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Target observations for improving initialization of high-impact ocean-atmospheric environmental events forecasting

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ABSTRACT

In this paper, we emphasize the importance of accurate initial conditions in predicting high-impact ocean-atmospheric environmental events, such as El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), tropical cyclone (TC), and Kuroshio large meander (KLM), by reviewing recent progresses toward target observations for improving the initialization of these events forecasting. Since field observations are costly and will never be dense enough to fully cover the vast space of these events, it is necessary to develop methodologies that guide the design of efficient and effective observation strategy. Of particular interest is a method called conditional non-linear optimal perturbation (CNOP), which has been shown to be very useful in determining the sensitive areas for target observations applicable to the predictions of ENSO, IOD, TC, and KLM. Further studies are needed to understand the predictability of these events under the influence of climate change, and to explore the possibility of implementing field programs of target observations. These studies are challenging but are crucially important for improving our forecast skill of the high-impact ocean-atmospheric environmental events, and thus for disaster prevention, climate change mitigation, and sustainable socio-economic development.

Keywords: atmosphere, ocean, predictability, target observation

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INTRODUCTION

High-impact ocean-atmospheric environmental events, such as El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), tropical cyclone (TC), and the Kuroshio large meander (KLM), are defined as the oceanic, weather or climate events that often induce aggressively large economic and societal loss on regional or global scales. Thus, understanding and predicting these events have been a focus of ocean and atmosphere research over the last few decades, and will continue to be so in the foreseeable future. Despite the tremendous progresses being made in the theory, observation and modeling of these events, there is still much room for improvement, especially in terms of effective observation and skillful prediction.

Of the high-impact events mentioned above, ENSO and IOD are interannual climate variations originating from the tropical Pacific and Indian basins, respectively. ENSO is known to be a coupled, ocean-atmospheric phenomenon oscillating irregularly between its warm phase (El Niño) and cold phase (La Niña), accompanied by a seesaw of low-level atmospheric pressure (Southern Oscillation) across the tropical Pacific [1]. IOD is also considered a coupled oscillation of contrasting sea surface temperature anomalies in the western and eastern tropical Indian Ocean closely coped with zonal wind anomalies along the central equatorial Indian Ocean [2]. Both ENSO and IOD have far-reaching impact, and often bring extreme weather and climate events [3,4]. It is argued that the global warming occurring during the previous decades exerted influence on ENSO and IOD and increased the frequency of related extreme events [4–6], causing much more serious natural disasters. If these events were successfully predicted, people would be able to deal with them in advance and greatly reduce the loss [7]. However, our current forecast skill for ENSO and IOD is still far from satisfactory, due to uncertainties arising from the diversity and long-term variability of these events, and also due to problems with our observation and forecast systems.

On synoptic scales, TC is by far the most influential weather event and, for many countries including China, it is the largest cause of natural disaster. TC is a rapidly rotating atmospheric storm system which originates and absorbs energy from the ocean. It is characterized by a low-pressure center, strong winds, and a spiral arrangement of thunderstorms that produce heavy rain. The forecast skill of TC track has been steadily increasing over the last few decades, due to largely improved simulation of atmospheric circulation that steers the movement of TC. In contrast, the forecast skill of TC intensity remains to be poor and poses a big challenge to the TC research community. A possible solution is to take the TC-ocean interaction into account, and to initialize TC forecasts with real-time ocean observations. On the other hand, KLM is an oceanic phenomenon characterized by large fluctuations of the Kuroshio path south of Japan, which significantly influences the atmosphere and the related temperature and precipitation. There are quite a few studies on the mechanism and predictability of KLM, but a forecast system of KLM has not yet been developed by any institutes or organizations.

