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Remarkable Increase in Global Sea Surface Temperature in 2014 and 2015: How Was It Related to El Niño and Decadal Variability?

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1. Introduction

The globally averaged sea surface temperature (GASST) exhibits centennial warming trend, well-known as global warming, with decadal time scale fluctuations (Fig. 1a). While the annual mean GASST for the 2000-2013 period has stayed below the previous highest record of 1997/98, the recent GASST shows the rapid warming after 2013 and continuously breaks the highest record in 2014/15 and 2015/16. The increase is accompanied by a strong El Niño event, presenting, at least qualitatively, consistent condition with those indicated by previous studies such as Trenberth *et al.* (2002). However, the recent increase of GASST and observed anomalies are rather insistent and it is worth examining how much the El Niño event attributed the recent warming of GASST and investigating other contributing factors.

2. Data and methods

SST and subsurface temperature distributions are obtained via objective analysis (COBE-SST; Ishii *et al.* 2005) and ocean data assimilation (MOVE-G2; Toyoda *et al.* 2013) operated by the Japan Meteorological Agency (JMA). The Japanese 55-year Reanalysis (JRA-55) dataset (Kobayashi *et al.* 2015) is used to investigate atmospheric circulation patterns. Climatology is defined as average for the period from 1981 to 2010. The SST anomaly averaged in the NINO-3 region (5°S–5°N, 150° –90°W) is referred to as "NINO-3 SST", and its anomaly is used as an indicator of the El Niño-Southern Oscillation (ENSO). Considering typical ENSO lifecycles, annual mean values are defined as average from July to June. Average from July 2014 to June 2015 is termed annual mean value for 2014/15, for example.

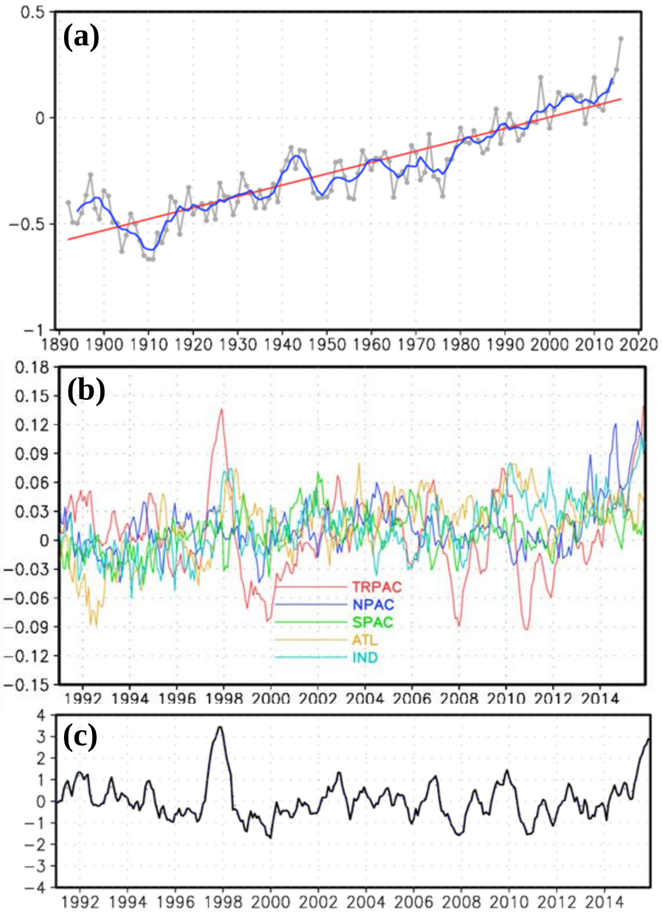

Fig. 1 (a) Time series of global averaged sea surface temperature (GASST) anomalies (°C). The gray, blue, and red lines represent annual mean GASST anomalies, their five-year running mean, and the long-term linear trend, respectively. (b) Monthly time series of contributions to a GASST anomaly in the tropical Pacific (10°S–10°N) (red line), North Pacific (dark blue line), South Pacific (green line), Atlantic (yellow line), and Indian Ocean (light blue line). (c) Monthly time series of anomaly of NINO-3 SST.

