Application of Ocean and Coupled Data Assimilation Systems to Scientific and Societal Benefits

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In order to make a further application of ocean and coupled data assimilation systems to important scientific and societal problems, we have attempted to build up comprehensive and coordinated datasets capable of providing high-level impacts on a wide-cross section of society. Consequently, for example, our integrated dataset works to strengthen our understanding of the dynamic nature of seasonal to internal (S-I) climate variations such as El Niño events and also to provide better initialization leading to the enhanced predictability of S-I and decadal variations. This type of research is increasingly required to reduce natural disasters and to make a good adaptation planning for global warming. In case of the application to fishery stock assessment, close relationship is identified in the late 1990s, for example, between the interannual variation of the catch per unit effort of neon flying squids in autumn and that of the eastern subtropical mode water formation. These results using the reanalysis products underline that our ocean and coupled data assimilation system has more ability in practical use than earlier systems.

Keywords: Data Assimilation, State Estimation, El Niño Prediction, Fishery stock assessment

1. Introduction

Accurate descriptions and forecasts of climate variabilities are of great importance to a wide cross section of society (Palmer et al., 2004; Mochizuki et al., 2007). Toward the better representation of the dynamical states of climate processes, recent studies have focused on an optimal synthesis of observational data and model results with the assimilation methods, since observational data available for the study are still too sparse in space and time to resolve the important energetics of climate variations on one hand and on the other hand numerical models are not enough to accurately quantify actual climate states due to the well-known uncertainties arising from initial conditions, sub-grid scale parametarization and so on (e.g., Fukumori and Wunsch, 1991, Stammer et al., 1998).

In fact, assimilation studies using ocean general circulation models (GCMs) or atmospheric GCMs have produced many fruitful outcomes such as the construction of important reanalysis datasets suitable for practical use in the identification and prediction of oceanic or atmospheric phenomena (e.g., Kalnay, 2003). However, the present use of data assimilation and its products are still limited. For this reason, we have attempted to enhance practical applications of data assimilation products to important aspects of scientific and/or societal problems. Here we present some results of the important applications to interdisciplinary scientific researches.

2. Enhanced coupled waves associated with anomalous El Niño development

Using reanalysis fields obtained from our 4D-VAR ocean-atmosphere coupled data assimilation experiments in the 1990s, we have diagnosed the air-sea coupled processes associated with anomalous SST increase in the central to eastern equatorial Pacific, focusing on the evolution of the historically strongest 1997–1998 El Niño event. Figure 1 shows that the onset of the 1997–1998 El Niño was triggered by westerly wind bursts (WWBs) in the western equatorial Pacific in February-March 1997 and the resulting downwelling Kelvin waves propagated eastward accompanied by positive sea surface temperature anomalies (SSTAs) and atmospheric fluctuations as reported by McPhaden (1999). When the coupled waves reached the central to eastern equatorial region, where larger horizontal gradients in the thermocline depth existed, they rapidly assumed large-amplitudes and were then capable of causing the strong El Niño. Such waves actually propagate

