UC San Diego

UC San Diego Previously Published Works

Title

The role of sea surface temperature in reanalysis

Permalink

<https://escholarship.org/uc/item/60017890>

Journal

Monthly Weather Review, 134(2)

ISSN

0027-0644

Authors

Kanamitsu, M

Hwang, S O

Publication Date

2006-02-01

Peer reviewed

The Role of Sea Surface Temperature in Reanalysis

Masao Kanamitsu

Scripps Institution of Oceanography, University of California, San Diego

La Jolla, California

Seung-On Hwang

Korea Meteorological Administration

Seoul, Korea

Corresponding author: Dr. Masao Kanamitsu, Mail Code 0224; CRD/SIO/UCSD; 9500
Gilman Drive; La Jolla, CA 92093-0224
E-mail: mkanamitsu@ucsd.edu

ABSTRACT

Aiming at understanding the role of SST in the Reanalysis for the pre-radiosonde, pre-satellite and satellite eras, a number of observation system experiments were performed using the NCEP/DOE reanalysis system. Five pairs of experiments were conducted using observed and climatological SSTs for cases 1) without any observation, 2) surface pressure observation-only with the observation density of 1915, 3) surface pressure observation with the observation density of 1997, 4) surface observation and radiosondes and 5) all observations, including satellite retrievals. The analyses were run for 4 months in 1997 (strong El Nino) and 1993 (near-normal SST). The impact of SST and the various observation systems on the analysis of near-surface parameters, upper-level field and several diagnostic fields were compared against the control analysis with observed SST and all available observations.

The most important finding of this study is that the impact of SST varies with the time scale of the analysis, which is most apparent in the surface pressure only observation experiments. The impact of SST is largest for the low frequency (seasonal) analysis and smaller for the high frequency (daily) analyses. This is particularly apparent for near-surface temperature and upper-level height field analyses. In our extreme case of the strong El Nino year, the simulation with observed SST without any observations (AMIP type run) produced seasonal mean 2-meter temperature (T2M) and 500-hPa height fields which agreed better with the control analysis than the analysis with surface pressure observation-only with climatological SST. On the contrary, the impact of surface pressure observation is greater on higher frequency analyses, and lower on low frequency analyses.

Generally speaking, accurate analysis of SST is important when limited atmospheric observation is available. But even for the full atmospheric observation system, climatological SST produces inferior analysis over ocean as well as land.

The introduction of radiosonde data drastically reduces errors in the analyses and diagnostic fields, thus, radiosonde data are indispensable for accurate estimation of the atmospheric state in both short and long time scales.

1. Introduction

Long-term historical analysis of atmosphere, land and ocean is essential in climate research. The usefulness of such analysis is demonstrated by nearly 3,000 references currently made to the NCEP/NCAR reanalysis (Kalnay et al., 1996). Recognizing this importance, several additional reanalysis projects have been launched (ERA-15, Gibson et al., 1997; ERA-40, Simmons et al., 2000; NCEP/DOE, Kanamitsu et al., 2002; Japanese Reanalysis, (<http://www.jreap.org/indexe.html>); U.S. national reanalysis project, Arkin et al, 2003). Some are now complete, while others are ongoing.

These analyses utilize a high level data assimilation method combining observation with guess field from a highly complex and accurate general circulation model. The greatest merit of this method is that the parameters in the resulting analyses are dynamically, physically and hydrologically consistent with the general circulation model and the constraints included in the analysis scheme. This consistency is extremely important in climate research, since finding unknown relationships between various parameters and understanding the physical processes that connect them is a central concern.

In addition to the consistency of analyzed parameters, minimization of artificial change in the climate signal due to changes in the analysis procedure is critical. To minimize these changes, modification of the analysis system during the course of the reanalysis production needs to be avoided, even to the extent that some errors found during the process need to be left uncorrected (Kistler et al, 2001; Kanamitsu et al., 2002).

With these careful system designs, artificial change in the climate signal should have been minimized. However, it soon became apparent that the climate signal was distorted by large changes in the observation systems which have occurred during the last 40 years (Chelliah

and Ropelewski, 2000). The primary reasons for the artificial change in the analyses are the systematic bias error in the guess field, as well as systematic error in the observation. The latter is caused by changes in instruments, data processing and even by changes in station locations. In particular, the introduction of satellite soundings in the late 1970's created distinct discontinuities in the analysis (Sturaro, 2003). These biases are extremely difficult to eliminate, and the minimization of the trends and discontinuities in the climate signal caused by changes in the observation system is now one of the critical targets of future reanalyses (Arkin et al. 2003).

The observations used in the reanalyses are not limited to free atmospheric observations of winds, temperature, pressure and humidity. Additional important observations are Sea Surface Temperature (SST) and sea ice cover. Biases and discontinuities in these analyses are also potential sources of false climate signal. Changes in vegetation types, coverage, urbanization and irrigation over land can also play an important role in the accuracy of analysis, but no reanalyses have ever taken account of these details.

For all the atmospheric reanalyses performed to date, the SST analyses are made independently from atmospheric analysis. The SST analyses are created by objective smoothing (Reynolds 1988), statistical techniques (Reynolds and Smith, 1994), and with more refined EOF fitting (Smith et al. 1996), which allows the analysis to run back to the pre-satellite period. Note that these analyses are based on statistical method. Combined ship and satellite observations are used for SST analysis. The accuracy of the analysis depends on the quality and density of these observations (Reynolds and Smith, 1994). Typical accuracy of the monthly average SST analysis is about 0.1 degrees for recent years, but could be much larger due to the bias existing in satellite data which is very difficult to estimate (Reynolds and Smith, 1994). The accuracy of SST analysis is worse before the satellite era, of the order of 0.3 degrees, and can locally exceed

1 degree (Smith et al., 1996). There is also a long term trend in the SST in situ measurements, which might affect the long term trend in SST analysis (Servain et al, 1990).

Surprisingly, all the data assimilation systems used in reanalyses assume that the SST analysis is error free. A major reason for this somewhat unrealistic assumption is that the SST is not explicitly used as observation to analyze the atmospheric parameters. Recent 4-dimensional variational ocean data assimilation (Stammer et al., 2002) assigns a range of errors to the atmospheric forcing (namely, the surface fluxes), and the resulting analysis provides “corrected” surface forcing consistent with the ocean analysis. The long-term average of “corrected” surface forcing provides an estimate of mean errors of the atmospheric forcing. Their long term ocean reanalysis showed there is a significant error in the atmospheric forcing field. Since the atmospheric forcing is a combination of surface winds, near-surface temperature, surface radiation fluxes and SST, the errors in the forcing are not necessarily the results of error in the SST analysis. Many errors can be explained by problems in the model cloudiness, but some errors are related to uncertainties in the SST analysis used in the Reanalysis.

