Research Development of 4-Dimensional Data Assimilation System Using a Coupled Climate Model and Construction of Reanalysis Datasets for Initialization

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A 4-dimensional variational data assimilation system with a full coupled model has been successfully developed and used to better define the climatological seasonal state of the global environment. Synthesis of available observation and a sophisticated climate model by our assimilation system produces a dynamically consistent time-varying dataset which exhibits realistic features of the atmosphere, ocean, sea-ice, land surface, and their interactions. Furthermore, our sensitivity experiment using the adjoint model clarified the probablity density distributions of moisture sources of rainfall on several key regions, in addition to the identification of source regions of some important water masses and their circulation pathways. These results illustrate that our coupled data assimilation system based on the variational approach is a very powerful tool for better assessment of global environmental change associated with global warming and for more reliable predictions.

Keywords: Copupled Data Assimilation, Ensemble Climate Reanalysis, Long-Term Ocean Reanalysis, Variability and Predictability

1. Introduction

A data assimilation approach has increasingly gathered attention from both scientific and social viewpoints (e.g., CLIVAR Report in 2004), since it enables us to obtain an optimum synthesis of observational data and model results for a better description of global environmental processes (Ghil and Malanotte-Rizzoli, 1991). In fact, a considerable amount of work based on data assimilation has already been done in the area of meteorology, oceanography, hydrology, and so on. The results so far show that among a variety of assimilation methods, the 4-dimensional variational (4D-VAR) adjoint approach is one of the most attractive assimilation methods, as it has the ability to provide the best time-trajectory fit to observational data and thereby produces a dynamically self-consistent space-time dataset. Such datasets are urgently required for more accurate seasonal to interannual (S-I) prediction and are essential to our understanding of the nature of climate variability and global warming processes. A further advantage is that, in contrast to other assimilation methods, the variational adjoint approach can be applied to large systems.

For these reasons, data assimilation experiments using the variational adjoint method have recently been performed in atmospheric and oceanic research and have significantly contributed to the identification and characterization of realistic features of the climate state (Palmer et al., 1998). However, all of the previous data assimilation systems lack some important aspect of the climate system, particularly in descriptions of multi-sphere interaction processes that play crucial roles in important climate events such as the monsoon, El Niño and

Southern Oscillation (ENSO) phenomena. This is due to the primary difficulty arising from two major problems; (1) the huge computational resources required for the use of a coupled model as a base state of the assimilation system and hence (2) the existence of large differences in the statistical characteristics of tempo-spatial variabilities inherent among atmospheric, oceanic, and land-surface processes. In fact, no truly coupled data assimilation system has yet been realized.

In our research project, we take up the challenge of developing a leading-edge 4D-VAR coupled data assimilation system, with the aim to better represent the dynamical state of climate variability and thereby construct a comprehensive reanalysis dataset offering greater information content and forecast potential than existing approaches. We use the Earth Simulator as it offers the highest computational performance in practical use and hence enables us to avoid problem (1) above. To cope with problem (2), our assimilation strategy is directed to the direct correction of the monthly-mean state (here described as the "slow-mode") in each sphere by data assimilation. Note that the monthly mean state is regarded as a background state from which many of meso-scale events characterizing "fast-mode" fluctuations emerge. Such a comprehensive correction can improve both fast- and slow-mode features through enhanced performance of the forward model calculation. Whether or not our assimilation strategy is appropriate can be assessed by comparison with existing knowledge.

2. Improvement of the climate model

In general, models used in any 4D-VAR approach inevitably require levels of performance sufficient to provide full descriptions of the essential physical processes. Hence, we have improved the coupled atmosphere-ocean-sea ice-land surface model for the Earth Simulator (CFES). For this reason, by collaborating with staff of the Earth Simulator Center, we have made many modifications and have generally fixed the system by improving key aspects of the physics, thereby enhancing the physical and computational performance of the CFES to levels suitable for a 4D-VAR system. For example, we have incorporated three important new schemes into the CFES: (1) A diagnostic calculation scheme for lower stratocumulus based on Slingo (1980; 1987), (2) a land parameterization scheme MATSIRO (Minimal Advanced Treatments of Surface Interaction and Runoff; Takata et al., 2003) instead of the so-called bucket model, and (3) a new version of radiative process scheme (MstrnX; Nakajima et al. 2000, Sekiguchi et al. 2003).

