Investigation on the Tendencies of the Land–Ocean Warming Contrast in the Recent Decades

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***Abstract*—In this letter, the surface climate temperature trends for the land and the oceans (land–ocean warming contrast) have been examined and compared based on five data sets. The five data sets included three reconstructed data sets of surface temperature observations and two data sets derived using the satellite microwave sounding unit retrieval products in the lower troposphere (LT) for the period from January 1980 to December 2014. Unlike previous studies, the current study shows that the warming trends significantly decreased over both the land and ocean since 1992 and reached their minimum (near zero) in the early 2000s, which is consistent with the occurrence of the warming hiatus. However, due to the sharp decrease in the surface warming trend over the land (1992 to 2007) in conjunction with an increase in the ocean surface warming trend after 2002, the combined trend carries an overall positive sign (between 2005 and 2007) due to the greater ocean warming trend. The rate of warming increase in the ocean, which began in 2002, is surprisingly fast and is approaching the highest warming trends observed over the land since 1980. These basic land and ocean trend results are confirmed by all five data sets with slightly different values due to the various techniques used in compiling the data sets. However, there is consistency in the overall trend pattern results.**

***Index Terms*—Global warming, land–ocean warming contrast (LOWC), remote sensing, temperature trend.**

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I. Introduction

ACCOMPANYING the global warming hiatus, observed in the roughly "flat" temperature anomaly (TA) trends in the late 1990s or the early 2000s [1]–[3], the response of the land–ocean warming contrast (LOWC) to the decadal hiatus received much attention [4], [5]. Due to the ocean having a much larger heat capacity, many earlier studies [4], [6] indicate that surface temperature of the land increases at a greater rate than the ocean during the rapid warming period before the 1970s. However, the LOWC is not simply a result of the different thermal inertias of land and ocean regions [7]. With a rapid global warming in recent decades and the significant decline in the sea ice extent and snow cover [8], the energy balance between land and ocean was changed [9]. Consequently, the response of the LOWC related to the changing global temperature balance is worth a study. In this research, the LOWC will be evaluated by comparing the surface temperature trends over the land and ocean separately to provide additional insight into this global phenomena.

This study attempts to quantitatively examine the uncertainty in the estimates of the asymmetric ocean–land temperature trends in the ground-based observations and satellite-retrieved products from 1980 to 2014. Section II describes the data sets, and Section III presents the discrepancies of the temperature trends over the global land and ocean. Section IV examines the variation of the LOWC. This letter is concluded in Section V with a final summary of our results.

II. Data

The temperature data sets used in this study are from two sources of observations.

1) Three reconstructed surface temperature (RST) observation data sets over the land and ocean: a) The latest version of HadCRUT4 is a blend of the CRUTEM4 land-surface air temperature data set and the HadSST3 sea-surface temperature data set [10]. b) The Goddard Institute for Space Studies (GISS) surface temperature (GISTEMP) is from the NOAA Global Historical Climatology Network (GHCN) version 3, the Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4) [11]. c) The National Climatic Data Center (NCDC) merges their surface air temperature using sea surface data from the ERSST.v4 and land surface air temperatures from the Global Historical Climatology Network-Monthly (GHCN-M) version 3.3.0 [12]. This data set will be named as NCDCT3 in this letter.

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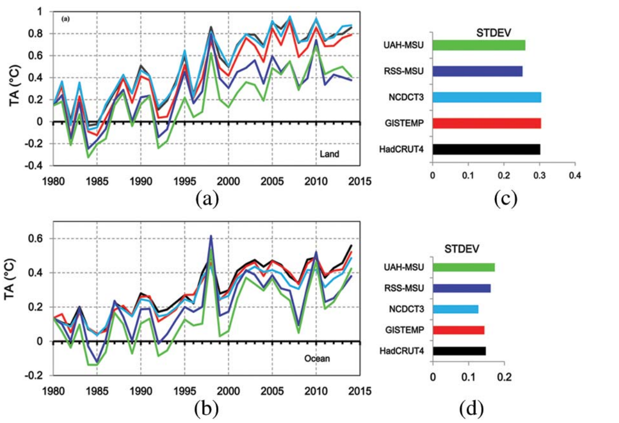

Fig. 1. Left panels present the time series of the global TAs from the land and ocean surface observations of HadCRUT4, GISTEMP, NCDCT3, and MSU satellite retrievals of the RSS and UAH data sets in the LT. (a) Land. (b) Ocean. UAH MSU LT (green), RSS MSU LT (deep blue), NCDCT3 (thin blue), GISTEMP (red), and HadCRUT4. The right panels present the SD of the time series, a measure of uncertainty. (c) Land. (d) Ocean.