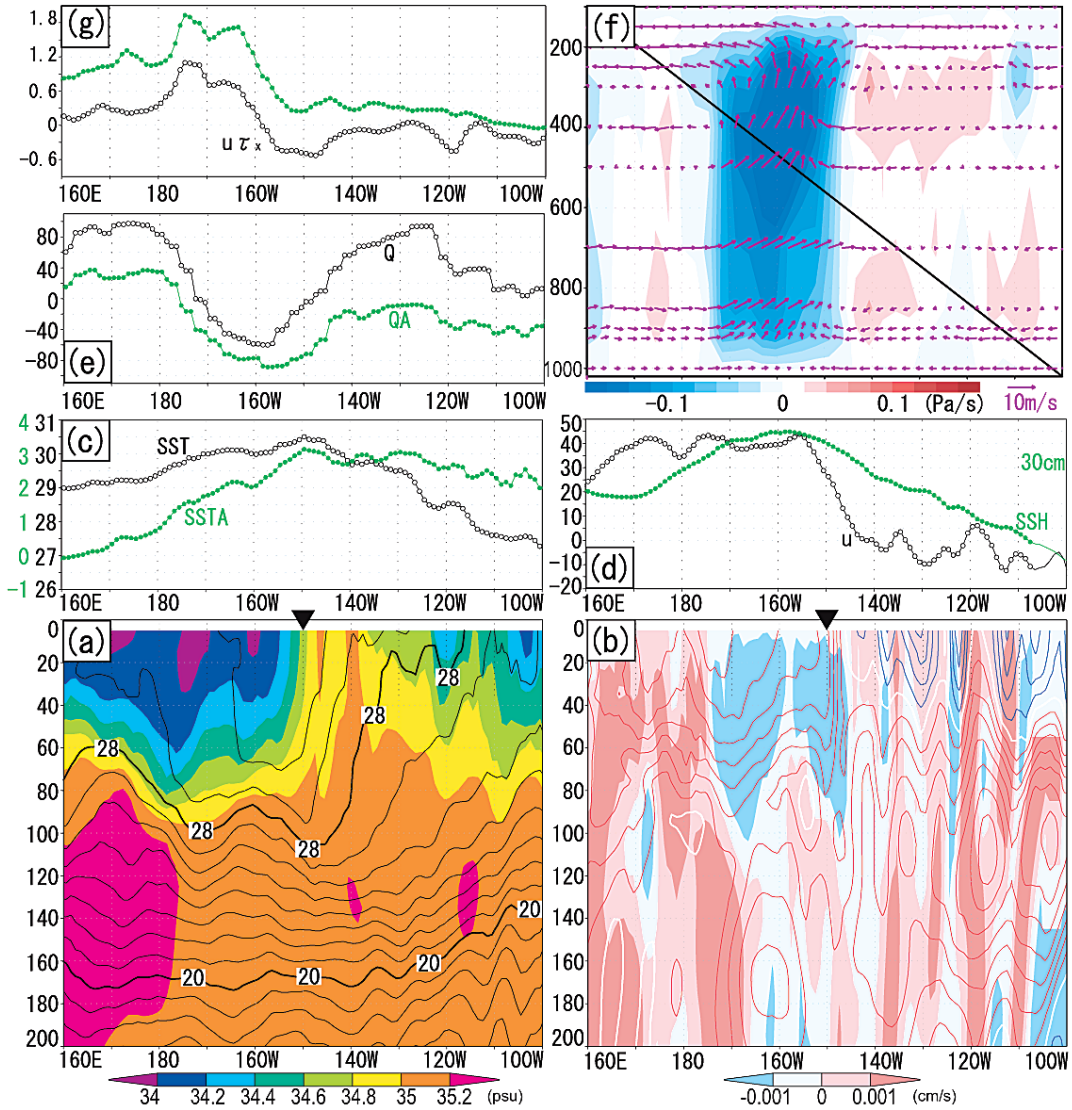

Fig. 1 Zonal distributions during the first 10 days of November 1997 of (a) salinity (shaded) and temperature (contours in ˚C), (b) vertical (shaded) and zonal velocity (contours with 10 cm/s intervals; red, white, and blue denotes eastward, zero, and westward, respectively), (c) SST (black) and SSTA (green; in ˚C), (d) oceanic surface zonal velocity (black; in cm/s) and sea-surface height (green; SSH), (e) surface downward net heat flux (black; in W/m^2) and its anomaly (green), (f) atmospheric p-velocity (shaded) and zonal velocity (horizontal components of arrows) field, and (g) power transfer from zonal wind stress to the upper 100 m ocean and its anomaly (black and green; in W/m^2). These values are averaged over 5˚S–5˚N except SSH, which is averaged over 2˚S–2˚N. SST maximum positions are indicated by black triangles in (a) and (b).

at lower speeds (50–60 cm/s) than free waves (180–200 cm/s), consistent with the dynamic nature of growing coupled modes. The coupled processes reproduced here are such that large SSTAs generate stationary twin Rossby waves off the equator to the west (Matsuno, 1966) by nonlinearly enhanced latent heat release. Equatorial westerly wind anomalies between the twin Rossby waves induce enhanced eastward wind stress anomalies, which strengthen the eastward oceanic surface flow, the depression of the thermocline, and hence the SSTAs. The coupled structure and the propagation speed of the amplified coupled waves are consistent with the unstable mode in the intermediate regime of coupled Kelvin and Rossby waves shown analytically by Yamagata (1985) and Hirst (type III, 1986).

