HIGH-RESOLUTION WEATHER FORECAST EXPERIMENTS ON THE EARTH SIMULATOR: CONNECTIONS TO AERONAUTICS

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Abstract

Some of the weather forecast experiments on the Earth Simulator (ES), one of the world's fastest supercomputers, are introduced in referring to their possible linkage to aviation. We use an atmospheric general circulation model, AFES, whose spatial resolution has been increased up to among the highest levels as a global model.

On one hand, increasing spatial resolution of a forecast model is beneficial to aviation by providing better representation of "meso-scale" phenomena (with horizontal scales on the order of 1~100 km) that will potentially cause severe weather conditions and/or vigorous turbulence. On the other hand, effective use of atmospheric data measured by aircrafts will lead to a better forecast by reducing errors and uncertainties in the initial field for numerical forecast. As the initial state, we must obtain the best estimate of the present state of the atmosphere under the unavoidable errors and spatial inhomogeneities in observations. As a method of this data assimilation, we adopt so-called Ensemble Kalman Filtering, where the spread of the state trajectories of the atmosphere, say, over the past 24 hours based an ensemble of forecast integrations provides information on how the small initial errors amplify in the nonlinear atmospheric circulation system, which is used for determining the best estimate for the initial field for the next forecast.

1 Introduction

Aviation and meteorology have been in close relation since the invention of aircrafts. Today, safe flight utilizes detailed information of the observed current state of the atmosphere and accurate prediction of its future state from the surface to the lower stratosphere. The latter is obtained as a numerical integration of the state-of-the-art model of the atmosphere. For the prediction up to a week, only the atmospheric general circulation model (AGCM) is used with sea-surface temperature (SST) and sea ice distribution fixed to their current state. An AGCM consists of a set of the global hydrostatic primitive equations that describe the evolution of the atmospheric state, including its circulation, temperature, moisture and clouds, and also the evolution ground temperature, snow cover and soil moisture. It also includes diagnostic equations, for example, for solving radiative transfer. Since subgrid-scale phenomena, including cumulus convection, (part of) gravity waves and small-scale boundary-layer turbulence, cannot be represented explicitly, their ensemble effects on the large-scale flow are parameterized in the model.

The short-term prediction is basically an initial value problem, which requires the knowledge of the current state of the atmosphere based on observations. For that purpose, a global observational network of radiosondes that are launched regularly from weather stations has been established. The network is by nature rather coarse over the oceans and in the tropics, despite a forecast model requires the initial values assigned on a global regular grid.

Owing to the spatial inhomogeneities and unavoidable errors in the observations, a "data assimilation" scheme is adopted to obtain the best estimate of the initial state for the numerical prediction. Weather conditions reported from commercial airliners are also incorporated into the scheme. Recently, the increasing number of measurements from satellites has been incorporated into the data assimilation scheme, which has contributed to the global improvement of the prediction score up to a week.

Since its first application upon the invention of a computer system around 1950, numerical weather prediction has been developed with the usage of the state-of-the-art computer system in each of the past decades. With the exponentially growing computational power, global forecast models used routinely today at the major prediction centers in the world can resolve phenomena with horizontal scales of 30~50 km, and their resolution will soon become as high as to resolve 20 km. Better representation of those "meso-scale" phenomena is beneficial to aviation, since they are sometimes associated with severe precipitation and lightening and/or small-scale turbulence that potentially affect flights. As the routine forecast procedures utilize the maximum computational power of the system, however, it is difficult to carry out forecast experiments on research basis with the highest model resolution in a prediction center. The recent advent of the Earth Simulator (ES) offers the research community certain opportunities for high-resolution modeling study of the atmosphere and ocean and their coupled system. The study includes climate modeling and forecast experiments as well. In this paper, some of the weather forecast experiments on ES are introduced in referring to their possible linkage to aviation.

2 ES and AFES

ES is a massively parallelized vector supercomputing system with shared memory architecture, manufactured by the Nippon Electronic Company (NEC) to realize ambitious foresight of late Dr. H. Miyoshi. It consists of 640 processor nodes that are interconnected by 640^2 single-stage crossbar switches [1]. With its 5120 processors and 10-TB shared memory as a total, ES can theoretically achieve the peak performance as high as 40.96 Tflops. Upon the commencement of its operation in 2002, ES was indeed the world's fastest supercomputer, and it still remains among the world's fastest general-purpose supercomputers.

