Improvements in tropical precipitation and sea surface air temperature fields in a coupled atmosphere–ocean data assimilation system

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Funding information
KAKENHI is grants-in-Aid for Scientific Research, Grant/Award Number: JP17H00728; Japan Society for the Promotion of Science (JSPS)

Abstract
A coupled atmosphere–ocean data assimilation system, the Meteorological Research Institute-Coupled Data Assimilation System Version 1 (MRI-CDA1), was developed based on the coupled atmosphere–ocean general circulation model and separate atmosphere and ocean analysis routines operated by the Japan Meteorological Agency (JMA). To implement coupled atmosphere–ocean data assimilation, 6-hr data assimilation cycles with the coupled model in the outer loop are adopted in atmospheric data assimilation, whereas incremental analysis updates with 10-day data assimilation cycles are adopted in ocean data assimilation. A coupled data assimilation (reanalysis) experiment (CDA-Exp) is conducted using MRI-CDA1 along with an uncoupled reanalysis experiment (UCPL-Exp) in which the same atmospheric component of the coupled model is forced by prescribed sea surface temperature (SST) similarly to the JMA reanalysis, JRA-55. Climatological precipitation and variations in precipitation and sea surface air temperature (SAT) are better represented in CDA-Exp than in JRA-55, which is brought about by the modification of the atmosphere model physics of the coupled model to better represent climate states. In CDA-Exp, the SST adjustment to the atmosphere amplifies the lead/lag correlations between subseasonal variations of SST and precipitation. The atmosphere–ocean coupling generates SST variations associated with tropical instability waves, and the SAT field responds to SST variations. The SST–precipitation and SST–SAT relationships on the weather timescale are also recovered in CDA-Exp, although they are hardly seen in UCPL-Exp. The coupled model physics generates weather-timescale SST variations consistent with the atmospheric state, and the atmospheric parameters respond to the SST variations through the coupled model physics. This study suggests that the benefits of coupled data assimilation would be more evident if the ability of MRI-CDA1 to represent SST variations and its interaction with the atmosphere are improved.

KEYWORDS
atmosphere–ocean coupling, coupled data assimilation, JRA-55, SST–precipitation relationship, surface air temperature, tropical instability wave

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Q J R Meteorol Soc. 2021;147:1317–1343. wileyonlinelibrary.com/journal/qj 1317
INTRODUCTION

Coupled atmosphere–ocean general circulation models (CGCMs; major acronyms are listed in Table 1) are widely used in operational climate predictions and have also been adopted in operational numerical weather prediction systems at some operational centres (Buizza et al., 2018; Smith et al., 2018). However, when making predictions, the initial states of the atmosphere and the ocean in a CGCM are often obtained separately by uncoupled atmosphere and ocean data assimilation systems. This strategy does not guarantee that the initial states satisfy the physical balance between the atmosphere and ocean represented by CGCMs. Such imbalance in the initial state is considered a trigger to induce a spurious drift referred to as “initial shock” or “model drift” in the course of the predictions, and potentially deteriorates the prediction capabilities (e.g., Balmaseda et al., 2009).

It should be noted that a data assimilation system is essentially designed to provide a state that satisfies the physical balance represented by the model used in the data assimilation system. Therefore, a data assimilation system that uses a coupled model is expected to generate an initial state that satisfies the physical balance between the atmosphere and ocean represented in the coupled model. This strategy, generally referred to as “coupled data assimilation”, is considered a promising option for reducing the initial shock and improving the prediction ability of CGCMs (Mulholland et al., 2015). In addition, coupled data assimilation is a suitable way of generating a coupled atmosphere–ocean reanalysis dataset in which the atmosphere and ocean states are well balanced (e.g., Toyoda et al., 2009).

Coupled data assimilation can be broadly categorised into two types (Penny et al., 2017). One is weakly coupled data assimilation, which assimilates atmosphere and ocean observations into a coupled model separately through uncoupled atmosphere and ocean analysis routines. The other is strongly coupled data assimilation, which assimilates atmosphere and ocean observations into a coupled model simultaneously through a single coupled atmosphere–ocean analysis routine. In a weakly coupled data assimilation system, information from atmosphere and ocean observations propagates to the other components by integrating the coupled model, and therefore it does not usually affect the analysis fields of the other components. In contrast, in a strongly coupled data assimilation system, observation information can propagate to other components, typically through the cross-correlations between forecast errors of atmosphere and ocean parameters, in the analysis process.

A coupled data assimilation system based on a CGCM was developed for the first time by the K7 consortium in Japan (Sugiura et al., 2008). Their study is still cutting edge because they constructed a strongly coupled data assimilation system by applying a four-dimensional variational (4DVAR) scheme directly to a CGCM. They developed adjoint codes of the CGCM and the system in which the trajectories of the CGCM that fit well with the atmosphere and ocean observation data are estimated. Therefore, their products are highly consistent with the CGCM. However, their strategy is not followed by other groups for the following two reasons. One is the difficulty in developing adjoint codes of the CGCM. The other and more critical reason is that the strategy eliminated weather-timescale variations in order to mitigate strong nonlinearity arising from the difference of the dominant timescales between atmosphere and ocean variations.

| Table 1: List of major acronyms |
|--------------------------------|
| CGCM  | Coupled atmosphere–ocean general circulation model |
| COBE-SST | The objective SST data in JMA. See Appendix A. |
| GPCP  | The objective analysis of daily precipitation. See Subsection 3.2. |
| GSM   | Global Spectral Model |
| IAU   | Incremental Analysis Updates |
| ITCZ  | Intertropical Convergence Zone |
| JMA   | The Japan Meteorological Agency |
| JRA-55| The Japanese 55-year reanalysis. See Subsection 3.2 |
| MRI   | The Meteorological Research Institute |
| MRI-CDA1 | The coupled data assimilation system developed in MRI. See Section 2. |
| RMSE  | Root-mean-square error |
| SAT   | Sea surface air temperature |
| SIC   | Sea ice concentration |
| SICZ  | South Indian Convergence Zone |
| SPCZ  | South Pacific Convergence Zone |
| SSH   | Sea surface height |
| SSS   | Sea surface salinity |
| SST   | Sea surface temperature |
| TIW   | Tropical instability wave |
| TAO/TRITON | The buoy array in the tropical Pacific |
| TP average | Average in the tropical Pacific domain (20°S–20°N, 120°E–80°W) |
| 3DVAR | Three-dimensional variational (method) |
| 4DVAR | Four-dimensional variational (method) |
In contrast, it is relatively easy to construct a strongly coupled data assimilation system by incorporating a complicated CGCM in an ensemble Kalman filter with few modifications. Zhang et al. (2007) applied this method for the first time at the Geophysical Fluid Dynamics Laboratory (GFDL). However, they found that the strongly coupled data assimilation configuration of the system in which the full forecast error covariance matrix was adopted in the analysis process degraded the data assimilation quality in comparison with the weakly coupled data assimilation configuration in which the cross-correlations between forecast errors of atmospheric and oceanic parameters were eliminated. Subsequently, several studies proposed methods to gain the advantage of the strongly coupled data assimilation configuration by extracting effective information from the cross-correlation of the atmosphere and the ocean (e.g., Lu et al., 2015; Sluka et al., 2016; Yoshida and Kalnay, 2018).

Meanwhile, most operational centres opted not to develop a new analysis routine specialised for coupled data assimilation, using instead existing atmosphere and ocean analysis/data assimilation routines employed in their operational systems. The National Centres for Environmental Prediction (NCEP) developed a weakly coupled data assimilation system using the uncoupled atmosphere and ocean three-dimensional variational (3DVAR) routines that were originally adopted in their operational systems, and created the Climate Forecast System Reanalysis (CFSR; Saha et al., 2006; 2010). The European Centre for Medium-Range Weather Forecasts (ECMWF) also developed a coupled data assimilation system for creating the Coupled European Reanalyses of the 20th century (CERA-20C, Laloyaux et al., 2016; 2018a) and the satellite era (CERA-SAT, Schepers et al., 2018). Although this system employed the atmospheric 4DVAR and the oceanic 3DVAR analysis routines that were adopted in ECMWF’s operational systems, the outer-loop coupling technique with 1-day data assimilation cycles enabled the analysis fields of the atmosphere and the ocean in the same cycle to influence each other. Therefore, it is categorised as a “quasi-strongly” coupled data assimilation system (Penny et al., 2017). More recently, ECMWF also developed a weakly coupled data assimilation system, which applies the operational atmosphere and ocean analysis routines without changing the periods of their data assimilation cycles (Browne et al., 2019). The UK Met Office also developed a weakly coupled data assimilation system based on their operational systems, but the periods of the atmosphere and ocean data assimilation cycles were equalised to 6 hr (Lea et al., 2015).

At the Japan Meteorological Agency (JMA)/Meteorological Research Institute (MRI), we have also adopted the same strategy to develop coupled data assimilation systems. At first, we developed a coupled data assimilation system in which ocean observations were assimilated into the ocean component of a CGCM through an operational ocean 3DVAR analysis routine (Fujii et al., 2009). This was not a fully coupled system, but a so-called semi-coupled data assimilation system because atmospheric observations were not assimilated. Subsequently, we developed the MRI Coupled Data Assimilation System Version 1 (MRI-CDA1), which is described in this paper. It is a fully coupled data assimilation system in which both atmosphere and ocean data are assimilated using operational atmosphere and ocean analysis routines that are not coupled.