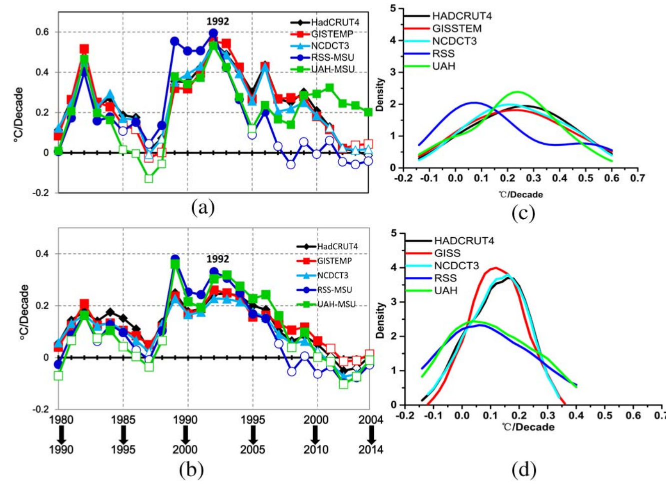

Fig. 2. (Left panel) Running linear trends for 11-year moving time window in the period of 1980 to 2014 over the land (a) and ocean (b). The x-axis shows the value for each 11-year period. Filled points represent trends that are significant at the 90% significance level. (Right panel) PDF for the running decadal trends (°C/decade) over the land (c) and ocean (d).

2) Two microwave sounding unit (MSU) satellite temperature retrievals of the lower troposphere (LT; e.g., MSULT): a) The University of Alabama in Huntsville (UAH) MSU LT is the updated version 6.0 including AMSU data [13]. b) RSS MSU LT was created by Remote Sensing Systems, Inc. (RSS V3.3) using different corrections and merging procedures than those used by UAH [14].

All monthly data spanned the period from January 1980 to December 2014. The TAs in the HadCRUT4 and NCDC data sets were computed against the period 1961 to 1990 and in the GISTEMP data set against the period 1951 to 1980. Land and ocean surface data are available separately from HADCRUT4, NCDC, RSS, and UAH. Land and ocean of GISS were determined using a land-fraction map provide by GISS.

III. Discrepancies of the Temperature Trends Over the Global Land and Ocean

Fig. 1 shows the global (land and ocean) surface TA time series of the three RST observations and the two MSULT-satellite-retrieved products over the period 1980 to 2014. The results are consistent across five different data sets that the amplitude of the TA increased with time [Fig. 1(a) and (b)]. However, the amplitude of land surface TA (LSTA) is larger than the sea surface TA (SSTA). The standard deviation (SD) representing the range or uncertainty of the TA shows that the global LSTA and SSTA averaged for the five data sets have peak values (amplitudes) of 0.28 ± 0.018 °C and 0.15 ± 0.026 °C, respectively. Additionally, the SD demonstrates a significant difference between the RST observations and MSULT-retrieved products. The two MSULT-satellite-retrieved products have smaller SDs over the land [Fig. 1(c)], but the three RST observations have smaller SDs over the ocean [Fig. 1(d)].

Fig. 2 shows the running linear trends of the LSTA and SSTA from the five data sets over the period 1980 to 2014. The dynamical trend using running linear least squares (LLS) fit approach with the moving 11-year time window (132 months) is used to estimate the decadal temperature trends. To test the robustness of any trends, we computed the statistical significance at 90% confidence level of the population of all of the 11-year trends. Those trends at 90% confidence level are indicated by filled points, and those not exceeding 90% significance are unfilled or open point marked. Different from the traditional LLS fit approach, in which the trend rate is one constant number for the full study period, the running LLS fit technique can provide more detailed information about the trend changes with time. Since we are assessing climate tendencies, the 11-year sliding window was selected for this analysis to provide enough sample periods to ascertain trend rates of change over time.