In our forecast experiments we use AFES (AGCM for ES). The model code was originally developed jointly by the Center of Climate System Research (CCSR), University of Tokyo and Japanese National Institute for Environmental Studies (NIES), but the original computational code has been modified substantially so as to achieve the best computational efficiency on the particular architecture of ES [1-3]. The code optimization was so high that, with the full usage of the 640 nodes, AFES achieved 65% of the peak performance of ES (26.5 Tflops) with its highest resolution: horizontally T1279 spectral truncation, equivalently 10-km grid spacing at the equator, and vertically 96 unevenly spaced levels from the surface to the top of the stratosphere [2]. For this remarkable performance, AFES received the Gordon-Bell award in the Super-Computing 2002 Conference.

With its highest resolution, AFES can resolve atmospheric phenomena with a wide range of horizontal scales, including planetary ($O(10^4)$ km), synoptic ($O(10^3)$ km), meso-α ($O(10^2)$ km) and part of meso-ß ($O(10^1)$ km) scales, and their multi-scale interactions as well. Although individual cumulus clouds cannot be resolved, AFES can represent their clusters on horizontal scales of about 50 km. With this ability, AFES is the first global model in which severe tropical storms (hurricanes or typhoons) are successfully generated, developed and then decayed, including their transition to extra-tropical cyclones, without any artificial "seeding". Figure 1 shows a snapshot of a typhoon generated on the 6th day of a 16-day simulation by AFES with a climatological SST condition for September. Within the next 5 days, it develops into a powerful typhoon with the lowest central surface pressure of 920.7 hPa [2]. It exhibits a realistic structure, including an annular cluster of well-developed cumulus clouds in the "eye wall" that surrounds the warm cyclone core, and other cumulus clusters organized into spiral bands in the outer domain.

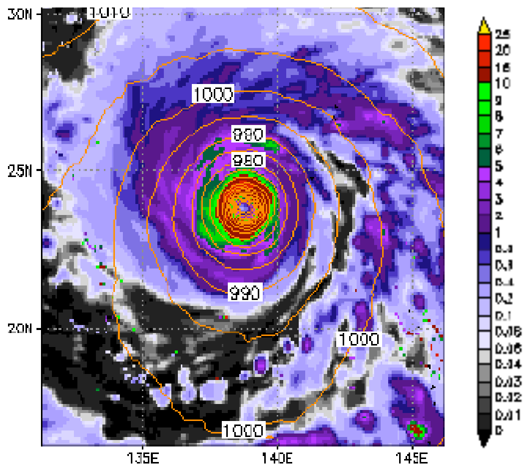

Fig. 1. A typhoon at its peak stage generated in AFES. Rainfall rate (mm/h, colored) and sea-level pressure (hPa, contoured) are plotted [2].

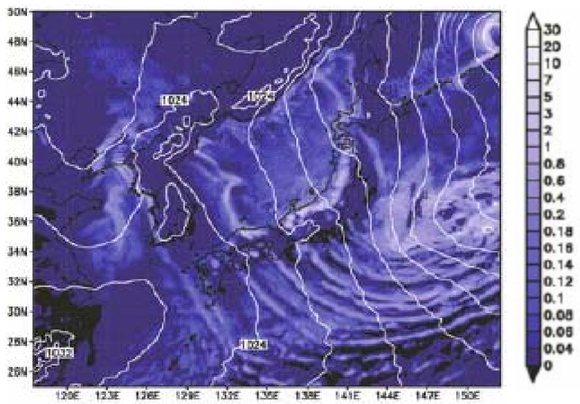

Fig. 2. Topographically enhanced precipitation during a strong cold-air outbreak in the Far East in an AFES simulation. Precipitation rate (mm/h, colored) and sea-level pressure (hPa, contoured) are plotted [2].