One of the purposes of this study is to evaluate the mean state and variations in precipitation reproduced by MRI-CDA1. In fact, several previous studies reported an improvement in precipitation generated by coupled data assimilation. For example, Fujii et al. (2009) reported that the mean and variation of the precipitation field were improved in the semi-coupled data assimilation system because of the plausible reconstruction of the lead/lag relationship between sea surface temperature (SST) and precipitation. Saha et al. (2010) also found that the SST–precipitation relationship on the subseasonal timescale was improved in CFSR over uncoupled atmospheric reanalyses. Kumar et al. (2013), however, indicated that the improvement was mostly caused by the adjustment of the SST field to atmospheric forcing in the coupled model and that the precipitation field was not improved in a manner that changed the SST–precipitation relationship. Feng et al. (2018) also reported a similar improvement in the subseasonal SST–precipitation relationship generated by coupled data assimilation through comparison between CERA-20C and the atmosphere-only climate reanalysis in ECMWF (ERA-20C; Poli et al., 2016). Kobayashi et al. (2021) discussed the SST–precipitation relationship in the western equatorial Pacific on the subseasonal timescale and its association with sea surface heat flux and near-surface ocean temperature variations based on the coupled reanalysis experiment using MRI-CDA1. These studies mostly focussed on variations on the subseasonal timescale. This study examines precipitation variations on the weather timescale (1–10 days) and those on the subseasonal timescale (10–60 days).

In addition, this study evaluates sea surface air temperature (SAT) fields. It is expected that the SAT field is strongly affected by coupled data assimilation through its adjustment to SST. Improvement of the forecasted air temperature near the surface brought about by coupled data assimilation was reported by Browne et al. (2019), and adjustment of near-surface air temperature to SST in coupled data assimilation systems was discussed in Laloyaux et al. (2018b). However, SAT fields produced by coupled
data assimilation systems have not yet been comprehensively evaluated.

In this study, we mainly evaluate the results of two reanalysis experiments using MRI-CDA1, which were also analysed by Kobayashi et al. (2021). One is a coupled reanalysis experiment in which MRI-CDA1 is adopted as it is, while the other is an uncoupled reanalysis experiment in which the atmosphere component of the coupled model in MRI-CDA1 is forced by prescribed SST.

The remainder of this paper is organised as follows. Section 2 provides the configuration of MRI-CDA1, and Section 3 describes the setting of the reanalysis experiments and the reference data. In Section 4, the precipitation and SAT fields produced in the reanalysis experiments are compared with the latest atmospheric reanalysis from JMA. In Section 5, the impact of coupled data assimilation is examined by comparing the coupled and uncoupled reanalysis experiments. In particular, we compare SST–precipitation and SST–SAT relationships and the consistency of precipitation and SAT variations with observation data on both the weather and subseasonal timescales, as well as the mean states and full variations of precipitation and SAT. This study is summarised in Section 6.

2 | COUPLED DATA ASSIMILATION SYSTEM

MRI-CDA1 is composed of the coupled model subsystem, atmosphere analysis subsystem and ocean analysis subsystem. All these subsystems are based on operational systems at JMA. The following subsections describe each subsystem and the procedure for implementing coupled data assimilation.

2.1 | Coupled model subsystem

MRI-CDA1 adopts the JMA/MRI-Coupled General Circulation Model Version 2 (JMA/MRI-CGCM2), which is used in the JMA/MRI-Coupled Prediction System Version 2 (JMA/MRI-CPS2) as the coupled atmosphere–ocean model component (Takaya et al., 2018). JMA/MRI-CPS2 is the current operational seasonal forecasting system at JMA.

The atmospheric component of the coupled model was developed based on the low-resolution version of the JMA Global Spectral Model (GSM) as of November 2010 (JMA, 2013). It applies TL159 (approximately 110 km) horizontal resolution with 60 vertical levels. Several modifications are applied to the atmosphere model to improve the model climatology (Takaya et al., 2018). The modifications include incorporation of the sub-cloud model (Jakob and Siebesma, 2003), the cloud overlap scheme (Nagashawa, 2013), the COARE3.0 sea-surface flux scheme (Fairall et al., 2003), and the diurnal SST scheme (Zeng and Beljaars, 2005; Takaya et al., 2010), and adjustment of the cumulus convection (JMA, 2013) and stratocumulus cloud schemes (Kawai, 2013). The Simple Biosphere (SiB) land model incorporated in the original GSM is used as it is in the atmospheric component.

The ocean component is constructed based on the MRI community ocean model (MRI.COM) version 3 (Tsujino et al., 2010). It adopts a tri-polar grid over the global domain with zonal resolution of 1° (approximately 100 km) and meridional resolution of 0.3–0.5° with refinement near the equator. It has 52 vertical levels. The 22 upper levels are placed at 1, 3.5, 7, 11.5, 23.5 and 31 m, then every 10 m between 40 and 190 m. The vertical mixing scheme of Noh and Kim (1999) and a mesoscale eddy parameterisation (Gent and McWilliams, 1990; Visbeck et al., 1997) are applied. A five-category sea-ice model, based on the thermodynamic formulation of Mellor and Kantha (1989) and the elastic-viscous-plastic dynamic formulation of Hunke and Lipscomb (2006) with a ridging and rheology scheme, is incorporated into the ocean component (Tsujino et al., 2011).

The atmospheric and ocean components exchange parameters necessary for the coupling every hour. The atmospheric component provides momentum, heat and freshwater fluxes for the ocean component. The heat and momentum fluxes are applied in the ocean component without any adjustments. The freshwater flux is modified to nudge sea surface salinity to its monthly climatology. In turn, the ocean component provides SST, sea ice concentration (SIC), sea ice temperature information and sea surface ocean current velocity for the atmospheric component. Here, the temperature and the current velocity at the uppermost level of the ocean component (i.e., 1 m depth) are considered as the SST and sea surface ocean velocity. In the atmospheric component, the heat flux at the sea surface is evaluated based on the SST received from the ocean component. The heat flux on the sea ice top is additionally calculated using the sea ice temperature information from the ocean component, and the average of the two heat fluxes weighted by SIC is adopted for the bottom boundary condition in the sea ice area. The heat flux at the sea surface is directly used in the area without sea ice. The ocean current velocity is used for evaluating the surface wind velocity relative to the ocean current in the calculation of the wind stress field. The coupled model subsystem has no ocean wave component, but the ocean current velocity is also used in the parameterisation of the ocean wave effect.
on the wind stress and heat flux using a simple Charnock relation (JMA, 2013).

### 2.2 Atmosphere analysis subsystem

The atmosphere analysis subsystem of MRI-CDA1 was developed based on the global atmosphere 4DVAR routine that composes the JMA global operational numerical weather prediction system employed in operation until May 2016 (JMA, 2013). The 4DVAR adopts the incremental 4DVAR form (Courtier et al., 1994) with one outer loop: the first guess or the background state of the atmosphere is provided by the outer model, and analysis increments are estimated using the inner model and its adjoint model.

The original nonlinear version of the inner model is based on the JMA GSM as of March 2014, but moisture processes are replaced with those of the GSM as of February 2001. It applies TL159 horizontal resolution (the same as the atmospheric component of the coupled model subsystem) with 100 vertical levels (model top is 0.01 hPa). The tangent linear version of the nonlinear model and its adjoint model are adopted in the actual 4DVAR system. The observation data assimilated in the atmosphere 4DVAR routine are surface pressure data from fixed land stations; radiosonde and pilot balloon observations (temperature, wind and relative humidity); upper-air observations by aircraft (temperature and wind); wind profiler data; various satellite data, including radiance, radio occultation, atmospheric motion vector, and sea surface winds observed by scatterometers; atmospheric signal delay measurements of ground-based Global Navigation Satellite System (GNSS) receivers; and bogus data for tropical cyclone structure. A detailed description of the impacts of these observation data in the original analysis routine can be found in Ishibashi (2018). It should be noted that in situ SAT observations, including those observed by the Tropical Atmosphere Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) array, are not assimilated, and that precipitation is a diagnostic variable. Therefore, the analysis increments for precipitation are not estimated in the subsystem. Information of ocean currents is not used in any part of the 4DVAR routine including the observation operator for satellite scatterometers.

Analysis increments in the middle of the 6-hr assimilation time window are estimated from the data observed in the time window using the inner model, and added to the prognostic variables of the outer model in the original routine. Here, analysis increments in the middle of the time window are adopted because the 4DVAR analysis is supposed to have the best accuracy at that time. However, the outer model is replaced by the coupled model subsystem in MRI-CDA1 as described in Subsection 2.4.