A pre-requisite for skillful predictions of these high-impact ocean-atmospheric environmental events is to understand their predictability. It is known that uncertainties in numerical weather and climate predictions are caused by errors in both models and initial conditions. Many studies have explored the ENSO predictability in terms of initial error growth [8–12]. In particular, Chen *et al.* [13,14] demonstrated that the initial error is the main factor that leads to the uncertainty of ENSO forecasting, and that improving initial condition may greatly enhance the forecast skill for ENSO. Furthermore, Mu *et al.* [15], Duan *et al.* [16], and Yu *et al.* [17] emphasized that the initial errors of certain spatial structures can cause much larger prediction errors for ENSO events. The importance of initial conditions for prediction has also been demonstrated for IOD [18], KLM [19], and TC [20–24]. Thus, improving the initial fields is an effective way to improve the forecast skill of these high-impact ocean-atmospheric environmental events.

Sufficient observations are required to properly determine the initial fields for the prediction of these events. Since field observations are costly and will never be dense enough to fully cover the vast space of these events, it is necessary to develop methodologies that help to design efficient and effective observation strategy, in which we place limited number of observations in some specific areas and expect them to have a considerable impact on forecast skills. Actually, a strategy called 'target observation' or 'adaptive observation' has been developed since 1990s. Its general idea is as follows. To better predict an event at a future time t1 (verification time) in a focused area (verification area), additional observations are deployed at a future time t2 (target time, $t2 < t1$) in some special areas (sensitive areas) where the additional observations are expected to have a large contribution to reducing the prediction errors in the verification area [25]. These additional observations would be assimilated by a data assimilation system to form a more reliable initial state, which would be supplied to the model for a more accurate prediction.

A key in target observation is the determination of sensitive areas or optimal locations for targeting. Since the mid-1990s, several types of mathematical techniques have been developed to identify such locations. One of them is based on sensitivity analysis. Examples include adjoint sensitivity [26], singular vectors (SVs) [27], the ensemble transform technique [28], and the adjoint-derived sensitivity steering vector (ADSSV) [29]. Another type incorporates observations and data assimilation schemes, including Hessian SVs (HSVs) [30], analysis error covariance SVs [31,32], and the ensemble transform Kalman filter (ETKF) [33]. For most of the techniques (except ETKF), the degree of forecast error reduction cannot be assessed by target observations, which is what the public really cares about. For some adjoint-based techniques, the use of linear approximation is a limitation, especially for medium and longer range forecasts.

Recently, a non-linear technique called conditional non-linear optimal perturbation (CNOP) [34] has been developed. The so-called CNOP represents the initial perturbation that causes the largest perturbation growth at a given future time and is the most sensitive initial perturbation, therefore can be used to identify sensitive areas for targeting. CNOP has been applied to determine the sensitive areas for targeting observation associated with ENSO, TC, and KLM [19,35,36] and shows great potential in identifying the optimal locations for target observations of high-impact events. Encouraged by the CNOP idea, the sensitive areas for IOD were also explored by an ensemble approach [37] and provided information on targeting observation of IOD.

In this paper, we discuss the sensitive areas of target observations for ENSO, IOD, TC, and KLM determined by several approaches including CNOP and evaluate their potential roles in optimizing observation systems. In the next section, we examine the current status of observation networks relevant to these high-impact ocean-atmospheric environmental events, and emphasize the necessity and importance of target observation. After this, we examine the sensitive areas of target observations for each type of the events, and discuss their potential role in optimizing observation networks and thus improving forecast skills. Finally, summary and discussion are presented in last section.

CURRENT STATUS OF RELEVANT OBSERVATIONS

Observation is the basis for understanding and monitoring the ocean–atmosphere coupled system; it is also crucial in providing initial and boundary conditions for numerical forecast models. Thus, all of the large international programs in ocean and climate research have a heavy component of field observations. As a result of extensive efforts over the last few decades, a global ocean and climate observation network has been established, with various observing platforms including satellites, moored buoys, autonomous floats, etc. This global network is designed to have a relatively uniform, broad-scale coverage, and thus is not particularly aimed at predicting high-impact events. Here, we review the current status of existing observations relevant to ENSO, IOD, TC, and KLM, and point out the urgent need for improvement and optimization.