AFES can also reproduce fine meso-scale features arising from regional topographic effect. Figure 2 shows a snapshot of precipitation in the Far East during a strong outbreak of dry, cold air from the continent, on the 6th day of a 16-day simulation of AFES with the climatological January SST [2]. Over the warmer ocean surface, the spill of dry, cold air destabilizes the low-level stratification and enhances evaporation, leading to the enhancement of moist convection and thereby precipitation. Blocked by mountains along the Asian coast and over Japan, the spill intensifies after passing through between mountain ranges, manifested as bands of convective clouds forming downstream. Precipitation (mainly snowfall) is enhanced also along the west coast of Japan, which faces the wind. In the mid- and upper troposphere above the cold-air outbreak near the surface, a westerly jet stream locally intensifies. Its lateral shear is so enhanced to form vorticity filaments (Fig. 3), which are believed to act as a source of gravity waves and associated turbulent motions that potentially affect aviation.

In addition to AFES, a high-resolution ocean general circulation model OFES (Ocean GCM for ES) has been developed [3-5]. With its 10-km resolution, among the highest in the world, OFES can resolve meso-scale eddies that form along strong currents, including the Gulf Stream and Kuroshio. It can also reproduce realistically frontal structure that form along the currents and their long-term variability. OFES also reveals that the world's ocean may be filled with a number of local jets, which could change our perception of ocean circulation drastically.

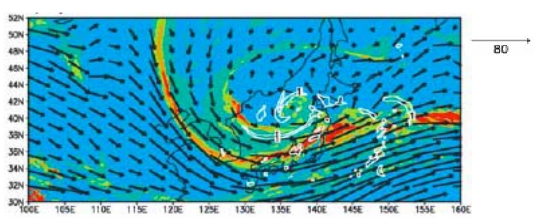

Fig. 3. Vorticity filaments (red/yellow) and wind vectors (m/s) in the mid-troposphere above the strong cold-air outbreak in the AFES simulation as in Fig. 2 [2].

3 Sensitivity/Forecast Experiments with AFES: European Floods in the 2002 Summer

As one of our forecast experiments with AFES, a set of "hindcast" integrations is briefly introduced in this section. In our additional sensitivity experiment, we attempt to find a specific domain in which the atmospheric status observed at a given time could bear the highest sensitivity to the particular atmospheric condition over another domain with a give time lag.

The target phenomenon of our experiment is the upper-level low-pressure system cut off over Europe from the westerlies around 10 August, 2002 [6]. The upper-level cyclone accompanying abnormally cold air lowered static stability over the heated landmass of the European Continent, leading to the pronounced enhancement of the convective activity with heavy precipitation in southern Germany and Austria. Unlike typical extra-tropical cyclones, the upper-level cold cyclone was accompanied by pronounced lowering of the tropopause but associated with a weak low-pressure system at the surface (Figs. 4e-f).

Our analysis reveals that the deepening of the cutoff low followed the amplification of the Azores high, a dominant semi-permanent subtropical anticyclone over the Atlantic, around 8 August. This sequence at the surface is found a low-level manifestation of the eastward group-velocity propagation of a quasi-stationary Rossby wave train in the upper troposphere [6]. Rossby waves are large-scale disturbances in the atmospheric (or oceanic) flow of such a fast rotating planet as Earth, whose westward intrinsic phase velocity increases with the wavelength. Thus, in a westerly jet, Rossby waves with a certain wavelength can be quasi-stationary relative to Earth, but their eastward group velocity can be nearly twice as large as the background westerly wind speed. In the sequence of the group velocity propagation, the amplification of an upper-level pressure ridge that accompanied the intensification of the surface Azores High followed the deepening of a upper-level pressure trough just off the east coast of North America around 7 August. The deepening appears to be contributed to partly by the injection of Rossby wave energy from upstream, diagnosed as a prominent eastward wave-activity flux from another pressure ridge over the North American Continent (Fig. 4a). Below the deepened upper-level pressure trough, there was a developed extra-tropical cyclone at the surface