### 2.3 Ocean analysis subsystem

The ocean analysis subsystem of MRI-CDA1 is the same as the analysis routine adopted in MOVE-G2 (Toyoda et al., 2013). MOVE-G2 is a global ocean data assimilation system used in JMA/MRI-CPS2 for global ocean monitoring and provides JMA/MRI-CGCM2 with oceanic initial values in JMA’s operational seasonal forecasting. The ocean model used in MOVE-G2 is identical to the ocean component of the CGCM. The analysis routine adopts the 3DVAR scheme named Multivariate Ocean Variational Estimation (MOVE) 3DVAR. It analyses oceanic temperature and salinity fields above a 2,000 m depth using coupled temperature–salinity empirical orthogonal functional decomposition (Fujii and Kamachi, 2003; Fujii et al., 2005). Temperature and salinity fields predicted by the ocean model are employed as the background fields in the 3DVAR analysis after slightly nudging to the monthly climatology in MOVE-G2, but those estimated in the ocean component of the coupled model subsystem are used instead in MRI-CDA1. Analysis increments obtained by the analysis routine are gradually applied to the ocean component over the data assimilation cycle period via incremental analysis updates (IAU; Bloom et al., 1996).

The bias correction scheme (Fujii et al., 2012) and the freshwater adjustment scheme for satellite altimetry data (Kuragano et al., 2014) are applied. In this study, MRI-CDA1 assimilates in situ ocean temperature and salinity profiles, gridded SST data and altimeter-derived sea surface height (SSH) observations through MOVE 3DVAR. The temperature and salinity profiles are collected from the World Ocean Database 2013 (WOD13; Boyer et al., 2013) and the Global Temperature Salinity Profile Program (GTSP; Hamilton, 1994). The gridded SST data are drawn from COBE-SST (Ishii et al., 2005; also see Appendix A). The SSH observations are AVISO along-track multimission products for Jason-2, Cryosat-2, Saral/AltiKa and HY-2A (AVISO, 2015). Sea ice observation data are not assimilated.

### 2.4 Coupled data assimilation procedure

MRI-CDA1 uses different data assimilation cycles for the ocean and the atmosphere. For the ocean, MRI-CDA1 applies data assimilation cycles with 10-day assimilation/observation windows for performing IAU (Figure 1a). The ocean data assimilation cycle includes the following three phases: In the first phase (only-atmosphere-assimilated coupled simulation phase), the coupled model is integrated for 5 days from the beginning of the assimilation window while assimilating...
atmospheric data as described below. In this phase, the ocean component freely evolves without data assimilation. Then, the final state of the ocean is adopted as the background field in the second phase (ocean analysis phase), in which ocean analysis increments are estimated from the data observed in the 10-day assimilation/observation window (i.e., the model equivalents for ocean observations are estimated from the ocean state in the middle of the window calculated in the first phase). It should be noted that, here, integration of the ocean model is not performed but the 3DVAR ocean analysis routine in MOVE-G2 is adopted alone. In the third phase (coupled atmosphere–ocean assimilation phase), the coupled model is integrated throughout the data assimilation cycle, applying ocean analysis increments incrementally, and assimilating atmospheric data in the same manner as in the first phase. A series of procedures is repeated every 10 days.

The atmospheric data are assimilated through a 6-hr data assimilation cycle with the coupled model in the outer loop in the first and third phases (Figure 1b). More specifically, 4DVAR analysis is performed using the atmosphere analysis subsystem for the periods of 2100–0300, 0300–0900, 0900–1500 and 1500–2100 UTC (here the observation window is the same as the analysis period), and the analysis increments at the centre times of the periods are applied to the atmospheric component of the coupled model, without partitioning, at 0000, 0600, 1200 and 1800 UTC. After applying the increments, the coupled model is integrated as the outer model for 9 hr to provide the background fields for the atmospheric analysis subsystem. The coupled model also provides the atmosphere analysis subsystem with SST fields averaged over 24 hr before the analysis times because the 4DVAR system is supposed to use daily SST for the ocean boundary condition. The atmosphere data assimilation cycle is iterated 20 times (for 5 days) from the beginning of the ocean assimilation window without applying oceanic analysis increments in the first phase of the ocean data assimilation cycle. The ocean fields obtained by the 6-hr integration of the coupled model after the atmospheric analysis increments at 1800 UTC on the fifth day are applied as the background field in the ocean analysis phase. Then, the atmosphere data assimilation cycle is iterated 40 times (for 10 days) from the beginning of the ocean assimilation window, applying ocean analysis increments in the third phase of the ocean data assimilation cycle. The atmosphere and ocean fields in the first 6 hr of each integration in the third phase are used as the final state of the coupled assimilation (where the integration period overlaps with the next atmospheric data assimilation cycle for the last 3 hr).

This procedure enables us to adopt the periods of atmosphere and ocean data assimilation cycles originally used in the operational assimilation systems (i.e., 6 hr for the atmosphere and 10 days for the ocean). These periods are determined from time-scales of atmosphere and ocean variabilities and the time necessary to obtain a sufficient number of observation data. In this procedure, ocean analyses are affected by the oceanic analysis performed in the first phase of the ocean data assimilation cycle and, in turn, affect the atmosphere analyses in the third phase. Therefore, following the definition described in Penny et al. (2017), the procedure is classified as a quasi-strongly coupled data assimilation, although
Table 2: Comparison of experimental settings

|                        | CDA-Exp | UCPL-Exp | NOOC-Exp | FREE-Exp |
|------------------------|---------|----------|----------|----------|
| Atmosphere data assimilation | Applied | Applied | Applied | N/A      |
| Ocean data assimilation  | Applied | Applied | Applied | N/A      |
| SST used in AC          | OC to AC| COBE-SST | OC to AC | OC to AC |
| Surface ocean current velocity for calculating wind stress in AC | OC to AC | Set to 0 | Set to 0 | OC to AC |
| Atmospheric forcing used in OC | AC to OC | AC to OC | AC to OC | AC to OC |

Note: Here “N/A” denotes “not applied”, “AC” and “OC” denote the atmosphere and ocean components of the coupled model subsystem, “OC to AC” denotes “given from OC to AC”, and “AC to OC” denotes “given from AC to OC”.

Atmosphere and ocean analyses are performed separately with uncoupled analysis subsystems.

3 | Experiments and Data

3.1 | Reanalysis experiments

In this study, we conduct a coupled atmosphere–ocean data assimilation (reanalysis) experiment (CDA-Exp) using MRI-CDA1 exactly as described in the previous section from October 28, 2013 to December 31, 2015. In addition, we carry out two supplemental reanalysis experiments to examine the atmosphere–ocean coupling feedbacks in the coupled reanalysis. One is an uncoupled reanalysis experiment (UCPL-Exp) in which MRI-CDA1 is used but the atmosphere component of the coupled model subsystem uses daily SST and SIC fields from the COBE-SST dataset as the sea surface boundary condition and sets the sea surface ocean current velocity to zero instead of receiving those data from the ocean component. The other is the no ocean-current coupling reanalysis experiment (NOOC-Exp) in which the atmospheric component receives SST and SIC from the ocean component but the sea surface current velocity is not received and is set to zero. We also carry out a free simulation experiment (FREE-Exp) in which the coupled model subsystem of MRI-CDA1 is integrated without data assimilation. The setting of each experiment is summarised in Table 2. Notably, in UCPL-Exp, the SST forcing the atmosphere component is a daily SST analysis of the COBE-SST, which differs from the SST estimated in the ocean component. We usually consider the former, that is, daily SST provided in COBE-SST, as the SST in UCPL-Exp.

All four experiments are conducted in two streams. The first stream spans from October 28, 2013 to December 31, 2014, and the second spans from October 28, 2014 to December 31, 2015. The final reanalysis fields are drawn from the first stream for 2013 and 2014 and from the second stream for 2015. We confirm that there is no large gap between the two streams, mainly because the atmospheric state is sufficiently constrained through the atmospheric data assimilation. This study uses the daily outputs of these reanalysis experiments.

3.2 | Reference data

To examine the performance of MRI-CDA1, we compare the results of the reanalysis and simulation experiments with the daily outputs of the Japanese 55-years reanalysis (JRA-55; Kobayashi et al., 2015). JRA-55 is produced by a global atmospheric data assimilation system based on the incremental 4DVAR analysis routine in the JMA’s operational global numerical weather prediction system as of December 2009. The outer model of the JRA-55 system applies TL319 (approximately 55 km) horizontal resolution with 60 levels. The horizontal resolution of the inner model is T106 (approximately 110 km). The outer model has no difference other than the resolution from the GSM originally employed as the atmospheric component of the coupled model subsystem of MRI-CDA1. However, a significant difference is made by the modification of the model to improve the climatology, particularly by replacing the sea surface flux scheme of Louis et al. (1982), which is used in the JRA-55 system, by the COARE3.0 scheme and the adjustment of the cumulus convection and stratocumulus cloud schemes, as seen in Section 4. In contrast, differences in the 4DVAR scheme, configuration of the inner model other than the resolution, and assimilated observation data are not significant between the JRA-55 system and the atmosphere analysis subsystem of MRI-CDA1. The daily SST and SIC fields of COBE-SST are adopted for the sea surface boundary conditions in JRA-55, the same as in UCPL-Exp. It should be noted that the SST field of COBE-SST is assimilated into the ocean component in CDA-Exp and NOOC-Exp.

In situ SAT observations are not assimilated in the 4DVAR analysis of JRA-55. However, the JRA-55 system also conducts a supplemental surface analysis to provide a distribution of atmospheric surface parameters consistent with in situ observations. Surface analysis is not reflected...
in the reanalysis fields after the valid time of the analysis. In this study, the daily SAT fields produced by surface analysis are also used to validate the SAT fields in the coupled reanalysis.