ENSO is probably the best observed high-impact phenomenon, largely due to the 10-year (1985–94) international Tropical Ocean Global Atmosphere (TOGA) program. A major accomplishment and legacy of TOGA are the successful development of the ENSO Observing System. The system was based on both *in situ* and satellite monitoring, consisting of the Tropical Atmosphere Ocean (TAO) array of moored buoys, an array of drifting buoys, volunteer observing ship (VOS) measurements, a network of island and coastal sea level measurement stations, and a constellation of complementary satellites [38–40]. With the addition of the Triangle Trans-Ocean Buoy Network (TRITON), the TAO array was renamed to TAO/TRITON array on 1 January 2000, which further improves the ENSO Observing System over the tropical western Pacific. This observation network has played and is still playing a significant role in our understanding and prediction of ENSO.

Despite these seemingly extensive observations, however, there still exists considerable uncertainty in real-time ENSO forecasting [41,42], and the current predictive skill is still far from the potential predictability of ENSO [14,43]. This might be due to deficiencies of the present forecast models, but inadequately placed observations could also be a problem. Note that the ENSO Observing System was designed at a time when we had rather limited knowledge of ENSO dynamics and predictability. It certainly needs to be updated and redesigned based on newly gained knowledge and understanding. For instance, we now realize that ENSO has different 'flavors' and such flavors change over time. Of particular interest is a type of El Niño events occurring around the dateline, being called El Niño Modoki, Warm-Pool El Niño, or Central-Pacific El Niño (CP-El Niño), which differs from the traditional Eastern-Pacific El Niño (EP-Niño) [44] in terms of both impact and mechanism, and has an apparent increase of occurrences since 1990s [45–48]. The diversity and long-term variability of ENSO, among its other complexities, pose new challenges for the tropical Pacific Observing System (TPOS). In fact, a new international program called TPOS-2020 has just been established to redesign and optimize the tropical Pacific observation network by 2020. A target observation strategy would be extremely useful for the implementation of TPOS-2020.

The Indian Ocean is historically starved of observational data, even though it plays an important role in the regional African—Asian—Australian monsoons and also in the global climate system. A long-term, sustained observing system in the Indian Ocean had not been started before this century, leaving the Indian Ocean the least observed ocean among the three major basins. In 1999, a community effort was initialized to develop the Indian Ocean Observing System (IndOOS). Under the coordination of the CLIVAR/GOOS Indian Ocean Panel, the planning and implementation are effectively done [49]. IndOOS is a multiplatform long-term observing system, which consists of Argo floats, surface drifting buoys, tide gauges, a mooring buoy array, VOS based XBT/XCTD sections, and satellite measurements as a backbone observation for sea surface conditions [50]. The system is designed to provide high frequency, near real-time climate-related observations, serving the needs of the climate studies and services in many national meteorological agencies. IndOOS has been implemented rapidly in recent years, largely through binational activities involving Japan, India, the USA, Indonesia, China, France, Holland, and South Africa. This observing system has helped to advance our understanding of IOD events, but its coarse coverage, especially in the critical regions of IOD events, is still a limitation to skillful prediction.

For TC monitoring and forecasting, there are extensive routine observations operated by meteorological agencies all over the world. Furthermore, to improve the understanding and prediction of TC, a number of regional field experiments have been conducted over the years, including the Fronts and Atlantic Storm-Track Experiment [25,51], the North Pacific Experiment [52], the Dropwindsonde Observations for TC Surveillance near the Taiwan region [53], and the Atlantic THORPEX Regional Campaign [54]. However, these observations are mostly atmospheric, and presently there are essentially no real-time ocean subsurface data suitable for the initialization of TC forecasting. Since the ocean is the breeding ground and energy supplier for TCs, the ocean-TC interaction has to play a significant role in TC development, especially in the variation of TC intensity. Therefore, the lack of oceanic data for initial fields is a serious limitation to TC forecasting. For KLM events, the existing observations are only for research purposes, and there is no operational observation network suitable for their prediction, despite their potentially large influence on regional extreme weather and climate. Therefore, in order to advance our understanding of KLM and provide accurate initial conditions for its forecast models, we are very much in need of a well-designed, targeted observing system for the Kuroshio path variations.