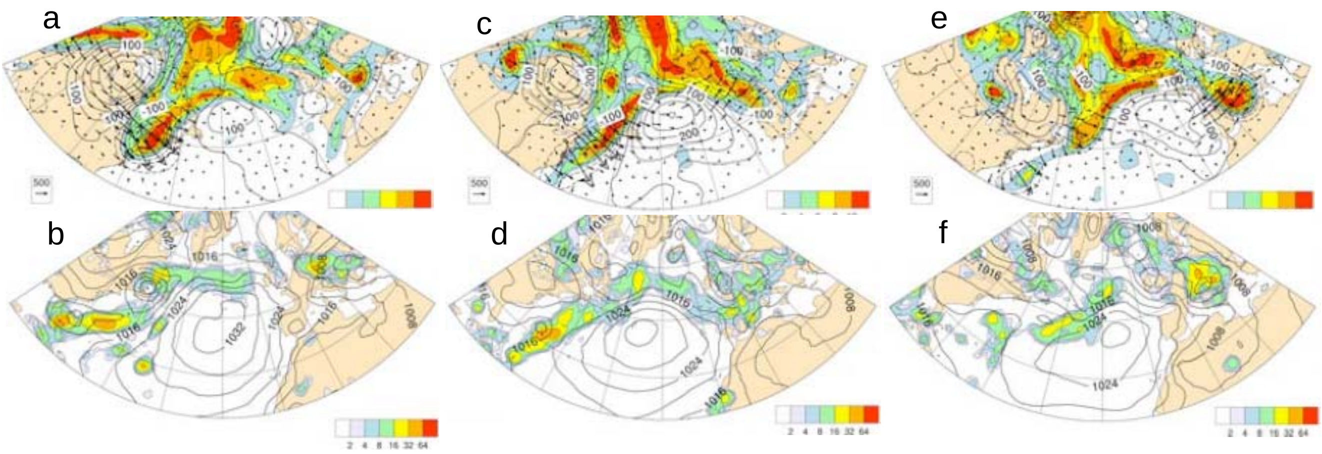

Fig. 4. (a, c, e) Upper-tropospheric anomaly fields (deviations from climatological mean) of height of the 250-hPa pressure surface (contoured for every 50 m; solid for anticyclonic anomalies) and potential vorticity (red/yellow for cold upper-level air) with wave-activity flux (arrows: parallel to local group velocity of Rossby waves), based on JMA analysis for (a) 7, (c) 9, and (e) 11 August, 2002. (b, d, f) As in (a, c, e), respectively but for sea-level pressure (contoured for every 4 hPa) based on JMA analysis, and precipitation (mm/day; colored) based on GPCP data set (rain gauge and satellite measurements blended). After [6].

off New England. To its south, a tropical storm "Cristobal" was observed just to the east of Florida (Fig. 4b) throughout our analysis period. Presumably, in the presence of Cristobal, moisture transport was enhanced into the surface frontal zone extending southward from the extra-tropical cyclone.

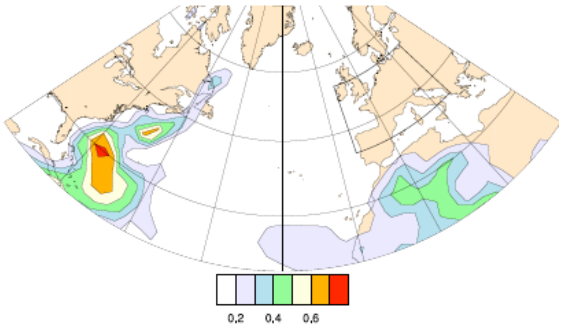

Fig. 5. Result of sensitivity analysis [6]. Distribution of initial disturbance as represented in vertically integrated total energy (J/kg) for 8 August 2002 that can influence most sensitively to the 72-h forecast field over the rectangular target domain over Western Europe as indicated. Based on 25-member ensemble forecast by JMA.

In fact, our sensitivity study suggests that a 72-h forecast for 11 August over Europe is most sensitive to uncertainties in the initial condition around Cristobal [6]. In that analysis, we used the 25-member ensemble 72-h forecasts from 1200 UTC on 8 August, performed weekly by the Japan Meteorological Agency (JMA). The forecast model adopts T106 spectral truncation, equivalently ~100-km grid intervals. Taking the fact into account that the initial guess of the atmospheric state includes a certain level of errors, a field of randomly generated small perturbations (with a given magnitude) was added artificially to the initial guess for each of the ensemble members. The initial perturbation field evolves differently from one forecast member to another, yielding deviations in the forecast field from the ensemble mean state over the given forecast time. A (25×25) covariance matrix for the forecast deviations was defined with vertically integrated energy norm for the target domain over Western Europe [40°~55°N, 10°W~20°E]. The most sensitive initial perturbation was defined as a particular linear combination of the 25 initial perturbations whose weights are given as the first eigenvector of the covariance matrix. The fist mode indeed represents that the 72-h forecast for 11 August within the target domain is most sensitive to the initial perturbations off the Florida coast around Cristobal (Fig. 5).