The SST analysis affects the accuracy of the estimate of latent and sensible heat fluxes over ocean as mentioned above. The resulting surface fluxes influence model precipitation and eventually the large-scale flow fields in the guess field. Thus, the impact of the accuracy of SST to resulting atmospheric analysis may be much greater for analysis before the 1950’s, for which very few atmospheric and surface observations are available. The impact will be even greater for pre-radiosonde years (before the early 1940’s), for which the analysis must be performed using surface observation-only.

The Atmospheric Model Intercomparison Project (AMIP) (Gates et al, 1999) demonstrated that current general circulation models are capable of simulating three-dimensional

structures of seasonal mean global atmosphere and their interannual variations reasonably well with SST forcing alone, especially when the tropical SST anomaly is large. These simulations clearly indicated that SST can be a significant source of information for analyzing the seasonal mean three-dimensional structure of atmosphere.

The purpose of this paper is to study the importance of SST in reanalysis using observation system experiments. Major focus will be placed on the impact of SST on daily and seasonal mean fields of surface pressure, surface temperature, upper-air fields, latent heat flux, cloudiness and precipitation. Recently, Bengtsson et al (2004) performed observing system experiments using the ERA40 reanalysis system to estimate the accuracy of analysis for the surface based, terrestrial-based, and satellite-based systems, roughly corresponding to the radiosonde, pre-satellite, and satellite eras. They concluded that the radiosonde observation is essential in obtaining reasonably accurate analysis useful for climate application. This paper also looks at some aspects of the importance of radiosonde and satellite observations.

The paper is organized as follows: Section 2 presents data and the experimental analysis procedure, Section 3 presents the impact of SST and surface pressure observation for daily analysis, and Section 4 for seasonal mean analysis. Section 5 describes the impact of radiosonde observation on the analysis of both time scales. Section 6 presents the impact of SST and observations on diagnostic fields, and Section 7 describes the geographical distribution of the seasonal mean analysis differences. Summary and conclusions are presented in Section 8.

2. Data and experimental analysis procedures

We utilized the NCEP/DOE Atmospheric Model Intercomparison Project (AMIP-II) Reanalysis-2 (R-2; Kanamitsu et al., 2002a) Climate Data Assimilation System (CDAS). The

forecast model physics are taken from the NCEP Seasonal Forecast Model (Kanamitsu et al., 2002b), and differ from the ones used in R-2, but details are omitted here. It should be noted that this CDAS 3-D variational assimilation is not a state-of-the-art system. For example, it does not utilize satellite radiance, but instead uses independently retrieved temperature. Over land, surface pressure observation is used but the wind, temperature and humidity observations were discarded. Over ocean, all the surface observations were used. In addition, the latest satellite data, such as SSM/I observations, are not used in the analysis system.

We performed five pairs of experiments with observed and climatological SSTs, the first pair without any observation (AMIP and AMIPC), the second pair with surface pressure only with the observation density of 1915 (PRSX and PRSXC), the third pair with surface pressure only and observation density of 1997 (PRS and PRSC), the fourth pair with surface pressure and radiosonde (SONDE and SONDEC), and the fifth pair with all the observations (CNTL and CNTLC). The climatological SST is a 30-year mean of the SST analyses used in this study. These experiments are summarized in Table 1. We assumed the results of the analysis with all the observations with observed SST (CNTL) to be true, and all other experimental analyses were compared against it. Note that one of the first pairs of experiments, observed SST without observation, is similar to the AMIP type runs, in which the atmospheric model is forced only by SST. The run with climatological SST without observation (AMIPC) does not have interannual variability in the external forcing, thus the simulation represents only the atmospheric internal variability. We presume that the AMIPC deviates most from the control analysis, since no information that differentiates from one year to another is contributed to the system.

The quantity of surface pressure data for the PRS and PRSC experiments numbers about ten thousand during ± 3 hours from the analysis time over the whole globe. The distribution of

full surface pressure observations is shown in Fig. 1. The observation distribution of early 1915 was obtained using World Monthly Surface Station Climatology and Global Historical Climatology Net (GHCN) available from the NCDC (National Climatic Data Center) website (Fig. 2). Detailed procedures to simulate the distribution of observation used for this experiment are described in Appendix A.

The majority of the assimilation experiments were performed for the period of Nov. 7th 1997 to Feb. 28th 1998 with the November analysis discarded to avoid the spin-up problem. Note that the winter of 1997-98 is a strong El Nino year (Barnston et al. 1999). Additionally, experiments for the same season but for the near-normal SST year, 1993, were also performed. The definition of near-normal SST is based on the Climate Prediction Center web page (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html). Initial guess data at the beginning of the analysis and land surface conditions are taken from R-2.

The choice of five observation systems is somewhat arbitrary; it is designed to examine the impact of observation coverage before the radiosonde era, before the satellite era, and during the satellite era.

We made no attempt to change the forecast error statistics or the observational errors in the analysis system, as this complicates the interpretation of the results. Since forecast error will increase when a smaller number of observations are injected, this approximation will place more weight on model forecast guess, and the fit of analysis to observation will deteriorate.

The use of climatological SST will amplify the impact of SST, particularly for the 1997-98 case. The experiment for 1993 is additionally performed to examine the impact of SST in more normal years. The difference of observed and climatological SSTs for 1993 and 1997 are shown in Fig. 3. Apparently, this difference is larger than the SST analysis error noted earlier.

As a relative measure of the magnitude of SST difference, we computed the root mean square difference (RMSD) of two independent SST analyses, one from the UK Met Office, HadISST, V1.1 (Rayner et al., 2003) and the other from NCEP, ERSST V2 (Smith and Reynolds, 2004) and compared it with the RMSD of the SST anomaly in 1993 and 1997. Roughly speaking, the RMSD of SST anomaly was twice as large as the difference of two independent SST analyses during 1870-1940 in the Northern Hemisphere (NH) (1.4 °K vs. 0.75 °K), three times as large in the Tropics (1.6 °K vs. 0.45 °K) and 2.5 times as large in the Southern Hemisphere (SH) (1.3 °K vs. 0.55 °K). Thus, the impact of SST in our experiment is exaggerated. However, since we attempted to examine the effect of SST on the three-dimensional structure of the atmosphere as well as on physical processes diagnosed in the data assimilation, and the experiments are performed only for two winters, the exaggerated SST difference was intentional to obtain a stronger and more meaningful signal.