SENSITIVE AREAS FOR TARGET OBSERVATIONS

From above discussions, it should have become clear that additional observations with optimal design are urgently needed for improving the prediction of high-impact events such as ENSO, IOD, TC, and KLM. Then the question is how to determine such an optimal design, which, as alluded to in the introduction, is exactly the goal of the target observation strategy. The key of the target observation is to identify the sensitive areas (or optimal locations) for targeting. This is a very challenging task, but nonetheless has been explored using various approaches. In this section, we review some recent progresses in the methodologies to determine the sensitive areas for ENSO, IOD, TC, and KLM, respectively, and discuss their potential role in optimizing observation networks and thus improving forecast skills.

El Niño-Southern Oscillation

To investigate the sensitive area for ENSO forecasting, Mu *et al.* [55] and Yu *et al.* [17] studied the CNOP-type initial errors by using the well-known Zebiak-Cane model [56]. They demonstrated that the prediction uncertainties for El Niño are extremely sensitive to initial errors and that the CNOP-type initial errors cause the largest prediction uncertainty and thus represent the most sensitive patterns for El Niño forecasting. Furthermore, these sensitive patterns of initial errors also existed in the initial analysis fields of the ENSO hindcasts generated by FGOALS-g and LDEO5 models [35,57]. The largest values of CNOP-type errors are found in the eastern equatorial Pacific (Fig. 1), indicating that the initial errors in this region make the largest contribution to the errors at the prediction time, and therefore can be considered a sensitive area for El Niño forecasting [16]. In particular, Yu *et al.* [35] demonstrated that for the CNOP-type errors, when eliminating the initial errors in the eastern equatorial Pacific but keeping those in other regions unchanged, the prediction errors are largely reduced. In addition, Mu *et al.* [58] emphasized the similarities between the optimal precursor (OPR) and the optimally growing initial errors (OGE) for El Niño events, and pointed out that target observations in the sensitive area identified by the CNOP cannot only improve the initial fields but also provide a means to detect the precursory signals for ENSO events so as to improve the ENSO forecast skill.

Based on observation system simulation experiment (OSSE), Morss and Battisti [59,60] suggested that for ENSO forecasting longer than a few months, the most important area for observations is the eastern equatorial Pacific, south of the equator; a secondary region of importance is the western equatorial Pacific. These sensitive areas are generally consistent to those determined by the CNOP method. Since the CNOP identifies the most sensitive perturbation, it may put more weight on the most sensitive area for ENSO forecasting, i.e. the eastern equatorial Pacific, than other areas such as the western equatorial Pacific. To be more general, one should further investigate the local CNOPs (i.e. the initial perturbations whose cost function reaches local maximal values at prediction time; see Mu *et al.* [34]) to identify other sensitive areas for ENSO forecasting. In any case, the sensitive areas shown in Morss and Battisti [59,60] serve as a verification for the CNOP sensitivity. By using sequential importance sampling assimilation method, Kramer and Dijkstra [61] also showed that the optimal observation locations for SST are located in the eastern tropical Pacific for minimizing the uncertainty in the NINO3 index, again in support of the CNOP results.

The sensitive areas for ENSO forecasting determined by above studies were mainly focused on the EP-El Niño events. The frequent occurrences of the CP-El Nino events after 1990s certainly pose a host of new questions for target observation. For instance, is the existing ENSO Observing System adequate for forecasting the CP-El Niño events? If not, how should it be updated and optimized? What are the sensitive areas for target observation for CP-El