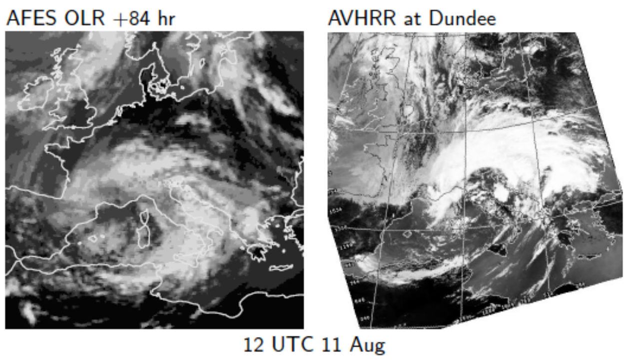

Fig. 6. Comparison of patterns of outgoing longwave radiation (OLR) over Europe for 1200UTC 11 August 2002 between (left) AFES 84-h forecast and (right) satellite measurement. White areas indicate low emission temperature of infrared radiation to space, corresponds to the cold tops of developed cumulus clouds.

A forecast experiment was then performed on AFES with its resolution reduced by 50% both horizontally and vertically (48 levels) [6]. Still, the spectral truncation of T639, equivalent to 20-km grid spacing, is among the highest ever adopted for a forecast experiment on a global model. A forecast integration was carried out from 0000UTC on each of the 5th~8th days of August to 0000UTC 12 August, to yield a set of 96~168-h forecasts. The initial guess was taken from the JMA analysis of the atmospheric state. The 96-h forecast was found to show a satisfactory skill. It successfully reproduced the group-velocity propagation of the Rossby wave train across the Atlantic and the subsequent formation of the upper-level cold cut-off cyclone. The simulated cloud pattern after 84 hours from the initiation of the forecast exhibits a marked similarity with the satellite observation (Fig. 6), indicating the successful forecast of the flooding situation in the northern slope of the Alps. Our forecast skill lowers substantially for a longer lead time, which may be attributable to the westward movement of Cristobal into the Gulf of Mexico predicted erroneously for the first few days. Consistently with our sensitivity analysis, the mis-forecast of Cristobal could result in the lack of its interactions with the extra-tropical cyclone system as a component of the propagating Rossby waves.

4 Ensemble Kalman Filtering Experiments on AFES

The forecast experiment on AFES described above and our sensitivity analysis based on JMA ensemble forecasts re-confirm the importance of the initial guess for accurate forecast. In the routine forecast, the initial guess is obtained through "data assimilation", where the forecast field from the previous time step is modified by adding latest observational data to reduce the errors in determining the initial guess. Therefore the data assimilation requires an estimate of probability distribution of errors not only for the observations but also for the forecast. The initial guess can be determined as a particular linear combination between the forecast and observations so as to minimize the combined estimation error in the analysis (Fig. 7). Gaussian distribution is usually assumed for the observation errors. In the conventional data assimilation, 3-dimensional variation method (3DVAR) is widely used, where the forecast error distribution is also assumed to be Gaussian and fixed to a distribution that has been obtained statistically. It is now realized, however, that the probability distribution of the forecast errors is non-Gaussian with a tendency of its strong projection onto a limited number of anomaly patterns (or modes) and that the distribution varies continuously depending on the configuration of the atmospheric flow. In Ensemble Kalman filtering (EnKF), the (non-Gaussian) forecast error distribution is determined as the spread of the initial perturbations in the latest ensemble forecasts and it is continuously updated in the forecast sequence [7-9]. The weight for the observations relative to the forecast in determining the initial guess is also updated continuously. It is a kind of Kalman filtering, in which the error covariance matrix is kept updating, but it does not utilize the adjoint of the (linearized) forecast model.

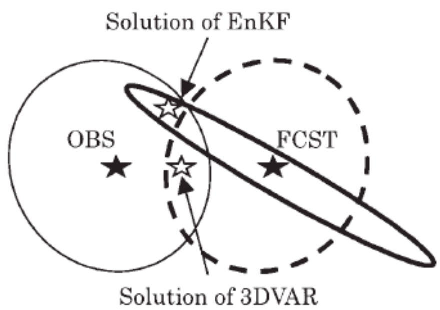

Fig. 7. Schematic diagram showing the determination of the initial guess by data assimilation. Solid and dashed circles around "OBS" and "FCST" represent observational and forecast errors obtained statistically. The latter is used for the 3-demeinsional data assimilation (3DVAR). Heavy solid oval denotes forecast error distribution updated by ensemble forecasting for EnKF. Solutions for the two data assimilation methods are indicated with open asterisks [7].