For the assimilations using surface only observation, and for the runs without any data (but using specified SST) in 1997, simplified ensemble analysis/simulation was performed. Five member ensemble runs were made by randomly perturbing the initial guess at the very first assimilation cycle analysis. The five separate analysis cycles were performed and the ensemble members were averaged to obtain the final analysis. The advantage of this simple ensemble data assimilation is briefly described in Appendix B. Note that the additional experiment for the near-normal SST year, 1993, is performed in a single member mode to conserve computer resources.

When comparing analyses with different observation systems but with observed SST (or with climatological SST), we expect that the addition of an observation system (or increase in the number of observations) makes the analysis fit closer to the control. This can be used to check the reliability of our experiments. From the pairs of experiments using observed and

climatological SST, we can determine that if the analysis with observed SST closely matches the analysis with climatological SST for the same observation system, the SST has a positive impact on the analysis. If the fit of the analysis that uses a reduced observation system but with observed SST is better than the increased observation system with climatological SST, we can conclude that the use of observed SST is more beneficial than the change in the observation system. However, it should be noted that since the difference between observed and climatological SST is large, particularly for the 1997 case, the impact of SST does not necessarily represent a real-world scenario. In this respect, the experiment for the normal SST year, 1993, may provide somewhat more reasonable measures of both the impact of SST and changes in the observation system. It is also important to mention that the choice of observation system is somewhat arbitrary, so that the comparison of the effect of SST and the change in observation system should be taken as simply a relative measure. In order to make more quantitative results, multi-year runs with more realistically perturbed SST (e.g. using SST analysis error) is required, but such experiments are beyond our capability at this time.

3. Impact of SST and surface pressure observation on daily analyses

For the sake of clarity, we will first focus on the impact of SST and surface pressure observation in the current and next sections. The impact of radiosonde observation will be described separately in Section 5.

3.1. Impact on surface pressure analysis

Figure 4a compares the RMSD normalized by the temporal variance between 9 experimental analyses with the control analysis of daily mean sea level pressure (MSLP)

averaged for three months in 1997 (left column) and 1993 (right column). The temporal variance is computed from three month daily control analysis. The un-normalized RMSD for 1997 is shown in Table 2-1. Except in the tropics, the RMSDs of MSLP analysis from CNTL decrease in the order of AMIPC, AMIP, PRSXC, PRSX, PRSC, PRS (from left to right in the figure). The un-normalized RMSD ranges from more than 10-hPa for AMIPC to 2.7-hPa for PRS in the extra-tropics. The RMSD is less than 3-hPa in the tropics (Table 2-1). Figure 4a shows that the decrease of MSLP RMSD between observed and climatological SST in the extra-tropics is smaller than the decrease in RMSD between analyses with different surface pressure observation density. This is seen in the pair of bars with the right bar slightly lower than the left, and the next pair separated by a large step. Considering that the impact of SST is small even though the magnitude of the SST difference is exaggerated, the impact of SST on MSLP analysis is less than the impact of adding surface pressure observation.

In the tropics, the impact of SST on MSLP analysis is as large as the impact of adding surface pressure observation. The impact of SST is much greater in 1997 than in 1993, due to the larger SST anomaly in 1997. Most of the results noted above hold for 1993, with the smaller impact of SST on surface pressure analysis as expected (Figure 4c). The RMSD is larger for the AMIP, PRSX and PRS experiments than those in 1997. In addition to the magnitude of the tropical SST anomaly, the use of the single member analysis is contributing to this difference.

3.2. Impact on 2-meter temperature analysis

Although the SST is not directly used by the analysis system, the SST information is passed to the T2M through model guess. From Fig. 4b, we can see that the greatest impact of SST on T2M is in the tropical oceans where the impact is much greater than adding the surface

pressure observation, as seen in the saw-tooth pattern. The un-normalized RMSD for 1997 is also shown in Table 2-1. The RMSD ranges from 6°K to 1.0° K, slightly larger than the SST anomaly itself. The impact is smaller in 1993, but still noticeable (Figure 4d). We also observe that over the tropical ocean, the surface pressure observations do not improve the T2M analysis, while they clearly do in the extra-tropics. Over tropical land, the impact of SST is still greater than that of surface pressure observation in 1997. In the extra-tropical oceans, use of observed SST reduces the T2M RMSD more than adding the surface pressure observations.

3.3 Impact on upper-air field analysis

The difference in the analysis near the surface should influence the analysis in the free atmosphere through hydrostatic relationship. The near-surface information also propagates upward during the data assimilation cycle modifying the analysis at upper levels through guess field. These processes affect the free atmospheric analysis especially when upper-air observation coverage is scarce. The impact of surface pressure observation and SST on free atmospheric analysis is of particular interest in the pre-radiosonde era, when observation cannot directly influence the upper-level analysis.

In Table 2-2, the RMSD of 500-hPa geopotential height is presented. Quantitatively, in the NH extra-tropics, the surface pressure only analysis (PRS) reduced the daily 500-hPa height (Z500) RMSD from 111 meters in AMIP runs to just 49 meters (Table 2-2). The PRS analysis is as accurate as a 2-3 day forecast of a respectable numerical forecast model. This remarkable capability of the data assimilation system was first demonstrated by Whitaker et al. (2004). For the reduced number of surface pressure observations (PRSX), the RMSD of Z500 increased to 91 meters, still better than AMIP, but considerably worse than PRS (Table 2-2). The RMSD of

PRSX (91 meters) is worse than the 64 meters from the similar experiment performed by Whitaker et al. (2004) shown in their Figure 3. The degradation in our analysis is due to fewer surface pressure observations, a different analysis period, and other tunings on the analysis system not made in our study. It should be emphasized that Whitaker et al. (2004) utilized ensemble Kalman filter technique to further improve the surface pressure observation-only analysis for the data coverage of 1915. With their method, the RMSD was reduced to 40 meters, a considerable improvement. In our experiment, increasing the number of surface observations by several factors (as in the PRS experiment) in conventional data assimilation seems to mimic the ensemble Kalman filtering analysis technique.

The SST has a fairly significant impact on the extra-tropical upper-level analysis. For the PRS experiment, the use of climatological SST increases the RMSD in the NH extra-tropics by 14 meters (from 49 to 63 meters), and by 11 meters (from 55 to 66 meters) in the SH. The importance of SST in the tropics is much more apparent, which can be seen in that the AMIP run RMSD is smaller than that of the PRSC run. This is more clearly demonstrated in the normalized RMSD (Fig. 5c). The use of climatological SST resulted in very large RMSD over the entire tropics. Closer examination of the RMSD indicated that the bias accounted for more than 90% of the RMSD (not shown). This height bias is caused by the bias in temperature, to be discussed later. The impact of SST increases with height in the extra-tropics, as the impact of SST in extra-tropical latitudes is more apparent at 200-hPa than at 500-hPa (Fig. 5a). For 1993, the impact of SST in the NH extra-tropics is not as apparent, but is still significant in the tropics (Fig. 5b, 5d).