Figure 1 demonstrates the effect of the new stratocumulus scheme on the representation of the global climate. The left panel of Fig. 1 was derived from the old model and lacks a stratocumulus component on the west of continents. The scarcity of stratocumulus works to generate a sea surface temperature (SST) bias, which is also found in many other climate models. On the other hand, the new scheme (right panel) works to increase an amount of stratocumulus so that the warm SST bias along the coasts significantly weakens.

The effect of including the MATSIRO scheme on the hydrological cycle over land is illustrated in Fig. 2, in which the difference in precipitation between the bucket model and

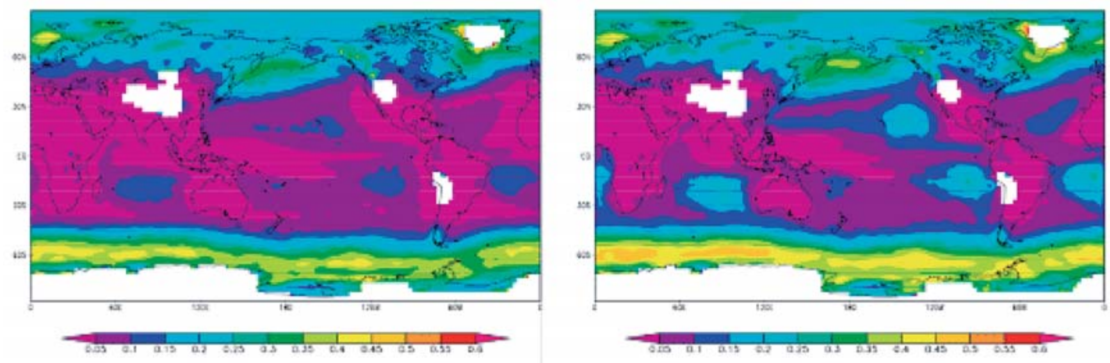

Fig. 1 Annual averaged cloud amount (925-775 hPa). Left: Old scheme. Right: New scheme.

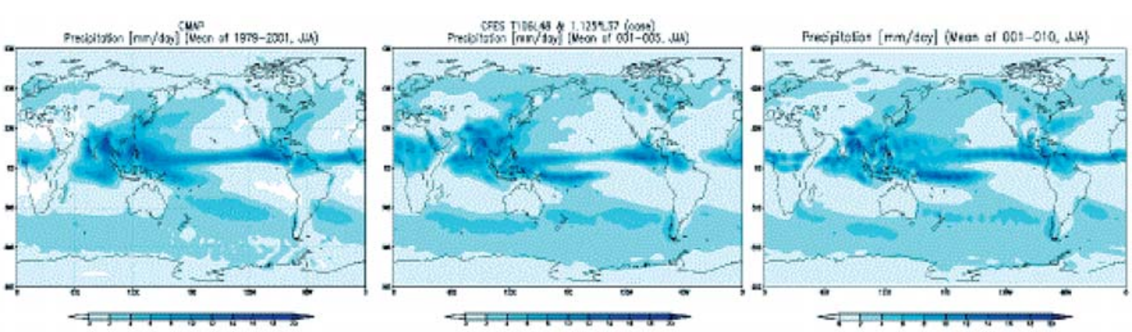

Fig. 2 Climatological mean precipitation from June to August. Left: Observation (CMAP). Middle: Calculation with the bucket model. Right: Calculation with the MATSIRO.

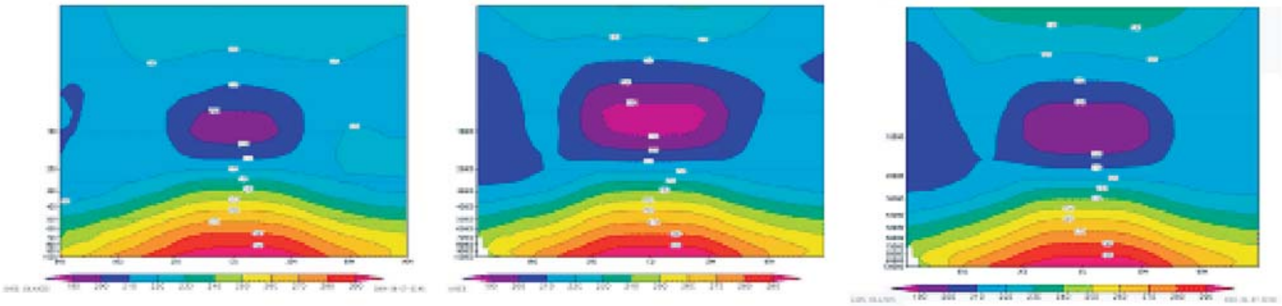

Fig. 3 Climatoligical annual mean of zonal averaged temperature. Left: the ECMWF. Middle: Calculation with the old scheme. Right: Calculation with the new scheme.