Our analysis reveals the important role played by seasonal SST increase in the central to eastern equatorial region in the amplification of air-sea coupling in the 1997–1998 El Niño event as demonstrated in Fig. 2, which augments the effects of sharp thermocline tilt. The annual march of climatological SST has its peak in boreal summer in this region. Anomalous latent heat release by interplay between the incident Kelvin waves linked to warm SST and the seasonal rise of SST most likely works to develop unstable coupled waves. The amplified coupled waves travel eastward with relatively little loss of energy, and abruptly cease to the east of 130˚W where mean SST rapidly decreases. Note that the

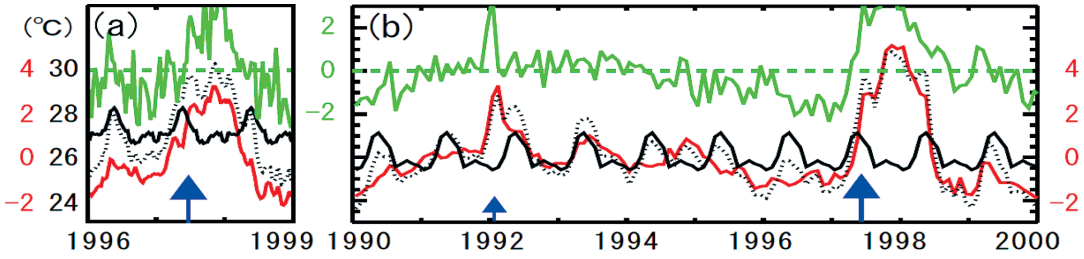

Fig. 2 Time series of the climatological seasonal march of SST (black), total SST (black dotted), SSTA (red), and zonal wind stress anomaly (green) averaged over 160°W–140°W and 2°S–2°N (a) from our CDA product and (b) from the ocean reanalysis dataset (Masuda et al., 2006).

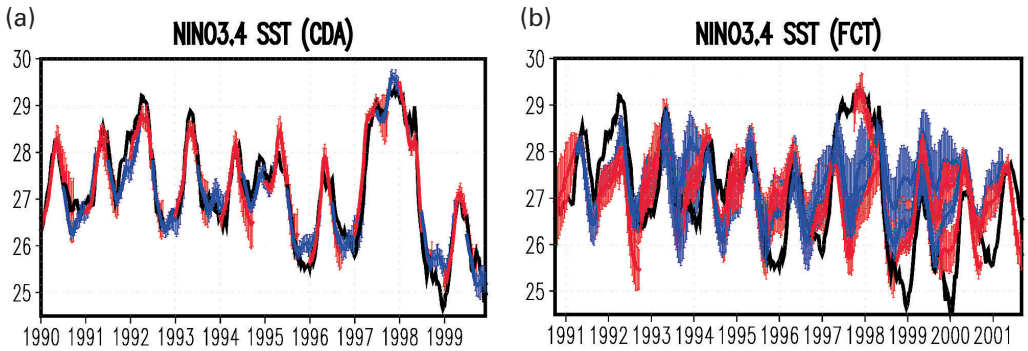

Fig. 3 (a) Reproduced NINO3.4 SST by CDA system and (b) predicted time change of NINO3.4 SST.

occurrence of such interactions around the central to eastern equatorial region is favorable to longer and hence more enhanced air-sea coupling than that suggested by Neelin et al. (2000), which develops in the eastern region. Moreover, the fact that La Niñas do not show a similar phase-locking behavior is likely explained by the absence of a nonlinear influence from the seasonal cycle on the coupling instability.