The Global Precipitation Climatology Project (GPCP) Daily Analysis Version 2.3 (hereafter simply referred to as GPCP), the objective analysis of daily precipitation by merging the data from rain gauge stations, satellites and sounding observations (Huffman et al., 2001; Adler et al., 2017), is employed for the validation of the daily precipitation fields and used for estimation of SST–precipitation relationship along with daily SST provided in COBE-SST (hereafter, this SST is simply referred to as COBE-SST). Daily average of in situ SST (at 1 m depth) and SAT (at 3 m height) observations, and daily precipitation (rain gauge) data acquired by the TAO/TRITON array (McPhaden et al., 1998; Ando et al., 2017) are also used to examine the accuracy of the reanalysis fields and for estimation of the SST–precipitation and SST–SAT relationships at the buoy positions. It should be noted that temperature and salinity profiles observed by the TAO/TRITON array are assimilated in the reanalysis experiments, and also used for generation of COBE-SST.

3.3 Data processing

All daily fields of atmospheric parameters and SST, including those in the reanalysis experiments, JRA-55, GPCP and COBE-SST, are horizontally interpolated to a 1.25° grid before use for analysis. In contrast, native-grid data are used for the ocean parameters except for SST. Here, the nominal depth of all SST data is 1 m, and SST is generally replaced by the average of the SST and the sea ice top temperature weighted by SIC in the sea ice areas because the weighted average of heat fluxes at the sea surface and on the sea ice top is adopted for the bottom boundary condition in the atmospheric component of the coupled model subsystem. Daily precipitations for the reanalysis experiments and JRA-55 are calculated from 6-hr predictions of the outer models (i.e., the coupled model for the reanalysis experiments and the uncoupled GSM for JRA-55) after adding atmospheric analysis increments. It should be noted that JRA-55 provides the precipitation in the 6-hr predictions as its standard precipitation product. Then, 1–10-day and 10–60-day timescale variation fields are extracted from the daily fields using cosine–Lanczos bandpass filters (Mooers and Smith, 1968). Hereafter, we refer to the timescales of 1–10 days and 10–60 days as the weather and subseasonal timescales, respectively.

To evaluate the accuracy of the daily precipitation in the reanalysis experiments, we compute mean errors (biases) and root-mean-square errors (RMSEs) of the precipitation with respect to GPCP, as well as correlations with GPCP, for the entire 2014–2015 period at each horizontal grid point. The same statistics are also calculated for JRA-55. It should be noted that “precipitation” in most instances indicates daily precipitation in this study. We also calculate SAT and precipitation biases in the reanalysis experiments and JRA-55 from the data observed by the TAO/TRITON buoys and correlations of these parameters with the TAO/TRITON data. The statistics are estimated from the available TAO/TRITON data for the period 2014–2015. Correlations with GPCP and the TAO/TRITON data are also estimated for the weather and subseasonal timescale variations of precipitation, SAT and SST in the reanalysis experiments. The correlations with GPCP are estimated for the period from January 1, 2014 to October 27, 2015 because the band-passed data for the 10–60-day timescale are not available for the first and last 30 days and we need to set further margins for the calculation of the lead/lag correlations and regressions described below. The correlations with the TAO/TRITON data are calculated from the available data for the same period. The statistics with respect to TAO/TRITON data are calculated only for the buoys at which data are available for more than 100 days during this period.

Correlation and regression coefficients of precipitation/SAT with leads/lags on SST at each grid point are also evaluated for the weather and subseasonal timescale variations in the reanalysis and simulation experiments, as well as the lead/lag correlations between GPCP and COBE-SST. The correlation and regression coefficients are evaluated for the period from January 1, 2014 to October 27, 2015. We also evaluate the lead/lag correlations of SST–precipitation and SST–SAT using the data from each TAO/TRITON buoy. The correlations are evaluated from all data observed by the TAO/TRITON buoys since the beginning of their deployments until the end of 2019 because there are not sufficient continuous data in the period of the reanalysis experiments for most buoy positions. Here, we assume that the statistical relationships do not change in the long period.

We also estimate the regression coefficients of SST, SAT and surface wind velocity at each grid point on SST at 2°N and 125°W for the subseasonal timescale variations in CDA-Exp and UCPL-Exp in order to evaluate the representation of tropical instability waves (TIWs). The regressions are estimated for the period from June 1, 2014 to January 31, 2015, in which the activity of TIWs is stimulated.

4 COMPARISON WITH JRA-55

First, we compare the precipitation and SAT fields of CDA-Exp, UCPL-Exp and JRA-55. Figure 2 shows the daily
precipitation fields averaged over the 2 years (2014–2015) in reanalysis experiments, JRA-55 and the GPCP data. Here, the daily precipitations for the reanalysis experiments and JRA-55 are calculated from 6-hr predictions of the outer models (i.e., the coupled model for the reanalysis experiments and the uncoupled GSM for JRA-55) after adding atmospheric analysis increments. Comparison of the precipitation field between JRA-55 and the GPCP data indicates that, although the general distribution is well reconstructed in JRA-55, it has excess rainfall in the tropics, particularly over the Pacific Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). In contrast, the excess rainfall is well suppressed in CDA-Exp. However, it should be noted that the excess rainfall is also reduced to a similar level in UCPL-Exp. This means that the improvement is not due to the implementation of coupled data assimilation, but due to the improvement of the atmosphere component of the coupled model subsystem over the atmosphere model used in JRA-55. It has been pointed out that the excess rainfall in JRA-55 is most likely related to the dry bias and the spin-down problem (precipitation is excessive immediately after the start of predictions and then gradually decreases) of the outer model in the regions of deep convection (Kobayashi et al., 2015). However, modifications of the atmospheric component performed as part of the coupled model development, such as the tuning of the cumulus convection scheme and the replacement of the flux bulk formula, result in mitigation of these problems in the reanalysis experiments. Thus, modification that aims to improve the climate representation of the coupled model could simultaneously improve short-term predictions.

JRA-55 also has spurious precipitation peaks around Sri Lanka and on the western coast of Sumatra Island. In contrast to the excess rainfall in the entire tropics, these spurious peaks remain in both reanalysis experiments. A similar spurious peak is often found near the east coast of India in atmosphere models developed in JMA, and Fujii et al. (2009) reported that a similar spurious peak found in a free simulation result of a JMA atmosphere model is suppressed as a result of a semi-coupled data assimilation experiment in which the atmosphere model
is coupled with an ocean data assimilation system. In contrast, coupled data assimilation does not affect the spurious peak effectively in the current study.

Figure 3a shows that the absolute value of the bias (absolute bias, or bias amplitude) of precipitation in CDA-Exp from GPCP is substantially reduced from that in JRA-55 over the tropical oceans, although it is considerably increased in broad areas of northern South America and Central Africa. Table 3 shows that, compared with JRA-55, CDA-Exp reduces the global average of the absolute bias by 30% and the bias averaged in the domain of 20°S–20°N and 120°E–80°W by 60% (the average in this domain is referred to as the TP average as the domain roughly represents the tropical Pacific). In CDA-Exp, the RMSE with respect to GPCP is also reduced and the correlation with GPCP is increased over a large part of the ocean area (Figure 3bc and Table 3). However, Table 3 indicates that the global and TP averages of these statistics for CDA-Exp are rather close to those for UCPL-Exp. Thus, we conclude that the improvements in the precipitation fields in CDA-Exp over JRA-55 (the reductions of the absolute bias and the RMSE, and the increase of the correlation) are mostly due to the difference in the atmospheric component of the coupled model subsystem from the atmosphere model used in JRA-55.

Comparison with precipitation data observed by the TAO/TRITON buoys also indicates that the precipitation bias is effectively reduced owing to the suppression of the
TABLE 3 Global and TP averages of absolute bias and RMSE of precipitation from GPCP, and correlation of precipitation with GPCP for JRA-55, CDA-Exp and UCPL-Exp

|            | Absolute bias (mm·day⁻¹) | RMSE (mm·day⁻¹) | Correlation (×10⁻²) |
|------------|--------------------------|-----------------|---------------------|
|            | Global average | TP average | Global average | TP average | Global average | TP average |
| JRA-55     | 0.796 (52%)       | 1.909 (58%)    | 4.916 (52%)       | 7.313 (58%)   | 55.12         | 54.96      |
| CDA-Exp    | 0.561 (70.5%)     | 0.776 (40.7%)  | 4.391 (89.3%)     | 6.177 (84.5%) | 57.33         | 57.23      |
| UCPL-Exp   | 0.565 (71.0%)     | 0.794 (41.6%)  | 4.396 (89.4%)     | 6.194 (84.7%) | 57.29         | 57.05      |

Note: The ratio of the averages of absolute biases and RMSEs for CDA-Exp and UCPL-Exp to the averages for JRA-55 are also denoted in parentheses.