the MATSIRO case is apparent. Precipitation with the bucket model (the middle panel) is too high over the continents as compared with observations (left panel), whereas that in the MATSIRO case becomes more realistic in both spatial distribution and intensity (the right). This is because the MATSIRO scheme has the ability to treat the evapo-transpiration process by vegetation adequately.

The new scheme for radiative processes also reduces the model biases. Figure 3 shows the climatological annual mean of the zonal averaged air temperature. The temperature within the stratosphere with the old scheme is too cool relative to the ECMWF. The new scheme largely removes this defficiency. This radiation scheme also refines the mid-latitude wind jets.

3. Coupled data assimilation experiment.

In line with our assimilation strategy, we have successfully constructed a 4D-VAR coupled data assimilation system on the Earth Simulator. To reproduce realistic seasonally-varying states of the global environment in a climatological sense, optimum values of the bulk parameters for air-sea fluxes (chosen as the control variables together with the initial condition) are sought by performing a 4-ensemble experiment that treats the climatological mean of the multi-year model state. In this experiment we assimilated all the observational data available (e.g., PREPBUFFER for the atmosphere, and Reynolds SST, World Ocean Database1998, FNMOC, and TOPEX/POSEIDON sea surface height anomaly data for the ocean). Based on Sasaki's (1970) "strong constraint formalism", we have obtained an optimized 4-dimensional dataset by minimizing a cost function (e.g., Awaji et al., 2003).

Our output exhibits significant improvement in the quantitative representation of annual mean states and seasonal change. For example, the map of global precipitation (Fig. 4) reflects most of the familiar features of past studies. The sea-surface temperature obtained by our experiment (Fig. 5) is in quantitatively good agreement with observational results, and the onset sequence of Indian monsoon rainfall is well reproduced (not shown). Furthermore, our sensitivity experiment using the adjoint model clarified the probability density distribution of moisture sources of rainfall in several key regions (for Russia in Fig. 6), thereby enabling us to identify the major source regions. These results confirm that our 4D-VAR coupled data assimilation system is better able to represent the dynamical state of the global environment than earlier models and, further, create new information for better understanding of climate change mechanisms.