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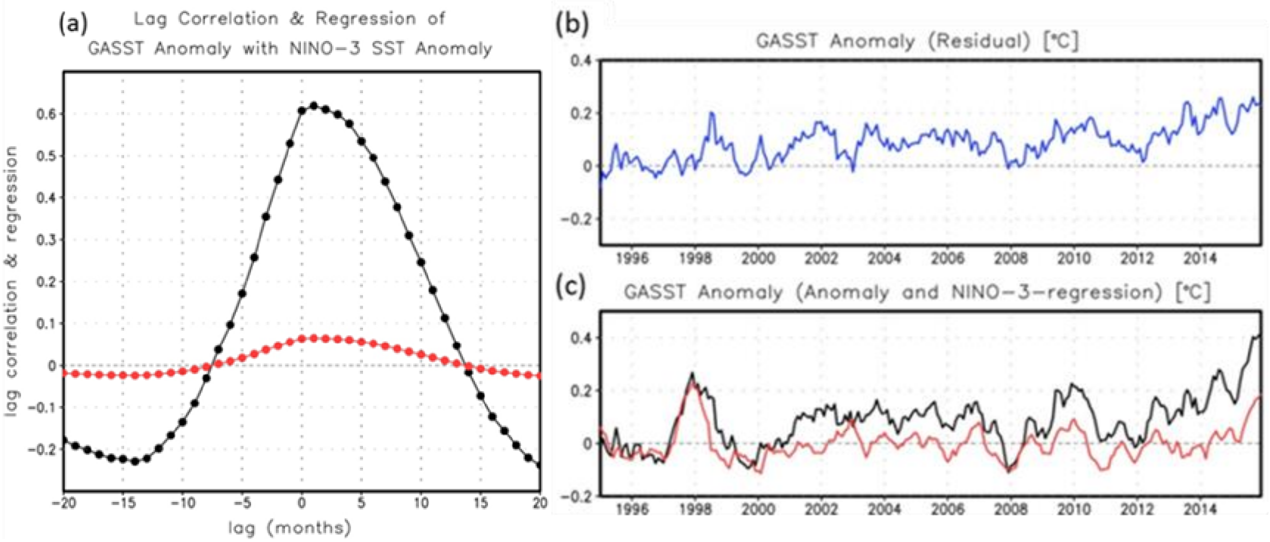

Fig. 2 (a) Lag correlation (black line) and regression (red line) coefficients between anomalies of GASST and NINO-3 SST. Positive lag means NINO-3 SST leads GASST. (b, c) Time series of GASST anomalies (black line) separated into the component calculated from the one month lag regression to NINO-3 SST anomalies (red line) and the residual component (blue line).

3. Time series and contributing factors

Figure 1b shows the time series of contributions of SST anomalies integrated in the each basin to GASST. These contributions are determined from the area-integrated SST anomaly in each basin divided by the area of the global ocean domain.

Historically, the tropical Pacific (red line) has the greatest contribution, and interannual variabilities in the tropical Pacific and Indian Ocean (light blue line) associated with ENSO are evident, which are consistent with previous studies (*e.g.* Klein *et al.* 1999). Indeed, the previous highest record was marked in 1997/98 when a strong El Niño event occurred and increases in GASST and NINO-3 SST are comparable to those observed in recent years. On the other hand, the North Pacific (dark blue line), which started to get warmer around 2013, stands out in recent years compared with 1997/98.

Trenberth *et al.* (2002) show that the global surface temperature increases accompanying El Niño events with a lag of several months. According to the lag correlation and regression coefficients shown in Fig. 2a, the GASST exhibits a similar response with rather small lag and a maximum regression of +0.08°C per 1°C anomaly of NINO-3 SST with one-month lag. Then, the GASST anomalies separated into a component calculated from the one-month-lag regression to NINO-3 SST anomalies (NINO-3-regression) and the residual component (Figs. 2b, c). NINO-3-regression compensates for much of GASST increase from 2014/15 to 2015/16, indicating that the remarkable increase in this period is mainly attributed to the development of a strong El Niño event (Fig. 2c). The residual component increased in around 2013 and 2014 and positive values persisted since then, which is supposed to correspond to the positive anomalies in the North Pacific and contribute to the extremely large GASST anomaly drastically exceeding that of 1997/98. The remarkably large positive anomaly observed in the North Pacific in 2013 is referred to as “blob” and attributed to atmospheric forcing including advection and entrainment in addition to surface heat flux in the recent study by Bond *et al.* (2015). However, detailed mechanism that induced the anomalous atmospheric forcing is still unclear and further investigation is necessary.

4. Variability in horizontal and vertical temperature distribution

In spatial distribution of anomaly of SST and vertically averaged temperature (VAT) from the surface to 300-m depth, La Niña-like condition, which is indicated to have persisted since around 2000 to 2013 (Urabe and Maeda, 2014; and references therein) is observed in 2013/14 (Fig. 3a, d). In 2014/15 (Fig. 3b, e), positive anomalies propagated from the western part to the central and eastern part, and the amplitude of which is