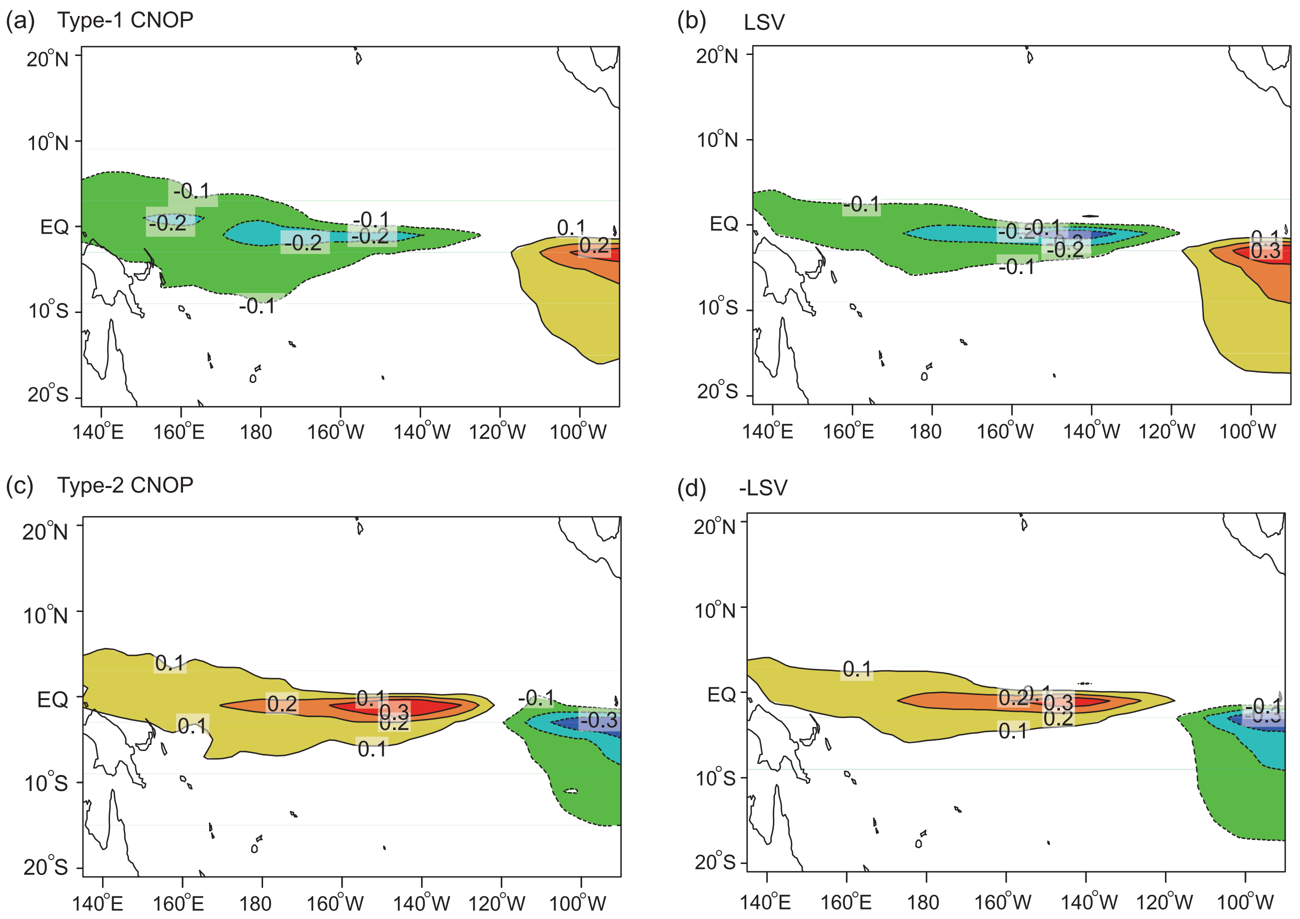

Figure 1. SSTA components of the composite CNOP-type and LSV-type errors, with a chosen norm magnitude of 2.0. Both CNOP-type and LSV-type errors have a large-scale dipole structure along the equator, though the latter is more localized as compared to the former. It is this difference that makes the prediction more sensitive to the CNOP-type errors.

Niño forecasting? How different are they from those for EP-El Niño? In addition, we should also explore the effects of global warming and its recent hiatus on ENSO, and design our target observation strategy accordingly. Addressing all these questions will be a big help for the future observation planning for ENSO forecasting, especially for the TPOS 2020 program.