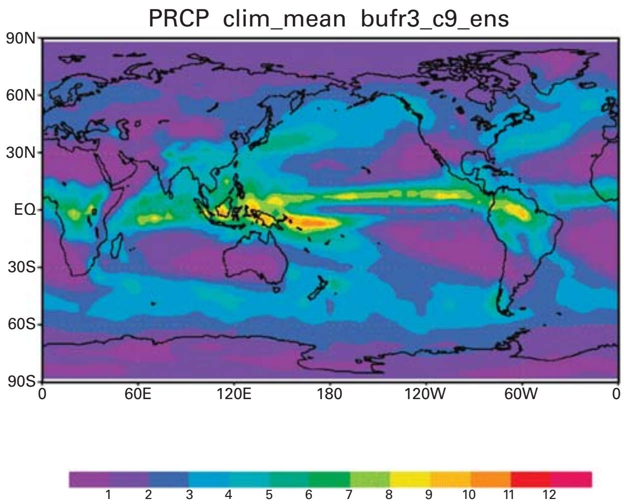

Fig. 4 Climatological global precipitation map

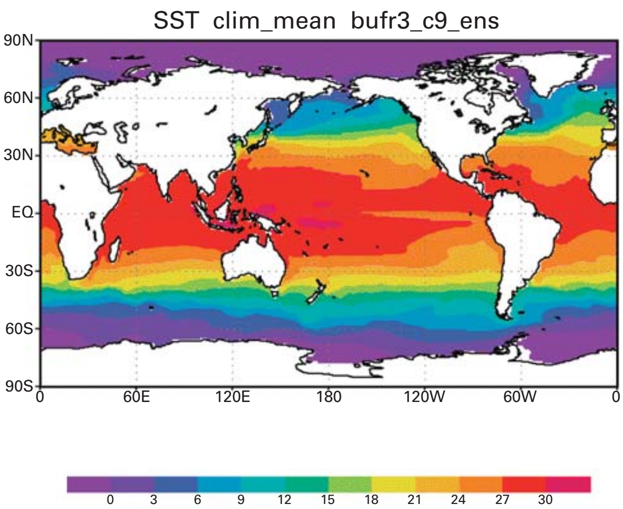

Fig. 5 Climatological global SST map

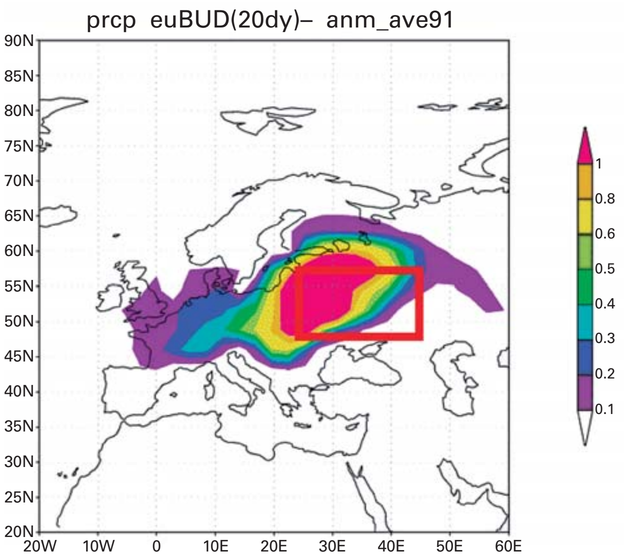

Fig. 6 Evaporative source distribution for precipitation around Russia. The red square is a target region for rainfall events

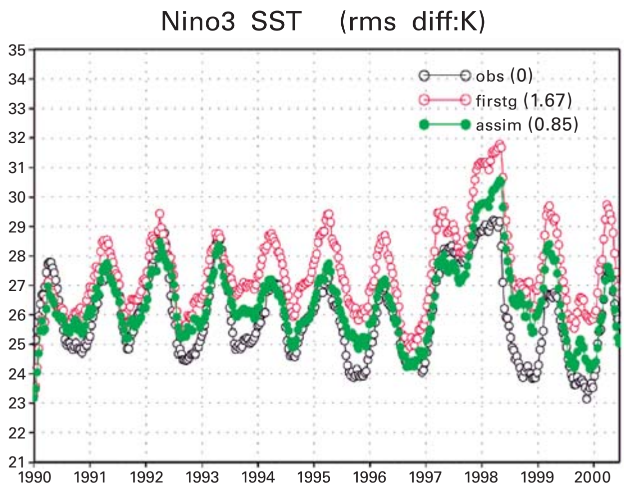

Fig. 7 Time change of NINO3 SST. Black line; observed SST. Red line: simulated SST. Green line: adjusted SST.

4. Dynamical ocean state estimation and water mass analysis using a 1990's ocean data assimilation experiment

During the period 1990-2002, the ocean component of our 4D-VAR data assimilation system was applied to a reanalysis experiment. Although it creates very high computational demand, the Earth Simulator enables us to execute one iteration of a full 10-year adjoint calculation within 8 hours on its 10 nodes. In this long-term experiment, recent ARGO float data are assimilated into the model, in addition to all the available observational data described above. The obtained reanalysis dataset shows good consistency with previous knowledge of important climate events. For example, the evolution of Niño3 SST is well reproduced (its error value reduces to about 1/2 of that from the earlier simulations of Fig. 7), which supports the notion that our dataset accurately represents the climate variability in this region. Further, our reanalysis dataset exhibits realistic subsurface water mass distribution and enables us to clarify the water mass formation and movement processes (Fig. 8). An application of a sensitivity experiment to the dichothermal and mesothermal water pathways that characterize the northwest North Pacific circulation is performed in which we investigate the sensitivity to an artificial cost given in the subarctic Pacific region. The distribution of adjoint variables shows good consistency with previous studies of the subtropical Kuroshio Extension region and western subarctic region. This result clearly represents the source region of this water.