Over the land [Fig. 2(a)], all of the time series tend to capture the same broad features of the warming trends, especially the strong decadal warming persistence within the periods of 1982 to 1992 (∼0.45°/decade) and 1989 to 2005 (∼0.39 °C/decade). The filled points clearly indicate that the trends exceed the significant test at the 90% confidence level. These warming trends are found in both RST observations and MSULT-satellite-retrieved data sets, and the results are similar to those found in previous studies [15]. The RST observations have much better agreement with MSULT-retrieved trends before 1992, and all warming trends decreased after that time. Of particular interest is the large trend differences found in the two MSULT-satellite-retrieved data sets. The RSS-derived temperature trend moves toward lower values, while the UAH-derived temperature trend increases after 1996 (with an average trend difference of about ∼0.25 °C/decade over the decadal period of 1996 to 2004). The RSS-derived temperature underestimates the warming, and the trend values from this data set are significantly lower than all of the other land decadal trends. Similarly, the UAH-derived temperature trends starting from 1998 [top row of labeled values on the abscissa in Fig. 2(a)] overestimate the warming. In addition, it is worth noting that the warming trends in the three RST observations are near zero starting in 2002, which is

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consistent with the occurrence of the warming hiatus discovered in previous studies [1], [2].

The running temperature trends over the ocean show a similar temporal characteristic as the land in all data sets [Fig. 2(b)]. Generally, the ocean trends have a lower magnitude than the land trends over the entire study period [6], [7]. However, 1992 is a special year in all five data sets. Starting in 1992, Fig. 2(a) clearly displays a decreasing warming trend over the land which is declining at a rate much faster than over the ocean.

To estimate the discrepancies in the temperature trends over the land and ocean, the fitted probability density functions (pdfs) of the 11-year running decadal trends during the period of 1980 to 2014 are calculated. We utilize general nonparametric kernel density estimation techniques for building pdfs. These techniques estimate the pdf directly from the data without any assumptions about the underlying distributions [16]. Fig. 2(c) shows that the two satellite data sets are quite different from the other data sets in terms of peak locations. The central values of UAH and RSS are much larger and smaller than the three RST data sets, respectively. As can be seen in Fig. 2(a), the large discrepancies between UAH and RSS after 1996 indicate opposing trends, with the UAH data set showing a warming trend and the RSS data set showing a cooling trend over the land. The land pdfs of HADCRUT4 (black line), NCDCT3 (aqua line), and GISS temperature (red line) have very similar shapes due to the high degree of consistency in the running decadal trends denoted in Fig. 2(a).

The distribution of the pdf shows a different pattern over the oceans [Fig. 2(d)]. The two MSU-satellite-retrieved data sets (RSS and UAH) display a relatively lower peak value than the three surface observation data sets. The main reason for the lower peak values is that the satellite data sets show greater fluctuations due to the exaggeration of the El Nino as well as greater sensitivity to volcanic activity over the oceans [17]. Moreover, MSU trends are less than the surface data set trends during the period of 1980 to 2014 over the oceans. A bigger discrepancy between GISTEMP and the other two RST observations over the ocean is noted in Fig. 2(d).

An interesting point illustrated by Fig. 2 is that the temperature trends in the two MSULT-satellite-retrieved data sets exhibit greater consistency over the ocean but larger discrepancies over the land, especially in the period after 1992.

IV. Opposite Tendency of the LOWC

The aforementioned analysis suggests that the surface temperature over land has not only a larger amplitude anomaly (Fig. 1) but also a stronger warming trend compared to their ocean counterpart (Fig. 2). Since 1992, the warming trends significantly decreased over both land and ocean, but the decreasing rate of the warming trend over the land is faster than that over the ocean (Fig. 2). The different decreasing rates over the land and ocean should produce changes in the LOWC. To evaluate the robustness of the variations of land–ocean contrast, the temperature trends were fitted using a decreasing length of the LLS which should provide a better indication of the most recent trends. This is contrasted with the increasing length for fitting trends used in [18]. The decreasing fitting length