FIGURE 4 SAT differences (units of K) in (a) CDA-Exp, (b) UCPL-Exp and (c) JRA-55 supplemental surface analysis averaged in 2014–2015 from SAT in JRA-55 averaged in the same period

overestimation in the western tropical Pacific in CDA-Exp (Figure S1a). In contrast, the correlation indicates that the variation of precipitation in CDA-Exp is less consistent with the observations in the western tropical Pacific than the variation in JRA-55 (Figure S1b). This partly reflects the fact that the correlation with GPCP is not consistently increased in the western equatorial Pacific, but it may also reveal a discrepancy between GPCP and the TAO/TRITON data.

The difference between the SAT fields of CDA-Exp and JRA-55 (Figure 4a), as well as the difference in precipitation, mainly originates from the difference between the atmosphere component of the coupled model subsystem and the JRA-55 atmosphere model as it is very similar to the difference between UCPL-Exp and JRA-55 (Figure 4b). Compared with JRA-55, SAT in the two analysis experiments is increased in areas with heavy rainfall, such as ITCZ and SPCZ, due to the decrease in convective clouds associated with the suppressed rainfall. In contrast, SAT is decreased in the whole ocean area, except for the heavy-rain and sea ice areas. This cooling is mainly caused by the replacement of the flux bulk formula performed when the coupled model subsystem was developed. The replacement removes excess latent and sensible heat fluxes into the atmosphere found in JRA-55 (Kang and Ahn, 2015; Valdivieso et al., 2015) and improves the global ocean heat budget (Figure S2). The reduction of latent and sensible heat fluxes in CDA-Exp is much larger than the difference of those fluxes between CDA-Exp and UCPL-Exp, and still larger than the difference between CDA-Exp and FREE-Exp, in the tropical and subtropical regions (Figure S3). The reduction of the sensible heat flux induces a decrease in the SAT in CDA-Exp. The SAT field also has a large difference between CDA-Exp and JRA-55 in the sea ice areas, probably due to the difference in the treatment of sea ice properties, which is not discussed further in this paper.

Comparison of SAT between JRA-55 and its supplemental surface analysis (Figure 4c) suggests that SAT in JRA-55 has a cool bias over most ocean areas other than the Arctic Ocean. Thus, the decrease in SAT in significant parts of the ocean in CDA-Exp (Figure 4a) indicates that the cool bias is generally increased in those areas. In contrast, the cool bias is mitigated over the tropical oceans in which the excess rainfall is suppressed. This tendency can be confirmed by comparison with the TAO/TRITON data (Figure 5). The absolute bias from the TAO/TRITON data is decreased in the western tropical Pacific and north of 5°N, but increased in the central and eastern equatorial and tropical South Pacific. The comparison also indicates that the reproducibility of the SAT variation, represented by the correlation, is generally improved over JRA-55.
in the western and central tropical Pacific in CDA-Exp. Because the correlation for UCPL-Exp generally increases, as well as the correlation for CDA-Exp (Figure S4), this improvement is mainly due to modifying the atmospheric component of the coupled model subsystem.

5 | COMPARISON BETWEEN CDA-EXP AND UCPL-EXP

5.1 | Mean state and full variability

Figure 6a demonstrates that the difference between the 2-year averaged precipitation fields of CDA-Exp and UCPL-Exp has a systematic pattern, but the difference is considerably smaller than that of the two experiments from JRA-55. Compared with UCPL-Exp, precipitation decreases in CDA-Exp south of ITCZ in the eastern equatorial Pacific and the equatorial Atlantic, and over SPCZ and the South Indian Convergence Zone (SICZ). Figure 7a indicates that the absolute bias of the precipitation from GPCP is reduced in these regions because the precipitation field in UCPL-Exp (Figure 2b) generally has a positive bias in the tropics. In contrast, precipitation is heavier in CDA-Exp north of ITCZ in the eastern tropical Pacific and the tropical Atlantic, over the western equatorial Pacific warm pool north of SPCZ and north of the equator in the tropical Indian Ocean. The absolute biases are generally larger in CDA-Exp in those areas. Precipitation also increases in the subtropical regions of the North Pacific and the North Atlantic. It is also interesting to note that the bias is reduced in the Gulf Stream Extension region and a part of the subtropical North Pacific. Both the global and TP averages of the absolute bias from GPCP are slightly reduced in CDA-Exp, as shown in Table 4. However, the comparison with the TAO/TRITON data does not show consistent reduction of the western equatorial Pacific bias in CDA-Exp (Figure S5a). The difference of precipitation generally causes the opposite pattern of the sea surface salinity (SSS; salinity at 1 m depth estimated in the ocean component) difference between CDA-Exp and UCPL-Exp (Figure S6a). SSS decreases over the western Pacific warm pool, north of the equator in the tropical Indian Ocean and around the Gulf Stream Extension Region, whereas it increases in the eastern equatorial Pacific and over the SPCZ and SICZ.

The mechanism responsible for the pattern in the precipitation difference between CDA-Exp and UCPL-Exp is not clear, but the difference in the SST field in CDA-Exp from the prescribed SST in UCPL-Exp (i.e., COBE-SST), shown in Figure 8a, is probably linked to the precipitation
difference. For example, the increased rainfall north of ITCZ in the eastern equatorial Pacific is likely to be associated with warmer temperatures in the band of the local temperature maximum along 6°N (Figure S7). The increased rainfall over the Gulf Stream Extension is probably due to the local temperature maximum and the sharper temperature front.

Figure 7b indicates that, compared with UCPL-Exp, the precipitation RMSE in CDA-Exp from GPCP is generally reduced in the tropical Atlantic, the eastern tropical Pacific and over SPCZ. Both the global and TP averages of the RMSE from GPCP are reduced (Table 4). Meanwhile, the global and TP averages of the precipitation correlation with GPCP in CDA-Exp are barely increased in comparison with UCPL-Exp. Figure 7c shows that the areas of increase and decrease in the precipitation correlation are scattered, although the areas of increase are slightly dominant. The correlation with the TAO/TRITON data is increased at more than half of the observation points in the western tropical Pacific in CDA-Exp (Figure S8).
TABLE 4 Differences in global and TP averages of absolute bias and RMSE of precipitation from GPCP, and correlation of precipitation with GPCP between CDA-Exp and UCPL-Exp (CDA-Exp minus UCPL-Exp), and between CDA-Exp and NOOC-Exp (CDA-Exp minus NOOC-Exp)

|                         | Absolute bias (mm day$^{-1}$) | RMSE (mm day$^{-1}$) | Correlation ($\times 10^{-2}$) |
|-------------------------|-------------------------------|----------------------|-------------------------------|
|                         | Global average | TP average | Global average | TP average | Global average | TP average |
| CDA – UCPL              | $-4.0 \times 10^{-3}$ (–0.71%) | $-18.0 \times 10^{-3}$ (–2.32%) | $-6.1 \times 10^{-3}$ (–0.14%) | $-17.5 \times 10^{-3}$ (–0.28%) | 0.03 | 0.18 |
| CDA – NOOC              | $-0.7 \times 10^{-3}$ (–0.13%) | $-0.3 \times 10^{-3}$ (–0.04%) | $0.0 \times 10^{-3}$ (0.00%) | $2.8 \times 10^{-3}$ (0.05%) | 0.03 | 0.03 |

Note: Additionally, the ratios of the differences for absolute bias and RMSE to the CDA-Exp averages are denoted in parentheses.

FIGURE 8 Differences in (a) SST that forces the atmosphere component, (b) SAT and (c) SST calculated in the ocean component (as the temperature at 1 m) averaged in 2014–2015 between CDA-Exp and UCPL-Exp (CDA-Exp minus UCPL-Exp). Units are K. SST is replaced by the mean of SST and the temperature at the top of sea ice weighted by the ice concentration ratio in the sea ice areas in (a). Sea ice temperature is not reflected in (c).

These results broadly indicate that precipitation variation in CDA-Exp is more consistent with the observation-based datasets than in UCPL-Exp. The explanation for this is discussed in the following subsections.

Meanwhile, the difference between the 2-year average SAT in CDA-Exp and UCPL-Exp (Figure 8b) can be mostly explained by the difference in SST (the mean of SST and the temperature at the sea ice top weighted by the sea ice concentration ratio in sea ice areas) that forces the atmospheric component, that is, the difference of SST in CDA-Exp from COBE-SST (Figure 8a). Compared with UCPL-Exp, SAT is generally increased in the tropical and subtropical regions in CDA-Exp. Notable increase is found on the West Coast of the USA and the continents of South America and Africa. SAT is considerably decreased in sea ice regions. In addition, SAT decrease can be seen in the subarctic and subpolar regions, the western subtropical Atlantic and the Arabian Sea, and on the west coasts of Mexico and Australia. This pattern is almost identical to that of the SST difference.

Here, it should be noted that the difference of SST in CDA-Exp from SST calculated in the ocean component in UCPL-Exp (Figure 8c) is much smaller than the difference between SST in CDA-Exp and COBE-SST in most ocean areas. This means that delivering SST and surface ocean currents from the ocean component to the atmosphere component minimally affects the mean SST in CDA-Exp. Therefore, the SAT difference between CDA-Exp and UCPL-Exp arises mostly because the ocean component does not completely reproduce the SST field assimilated (i.e., COBE-SST). This is allowed by the loose constraint to the SST data through the ocean data assimilation with 10-day cycles (see Appendix A).

