A only)
- Sea ice assimilation does not change local freshwater or salt budget (added/subtracted from the top ocean layer)

✓ These heuristic rules are set so that we can avoid problems like sea ice volume building up in summer (in that case, model's thin ice was melting too quickly, and SIC assimilation was trying to compensate it by adding thick ice)

Sea Ice Extent in reanalysis (10^6 km^2, year-to-year and seasonal)

MOVE-G2 (old) | MOVE-G3 (G3F; new)

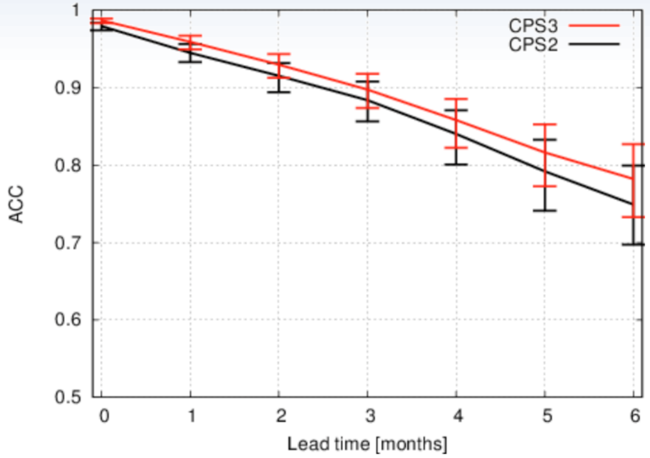


✓ Year-to-year and seasonal variabilities get closer to the reference in both hemispheres

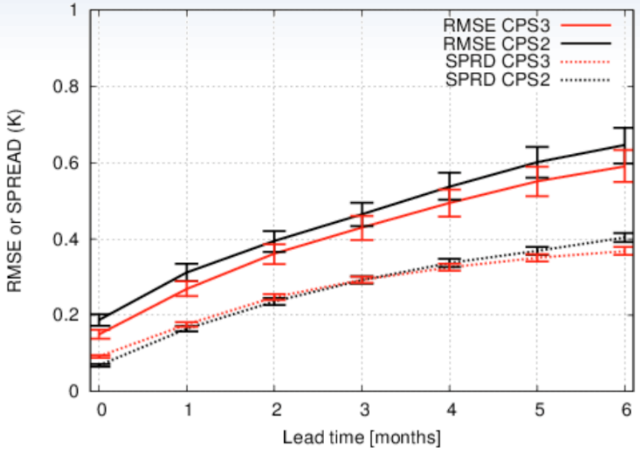
*Not an independent reference

El Nino prediction (hindcast)

Anomaly correlation

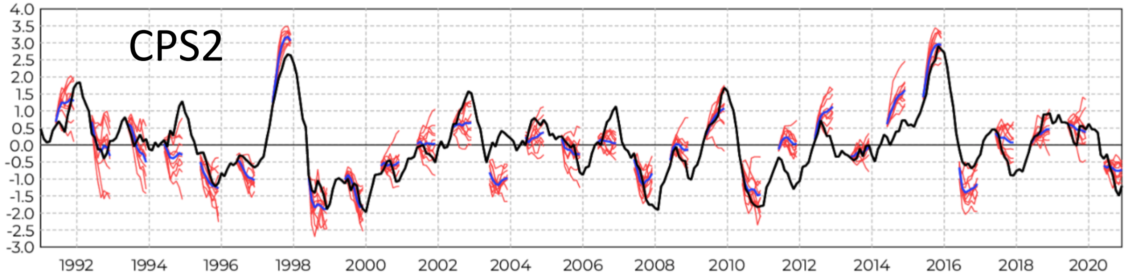


RMSE and Spread [K]

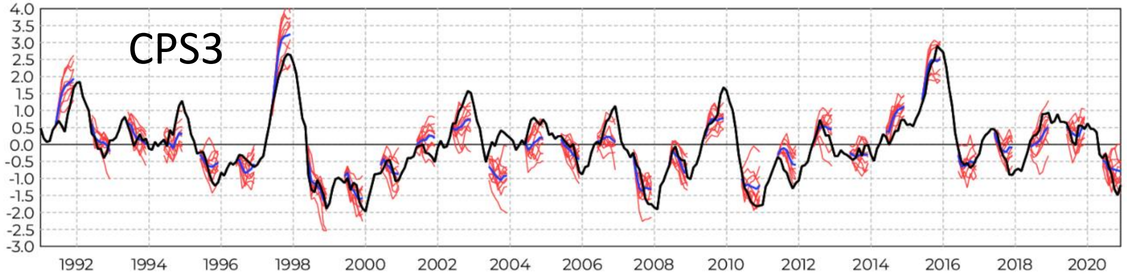


← Anomaly correlation, RMSE, and Spread of NINO 3.4 SST for different lead time. Based on 360 instances from hindcast (1991-2020).