4. Impact of surface pressure observation and SST on monthly and seasonal mean analyses

In this section characteristics of the impact of SST and surface pressure observation on seasonally averaged parameters are described. The impact of SST was found to be very different from daily time scale in the free atmosphere. This is one of the key findings of this paper.

4.1. Impact on surface pressure analysis

Figure 6 presents normalized RMSD of surface pressure for seasonal (3-month) average, shown in a similar manner as Fig. 4. The RMSD is normalized by the variance of seasonal mean computed from 20-yr reanalysis data. Many of these features are similar to the daily figures (Fig.4a), except that the impact of SST is more enhanced in the seasonal figures, particularly over NH ocean and land. This enhancement is less for 1993. Clearly the analysis of surface pressure in the extra-tropics is responding to the tropical SST anomaly in this time scale.

4.2. Impact on 2-meter temperature analysis

The normalized T2M RMSD (Fig. 6b) is drastically different from daily figures (Fig. 4b) in the extra-tropics. The difference increases as the time average period increases from monthly to seasonal (not shown). Over the ocean in particular, the impact of SST is significant in the seasonal mean. At the same time, the difference between AMIP and analysis with observations decreases. Particularly noteworthy is that in 1997, the AMIP T2M is as accurate as the analysis with the full observation system with climatological SST. Apparently, the impact of observation is different for different time scales of the analysis. For the non-ENSO year (Fig. 6c and 6d), the impact of SST is generally smaller but still significant.

4.3 Impact on upper-level field analysis

The RMSD of 500-hPa height in the NH (Fig. 7b) does not decrease from the AMIP, PRSX and PRS experiments, indicating that the surface pressure observation does not have a very strong influence on seasonal mean 500-hPa analysis. Alternatively, the SST drastically decreases the RMSD for the same observation system. This is in sharp contrast to the role of surface pressure observation and SST on *daily* 500-hPa analysis (Fig. 5b), where the surface pressure observation reduces the RMSD much more. Table 2-2 shows that the RMSD for daily analysis decreased from 111 for AMIP to 49 meters for PRS, i.e., a 62 meter decrease using surface pressure observation, and the maximum decrease of RMSD is from 105 for PRSXC and 91 for PRSX, a 14 meter decrease, using observed SST. In comparison, Table 3 shows that RMSD does not decrease from AMIP to PRS, but it decreases 20 meters from PRSC and PRS. Although the RMSD of daily and seasonal averages cannot be compared directly, it is very clear that SST dominates the analysis of seasonal mean upper-level height field, while surface pressure observation dominates for daily analysis. Apparently, the high frequency observations (synoptic surface pressure observation) provide the greatest impact on high frequency analysis (daily), while low frequency observations (monthly averaged SST interpolated to daily) provide the greatest impact on low frequency analysis (seasonal).

It is important to ask why the data assimilation used in this study (3D variational analysis scheme) filters out low frequency signal from surface pressure observation for upper-level analysis. It is also important to examine whether a different analysis system has different filtering characteristics. Since surface pressure is a total mass of the air column, and it is strongly influenced by the external gravity wave, the balance equation constraints built into the analysis system (Parrish and Derber, 1992) may have some role in this filtering property. In this context, it is of great interest to examine the time scale of information included in various

observation systems, such as radiosondes, satellite observation, aircraft observation and conventional surface observation and how they are filtered out in the analysis forecast system, namely through the forecast model and the objective analysis scheme. In addition, whether this result holds for other analysis systems, such as the more advanced ensemble Kalman Filter method, is not clear at this point. We hope such a study will be performed by institutions and operational centers.

One reason for the strong dependency of the time mean analysis to SST obtained in this study may be due to the very large SST anomaly in the tropics. However, the experiments for the near-normal tropical SST anomaly year, 1993, still show reduced magnitude but significant impact. For this year, the accuracy of the AMIP experiment is similar to or slightly worse than the analysis with full surface pressure observation with climatological SST. Thus, even for near-normal SST years, SST is important in determining the low frequency part of the upper-level analysis (Fig. 7c).

Similar results are obtained for 200-hPa height (Fig. 7a), 850-hPa and 300-hPa temperature (not shown). We see in Figure 7 that the role of SST tends to amplify with height. In the tropics and in the SH, SST is again important, but surface pressure observation is also as important.

4.4. Bias

The large reduction of RMSD by the use of observed SST in the tropics is mostly due to the reduction in the systematic part of the error which amounts to more than 90% of total RMSD. The vertical distribution of the effect of SST and surface pressure observation on the zonally averaged temperature is shown in Figure 8. The use of climatological SST (left columns)

produces cold bias in the tropical upper troposphere, extending to lower levels in the NH subtropics. This bias is caused by the difference in precipitation in the climatological SST and observed SST runs (Fig. 13). The surface pressure observation almost entirely eliminates temperature bias in the tropics and NH troposphere. The large positive bias in the NH polar region is replaced by a small cold bias resulting from the introduction of surface pressure observation.

The differences between observed SST runs and control analyses (right column) show a large cold bias in the stratosphere. Note that the control analysis uses satellite data in the stratosphere. Thus the surface pressure observation does not have any impact on analysis in the stratosphere, and even radiosonde cannot eliminate the cold bias as also shown by Bengtsson et al (2004).

5. Impact of radiosonde observation

The impact of radiosonde on analysis is generally significant and overwhelms the effect of SST as seen in all the RMSD figures (Figs. 4 - 7). However, close examination of the results suggests that we can still detect the impact of SST. For example, there is a small degradation in the analysis over land (about 0.8-hPa) using all observations with climatological SST (CNTLC) compared with the analysis with full observation but with observed SST (CNTL) (see Table 2-2). The SST signal propagates from ocean to land in the data assimilation system and thus the inaccurate information over ocean also propagates to land and contaminates the analysis over land even when full observations are used.

6. Impact of SST and observation on diagnosed fields

The change in observation system affects model diagnosed fields through the change in the analysis variables. We here present RMSD of latent heat flux (LHF), cloudiness (CLD) and precipitation (PRCP).