In terms of the forecasting of El Niño events in the 1990s, we have made the ensemble prediction using the reanalysis dataset obtained by the coupled data assimilation experiment. Figure 3 displays the time series of Niño 3.4 SST values in the reanalysis field obtained by our assimilation experiment, which exhibit extremely realistic time-trajectories. Using this reanalysis field as the initial condition, we have attempted the ensemble prediction. The result (Fig. 4) suggests that the longer predictability over 1-year-lead-time is realized for all the El Niño events in the 1990s. These results underline that our 4D-VAR coupled data assimilation has more ability to create important information on climate variabilities and longer forecast potential for the S-I phenomena, although further investigations are required in order to reveal the details of individual events.

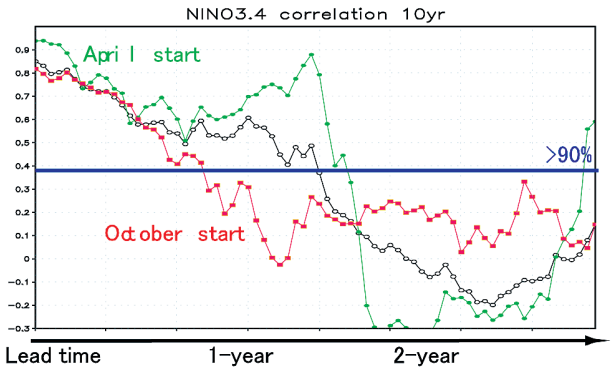

Fig. 4 NINO3.4 SST ACC for the 1990s prediction experiment.

3. Application to water resources and fishery stock assessment

In parallel with the ocean-oriented climate analysis using the high-quality reanalysis datasets obtained by our 4D-VAR reanalysis experiments, we have attempted to make high-impact applications that warrant social benefits such as water resource management and fishery stock assessment as below.

In terms of the water resource management, the source distribution and the transport process of individual rainfall events are able to be identified by the adjoint sensitivity experiment using the 4D-VAR system. As a result, evaporative sources for the typical events of heavy rainfall at some target areas are successfully traced back to their origins as observed (not shown). This gives us important information to construct the flood monitoring system that contributes to the reduction of regional damages for human activities and hence the effective risk management. Also, the left bottom panel of Fig. 5 displays an example of the estimated evaporative source distribution associated with Asian summer