Figure 9a indicates that the increase of SAT in the tropical Pacific in CDA-Exp generally mitigates the cool bias from SAT data observed by TAO/TRITON buoys found in UCPL-Exp. On the contrary, in CDA-Exp, the correlation is generally increased in the central and western tropical Pacific, and is generally decreased in the eastern tropical Pacific compared with UCPL-Exp.

It should be also noted that the precipitation difference between CDA-Exp and UCPL-Exp (Figure 6a) is quite similar to the difference between NOOC-Exp and UCPL-Exp (Figure 6b). The differences in the global and TP averages of the statistical scores (the absolute bias, the RMSE and the correlation) between CDA-Exp and NOOC-Exp are also much smaller than the differences between CDA-Exp and UCPL-Exp (Table 4, and the difference distributions in the statistics between CDA-Exp and NOOC-Exp shown in Figure S8). These results suggest that delivering surface
ocean currents from the ocean component to the atmospheric component does not affect the precipitation field effectively in CDA-Exp. In addition, the SST difference between CDA-Exp and NOOC-Exp (Figure S9a) is as small as the difference between SST in CDA-Exp and that calculated by the ocean component in UCPL-Exp (Figure 8c). Therefore, the SAT differences between CDA-Exp and NOOC-Exp (Figure S9b) are also negligible in comparison with the SAT difference between CDA-Exp and UCPL-Exp (Figure 8a). Thus, the coupling of the surface ocean currents does not cause notable change in the SAT field in CDA-Exp.

Coupling of the surface ocean currents, mainly the use of current velocities in the ocean component to estimate wind stress fields, strengthens the easterly trade winds over westward South and North Equatorial Currents and weakens them over the eastward North Equatorial Counter Currents (shown in Figure S10ab). It also shifts the ocean currents above the thermocline eastward, causes an El-Niño-like temperature anomaly (Figure S10cd) and intensifies the high salinity anomaly in the eastern equatorial Pacific (Figure S6b). However, these influences are small and hardly affect the other atmospheric fields.

5.2 Subseasonal variations

This subsection examines the variation in the precipitation and SAT fields on the subseasonal (10–60-day) timescale. First, the distributions of the precipitation regression coefficients with a 7-day lag, with no lead/lag and with a 5-day lead on SST are examined in Figure 10. In CDA-Exp, there is a strong negative regression with a 5-day lead in the heavy rainfall area of the tropics. This negative regression is caused by the SST decrease after atmospheric convection and rainfall and the SST increases after droughts. In contrast, the positive regression of precipitation with a 7-day lag implies that SST rises tend to induce atmospheric convections approximately 7 days later. It should be noted that the simultaneous regression is negative over ITCZ in the tropical western and central North Pacific, SPCZ and SICZ, although it is weakened in comparison with a 5-day lead. Kobayashi et al. (2021) suggested that negative values of the simultaneous correlation are associated with the downwards propagation of temperature signals to the ocean interior by ocean mixing.

It is, therefore, noted that Figure 10 indicates that the negative regressions with a 5-day lead and with no lead/lag and the positive regression with a 7-day lag are enhanced in CDA-Exp compared with UCPL-Exp. In addition, Figure 11a shows the lead–lag correlation coefficients between SST and precipitation averaged in the 10°S–10°N, 150–170°E area in the western tropical Pacific. This figure indicates that, compared with UCPL-Exp, the lead–lag correlation between SST and precipitation in this area is amplified and brought closer to the correlation between COBE-SST and GPCP in CDA-Exp, although the lag for the precipitation peak in UCPL-Exp, which corresponds well to the lag between GPCP and COBE-SST, is shorter in CDA-Exp. Kobayashi et al. (2021) reported that CDA-Exp has a similar improvement in the SST–precipitation correlation in the area further west in the tropical Pacific (10°S–10°N, 130–150°E), and these improvements are consistent with those noted in previous studies (Saha et al., 2010; Feng et al., 2018). They further indicated that the speed difference of the heat propagation in the ocean mixed layer causes the precipitation phase difference between CDA-Exp and UCPL-Exp (i.e., GPCP).

Meanwhile, the amplitude of the lead–lag correlation calculated from SST and precipitation data from the TAO/TRITON array is much smaller than that of the correlation between COBE-SST and GPCP. Thus, the plot for the TAO/TRITON data has a smaller amplitude than that for UCPL-Exp, and it deviates further from the plot for CDA-Exp, although the lag of the precipitation peak for CDA-Exp is more consistent with the TAO/TRITON data. The reason for the discrepancy between the two observation-based correlation plots (for GPCP and the TAO/TRITON data) is not clear. This may stem from the analysis errors induced when GPCP was generated or the difference in the period for which the correlation coefficients were estimated. We should also consider the
The large negative regression with a 5-day lead and the large positive regression with a 7-day lag around the heavy rain areas also appears in FREE-Exp, although the distribution somewhat differs from that in CDA-Exp due to the deviation of the heavy rain areas (Figure 10). The amplitude of the lead–lag correlation change in the western Pacific area for FREE-Exp is smaller than that for CDA-Exp because of the absence of heavy rains around the Equator (Figure 11a). However, the lag of the positive peak agrees well between CDA-Exp and FREE-Exp. These rough agreements indicate that the SST–precipitation relationship is mostly reconstructed by the model physics in the coupled model subsystem.

Figure 11a also indicates that the lead–lag correlation in CDA-Exp (red line) is almost unchanged even if the precipitation data are replaced by those in UCPL-Exp (green line). This means that the coupling of the atmosphere and ocean components does not change the precipitation field in a manner affecting the SST–precipitation relationship and suggests that the relationship is improved by the SST response to atmospheric forcing in the coupled data assimilation system. This result is also consistent with previous studies (Kumar et al., 2013; Feng et al., 2018). Figure 12a shows that the correlation of the precipitation subseasonal variation with GPCP in CDA-Exp does not notably increase in comparison with UCPL-Exp, although Table 5 shows a slight increase in its global and TP averages. The correlation with the TAO/TRITON data was, also, not consistently increased (Figure S11a).

Next, we examined the relationship between SAT and SST. Figure 13a shows that the subseasonal variations of SAT and SST are positively correlated in most of the ocean area. Then, the coupling of SAT with SST is generally enhanced in CDA-Exp in comparison with UCPL-Exp (Figure 13b). Additionally, Figure 13c indicates that, in CDA-Exp, the SAT field is changed to increase the SAT regression on SST in the off-equatorial band in
FIGURE 11  (a) SST–precipitation relationship for the variations on the subseasonal timescale in the area of 10°S–10°N, 150–170°E, showing the plots of correlation coefficients between SST and precipitation at each grid point against lag/lead time of precipitation (day) averaged in the area. Red: CDA-Exp. Blue: UCPL-Exp. Cyan: FREE-Exp. Green: Precipitation in UCPL-Exp and SST in CDA-Exp. Orange: GPCP and COBE-SST. Black: TAO/TRITON data (the average of 13 observation points located in the area). (b) Same as (a) but for the relationship between SST and SAT in the area of 1–6°N, 90–170°W; the green line denotes the correlation between SST in CDA-Exp and SAT in UCPL-Exp, the orange line is omitted, and the average of 12 observation points located in the area are depicted for the TAO/TRITON data.

FIGURE 12  Global distribution of differences in correlation of precipitation with GPCP between CDA-Exp and UCPL-Exp (CDA-Exp minus UCPL-Exp) for (a) the subseasonal and (b) the weather timescales (left panels) and plots of their zonal means (right panels).

the central and eastern tropical Pacific, where TIWs are active. In fact, we can see a distinct TIW signature in the Hovmöller SST diagram averaged at 1–6°N in CDA-Exp (Figure 14a). We can also see the propagation of SAT anomalies induced by TIWs (Figure 14c). In contrast, TIWs are hardly represented in the prescribed SST field.
TABLE 5  Global and TP averages of correlation coefficients \((\times 10^{-2})\) of precipitation in CDA-Exp and UCP-Exp with GPCP and their differences between CDA-Exp and UCP-Exp

|                  | Subseasonal timescale | Weather timescale |
|------------------|-----------------------|-------------------|
|                  | Global average        | TP average        | Global average | TP average |
| CDA-Exp          | 62.081                | 65.176            | 48.202         | 38.761     |
| UCPL-Exp         | 62.050                | 64.819            | 48.194         | 38.704     |
| Difference       | 0.030                 | 0.358             | 0.007          | 0.058      |

Note: The correlation coefficients are calculated for the variations on the subseasonal and weather timescales.

in UCPL-Exp (Figure 14b) because the SST field (i.e., COBE-SST) is generated by a statistical method without imposing any physical constraints (see Appendix A). Consequently, the TIW signature is also scarcely generated in the SAT fields of UCPL-Exp (Figure 14d).