6.1 Impact on daily diagnostic fields

6.1.1 Latent heat flux

The un-normalized RMSD of LHF ranges from the lower 80s to about 20 watts per meter square (Table 2-3) among the experiments. The RMSD is smaller over land, probably due to the memory of soil moisture. The bar graphs of normalized LHF (Fig. 9a) show that the RMSD decreases with the use of observed SST as well as with the improved observation system, almost equally over the globe. The exception is the impact of SST on the full observation system over ocean (CNTLC), which is less inaccurate than observed SST with full surface observation and radiosondes (SONDE), showing the importance of SST which cannot be compensated by the conventional observations. Interestingly, the improvement of latent heat flux with the use of observed SST is also found over NH land regions. Surface pressure observation improves latent heat flux in the extra-tropics, but not so much in the tropics. This is consistent with the impact of surface pressure observation on T2M (Fig. 4b).

6.1.2. Cloudiness

Consistent improvement in cloudiness due to SST is observed over the globe, but the magnitude is small, of the order of 1 to 2 percent (Fig. 9b and Table 2-3). The observation system also contributes to the improvement of clouds. Of particular interest is the drastic reduction (nearly 10%) in cloudiness RMSD over land in the NH as soon as the upper-air observations are introduced. This is most likely due to the bias in the model relative humidity which is corrected by radiosondes over land. It is noted that the cloudiness in the R-2 CDAS system is diagnosed from relative humidity.

6.1.3 Precipitation

The response of precipitation to SST is the weakest of all parameters we examined. Precipitation is more affected by the change in observation system, about a 10% decrease in RMSD as the observation system is increased (Table 2-3). We only see a small improvement in precipitation over tropical ocean by SST in both 1997 (Fig. 9c) and in the near-normal SST year, 1993 (Fig. 9d). Closer examination of the figures reveals that the SST has a small positive impact on extra-tropical land areas, which is more pronounced in the near-normal SST year (Fig. 9d). The greatest contribution to the decrease in RMSD is the radiosonde observation. The impact is the largest over NH extra-tropical land, as seen in the abrupt decrease of RMSD when radiosonde observations are used (Fig. 9c).

6.2. Impact on seasonal averaged diagnostic fields

6.2.1. Latent heat flux

The impact of observation and SST on seasonal mean latent heat flux is shown in Figure 10a. Compared to the daily RMSD (Fig. 9), the impact of SST is much larger in the NH extra-tropics. The responses in the NH resemble those of T2M (Fig. 6b). Over the NH extra-tropical oceans, the RMSD does not change much with the introduction of surface pressure observations, until the radiosonde observation is introduced. The seasonal mean latent heat flux in the extra-tropical ocean is controlled by SST more than by surface pressure observation. The importance of surface pressure observation is a little stronger over extra-tropical land. Over the SH extra-tropics, the impact of SST and surface pressure is about equal. In the tropics, the impact of SST is weak and only apparent for SONDE experiments. The large RMSD for CNTLC (right-most bar) indicates the importance of SST for latent heat flux over the globe, even when all the observations are used.

6.2.2. Cloudiness

As to seasonal mean cloudiness (Fig. 10b), the impact of surface pressure is small. We observe some impact of SST over the tropical ocean. The radiosonde data is essential in bringing the cloudiness down to the control analysis, which is particularly significant over extra-tropical land.

6.2.3 Precipitation

For the seasonal mean precipitation over NH extra-tropical land and over tropical ocean, the impact of SST is clear, but its magnitude is not large (Fig. 10c). Note that SST had no impact on daily precipitation (Fig. 9c). The impact of radiosondes is very clear over the globe.

The impact of SST on the near-normal year, 1993 (Fig. 10d), is somewhat greater than that in the strong El Nino year, 1997. This can simply be an artifact of the use of single member analysis.

7. Geographical patterns of differences in seasonal mean field

7.1 MSLP

Figure 11 shows the differences of seasonal mean MSLP between the experiments. The analysis with surface pressure observations only (PRS) analysis shows a significant SST impact in the Pacific, roughly corresponding to the area of SST difference (Fig. 3). There is a clear anti-correlation between the difference in SST and that of the surface pressure analysis. The impact of SST can be seen even for CNTL analysis over the El Nino region, where the SST difference reaches 4-5 degrees, and surface observation is scarce (Fig. 1). Comparing the analysis with control for observed SST experiments (right column), the differences are generally larger for AMIP and PRSX, particularly over ocean. There is a marked similarity in the patterns between AMIP-CNTL and PRSX-CNTL. The difference of the PRS experiments is much smaller, simply indicating that the data assimilation system is properly incorporating the surface pressure observation information into the analysis, and the influence of SST is clear where the surface pressure observation is absent.

7.2 500-hPa height

The geographical distributions of the difference of 500-hPa height between various analyses are shown in Fig. 12. The top left panel shows the difference between AMIPC and AMIP, which is the response of the atmosphere to observed SST. The panels below are the response pattern modified by the injection of surface pressure observation. The use of all the surface pressure observations eliminated differences located at the west coast of the U.S.,

northeastern North America, and Europe. Even the tropical dipole pattern is reduced. On the right column, we see that the difference of each observation system is independent from the error using climatological SST. The patterns of differences in the NH vary somewhat from the AMIP to PRS experiments. Note that some of the difference increases as more surface pressure observations are added. The areas of large difference in the PRS experiment roughly coincide with the areas of coarse surface pressure observations (Fig. 1). In the SH, the difference pattern does not change much, due to the small number of surface pressure observations available.

7.3 Precipitation

The geographical pattern of the impact of SST and observation on model diagnosed precipitation is shown in Figure 13. The difference is larger and extends to the extra-tropics for SST impact experiments (left column), while the impact of the observation system (right column) is smaller and more concentrated in equatorial latitudes. This is in sharp contrast to the RMSD of daily precipitation (not shown), for which the RMSD is larger and extends into the extra-tropics for observation system experiments.

8. Conclusions

The importance of SST in Reanalysis is examined using the NCEP/DOE reanalysis system. The winter season in the strong El Nino year of 1997 as well as in the near-normal SST anomaly year of 1993 were chosen for the experiment. The analyses with climatological and observed SST were performed and compared for no observation, surface pressure only observation of 1915 observation distribution, surface pressure only observation of 1997 observation coverage, surface pressure and radiosonde observation, and complete observation

for 1997. The impact of SST and observation systems was measured using the RMSD of analysis from Control analysis with observed SST and the complete observation system.