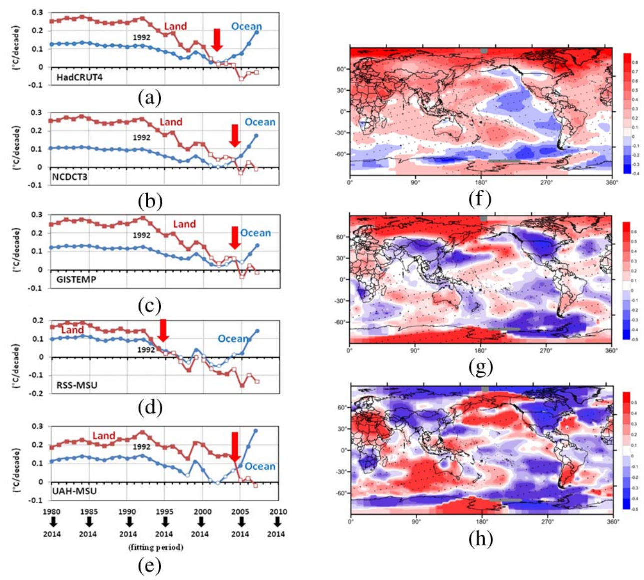

Fig. 3. (Left panels) Decreasing length for trend fits by moving the start date from January 1980 to January 2007. The x-axis shows the decreasing length of the period. (a) HadCRUT4. (b) NCDCT3. (c) GISTEMP. (d) RSS-MSU LT. (e) UAH-MSU LT. Filled points represent trends that are significant at the 90% significance level. The arrow indicates the transition time of the LOWC. (Right panels) The linear trends in the three subperiods for GISTEMP data. (f) 1980 to 2014. (g) 2000 to 2014; (h) 2005 to 2014. The color shading represents the trends (°C/decade), and stippling in (f)–(h) indicates the 90% confidence level from t *test*.

approach is described as follows. The end date of the time series is first fixed at December 2014 using the monthly data, and then, the length of the time series is gradually reduced by 12 months for each year. This results in the trends being calculated over a total of 35 years (420 months) over the period 1980 to 2014. Eleven-year trend periods (132 months) are initially used in the calculations and reduce to 8 years (96 months) in 2007 (2007 to 2014) by moving the yearly start date toward the end of the data set. This means that 2004 was the last full 11-year trend calculation. This is different from the fixed-length running decadal trends for trend fitting. The statistical significance tests are computed with multiple periods according to the decreasing length of the trend fitting period. The global mean temperature trends over the land and ocean are shown in Fig. 3(a)–(e). Generally, the trends are consistent with previous analyses [6], [7], where the warming trends over the land are larger than those over the ocean. However, the magnitude of the warming trends decrease after 1992, which is consistent with the running decadal trends discovered in Fig. 2(a) and (b). Furthermore, the decreasing rate of the warming trends over the land is significantly faster than that over the ocean.

Over the ocean, the temperature trends in all data sets show a declining warming trend after 1992. The minimum ocean trend is generally near zero in 2002 [blue line in Fig. 3(a)–(e)] and then tends to increase after the minimum point. However, the temperature trends over the land continued to decrease [red line in Fig. 3(a)–(e)], which leads toward a contrasting distribution of the LOWC after 2005 where the warming trend over the ocean is clearly larger than the trend over the land. It is worth noting that this characteristic change in the trends is found in all of the data sets regardless of whether the primary source data were RST observations or MSULT-satellite-retrieved products. For example, the RSS MSU LT derived temperature trends show that the opposite tendency of the LOWC occurred around 1995, when the decline in the land trend became smaller than the decline in the ocean trend, much earlier than the other data sets (versus 2002 in the HadCRUT4 and 2005 in the NCDCT3, GISTEMP, and UAH MSU LT). As the trends approach zero and the trend in the ocean changes from decreasing to increasing, in spite of the reduced statistical significance in the periods (approximately 2000 to 2014 to 2004 to 2014), the filled points in Fig. 3(a)–(e) demonstrate that the trends exceed the significance test at the 90% confidence level after approximately 2005 in most of the data sets. This suggests sufficient confidence in the reliability of the temperature trend reversal in the ocean to look for the impacts of the trend changes regionally.

It is not hard to find that the LOWC has been changed after the occurrence of the hiatus with the key transition years being from 2002 to 2005. According to our previous studies [19], the temperature trends depend on the global or regional scales. To measure those discrepancies, the spatial pattern of the trends in the three subperiods of 1980 to 2014, 2000 to 2014, and 2005 to 2014 are discussed. Because the GISTEMP data have a good coverage over the polar areas for a surface-based observation set, it was used to create the analysis. The results indicate [Fig. 3(f)–(h)] that the distributions of temperature trends are highly sensitive to the selected periods and locations. During the period of 1980 to 2014, the warming trends dominated all land and most ocean areas except for part of the eastern tropical Pacific Ocean and the narrow belt around 60° S over the southern oceans. The largest warming trend exceeded 0.3 °C/decade over the Arctic, Eurasian land, and western part of extratropical Pacific Oceans. During the period of 2000 to 2014, the warming trends over both polar regions decreased. The original warming trends are replaced by cooling over the central Eurasian, North American, and central South African continents. Most of the Pacific Ocean, central Atlantic Ocean, and southern Indian Ocean have started to show strong cooling trends. It is clearly consistent with the occurrence of the early 2000 hiatus.