INDIAN OCEAN DIPOLE

To the authors' knowledge, there were no attempts on the target observation for forecasting IOD events until recently. Encouraged by the CNOP idea, Feng and Duan [62] tried to find the initial errors that most likely will cause a significant winter predictability barrier (WPB) for IOD events (hereafter 'optimal initial errors'; also see [18]) by an ensemble approach, and explored the sensitive areas of target observation for IOD events based on the perfect model predictability experiments using the Geophysical Fluid Dynamics Laboratory Climate Model version 2p1 [37]. They found that the optimal initial errors exhibit an eastern-western dipole pattern in both surface and subsurface temperature, which tends to cause larger prediction errors than random initial errors and thus induce a much more significant WPB for IOD events. Therefore, if we can filter out the initial errors of dipole structure, we may be able to largely reduce the WPB and improve the IOD forecast skill. Considering that the large values of the dipole initial errors are concentrated in localized areas, we should use the target observation strategy to eliminate the IOD-related optimal initial error. Actually, Feng [37] showed that the areas where the dipole-pattern initial errors are large may be considered the sensitive areas of target observation for IOD events. In particular, they suggested that additional observations should be placed at about 95-m depth (close to the climatological thermocline depth) in the eastern tropical Indian Ocean near the equator (5°S–5°N and 85°E–105°E) (see Fig. 2).

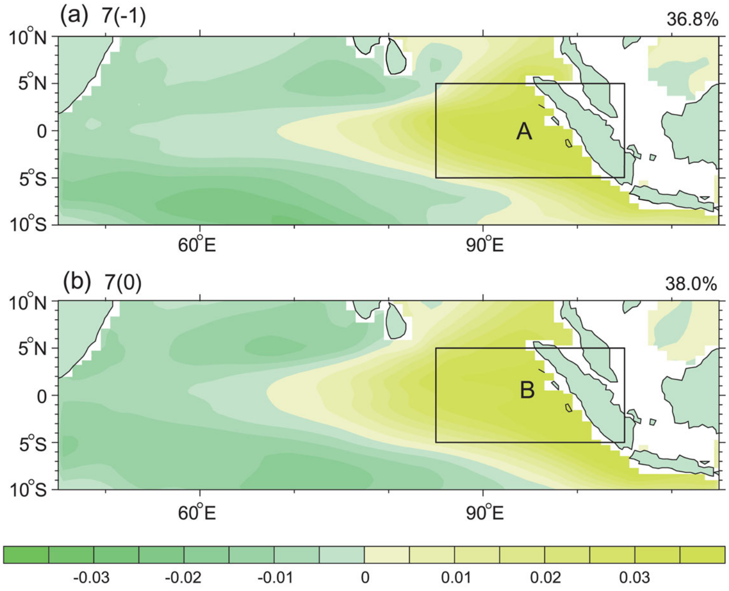

Figure 2. The subsurface component of the leading mode of combined empirical orthogonal functions (CEOF) for initial errors that cause significant WPB with start months (a) July(−1), and (b) July(0) ('−1' signifies the year preceding the IOD year and '0' signifies the IOD year; units: °C). The black squares (A) and (B) denote the areas 5°S–5°N and 85°E–105°E, respectively.

Horii *et al.* [63] identified the preconditioning signal of IOD development at the subsurface thermocline depth, based on the buoy data during 2006–2008, and there were significant negative signals in the thermocline depth several months preceding the appearance of the SST anomalies. This indicates that the precursor of positive IOD events mainly occurs in the subsurface of the tropical eastern Indian Ocean. This location is consistent with the sensitive area identified by Feng [37]. Consequently, if we increase observations at this location, especially in the subsurface ocean, we will not only improve the accuracy of initial field, which will reduce the prediction errors in winter, but also help to capture the precursor of IOD events, thus enhance the chance of predicting the occurrence of IOD events in advance. Of course, this hypothesis should be further verified by OSSEs and OSEs (observing system experiments) to increase their credibility. It is expected that the resulting sensitive areas for IOD forecasting will provide useful information to the optimization of the ongoing and planned Indian Ocean observation programs.

