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Multiyear climate prediction with initialization based on 4D-Var coupled data assimilation

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Abstract

An initialization relevant to interannual-to-decadal climate prediction has usually used a simple restoring approach for oceanic variables. Here we demonstrate the potential use of four-dimensional variational (4D-Var) data assimilation on the leading edge of initialization approach particularly in multiyear (5 year long) climate prediction. We perform full-field initialization rather than anomaly initialization and assimilate the atmosphere states together with the ocean states to an atmosphere-ocean coupled climate model.

Ensembles of multiyear hindcasts using our assimilation results as initial conditions exhibit an improved skill in hindcasting the multiyear changes of the upper ocean heat content (OHC) over the central North Pacific. The 4D-Var approach enables us to directly assimilate a time trajectory of slow changes of the Aleutian Low that are compatible with the sea surface height (SSH) and the OHC. Consequently, we can estimate a coupled climate state suitable for hindcasting dynamical changes over the extratropical North Pacific as observed.

Ensembles of decadal hindcast experiments

Model: CFESda, T42L24 AGCM(AFES) +1deg. 45levs. OGCM(OIFES)

Initialization: 4D-VAR data assimilation system (*Sugiura et al. 2008 JGR*)
Observations: u,v,T,q (PREP-BUFR, NCEP), 10m wind speed (SSM/I)
T, S (WOD01), SST (Reynolds), ssh (TOPEX/Poseidon), Argo
Control variables: Ocean initial conditions (T, S)
Bulk adjustment factors, $\alpha_i(x,y,t)$ $Q_E^{adj} = \alpha_E \cdot Q_E^{ctl} = \alpha_E \cdot \rho_a L C_E |u_a|(q_a - q_o)$

Cost function: $J = (\alpha_i - 1)^T B_a^{-1}(\alpha_i - 1)$
$+(x_{atm} - y_{atm})^T R_{atm}^{-1}(x_{atm} - y_{atm})$
$+(x_{ocn} - y_{ocn})^T R_{ocn}^{-1}(x_{ocn} - y_{ocn})$

$Q_H^{adj} = \alpha_H \cdot Q_H^{ctl} = \alpha_H \cdot \rho_a c_{pa} C_H |u_a|(T_a - T_o)$
$\tau^{adj} = \alpha_M \cdot \tau^{ctl} = \alpha_M \cdot \rho_a C_D |u_a| u_a$

*x:model variable, y:observation

Hindcasts: 3 member ensembles of 1yr approach run + 5yr prediction run starting from January 1st of each year (1961-2006)
Boundary Conditions: Historical and rcp4.5 scenario-based data (CMIP5)
Initial Conditions (Ocean): Optimized states by the assimilation
Initial Conditions (Atmosphere): First guess states using LAF (2dy intvl.)

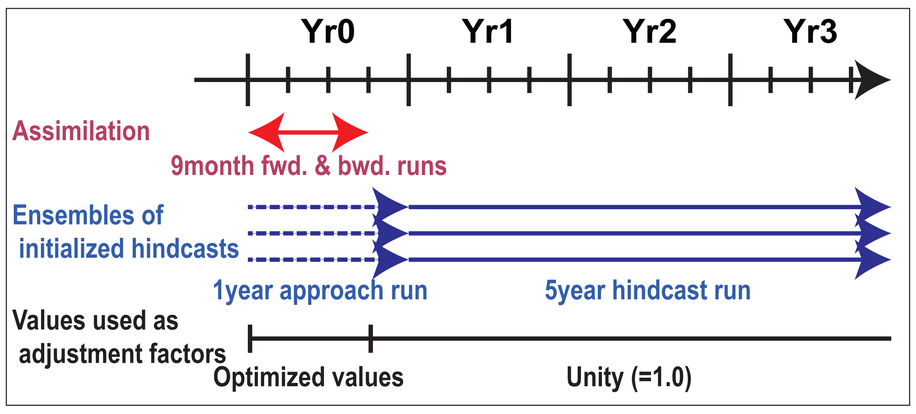


Fig. 1. Schematics of the experimental designs of the data assimilation and the subsequent ensembles of multiyear hindcasts.