With these advantages, EnKF is believed to be one of the promising methods of data assimilation. Yet, there are some technical issues on EnKF that have to be cleared out before its implementation into a routine forecast system. For example, we need to know how many ensemble members are necessary for its stable operation in a data assimilation system with a high-resolution model as actually used for routine forecasting. Should EnKF requires a large ensemble size for its stable operation on a high-resolution model, the excessive computational burden would render EnKF too time consuming to be implemented in a routine forecast system. It is therefore beneficial to examine this particular issue on AFES, in taking advantage of its extreme computational efficiency. Two types of "observation system simulation experiments" (OSSEs) were performed on AFES with spectral truncation T159 (equivalently ~ 80 km in horizontal) and 48 vertical levels [8, 9]. In each of the OSSEs, a particular model forecast is regarded as if it represented the actual evolution of the atmosphere, from which "observed data" are sampled for data assimilation with EnKF. The particular method used for our EnKF assimilation is so-called local ensemble transform Kalman filter (LETKF), proven to be computationally efficient [10].

In one of the experiments, the number of the ensemble members was changed while the three-dimensional coverage of the spatially regular "data sampling" was fixed to 1% of the model physical space. The sampling was performed for the same atmospheric variables as in radiosonde observations with their typical Gaussian errors added uniformly in space. The assimilation cycle with 6-hourly "observations" starts for 0600UTC 1 May 2004, after a 5-month spin-up. Our experiments show that with 20 or more ensemble members, the analysis error is reduced rapidly for the first few days and almost converges within 10 days in the forecast cycle. The experiment suggests that 40 members are likely sufficient for a stable operation of LETKF with 80-km resolution. With AFES, it takes only 3~4 minutes for LETKF when each of the ensemble members is assigned to a single node of ES for parallel computing if the ensemble size is 80 or less.

In the other experiment, the "sampling" was performed irregularly in space at the same locations as in the operational JMA system for the same variables except for satellite measurements of radiance. They include surface observations, radiosonde soundings, aircraft reports and satellite-measured wind fields. The same error as in the actual observation was assigned to each of the sampling. 40 ensemble members were used for the experiments. As in the experiment with spatially uniform sampling, the analysis error measured again as total energy in this experiment also decreases rapidly to converge within 10 days, but it is more than 5 times larger reflecting sparse observations in the polar regions, especially over Antarctica. The distribution of analysis error in LETKF mostly reflects that of observational errors, suggesting that no serious errors are introduced from the ensemble forecasting system.

4 Concluding remarks

Some of our high-resolution forecast experiments on ES have been introduced. AFES simulations and forecast experiments show the advantage of high-resolution atmospheric modeling in its ability to represent meso-scale features of atmospheric phenomena interacting with its synoptic and planetary-scale environment. Downscaling into a regional atmospheric model nested in a global model can be useful in representing meso-scale disturbances, but their interaction with their ambient flow cannot be fully represented without two-way nesting. Sooner or later an operational global forecast model will have a horizontal resolution of ~20 km. Nesting a cloud-resolving regional model will be expected to provide even better forecast of finer structures (with meso-γ scales) of atmospheric phenomena that could affect aviation.

Our forecast experiments and sensitivity analysis reconfirm the importance of the initial guess for the (short-range) forecast up to about a week. More effective use of atmospheric data measured or monitored by commercial aircrafts in data assimilation (including EnKF) will contribute to the determination of better initial guesses. Our EnKF experiments suggest that

EnKF is likely a promising method for future data assimilation method, and a combination of EnKF and ensemble forecasting are expected to lead to further improvement of forecast skill. If the system is efficient enough, ensemble forecasting can identify a particular domain in which the initial guess can influence most sensitively to the forecast field in a remote target domain over a given time frame. Then, additional aircraft measurements if made over that the "sensitive domain" can potentially improve the initial guess, leading to a better forecast in the target domain. This kind of "adaptive observation" has recently been considered as a promising new direction for the future weather forecasting [11].

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