Compared to the hiatus period (approximately 1997 to 2005 and represented by the middle graph in Fig. 3(g) identified as the 2000 to 2014 trend period), there are some remarkable differences compared to the 2005 to 2014 period [Fig. 3(h)]. First, the warming trends over the Arctic switched to cooling trends; second, the cooling continued over three continents (Asia, North America, and South America); and third, warming trends significantly increased over the North Pacific and Indian Ocean. The results clearly demonstrate that the LOWC changed some time in the period 2002 to 2005, which is closely related to continued cooling over land and increased warming over the Pacific and Indian Oceans. The results shown in Fig. 3(f)–(h) are consistent with the results from the other data sets, except in the Arctic region. Since the GISTEMP data set has the best coverage of the Arctic and the other data sets have less coverage in the Arctic, the results of GISTEMP in the Arctic need to be validated by additional or other observations in the Arctic.

V. Conclusion

Based on two primary types of data sets, the reconstructed surface-based data sets and the satellite-based data sets, the land–ocean temperature trend contrast has been examined over the period of 1980 to 2014. The land surface temperatures have larger anomalies and trends than the ocean in the last three decades (1980 to 2014). The results indicate that, in the satellite-based MSU LT data sets, UAH and RSS, the amplitude of the TAs is smaller than in the surface-based observations (HADCRUT4, GISTEMP, and NCDCT3) over the land. However, in the satellite-retrieved data sets, the TAs are larger over the oceans than in the surface observation data sets.

The running decadal trends show that the warming trends are generally larger over land (even though they are declining) than the oceans. Since 1992, the rate of warming has significantly decreased over both land and ocean, but the decreasing rate of the trends over the land is greater than that over the ocean. The different decreasing trend rates over land and ocean should produce changes in the LOWC, particularly after the ocean trend begins to increase after 2002.

The pdfs of the running decadal trends show that the GISTEMP data are different from the other two reconstructed surface observation data sets over the oceans [Fig. 2(d)], but three surface-observation-based data sets are in much better agreement over the land [Fig. 2(c)]. The RSS- and UAH-retrieved data sets both underestimated and overestimated the warming trends in comparison with the three surface-based observations over land [Fig. 2(a) and (c)], respectively. However, temperature trends in the two MSU-retrieved data sets exhibit greater consistency over ocean, and both of them underestimate most of the temperature trends during the period of 1980 to 2014 [Fig. 2(d)].

The decreasing length approach to fitting the trend confirmed that the warming trends are larger over land than over oceans before the early 2000s. After 1992, there is a general decrease of the observed warming trend, and the decreasing rate of the warming trend is significantly greater over land. Furthermore, the trend reaches a minimum near zero in the early 2000s, which is consistent with the global warming hiatus discovered in previous studies. However, due to the decreasing trend over land and increasing trend over the oceans after 2002, the land–ocean temperature trends support contrasting patterns after 2005 with the ocean warming while the land continues its cooling trend. This pattern has been consistently found in all five different data sets analyzed for this research.

The global trends analyzed in the three subperiods using GISTEMP data set demonstrated that the temperature trends are highly sensitive to the selected periods and regions. During the period of 1980 to 2014, the warming trends dominated all land and most ocean areas except for part of the eastern tropical Pacific Ocean and the narrow belt around 60° S over the southern oceans. The largest warming trend exceeded 0.3 °C/decade over the Arctic, Eurasian land, and western part of extratropical Pacific Oceans.

Consistent with the warming hiatus over the period of 2000 to 2014, the warming trends over both polar regions significantly decreased. The original warming trends are replaced by cooling over the central Eurasian, North American, and central South African continents. Most of Pacific Ocean, central Atlantic Ocean, and southern Indian Ocean showed strong cooling trends. It clearly indicates that the global warming hiatus is affected not only by cooling in the eastern Pacific Ocean discovered in many previous studies [2], [3], [20] but also by the cooling over the land.

In contrast, there are some remarkable differences in the period of 2005 to 2014. The three continents including Eurasian, North American, and South African continents showed enhanced cooling during the period of 2005 to 2014, with warming trends increasing over the North Pacific and Indian Ocean. These trends, if accurate, will lead to the opposite land–ocean contrast that was observed prior to 2000. It seems that the cooling over the land may dominate the projected pattern of land–ocean contrast derived from this analysis. However, the increasing trend of ocean warming could ultimately be the largest long-term trend factor since the ocean has a significantly greater heat capacity. Future work will address different data sets, such as climate model simulations, and extensions to the length of the data sets to confirm the findings and improve our understanding of the land–ocean contrast. The reasons responsible for the enhanced cooling over the continents [21] and enhanced warming over the oceans in the recent 10 years will be an area for future research.

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