Overall quality in surface air temperature (SAT)

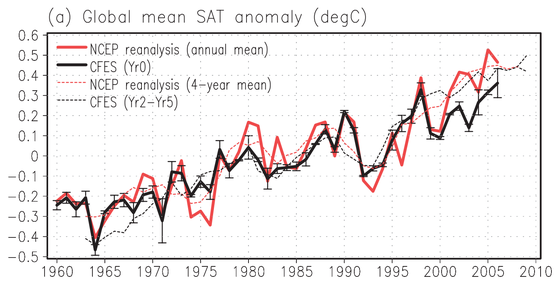
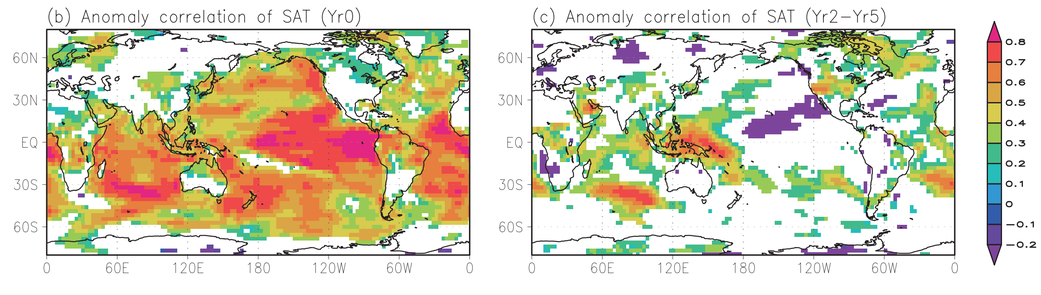


Fig. 2. (a) Global mean SAT anomalies (relative to the average during 1971-2000) derived from the CFES ensemble mean and the NCEP reanalysis. (b) Anomaly correlation coefficients of the CFES approach run (i.e., yr0) with the NCEP reanalysis at each grid point (>95% confidence levels). (c) The same as in panel b, except data are 4 year means of the CFES hindcasts in yr2-yr5.



The approach run results in broad agreements with the reanalysis (Figs. 2a and 2b). The hindcasts in yr2-yr5 fairly reproduce the global mean states (Fig. 2a) and exhibit high skills over the North Atlantic and Indian Oceans (Fig. 2c), consistent with the CMIP5 results (e.g., *Kim et al. 2012 GRL*).

Overall quality in upper ocean heat content (OHC)