Tropical cyclone

Great efforts have been made to identify the sensitive areas for TC by various mathematical techniques such as SVs, ADSSV, ETKF, etc. Furthermore, field campaigns were conducted for TCs according to the information provided by the predetermined sensitive areas [64–66, etc.]. However, there are deficiencies in the above-mentioned targeting techniques [67]. In particular, these techniques are derived based on a linear approximation to prediction errors in non-linear models and therefore the resulting sensitive areas are of uncertainties. To overcome the problem, Mu *et al.* [36] introduced the CNOP approach to target observations and illustrated how to use CNOP to identify the sensitive areas for TC forecasting [also see 68–70]. A series of OSSEs and OSEs confirmed the validity of the CNOP sensitivity in improving TC forecast skill [71–73]. The benefits associated with the CNOP sensitivity are often much larger than those obtained by other three alternatives [SVs (combination of several SV), LSV, and randomly chosen regions] (Fig. 3). It is especially encouraging that the CNOP sensitivity produced by the MM5 is also applicable to the WRF, implying that the CNOP sensitivity obtained by MM5 may be model independent. In general, the CNOP sensitivity, compared to LSV and SVs, is much more effective in identifying the sensitive areas of target observation for TC forecasting, perhaps due to the nonlinear nature of CNOP.

As mentioned earlier, TCs originate and absorb energy from the ocean and spend most of their lifetime on the ocean. As such, the ocean is bound to have a large influence on TC development and thus on its prediction. However, almost all of the existing target observations for TC forecasting are focused on the atmospheric aspects. As a result, these target observations have only improved the forecast skill of TC track, but showed little impact on the forecast skill of TC intensity [74,75]. Due to the strong feedback from the ocean, taking the ocean-TC interaction into account may greatly improve the intensity forecasting of TCs [76–78]. It is therefore necessary to promote studies of oceanic target observations aiming at TC intensity forecasting.

Kuroshio large meander

The sensitive areas associated with KLM prediction have not been investigated until recently. Wang *et al.* [19] used the CNOP approach to study the OGE and the OPR for KLM and demonstrated the similarities between them (Fig. 4), thereby identifying the sensitive area of target observation for KLM. They found that the area is located southeast of Kyushu, where the total energy of CNOP shows large amplitude. A hindcast experiment verified the validity of this sensitive area by showing the strong dependence of hindcasts on the initial errors in the area. These results lay the foundation for improving

Figure 3. Ratio of track forecast errors of assimilating. All available data and dropwindsonde data according to CNOP, FSV, and Random (Ran) guidance, to assimilating no data at (a) 24 h and (b) 36 h using MM5 for 20 cases. Positive (negative) percentage means improvement (deterioration).

the KLM forecast skill by target observations and provide the theoretical basis for designing the observation network associated with KLM.

We note that the Kuroshio extension region is a region of intense ocean–atmosphere interaction and thus exerts significant influences on the regional weather and climate. During the last several years, quite a few research programs, including Kuroshio Extension System Study, were initiated to observe and study the oceanic and atmospheric variations in the Kuroshio extension region. However, the field observation locations of these programs were chosen for the purpose of process studies rather than prediction. How to effectively select the observation locations in this region, for both research and prediction, is still an open question. It is expected that further studies of target observations for the region can provide useful information for the optimal design of an observation system for the Kuroshio extension in general and KLM in particular.

SUMMARY AND DISCUSSION

This paper briefly reviews recent progresses toward target observations for improving the prediction of high-impact ocean-atmospheric environmental events, including ENSO, IOD, TC, and KLM. By examining the current status of relevant observations, we first point out that the existing observations