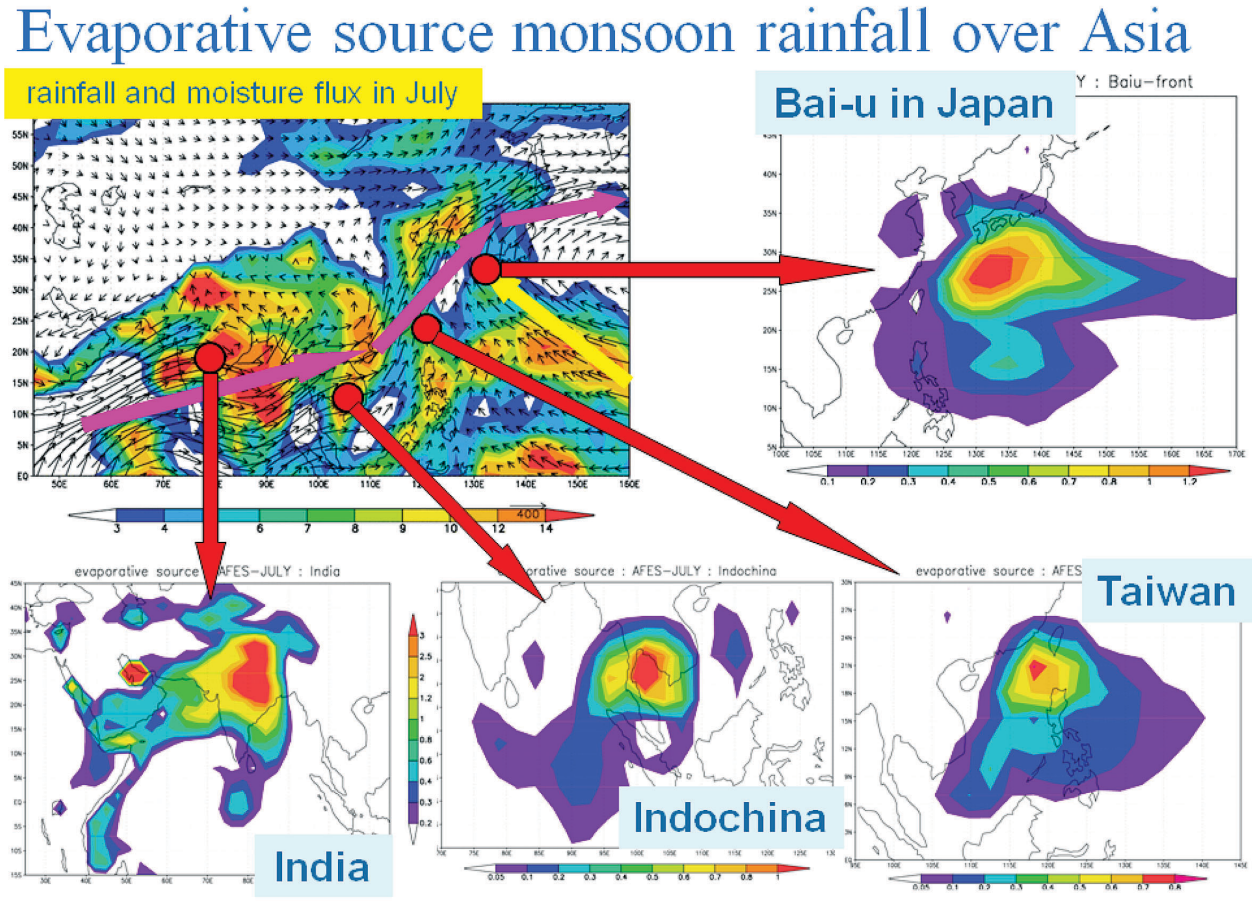

Fig. 5 Evaporative source distribution of rainfall over Asia derived from 4D-VAR adjoint sensitivity experiment.

monsoon rainfalls at specified areas of the Indochina Peninsula, through which we can detect the tempo-spatial structures of the "key phenomenon" causing the flood and drought at each area. Furthermore, the mechanism of water cycle modulations by ENSO could be elucidated by applying the 4D-VAR method to the time series of the anomalies.

Previous studies show that an accurate ocean state estimation is one of the most important factors for fishery stock assessment because almost all kinds of fishes adapt their life cycle to the ocean environment around their living field. In case of neon flying squids in the North Pacific (right panel of Fig. 6), the close relationship is found between the inter-annual variation of the catch per unit effort (CPUE) of the autumn cohort in the late 1990s and that of eastern subtropical mode water formation where is the main spawning area. On the other hand, the decadal ocean regime shift has a great influence on squid catch after 1999. These results suggest that the survival of young squids could be strongly affected by the variation in the time-varying subtropical upper ocean structure. We will make further analysis to gain more knowledge about such relationships by collaboration with fishery scientists on the 4D-VAR DA research platform.

4. A near-term global warming ensemble prediction experiment

As a first step toward more reliable global warming projection, we focus on the reduction of forecast errors for low frequency variabilities by developing a data assimilation technique. In doing so, we combined a pre-processing of observational data (nearly 5-year averaging) and the IAU method for selection and initialization of low frequency components from noisy observational data. Figure 7a displays both the observed sea surface temperature (SST; red) associated with the Pacific decadal oscillation (PDO) in the latter half of 20 century and the reproduced one (green) by our data assimilation. In addition, the result with no assimilation is denoted by a green curve. It is visible that the reproduced PDO reflects the familiar gross features of the observed one, much better than that with no assimilation. Using this analysis field as the initial condition, we performed near-term ensemble forecasts staring at 3 different years (Fig. 7b). The error bars represent the ensemble spread and hence is considered to indicate uncertainty of the forecast result. The time trajectory of the ensemble mean well follows the observed time change of low frequency variability of SST with moderate ensemble spreads. This fact suggests that our method is useful in improving near-term global warming prediction of climate variability.