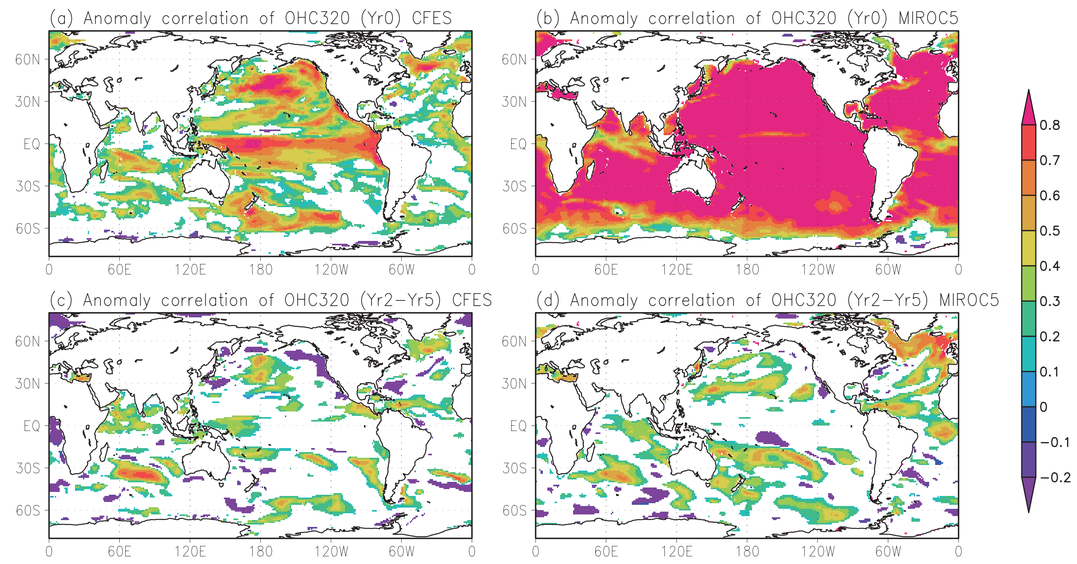


Fig. 3. Anomaly correlation coefficients of the simulated OHC upper 320m with the ocean objective analysis (Ishii and Kimoto 2009 JO) (>90% confidence levels). Climate drifts and linear trends are removed at each grid point. Plotted values in the left and right panels are calculated using the CFES and MIROC5 simulations, respectively.

** MIROC5 initialization for decadal hindcast (an example of the CMIP5 dacadal hindcasts): Temperature and salinity anomalies of the ocean objective analysis are assimilated to the atmosphere-ocean coupled model, MIROC5, by using IAU method (see, Tatebe et al. 2012 JMSJ, Mochizuki et al. 2012 JMSJ).*

The CFES approach run (i.e., yr0) is usually inferior to a snapshot-like control (e.g., MIROC5 assimilation) (Figs. 3a and 3b) due to the self-consistency as a coupled climate state in the 4D-Var approach. While the CFES hindcasts in yr2-yr5 represent the relatively low quality over the North Atlantic (Figs. 3c and 3d), predictive skills over the central North Pacific (Fig. 3c) suggest a potential benefit of our assimilation.

Potential benefit in the central North Pacific

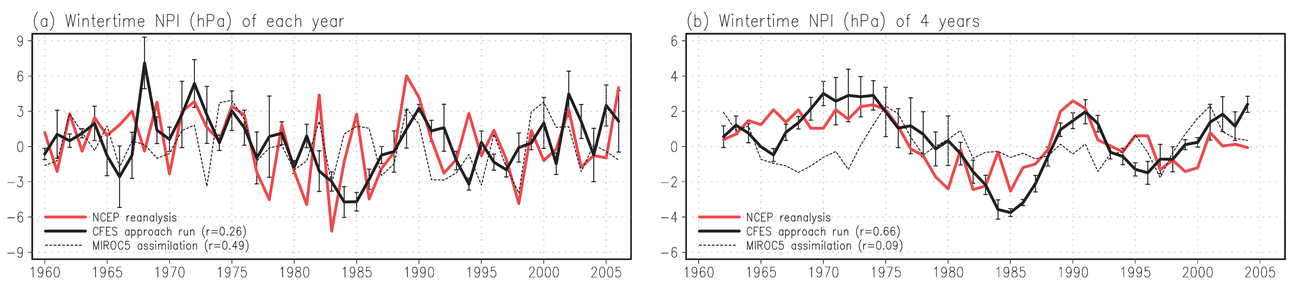


Fig. 4. (a) Time series of the wintertime North Pacific Index (NPI), definded as the sea level pressure (SLP) anomaly averaged over 30N-65N and 160E-140W from January to March. Plotted values are derived from the CFES approach run, the MIROC5 assimilation and the NCEP reanalysis. Linear trends are removed at each grid point. (b) The same as in panel a, except data are averages over four neighboring winters.

The CFES approach run well reproduces decadal changes (Fig. 4b) rather than interannual changes (Fig. 4a) of the Aleutian Low, which can largely control hindcast skills of OHC over the central North Pacific (e.g., *Mochizuki et al. 2014 SOLA*).