*Verified with MGDSST



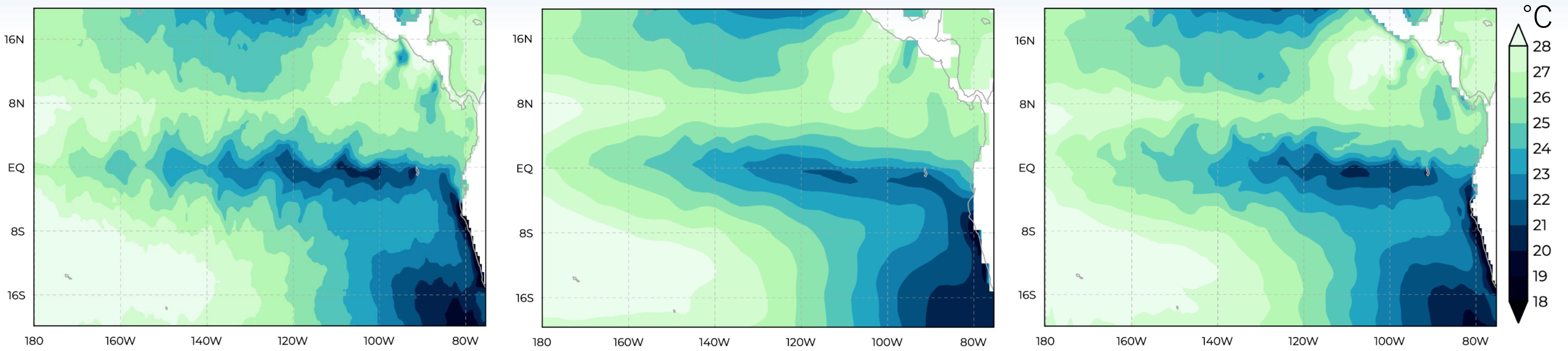
Timeseries of NINO 3.4 SST anomaly [K] →



Black: MGDSST (reference)
Red: hindcast members (from April 11 and 26)
Blue: hindcast ensemble mean (10-member LAF)

Tropical instability wave (hindcast example)

CCI SST (reference, 0.05°) — CPS2 (1°×0.3-0.5°ocean) — CPS3 (0.25°ocean)



5-day mean SST valid on December 22-26, 1999.
(CPS2 and CPS3 are 11th-15th day of prediction.)