5. Concluding remarks

By developing an innovative 4D-VAR coupled data assimilation system and by applying it to an ensemble climatological experiment, we have obtained a dynamically self-consistent reanalysis data set for the first time, and have confirmed that out data set reproduces realistic features of the atmosphere, ocean, sea-ice, land surface, and their interactions. These results illustrate the superiority of our 4D-VAR coupled data assimilation system and therefore underline its usefulness for understanding the nature of climate variability and in formulating accurate forecasts.

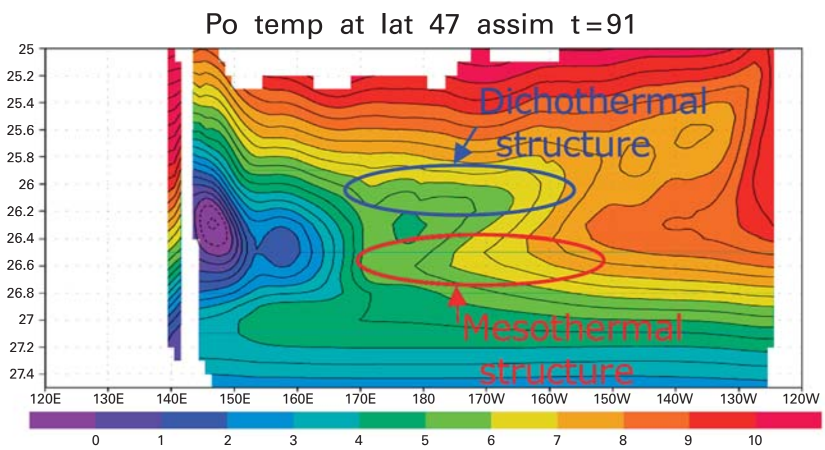

Fig. 8 Dichothermal and mesothermal water structure reproduced by our assimilation experiment

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フル結合四次元データ同化システムの研究開発と初期値化・再解析データの構築

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フル結合四次元変分法データ同化システムの構築・運用に必要な統合観測情報データセットの入手・整備及び大気・海洋アジョイントモジュール等の要素技術の研究開発を行い、例えば水循環変動の現況解析と予測に資する初期値・再解析データの作成やパラメータの最適化、及び新たな価値創生の実現につながる新規性の高いデータセットの構築が可能な最先端の四次元データ同化システムのプラットフォームを成功裏に構築するとともに、アンサンブル気候値再解析実験を開始した。具体的には、同化システムのプラットフォームである結合モデルに関しては、四次元変分法データ同化に耐えうるよう各要素モデルの物理性能を向上させ、かつ高速化を行った。これにより、2001年IPCC報告においても重要な研究開発対象として指摘されている熱帯収束帯の南北対称性や、陸面モデルの不十分性に由来する季節場の再現の不十分性、ならびに対流圏・成層圏結合過程の再現性に起因する問題点等のモデル・バイアスを大幅に軽減させることが可能となり、現状におけるモンスーンやエルニーニョ等の季節内・季節・経年変動現象の再現精度を大きく向上させる等、世界レベルの地球気候モデルの開発・改良に成功した。

同化モデルに関しては、海洋アジョイントモデルのシステム性能を一層向上させて1990年代を対象とした海洋再解析実験を前倒し的に実施し、20世紀最大の97/98のエルニーニョ現象の海面水温変動の時系列解析値を0.8°Cの偏差で再現するなど、海況変動の現実的な再現に成功した。大気アジョイントモデルについては気候値実験に適用することにより、同化解析値のエラーがシミュレーションのエラーの1/3に減少する等、十分な物理性能を有することを確認した。

以上により、各モジュールを実装したフル結合四次元変分法データ同化システムを完成させ結合初期値化実験を開始した結果、これまでにフル結合四次元変分法でのみ可能な、(1)結合データ同化により、その後の大気運動の予測に対する重要な因子である海面水温の連続的な初期値化を実現、(2)大気海洋相互作用現象の再現・予測精度の向上につながるバルク結合係数の推定、(3)従来のアプローチでは不可能であった降雨水蒸気の起源とルートを特定できる感度解析データの作成等に関して目処がついた。

キーワード：結合データ同化，アンサンブル気候値再解析，海洋長期再解析，変動と予測