The most important finding of this paper is that the effect of SST and the observation system is different for different time scales. It is found that low frequency observation, such as SST, provides greatest impact on low frequency analysis, such as the seasonal mean. On the other hand, high frequency observation, such as synoptic surface pressure observation, provides the largest impact on high frequency analysis, namely daily analysis. The latter does not necessarily provide information on low frequency analysis. This is most clearly demonstrated in T2M and upper-level height field analysis in the extra-tropics. Whether this finding is characteristic only to the data assimilation system used in this study is uncertain and needs to be examined using other data assimilation systems, including those using the latest techniques, such as the ensemble Kalman filter.

More concise conclusions of the impact of SST, surface pressure observation and upper-air observations for the analysis in the NH extra-tropics are summarized in Table 4. It shows the qualitative importance of each observation system (top row) on the analysis of variables shown in the left-most column, separated for daily (high frequency) and seasonal mean (low frequency) analyses. Note that the table is based on a somewhat subjective judgment and only shows results for the NH extra-tropics. It does not differentiate land from ocean. Thus, the table should be used for a rough estimate of the importance of SST, surface pressure and radiosonde observations in the data rich extra-tropics. The table shows that SST has an important effect on the analysis of all the parameters in daily and seasonal time scales, but its importance increases for seasonal mean. The SST is also very important in obtaining a good estimate of diagnostic quantities such as surface fluxes, cloudiness and precipitation. Alternatively, surface pressure

observations are more important for daily analysis, but have little or no effect on seasonal average. They are also not so important for the diagnostic quantities. The radiosonde observations have the greatest impact on all the parameters for both daily and seasonal mean analyses, and are the essential source of observation for accurate analysis of all the parameters.

In the tropics, the impact of SST and the observation system is about equal for daily and seasonal mean analysis. This is probably due to less activity of high frequency modes compared to the extra-tropics. When the SST observation is replaced with climatology, the impact of surface pressure observation becomes larger for many of the parameters examined in this study, but the improvement of analysis resulting from the pressure observation is always less than that from observed SST.

This study indicates that obtaining accurate analysis of all the parameters before the radiosonde era is difficult. The importance of SST observation increases considerably for the pre-radiosonde era, particularly for the analysis of low frequency modes, such as the monthly and seasonal mean. In addition, improving the analysis of derived quantities such as cloudiness and precipitation is even more challenging, since these parameters are not strongly affected by surface pressure, or only weakly affected by SST observations. Considering the importance of SST in the analysis of low frequency modes, it is strongly recommended that the SST be analyzed as part of the objective analysis scheme. Since surface pressure, near-surface temperature, moisture and even winds are statistically (or dynamically and thermodynamically) correlated with SST, such a method may not be difficult to develop. We also hope that the use of advanced analysis technique, such as the ensemble Kalman filter, improves this situation. This study also suggests that the analysis of low frequency modes may require special consideration and research.

Acknowledgements

We sincerely thank Professor Song-You Hong of Yonsei University for enabling one of the authors to visit SIO to perform this research. We also thank Jack Woollen and Wesley Ebisuzaki for assisting with the data assimilation experiments. Dr. Tosiuyuki Nakaegawa provided information on the difference of two independent SST analyses. We also thank Dr. John Roads for his continuous encouragement throughout this study. Diane Boomer contributed in improving and making the paper much more readable. This project is supported by Cooperative Agreement NOAA-NA17RJ1231 and by the project, “Development of the Technology for the Improvement of Medium-Range Forecast”, one of the Research and Development on Meteorology and Seismology funded by the Korea Meteorological Administration (KMA).

APPENDIX A

Observation distribution for the 1915 experiment

The total number of land stations in 1915 was around 380. Not all surface stations took observation at all times. The averaged number of ocean observations was 41 per hour. Using the observation density of 1000 per day during the early 20th century, estimated by Whitaker et al. (2004), we assigned about 200 stations per each analysis time, 50 of which are located over ocean. Land observations are extracted from stations that coincide with land stations in Fig. 1. Oceans are divided into six areas and observations in each area are randomly selected according to the observation density shown in the right panel of Fig. 2. For example the Atlantic has 30% of global observation, while the Southern Indian Ocean has 5%. An example of simulated distribution (reduced 1997 network) used to run the 1915 experiment is shown in Fig. A1. Approximately 200 land stations are nearly fixed because they are selected from 380 predefined 1915 station networks. The number of both land and ocean observations are reduced to 170~220 (average number 200) after the data quality control procedure.

APPENDIX B

Simple Ensemble data assimilation

Simple ensemble analysis is performed to minimize uncertainty in the analysis resulting from uncertainty in the model initial guess. The method is to extend the ensemble AMIP runs methodology to analysis by randomly perturbing the initial guess of the first analysis of the data assimilation cycle. We performed 5 member ensemble analyses. The analysis for each cycle is obtained by the ensemble averages. Figure B2 shows daily RMSD of 500-hPa height for each analysis from control as well as the RMSD of the ensemble mean. Clearly, the ensemble mean reduces the RMSD by as much as 20 meters using this simple method.

REFERENCES

- Arkin, P., E. Kalnay, J. Laver, S. Schubert and K. Trenberth, 2003: Ongoing Analysis of the Climate System: A Workshop Report. Boulder Colorado, August, 18020, 2003.
http://www.joss.ucar.edu/joss_psg/meetings/climatesystem/FinalWorkshopReport.pdf
- Barnston A. G., A. Leetmaa, V. E. Kousky, R. E. Livezey, E. A. O'Lenic, H. Van den Dool, A. J. Wagner, and D. A. Unger, 1999: NCEP Forecasts of the El Nino of 1997-98 and Its U.S. Impacts. *Bull Amer. Meteor. Soc.*, **80**, 1829-1852.
- Bengtsson, L., K. I. Hodges, and S. Hagemann, 2004: Sensitivity of the ERA40 reanalysis to the observing system: determination of the global atmospheric circulation from reduced observations. *Tellus*, **56A**, 456-471.
- Chelliah, M., and C. F. Ropelewski, 2000: Reanalyses-Based Tropospheric Temperature Estimates: Uncertainties in the Context of Global Climate Change Detection. *J. Climate*, **13**, 3187–3205.
- Gates, W. L., J. S. Boyle, C. Covey, C. G. Dease, C. M. Doutriaux, R. S. Drach, M. Fiorino, P. J. Gleckler, J. J. Hnilo, S. M. Marlais, T. J. Phillips, G. L. Potter, B. D. Santer, K. R. Sperber, K. E. Taylor, and D. N. Williams. 1999: An Overview of the Results of the Atmospheric Model Intercomparison Project (AMIP I). *Bull. Amer. Meteor. Soc.*, **80**, 29–55.
- Gibson, J. K., P. Kallberg, S. Uppala, A. Nomura, A. Hernandez, E. Serrano, 1997: eRA Description, ECMWF Re-Analysis Final Report Series, 1, 71pp. ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX UK.
- Kalnay, E., M. Kanamitsu, R. E. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C.

- Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.
- Kanamitsu, M., A. Kumar, H. -M. H. Juang, W. Wang, F. Yang, J. Schemm, S. -Y. Hong, P. Peng, W. Chen, and M. Ji, 2002a: NCEP Dynamical Seasonal Forecast System 2000. *Bull. Amer. Meteor. Soc.*, **83**, 1019-1037.
- _____, W. Ebisuzaki, J. Woollen, J. Potter, and M. Fiorino, 2002b: NCEP/DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.*, **83**, 1631-1643.
- Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Chelliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne, and M. Fiorino, 2001: The NCEP–NCAR 50–Year Reanalysis: Monthly Means CD–ROM and Documentation. *Bul. Amer. Meteor. Soc.*, **82**, 247–268.
- Parrish, D. F., and J. C. Derber. 1992: The National Meteorological Center's Spectral Statistical-Interpolation Analysis System. *Mon. Wea. Rev.*, **120**, 1747–1763.
- Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, and D. P. Rowell, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**, 4407, doi: 10.1029/2002JD002670.
- Reynolds, R. W., 1988: A Real-Time Global Sea Surface Temperature Analysis. *J. Climate*, **1**, 75-86.
- _____, 1993: Impact of Mount Pinatubo Aerosols on Satellite-derived Sea Surface Temperatures. *J. Climate*, **6**, 768–774.
- _____, and T. M. Smith, 1994: Improved Global Sea Surface Temperature Analyses Using Optimum Interpolation. *J. Climate*, **7**, 929–948.

- Servain, J., M. Seva, and P. Rual, 1990: Climatology comparison and long-term variations of sea surface temperature over the tropical Atlantic Ocean. *J. Geophys. Res.*, **95**, 9421-9431.
- Simmons A. J., and J. K. Gibson, 2000: The ERA-40 Project Plan. ERA-40 Project Report Series. ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX, UK.
- Smith, T. M., R. W. Reynolds, R. E. Livezey, and D. C. Stokes, 1996: Reconstruction of Historical Sea Surface Temperatures Using Empirical Orthogonal Functions. *J. Climate*, **9**, 1403–1420.
- _____, and R. W. Reynolds, 2004: Improved Extended Reconstruction of SST (1854-1997). *J. Climate*, **17**, 2466-2477.
- Stammer, D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. N. Hill, and J. Marshall, 2002: Global ocean circulation during 1992-1997, estimated from ocean observations and a general circulation model. *J. Geophys. Res.*, **107**, 1-27.
- Sturaro, G., 2003: A closer look at the climatological discontinuities present in the NCEP/NMCAR reanalysis temperature due to the introduction of satellite data. *Climate Dynamics*, **21**, 309-316.
- Whitaker, J. S., G. P. Compo, X. Wei, and T. M. Hamill, 2004: Reanalysis without Radiosondes Using Ensemble Data Assimilation. *Mon. Wea. Rev.*, **132**, 1190-1200.

Table 1. Summary of experiments configuration.

Exp #	Name	SST	Observation data
5	CNTL	Analyzed	All observation
	CNTLC	Climatology	All observation
4	SONDE	Analyzed	Surface pressure and radiosondes
	SONDEC	Climatology	Surface pressure and radiosondes
3	PRS	Analyzed	Surface pressure only
	PRSC	Climatology	Surface pressure only
2	PRSX	Analyzed	Surface pressure only with less density
	PRSXC	Climatology	Surface pressure only with less density
1	AMIP	Analyzed	None
	AMIPC	Climatology	None

Table 2-1 Root Mean Square Difference of daily analysis from control analysis averaged for three months (1997). NH stands for latitudinal band of 30N-90N, EQ for 30S-30N and SH for 90S-30S.

		<u>NH</u>	<u>EQ</u>	<u>SH</u>	<u>Land</u>	<u>Ocean</u>
MSLP	AMIPC	10.3	2.8	9.6	8.1	8.3
	AMIP	9.8	2.1	8.3	7.4	7.5
	PRSXC	8.1	2.4	8.8	6.4	7.2
	PRSX	7.2	1.5	8.6	5.8	6.8
	PRSC	3.1	1.8	4.4	2.9	3.4
	PRS	2.7	1.6	4.1	2.7	3.1
	SONDEC	1.1	1.0	2.7	1.4	1.9
	SONDE	0.7	0.7	2.7	1.2	1.8
	CNTLC	0.7	0.8	0.6	0.8	0.6
T2m	AMIPC	5.9	2.1	2.4	6.1	2.5
	AMIP	5.2	1.4	2.0	5.4	2.0
	PRSXC	5.6	2.1	2.3	5.8	2.4
	PRSX	4.6	1.2	2.0	4.8	1.8
	PRSC	3.8	1.9	2.0	4.1	1.9
	PRS	2.9	0.9	1.6	3.2	1.2
	SONDEC	1.9	1.2	1.4	2.0	1.3
	SONDE	1.0	0.6	1.1	1.4	0.7
	CNTLC	1.8	1.2	1.0	1.6	1.2

Table 2-2. Root Mean Square Difference of daily analysis from control analysis averaged for three months (1997).

		<u>NH</u>	<u>EQ</u>	<u>SH</u>
Z500	AMIPC	120.	63.	115.
	AMIP	111.	27.	98.
	PRSXC	105.	57.	108.
	PRSX	91.	21.	101.
	PRSC	63.	40.	66.
	PRS	49.	16.	55.
	SONDEC	12.	9.	35.
	SONDE	11.	7.	32.
	CNTLC	4.	7.	6.

Table 2-3. Root Mean Square Difference of daily analysis from control analysis averaged for three months (1997).