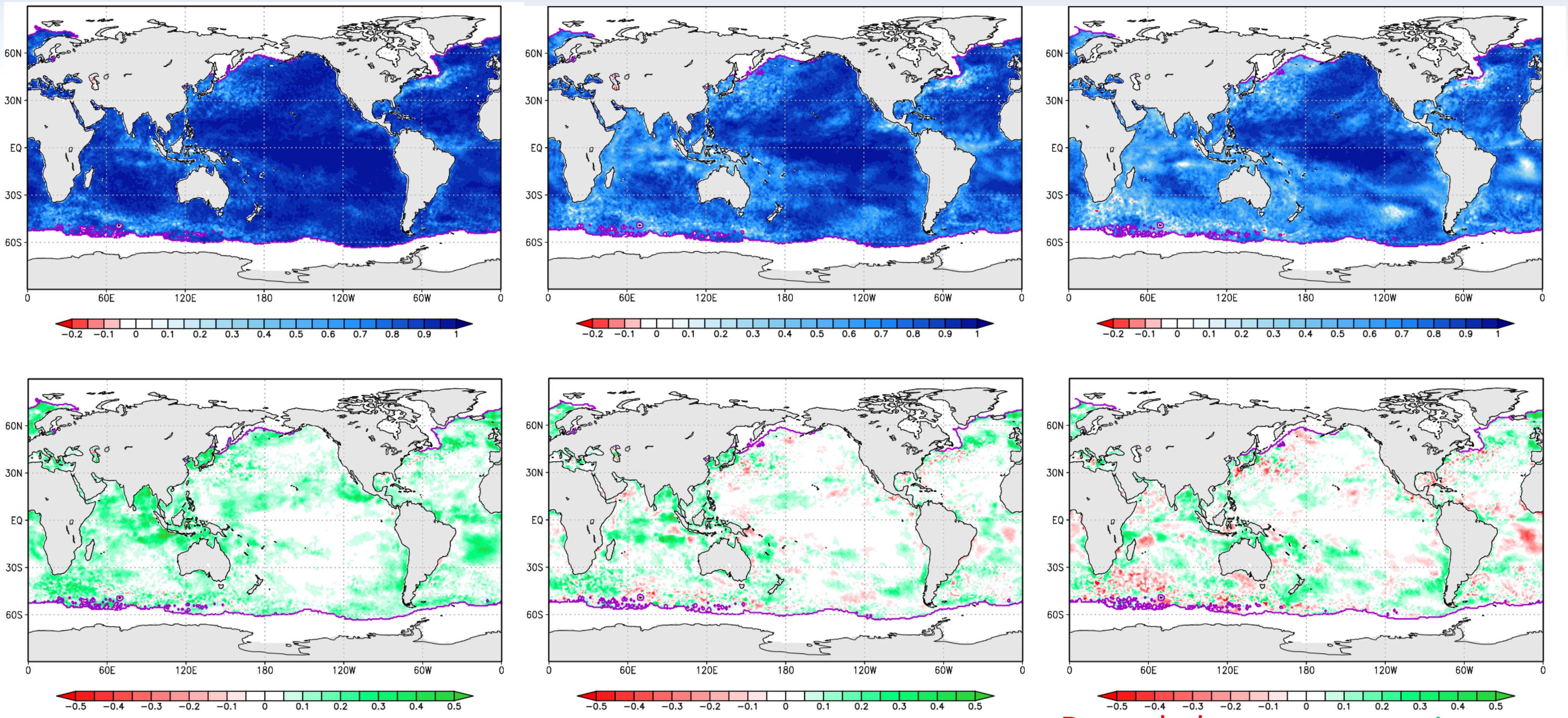
- ✓ With higher ocean resolution, CPS3 better reproduces the fine-scale TIW features.
- ✓ TIW is known to provide negative feedback to anomalous equatorial SST via meridional heat transport. This improved TIW may have alleviated over-development bias for ENSO found in CPS2.

Anomaly correlation of SST in subseasonal timescales (hindcast)

1st week of prediction | 2nd week of prediction | 3rd-4th weeks of prediction

ACC of CPS3

ACC diff CPS3 – CPS2

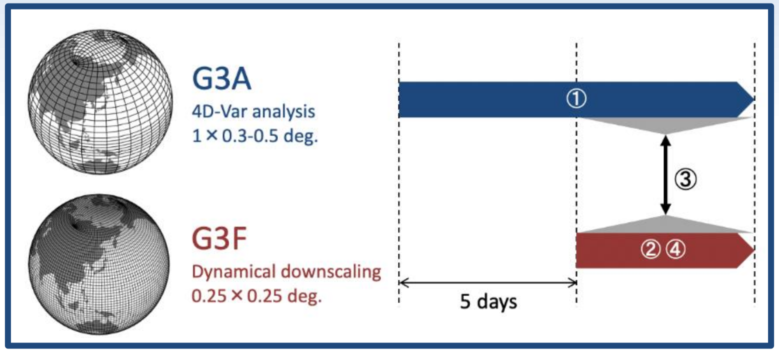


Degraded   Improved

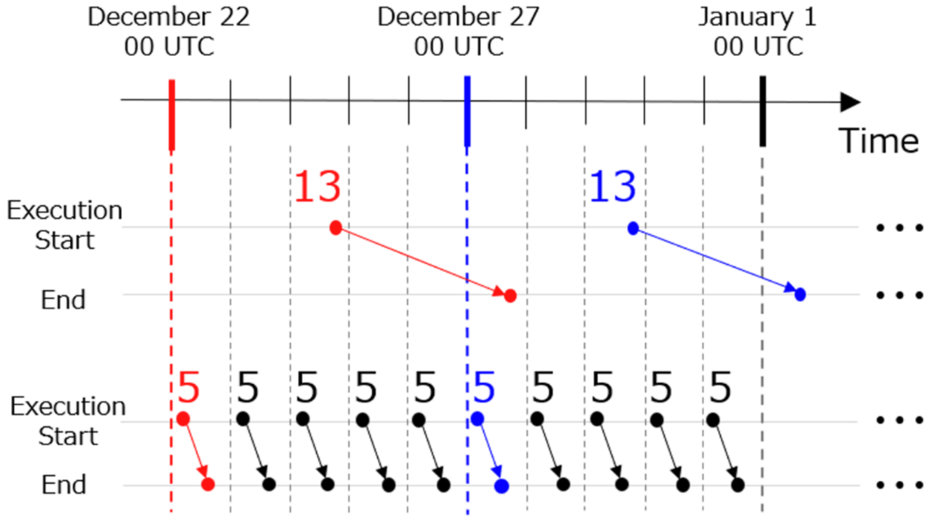
✓ This improved SST is used in GEPS (2-tiered SST, from the 6th day in the tropics)