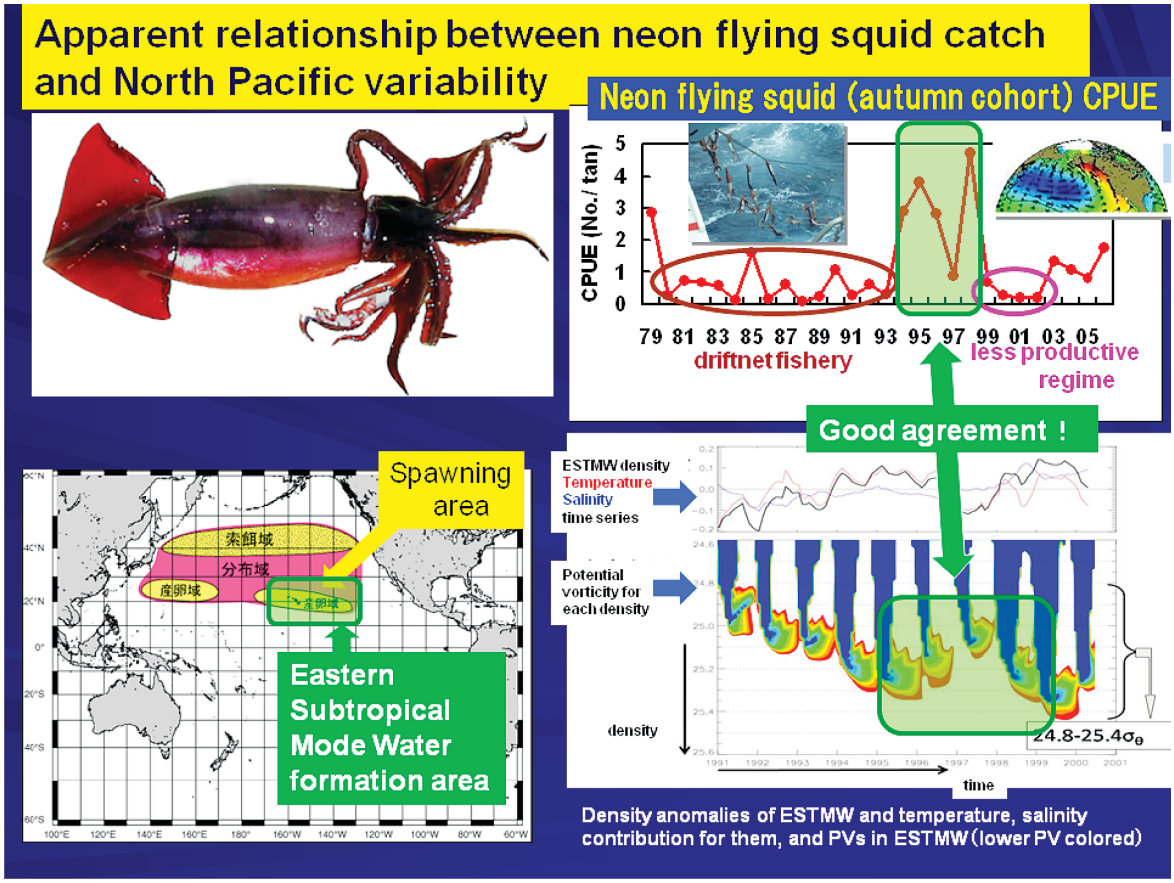

Fig. 6 Rerationship between the interannual variation of neon flying squid CPUE in North Pacific and that of eastern subtropical mode water formation.