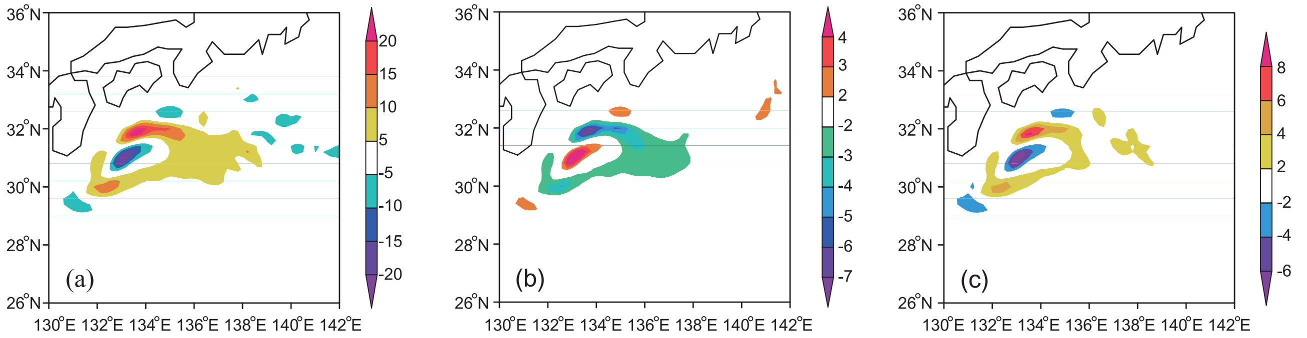

Figure 4. The upper-layer thickness component of the OPR (a) for the Kuroshio large meander, (b) the type-1, and (c) the type-2 OGEs in the prediction of the large meander path (units: m).

are not adequate to provide accurate initial conditions for the prediction of these events, and that the target observation strategy is urgently needed for the improvement and optimization of the observing systems. Then we demonstrate the applicability of newly developed techniques, especially CNOP, to the identification of the sensitive areas (optimal locations) of target observations for high-impact events. For TC, the CNOP approach seems superior to other methods in identifying the sensitive area; while for ENSO and IOD, the results from different methods are generally similar, giving credibility to the sensitive areas identified. To the authors' knowledge only Wang *et al.* [19] studied the target observation of KLM by CNOP approach. We also note that Li *et al.* [79] recently investigated the effect of target observation on improving the midrange (30 days) forecast skill of ocean state of the South China Sea (SCS) by using CNOP approach. They demonstrated that the region associated with the South China Sea Western Boundary Current (SCSWBC) is the sensitive area for target observation. Especially, they showed that implementing target observation in this sensitive area is a cost-saving way to improve an ocean model's forecast skill over the SCS. We therefore conclude that the target observation strategy is an efficient and effective approach to improve the forecast skill of the high-impact events, and it will provide guidance for the ongoing and planned observation networks, including TPOS-2020.

In spite of the considerable progresses being made, much more work is needed to further our understanding of the complexity of these high-impact events and to sharpen our tools of target observation accordingly. For ENSO, the presently identified sensitive areas for target observation may only be applicable to the stationary EP-El Niño events, and our future work will have to account for the uncertainties caused by the CP-El Niño events and by the global warming and its recent hiatus. For IOD, while it is encouraging to see mutually corroborating results on the sensitive area from previous studies, we have to further validate the results through hindcast and forecast experiments. For TC, we should pay particular attention to the effect of ocean on TCs, and investigate the oceanic target observation for TC forecasting, especially in terms of TC intensity. For KLM, a dedicated target observation system may not be feasible; thus, a practical task is to coordinate and optimize the existing observations in the Kuroshio Extension region.

The success of target observation depends on the superior performance of the numerical models and related assimilation system. If a model simulates the high-impact events very poor due to model errors, we cannot adopt this model to implement target observation for improving the initial condition and then the forecast skill. Also, if the assimilation system is not good enough, the effects of target observation cannot be sufficiently demonstrated. Studies of target observations are therefore challenging. Especially, studies of target observations for high-impact ocean-atmospheric environmental events are multidisciplinary in nature, requiring collaboration from different fields of science, including meteorology, oceanography, mathematics, and physics. Therefore, we should go through joint efforts of researchers of model development, assimilation system, and targeted observation. The work in this new research field has just begun to show promises, and there is every reason to believe that more exciting progresses are yet to come and then to significantly improve the forecast skills of the high-impact ocean-atmospheric environmental events, and thus for disaster prevention, climate change mitigation, and sustainable socio-economic development.

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