Figure 15 displays the regression maps of SST, SAT and surface winds on SST at 2°N and 125°W for CDA-Exp and UCPL-Exp. The regression maps of SST and surface winds for CDA-Exp recover well the observed features of TIWs reported by Hashizume et al. (2001) (their fig. 5). The interval of warm and cool SST anomaly peaks aligned along 2°N generally represents the wavelength of TIWs. The north-eastward extension of each anomaly is also recovered. The SAT anomaly pattern is almost the same as the SST anomaly, but the SAT anomaly deviates slightly westward owing to the lead of SAT variation on SST. The north-westerly winds blowing across the dense contours at the north-western side of the positive peak at the reference point (2°N, 125°W) in CDA-Exp are also consistent with the observation-based analysis, although winds blowing into the peak from other directions are weaker in the experiment. In contrast, the SST regression map for UCPL-Exp shows a positive anomaly extending zonally from the reference point, and the TIW features are not properly represented. Consequently, the north-westerly winds found in CDA-Exp and the observation-based analysis disappear and northerly winds are dominant at the same location in UCPL-Exp.

The lead–lag correlations between SST and SAT averaged in the 1–6°N, 90–170°W area in the two experiments are compared with the correlation calculated from the TAO observations in Figure 11b. The lead–lag correlation variation based on TAO observations is larger than the variation for UCPL-Exp, but the plot for CDA-Exp is closer to the TAO observations plot due to the coupling enhancement between SST and SAT. The TAO correlation reaches its maximum with a 1-day lead. The lead does not exist in the SST–SAT correlation for UCPL-Exp, but is recovered in CDA-Exp. The correlations between SST in CDA-Exp and SAT in UCPL-Exp are different from those calculated for SST and SAT in the same experiments, which means that SAT is adjusted to different SST in each experiment. The good agreement of the FREE-Exp plot with the observational counterpart in Figure 11b indicates that the TIW variations and the atmospheric response are fairly well represented by the coupled model, which mostly contributes to the improvement of the SST–SAT relationship in CDA-Exp in comparison with UCPL-Exp.

From the analysis above, we expect that the SAT subseasonal time series in CDA-Exp is more consistent with observation data than that in UCPL-Exp. However, if we examine the time series correlation of the time series with the TAO/TRITON data, we find that the correlation does not increase (Figure S11b). In fact, the correlation of subseasonal SST variation in CDA-Exp with the TAO/TRITON data is also not higher than that for UCPL-Exp (Figure S11c). The SST correlations for CDA-Exp are low in the eastern tropical Pacific in which TIWs are active (Figure S11d). The low correlations probably imply that

![Figure 13](https://example.com/f13)  (a) Distributions of the SAT regression coefficients with no lead/lag on SST at each horizontal point for the variations in CDA-Exp. (b) Difference of the values depicted in (a) from the regression coefficients of SAT on SST in UCPL-Exp. (c) Difference of the values depicted in (a) from the regression coefficients of SAT in UCP-Exp on SST in CDA-Exp. This difference indicates the effect of the change in SAT due to the atmosphere–ocean coupling. All regression coefficients are calculated for the variations on the subseasonal timescale.
5.3 Weather-timescale variations

This subsection discusses weather (1–10-day) timescale variations. Figure 16 shows the distributions of precipitation regression coefficients on the weather timescale with a 1-day lag and a 1-day lead on SST. In CDA-Exp, SST rises tend to be induced by droughts about 1 day before and, in turn, tend to induce atmospheric convections about 1 day later owing to coupled atmosphere–ocean physics represented in the system. Consequently, there is a strong negative regression with a 1-day lead and a strong positive regression with a 1-day lag in the tropical heavy rainfall areas. This mechanism for causing the regressions is the same as for the subseasonal variations, but lead and lag times are shorter. The negative regression with a 1-day lead and the positive regression with 1-day lag are also reproduced in FREE-Exp, although the amplitudes are somewhat smaller. In contrast, the regression coefficients are close to zero over the entire ocean with both a 1-day lead and lag in UCPL-Exp. SST variation caused by the atmospheric adjustment on the weather timescale is scarcely recovered in COBE-SST owing to a lack of physical constraints and the time-smoothing effect of the statistical method in its generation (see Appendix A), and the SST forces the atmospheric model component in UCPL-Exp. Thus, the regressions are missed in the experiment. In addition, the relationship between SAT and SST reconstructed in CDA-Exp and FREE-Exp is also weaker in UCPL-Exp (Figure 17). CDA-Exp and FREE-Exp have
positive regressions of the simultaneous SAT variation on SST in most ocean areas other than the eastern equatorial Pacific and the equatorial Atlantic, but they are substantially reduced in UCPL-Exp. Moreover, the negative SAT regression with a 2-day lag on SST observed in the same areas in CDA-Exp and FREE-Exp disappears in UCPL-Exp.

The distinct relationship between SST and the atmospheric parameters (precipitation and SAT) in CDA-Exp is also demonstrated by the plots of the lead–lag correlation coefficients averaged in the western tropical Pacific (10°S–10°N, 150–170°E) in Figure 18. The plot of the lead–lag correlations between SST and precipitation averaged for the buoys positioned in the area displays a
FIGURE 18  (a) SST–precipitation and (b) SST–SAT relationships for the variations on the weather timescale in the area of 10°S–10°N, 150–170°E. Showing the plots of correlation coefficients between SST and precipitation/SAT at each grid point against the lag/lead time of precipitation/SAT (day) averaged in the area. Red: CDA-Exp. Blue: UCPL-Exp. Cyan: FREE-Exp, Green: precipitation/SAT in UCPL-Exp and SST in CDA-Exp. Black: TAO/TRITON data (the average of 13 observation points located in the area)

clear relationship, with the minimum at a 1-day lead and the maximum at a 1-day lag. However, the plot for UCPL-Exp is almost flat because weather-timescale variation is scarcely recovered in COBE-SST. In contrast, the relationship is recovered in CDA-Exp owing to the reconstruction of the weather-timescale SST variation by the ocean model physics, although the amplitude of the correlation change with lead/lag time is larger. The similarity between the plots for CDA-Exp and FREE-Exp implies the importance of model physics for recovering the lead–lag correlation between SST and precipitation.

The SST–SAT correlation plot estimated from TAO observations also shows a distinct relationship, with the maximum at zero lead/lag and the minimum at a 2-day lag. However, the plot for UCPL-Exp has no distinct peak. In contrast, the simultaneous correlation for CDA-Exp is close to the correlation for TAO observations, and the negative peak around 2-day lag is also recovered, although the positive peak appears 1 day earlier. The lead–lag correlation for CDA-Exp is also close to that for FREE-Exp, which indicates that the model physics plays a dominant role in recovering the SST–SAT relationship.

A comparison between the red and green lines in Figure 18a shows that atmosphere–ocean coupling changes the precipitation field in the manner that intensifies the SST–precipitation relationship. However, the deviation from the plot for the TAO/TRITON data increases with this change. However, Table 5 indicates that the global and tropical averages of the precipitation correlation with GPCP on the weather timescale increase slightly. Figure 12b shows that the areas of increase and decrease in the correlation are scattered, and no clear tendency exists.

In the SST–SAT relationship, a comparison between red and green lines in Figure 18b indicates that their simultaneous correlation is improved by the change of SAT due to the coupling. Figure 19c demonstrates that weather-timescale SST variations in the tropical Pacific are robustly improved in CDA-Exp over UCPL-Exp owing to the reproduction of short-timescale variability by the ocean component of the coupled model subsystem. Figure 19b indicates that the SAT consistency with the TAO/TRITON data on the weather timescale is improved at more than half the observation points in CDA-Exp. Thus, the adjustment of SAT to the SST variation generated by the atmosphere–ocean coupling is likely to improve the SAT variation on the weather timescale in the tropical Pacific.

6  | SUMMARY

This paper introduces MRI-CDA1, a coupled atmosphere–ocean data assimilation system developed at JMA/MRI, and evaluates the precipitation and SAT fields generated by the system in a coupled reanalysis experiment. MRI-CDA1 was developed from the coupled atmosphere–ocean model and the 3DVAR ocean analysis routine used in JMA’s operational climate prediction system and the 4DVAR atmosphere analysis routine used in JMA’s operational numerical weather prediction system. To implement coupled atmosphere–ocean
data assimilation, 6-hr data assimilation with the coupled model in the outer loop is adopted for atmospheric data assimilation, and 10-day data assimilation cycles based on IAU are adopted for ocean data assimilation. In this strategy, we can use the operational coupled model and atmosphere and ocean analysis routines almost as they are without equalising the period of the atmosphere and ocean assimilation cycles. Therefore, we can take advantage of the latest developments in the operational systems.

The coupled reanalysis experiment (CDA-Exp) is conducted for the period from October 28, 2013 to December 31, 2015. We also conduct an uncoupled reanalysis experiment (UCPL-Exp), in which the atmospheric component of the coupled model does not receive any data from the ocean component and employs COBE-SST as the prescribed ocean boundary condition instead. Additionally, we conduct another sensitivity experiment (NOOC-Exp), in which the atmosphere component does not use the surface ocean current information received from the ocean component and a free simulation experiment of the coupled model used in MRI-CDA1.

Comparison with JRA-55 suggests that excess precipitation in the tropical heavy rainfall areas found in JRA-55 is suppressed in the reanalysis experiments. In addition, MRI-CDA1 generally improves the consistency of the precipitation and SAT variations with GPCP and TAO/TRITON data over JRA-55. We conclude that these improvements are generated by the modification of the atmospheric model physics through the development of the coupled model for improving climate predictions. Although these improvements do not stem from the introduction of atmosphere–ocean coupling, it should be noted that the use of the coupled data assimilation system allows us to use the modification of the atmospheric component from the original atmospheric model, which is not reflected in the initial atmospheric conditions in JMA’s current operational seasonal forecasts. The comparison indicates the possibility that modifications of the atmospheric component to improve the climate state of the coupled model could simultaneously mitigate problems affecting short-term predictions, such as the spin-down that occurs immediately after the start of predictions. It is an advantage of introducing coupled data assimilation that modifications of a coupled model for improving representation of the climate state and variability can be directly used in a coupled data assimilation system.