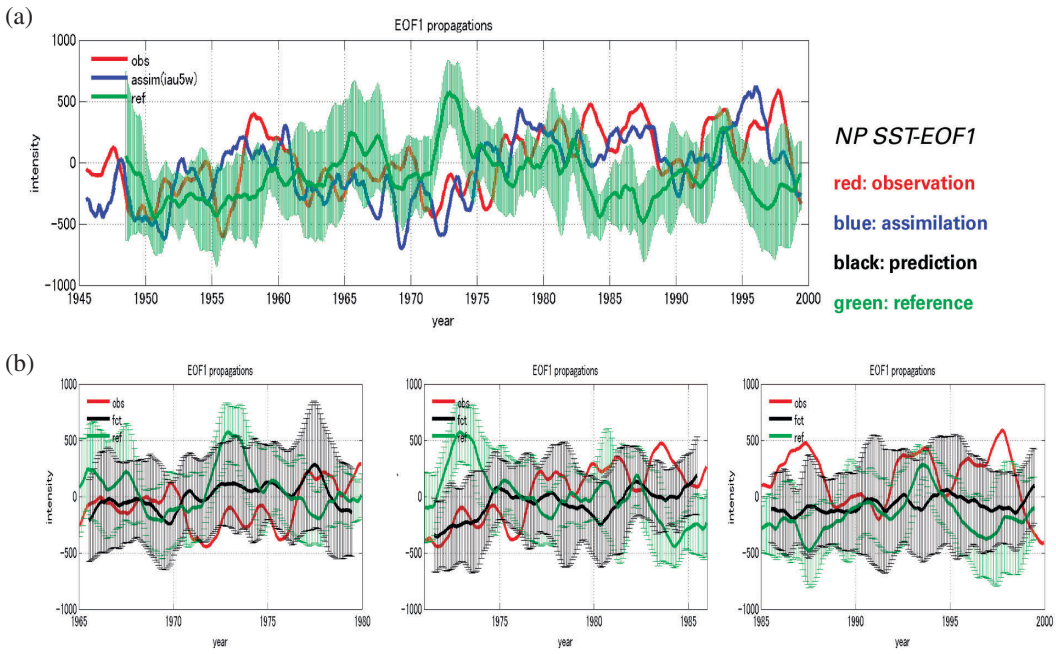

Fig. 7 (a) time series of low frequency variabilities (red: observation, blue: assimilation, black: prediction, and green: reference with no assimilation), and (b) near-term ensemble forecast results (left: starting from 1965, middle: from 1971, and right: from 1985).

5. Concluding remark

With an aim to make a further use of ocean and coupled data assimilation systems toward important scientific and societal problems, we have attempted to build up a comprehensive and coordinated datasets capable of providing high-level impacts on a wide-cross section of society. For example, the integrated dataset works to strengthen our understanding of the dynamic nature of seasonal to internal climate variations such as El Niño events and also to provide better initialization leading to the enhanced predictability of S-I phenomena in the 1990s when a variety of El Niño events took place. In case of the application to fishery stock assessment, close relationship is identified in the late 1990s, for example, between the interannual variation of the catch per unit effort of neon flying squids in autumn and that of the eastern subtropical mode water formation. These results using the reanalysis products underline that our ocean and coupled data assimilation system has more ability in practical use than earlier systems and, further, has the potential to create an interesting new prospect of ocean-related processes.

Acknowledgments

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海洋および結合データ同化システムの科学的・社会的課題解決への適用

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ＥＳ上で開発した海洋データ同化システムならびに結合データ同化システムを、一層広範かつ社会的・科学的にインパクトの大きな諸問題への利用拡張を図るため、世界の気候・水循環変動の発生源であり、甚大な自然災害をもたらすエルニーニョの科学的理解の深化及び予測性能の向上に適用した結果、多様性豊かで不規則な1990年代の全エルニーニョに対して1年先行予測に成功した。また、1980年以降の気候のレジームシフトに伴う水産資源変動と海洋物理環境変動とのかかわりを明らかにするために、当グループが作成した四次元再解析データと中央及び遠洋水産研究所提供のアカイカ資源変動データとの相関解析を行い、資源変動に果たす海洋物理環境の影響を評価するとともに、その要因を特定した。さらに「革新プログラム」における近未来予測に関して、データの前処理とＩＡＵ法を併用することにより、十年スケール変動成分の抽出と予測に良好な結果を得た。

キーワード：データ同化, 状態推定, エルニーニョ予測, 水産資源評価