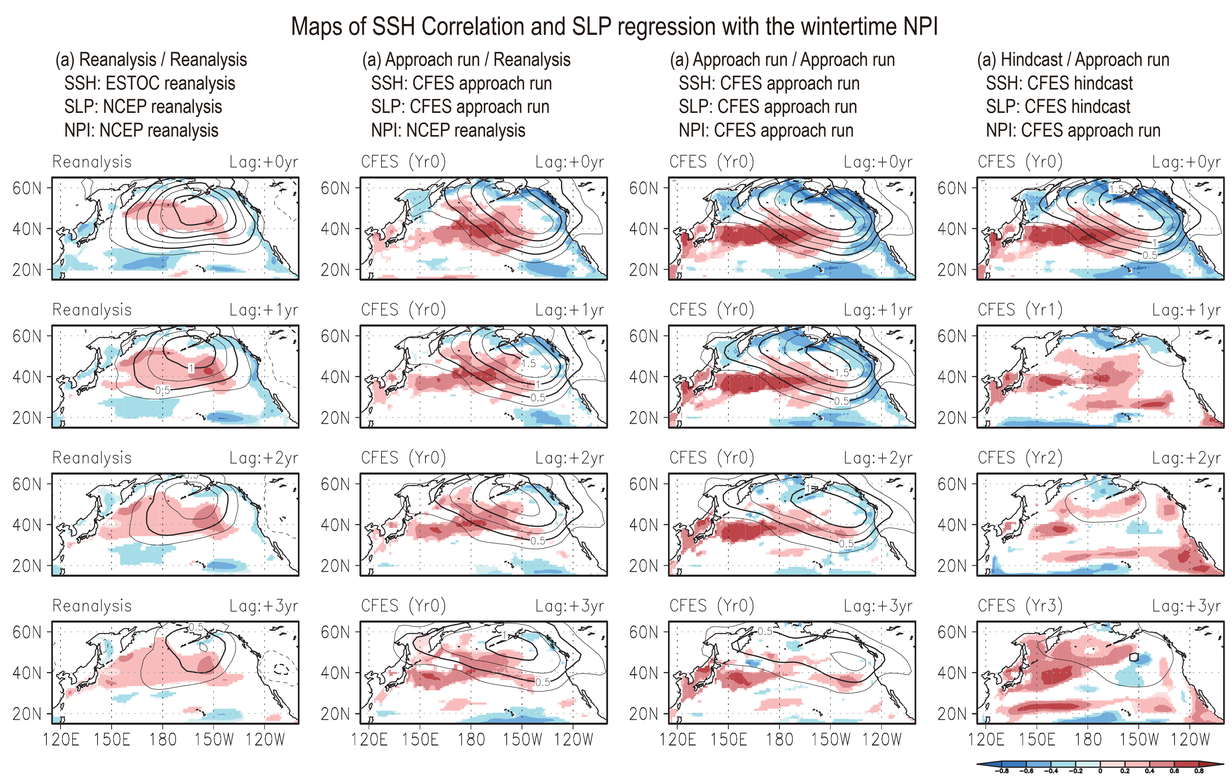


Fig. 5. Shaded areas represent lagged correlations of the 4 year mean SSH with the wintertime NPI (>90% confidence levels). Contours represent lagged regressions of the 4 year means of the wintertime SLP to the wintertime NPI (i.e., the statistical SLP anomalies corresponding to 1 hPa changes of the wintertime NPI). Climate drifts and linear trends are removed at each grid point.

As part of the comprehensive correction of the coupled states by the 4D-Var approach, the CFES approach run well reproduces the NPI anomaly accompanied by significant SSH anomalies over the central North Pacific while the centers of action are slightly shifted (upper panles of Fig. 5). The CFES hindcasts successfully simulate the SSH anomaly that slowly propagates westward through the ocean dynamics and controls the ocean states over the extratropical North Pacific (Fig. 5).