		<u>NH</u>	<u>EQ</u>	<u>SH</u>	<u>Land</u>	<u>Ocean</u>
LH	AMIPC	77.2	72.7	58.3	35.7	79.4
	AMIP	73.4	64.9	59.9	33.9	75.3
	PRSXC	67.8	70.3	55.8	32.3	74.1
	PRSX	58.8	61.4	57.2	29.9	67.3
	PRSC	49.4	56.5	43.2	32.1	55.6
	PRS	43.6	54.6	43.6	28.2	53.4
	SONDEC	33.1	53.6	32.8	26.5	45.7
	SONDE	21.0	42.3	28.3	20.8	35.4
	CNTLC	28.3	45.5	22.4	21.6	37.4
Precip.	AMIPC	5.7	10.1	6.2	5.8	8.2
	AMIP	5.6	9.4	6.2	5.8	7.8
	PRSXC	5.5	10.1	6.1	5.6	8.2
	PRSX	5.2	9.1	6.1	5.5	7.6
	PRSC	4.8	8.9	5.6	5.2	7.2
	PRS	4.7	8.2	5.6	5.1	6.8
	SONDEC	2.7	9.0	4.8	4.4	6.7
	SONDE	2.4	9.2	4.9	3.6	7.0
	CNTLC	1.4	6.7	2.8	2.8	4.8
Cloud	AMIPC	32.5	23.7	29.7	32.5	27.2
	AMIP	32.3	22.1	29.4	32.4	26.4
	PRSXC	31.7	23.6	29.5	32.0	26.8
	PRSX	30.8	21.8	29.1	31.3	25.7
	PRSC	28.2	24.5	27.8	28.7	26.1
	PRS	27.9	23.2	26.9	28.2	25.1
	SONDEC	17.4	24.7	26.5	18.1	25.0
	SONDE	16.3	22.1	25.7	17.5	23.2
	CNTLC	11.6	19.2	13.7	11.3	16.5

Table 3. Root Mean Square Difference of seasonal mean analysis from control analysis (1997).

		<u>NH</u>	<u>EQ</u>	<u>SH</u>
	AMIPC	50.	61.	74.
	AMIP	24.	23.	48.
	PRSXC	51.	55.	66.
	PRSX	32.	17.	54.
Z500	PRSC	44.	38.	40.
	PRS	24.	6.	22.
	SONDEC	6.	7.	15.
	SONDE	5.	3.	11.
	CNTLC	3.	6.	4.

Table 4. Impact of SST, Surface Pressure and Radiosonde Observations on analysis in the Northern Hemisphere extra-tropics.

Obs. System	Sea Surface Temp.		Surface Pressure		Sondes	
	Daily	Seasonal	Daily	Seasonal	Daily	Seasonal
T2m	++	++	+	+	++	++
Ps	+	+	++	+	++	++
Z500	+	++	++	+	++	++
LHF	+	++	+	0	++	++
CLD	+	+	+	0	++	++
Precip	+	+	0	0	++	++

0: no impact

+: marginal impact

++: strong impact

Figure Captions

Fig. 1. The distribution of observation sites for surface pressure at 00UTC November 7 1997.

Fig. 2. Simulated Psfc data distribution of land (left panel) and ocean (right panel) extracted from surface observation data on November 7th 1997.

Fig. 3. Seasonal mean SST anomaly for 1993 (top) and 1997 (bottom).

Fig. 4. Time averaged normalized RMSD of daily mean sea level pressure (a) and T2M (b) for 1997 (left panels) and 1993 (c and d). For each panel, top is over ocean, middle is over land and the bottom is ocean plus land. RMSD is normalized by the daily temporal variance.

Fig. 5. Time averaged normalized RMSD of daily mean 200-hPa height (Top), 500-hPa height (bottom), for 1997 (left) and 1993 (right) columns. For each panel, top panel is over ocean, middle panel is over land and the bottom panel is ocean plus land. RMSD is normalized by the daily temporal variance.

Fig. 6. RMSD of seasonal average MSLP (upper panel) and T2M (lower panel) for 1997 (left) and 1993 (right).

Fig. 7. RMSD of 500-hPa (lower) and 200-hPa (upper) height of seasonal mean for 1997 (left) and 1993 (right).

Fig. 8. Difference of zonally averaged temperature (°C).

Fig. 9. Time averaged normalized RMSD of daily mean Latent heat flux (a), total cloudiness (b), precipitation (b) for 1997, and precipitation for 1993 (d). For each panel, top portion is over ocean, middle is over land and the bottom is ocean plus land. RMSD is normalized by the daily temporal variance.

Fig. 10. RMSD of seasonal mean Latent heat flux (a), cloudiness (b), precipitation (c) for 1997 and precipitation (d) for 1993.

Fig. 11. Difference of seasonal mean MSLP.

Fig. 12. Difference of seasonal mean 500-hPa height.

Fig. 13. Difference of seasonal mean precipitation.

Fig. A1. Monthly distribution of land surface station (left panel) and observation point at ocean (right panel) in November 1915.

Fig. B1. Daily RMSD of 500-hPa height of individual members and ensemble mean (think soil line) from control analysis. Unit in meter.

Fig. 1. The distribution of observation sites for surface pressure at 00UTC November 7 1997.

Fig. 2. Simulated Psfc data distribution of land (left panel) and ocean (right panel) extracted from surface observation data on November 7th 1997.

Fig. 3. Seasonal mean SST anomaly for 1993 (top) and 1997 (bottom).

Fig. 4. Time averaged normalized RMSD of daily mean sea level pressure (left top) and T2M (bottom) for 1997 (left panels) and 1993 (right panels). For each panel, top is over ocean, middle is over land and the bottom is ocean plus land. RMSD is normalized by the daily temporal variance.

Fig. 5. Time averaged normalized RMSD of daily mean 200-hPa height (Top), 500-hPa height (bottom), for 1997 (left) and 1993 (right) columns. For each panel, top panel is over ocean, middle panel is over land and the bottom panel is ocean plus land. RMSD is normalized by the daily temporal variance.

Fig. 6. RMSD of seasonal average MSLP (upper panel) and T2M (lower panel) for 1997 (left) and 1993 (right).

Fig. 7. RMSD of 500-hPa (lower) and 200-hPa (upper) height of seasonal mean for 1997 (left) and 1993 (right).

Fig. 8. Difference of zonally averaged temperature ($^{\circ}\text{C}$).

Fig. 9. Time averaged normalized RMSD of daily mean Latent heat flux (a), total cloudiness (b), precipitation (c) for 1997, and precipitation for 1993 (d). For each panel, top portion is over ocean, middle is over land and the bottom is ocean plus land. RMSD is normalized by the daily temporal variance.

Fig. 10. RMSD of seasonal mean Latent heat flux (a), cloudiness (b), precipitation (c) for 1997 and precipitation (d) for 1993.

Fig. 11. Difference of seasonal mean MSLP.

Fig. 12. Difference of seasonal mean 500-hPa height.

Fig. 13. Difference of seasonal mean precipitation.

Fig. A1. Monthly distribution of land surface station (left panel) and observation point at ocean (right panel) in November 1915.

Fig. B1. Daily RMSD of 500-hPa height of individual members and ensemble mean (think soil line) from control analysis. Unit in meter.