A comparison of the climatological precipitation between CDA-Exp and UCPL-Exp shows that precipitation is decreased south of ITCZ in the eastern equatorial Pacific and equatorial Atlantic and over SPCZ and SICZ, but increased north of ITCZ in the eastern tropical Pacific and tropical Atlantic, over the western equatorial Pacific warm pool north of SPCZ and north of the Equator in the tropical Indian Ocean. The reason for this pattern is not identified, although the difference in SST in CDA-Exp from COBE-SST, which forces the atmospheric component in UCPL-Exp, is likely to be the primary driver generating the pattern. Meanwhile, the SAT difference between CDA-Exp and UCPL-Exp is mostly explained by the SST difference. The comparison with NOOC-Exp suggests that the use of the surface ocean current information for the calculation of the wind stress and the ocean wave effect in the atmospheric component hardly affects the climatological precipitation and SAT fields.

The atmosphere–ocean coupling amplifies the lead–lag correlations between subseasonal variations of SST and precipitation in CDA-Exp, and improves the consistency of subseasonal variations of precipitation with GPCP. The amplification is mainly due to the adjustment of SST to the atmosphere by coupled model physics. The coupling also intensifies the SST–SAT relationship on the subseasonal timescale. In particular, the atmosphere–ocean coupling generates SST variations associated with TIWs that propagate westward, and the SAT field is adjusted to the SST variations in CDA-Exp.
The SST–precipitation and SST–SAT relationships on the weather timescale are also reconstructed in CDA-Exp, although the relationships are hardly seen in UCPL-Exp. The coupled model physics generates weather-timescale SST variations that are consistent with the atmospheric state, and the atmospheric parameters adjust to the SST variations through the coupled model physics. Comparison with the TAO/TRITON data indicates that the SST variations on the weather timescale are substantially improved in the equatorial Pacific, and adjustment to the SST variations in CDA-Exp increases the correlations of precipitation and SAT variations with the observation data. The precipitation correlation with GPCP is also generally increased in CDA-Exp.

In this study, improvements in precipitation and SAT fields induced by the atmosphere and ocean coupling mostly stem from an improved representation of SST variations. Better SST variations make the relationship with variations of the atmospheric parameters more realistic, and they also induce atmospheric state adjustments. It should be emphasised that it is difficult to represent SST variations consistently with ocean physics and atmosphere–ocean interaction by means other than coupled data assimilation, even if high-frequency satellite data are available. Coupled data assimilation becomes more essential when reconstructing historical SST from sparse data in the period before the modern satellite era. Thus, the ability to represent physically consistent SST is a major advantage of coupled data assimilation systems.

However, atmospheric parameters are not so clearly improved in CDA-Exp despite the ability indicated above. This is partly because MRI-CDA1 does not sufficiently reproduce SST variations. For example, the subseasonal-timescale SST variations, including the variations associated with TIWs, in CDA-Exp are not more consistent with the TAO/TRITON data than COBE-SST, and consequently, variations in SAT fields are not improved. If the ability of the coupled data assimilation system to represent SST variations is improved, we can obtain a better representation of the atmospheric state. The refinement of the surface ocean mixing scheme is likely to be essential to accomplish this improvement.

On the other hand, the weather-timescale variations of SST are substantially improved in the coupled reanalysis, but SAT and precipitation variations on the same timescale show only moderate improvements. Coupled data assimilation may bring more significant improvements of atmospheric parameters if the adjustment of the atmospheric state to the weather-timescale SST variations is represented more accurately. In addition, SST variation is highly influenced by short-wave radiation, and therefore better representation of atmospheric convection and cloud generation induced by SST variations will have a large feedback on the reproducibility of SST variations.

Another possible reason for the lack of substantial improvement of atmospheric parameters is that the connection between atmospheric and oceanic parameters is neglected in the analysis process. Changes in atmospheric parameters caused by the application of atmosphere–ocean coupling in CDA-Exp are minimal despite the SST improvement, partly due to the lack of model constraints representing the coupled physics in the 4DVAR atmosphere analysis routine. If a strongly coupled data assimilation procedure is introduced, the atmospheric parameters are expected to be more effectively corrected based on the correlations between SST and atmospheric parameters represented in the model constraints or the background error statistics used in the assimilation system.

Developing a more sophisticated method to assimilate observation data associated with the near-surface atmospheric and oceanic state is also a possible way to improve atmospheric parameters. A coupled data assimilation system has the potential to assimilate these observations in a manner that does not perturb the physical balance between the atmosphere and the ocean, and to extract more information from observations reflecting both the atmospheric and oceanic states. Near-surface observations are also indispensable to stimulate new developments for coupled models to improve near-surface ocean representation and atmospheric adjustments to oceanic variations. From this perspective, enhanced near-surface observations in the tropical Pacific recommended by the Tropical Pacific Observing System 2020 (TPOS2020) project (Cra-vatte et al., 2016) support deriving clear advantages from coupled data assimilation.

Although the benefits of coupled data assimilation found in this study may still not be evident enough, we consider that a coupled data assimilation system is required for operational weather and climate predictions and reanalysis at JMA in the future. To achieve the operational use of coupled data assimilation, we plan to develop a data assimilation method to extract both atmosphere and ocean information from satellite observation data and further refinement of the coupled model. In addition, we plan to introduce an ocean 4DVAR analysis scheme and modify the coupled data assimilation procedure to derive full benefits from the new scheme. We expect these developments to show the advantage of coupled data assimilation.

ACKNOWLEDGEMENTS

We are very grateful to two reviewers for their constructive comments. The authors also thank those who participated in the project, including Masaomi Nakamura, Yoshiaki Takeuchi, Kazutoshi Onogi, Takeshi Iriguchi,
Nariaki Saito and Takahiro Toyoda. This work was supported by JSPS KAKENHI grant number JP17H00728. GPCP Daily Analysis Version 1.3 was downloaded from https://www.ncei.noaa.gov/data/global-precipitation-climatolology-project-gpcp-daily/. The daily COBE-SST can be obtained by request to the Climate Prediction Division, JMA. The data observed by the TAO/TRITON array were downloaded from https://www.pmel.noaa.gov/tao/drupal/disdel/. The JRA-55 reanalysis data are publicly available from the JMA Data Dissemination System https://jra.kishou.go.jp/JRA-55/index_en.html and collaborative organisations (detailed information is available on the JRA-55 website). The daily precipitation, SAT, SST, surface winds, surface fluxes, ocean temperature and ocean currents simulated in the reanalysis experiments (CDA-Exp, UCPL-Exp and NOOC-Exp) can be provided by the authors upon request. The calculations of this study were performed on the FUJITSU PRIMEHPC FX100 supercomputer system of the Meteorological Research Institute. We would like to thank Editage (www.editage.com) for English language editing.

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APPENDIX A

COBE-SST and its assimilation in MRI-CDA1

The Centennial Observation-Based Estimates of the variability of SSTs and marine meteorological variables (COBE-SST) is the dataset of daily SST and SIC on a 1° × 1° grid compiled at JMA. The SST field in COBE-SST is represented by the sum of the daily field interpolated from monthly SST climatology and the anomaly from the daily field. The anomaly field is estimated from in situ SST observations using optimal interpolation (OI). The background field for the OI is given by the anomaly field of the previous day multiplied by the damping factor determined so that the anomaly reduces by half in 15 days if no observation is assimilated. The ratio of the background error standard deviation to that of the observation error,
and the background error decorrelation scale are set to four, and 600 km, respectively. No physical ocean model is used for the estimation of the SST fields. Although the measurement depth varies among in situ SST observations used in the estimation, we generally regard the nominal depth of the SST data in COBE-SST as 1 m. The SIC fields in COBE-SST are estimated from brightness temperature measured by the special sensor microwave imager (SSM/I) using NASA-team algorithms (Cavalieri et al., 1991). A detailed description of COBE-SST is found in Ishii et al. (2005).

It should be noted that relaxation of the SST field in the ocean component to the SST data is not applied in MRI-CDA1. Instead, the system assimilates the SST data in COBE-SST as follows: First, SST data are averaged over the 10-day period of the ocean data assimilation cycle. Then the data are input to the oceanic 3DVAR analysis routine as temperature observations at the uppermost level of the ocean component, that is, 1 m depth. The 3DVAR routine uses the data in the same manner as in situ temperature profiles. Here, the ratio of the background error standard deviation to that of the observation error is set to one, which implies that the decorrelation time scale is roughly 20 days. Thus, the SST field in MRI-CDA1 is allowed to vary according to oceanic and coupled atmosphere–ocean physics on the weather timescale. The SST data affect the temperature and salinity of the interior ocean, as well as sea surface salinity, through vertical background error correlations adopted in the 3DVAR routine (see Fujii and Kamachi, 2003).