*Verified with MGDSST

Enhanced operational schedule



×(5 mutually independent, staggered streams)×(Early/Delayed analysis)
＝Daily initial conditions available with minimal delay and data loss



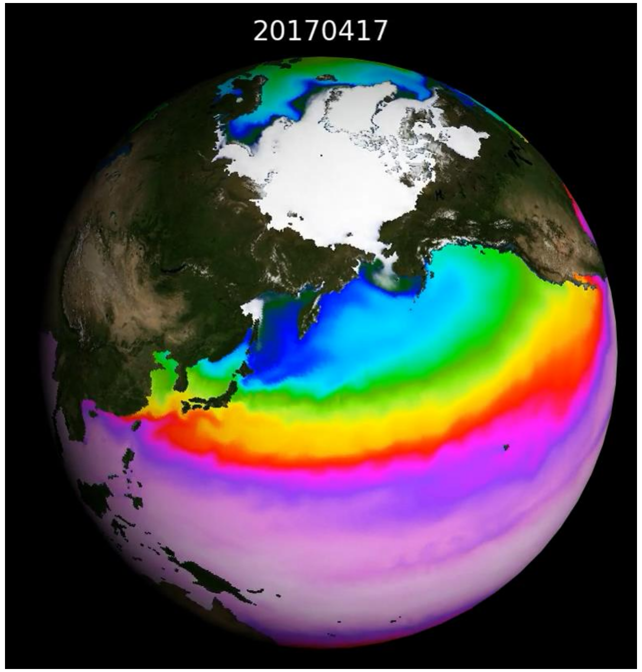
Operational schedule of prediction

	Integration starts	Whole integration available at	Frequency
CPS2	Init + 2 days	Init + 5 days	Every 5 days
CPS3	Init + 6 hours	Same day	Every day

✓ More timely initial conditions will be beneficial for shorter lead time
（also as the lower boundary condition of Global Ensemble Prediction System）

Summary

- Our CPS is now Version 3 (updated Feb. 2022)
  - ✓ Enhanced resolution and data production
  - ✓ Used for seasonal prediction and ENSO outlook
- CPS3's ocean model is initialized with MOVE-G3, which features
  - ✓ 4DVAR with 10-day analysis windows
  - ✓ Dynamical downscaling of a quarter-degree ocean model
  - ✓ Initial perturbation approximating analysis errors
  - ✓ Sea ice concentration analysis
- Substantial improvements over CPS2 and MOVE-G2
  - ✓ Analysis is closer to withheld in-situ observations
  - ✓ Better TIW and ENSO reproduction
  - ✓ Overall more skillful seasonal prediction (not shown)



SST and SIC from G3F reanalysis

References

Hirahara et al., (submitted to J. Meteor. Soc. Japan) Japan Meteorological Agency/Meteorological Research Institute Coupled Prediction System version 3 (JMA/MRI-CPS3).

Fujii et al., (submitted to Frontiers in Marine Science) Evaluation of a global ocean reanalysis generated by a global ocean data assimilation system based on a Four-Dimensional Variational (4DVAR) method.

Fujii et al., (2022, accepted by Proceedings of the Institute of Statistical Mathematics) Ensemble Member Generation Based on the BFGS Formula in a Variational Data Assimilation System (in Japanese).

Kobayashi et al., (2021, WMO/WCRP) JRA-3Q: Japanese reanalysis for three quarters of a century. Available at https://symp-bonn2021.sciencesconf.org/data/355900.pdf.

Niwa and Fujii (2020, Quart. J. Roy. Meteor. Soc.) A conjugate BFGS method for accurate estimation of a posterior error covariance matrix in a linear inverse problem.

Takaya et al., (2018, Clim. Dyn.) Japan Meteorological Agency/Meteorological Research Institute-Coupled Prediction System version 2 (JMA/MRI-CPS2): atmosphere-land-ocean-sea ice coupled prediction system for operational seasonal forecasting.

Toyoda et al., (2016, J. Oceanogr.) Data assimilation of sea ice concentration into a global ocean-sea ice model with corrections for atmospheric forcing and ocean temperature fields.

Usui et al., (2015, Mon. Wea. Rev.) Development of a Four-Dimensional Variational Assimilation System for Coastal Data Assimilation around Japan.