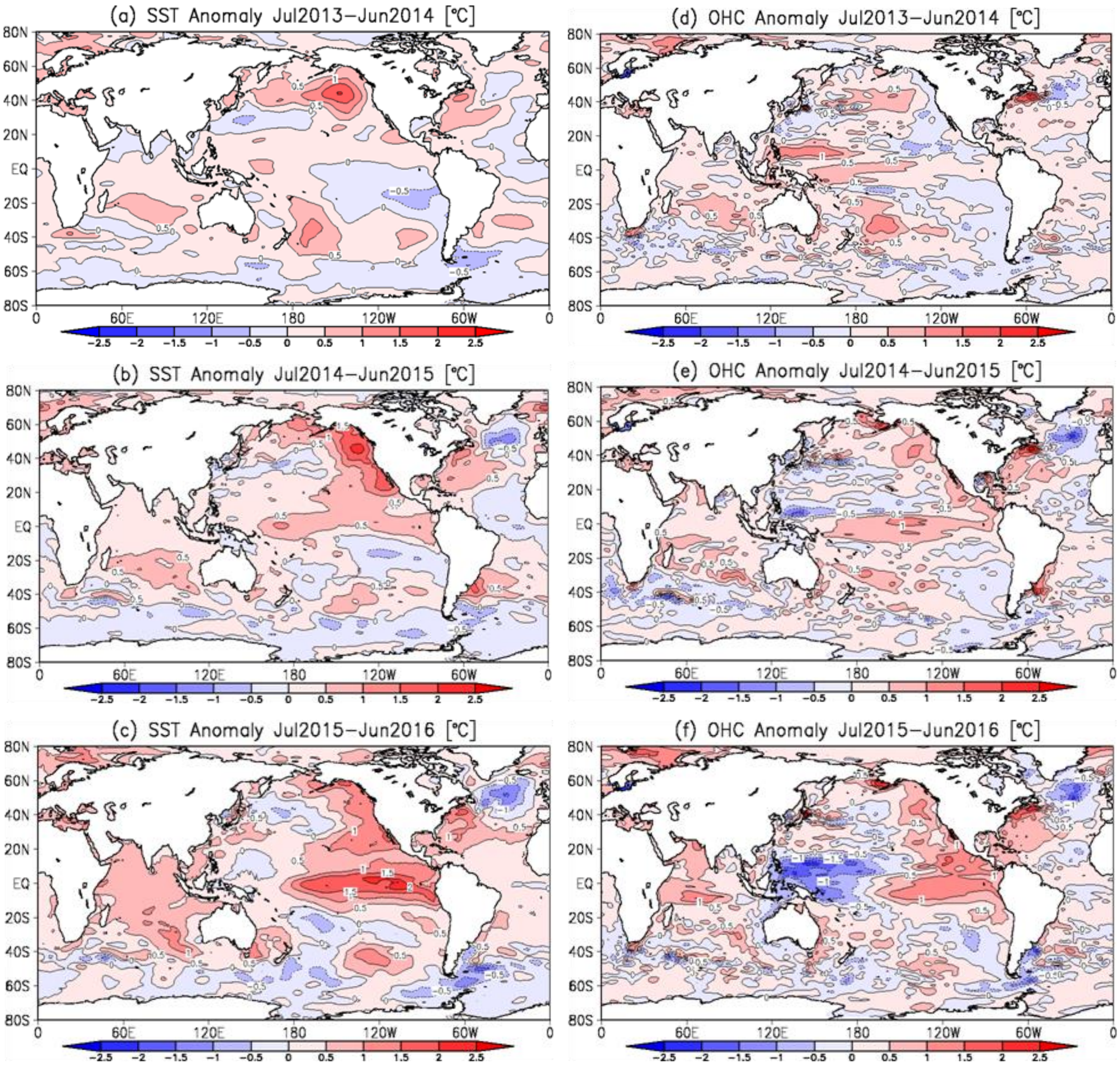

Fig. 3 Annual mean anomalies of SST in (a) 2013/14, (b) 2014/15, and (c) 2015/16. (d–f) Same as (a–c) for vertically averaged temperature (VAT) from sea surface to 300-m depth. Units are °C.

significantly enhanced in the eastern part in 2015/16 (Fig. 3c, f). Significant warming in SST is also recognized in the North Pacific around the west coast of North America (Figs. 3a-c). These spatial patterns of warming are quite consistent with the area-integrated anomalies presented in Fig. 1b. These variabilities indicate that drastic changes have occurred not only at the sea surface but also in the ocean subsurface associated with the development of El Niño.

Along with the changes in horizontal patterns, distinct changes in vertical temperature profile also proceeded in 2014/15/16. In a time–depth diagram of the area-averaged temperature in the tropical Pacific, positive anomalies had been observed at a 100–300-m depth, with no clear anomalies detected near the sea surface until the beginning of 2014 (Fig. 4a). Subsequently, the positive anomalies were replaced to a 30–100-m depth in around spring 2014, which indicates vertical temperature profile in the subsurface remarkably changed along with the surface warming and subsurface cooling, which can be consistently understood as weakening of thermocline gradient which is well known as the typical variability associated with El Niño, despite the El Niño event not being evident in the SST field (Fig. 3b). Finally, the positive anomalies expanded into the sea surface and intensified in 2015 along with the development of a strong El Niño event and negative anomalies appeared around 100–300-m depth.

The warming near the surface was observed in 1997/98 (Fig. 4b) as in 2015/16. However, significant positive temperature anomalies in subsurface region (deeper than 100m) before an occurrence of El Niño event, which had been continuously observed until 2013 in Fig.4a, were not recognized before the early 1997. In the recent years, the subsurface positive anomalies persisted during surface warming in 2014, which could contribute to further surface warming in 2015/16. As a result, significant positive anomalies near the surface continued for more than two years. In contrast, for 1997/98, vertical reversal of temperature anomalies between surface and subsurface started around the beginning of 1997 from temporal and weak La Niña condition and after that positive anomaly near the surface continued only for a little more than one year. The results shown here suggest that the background oceanic condition, i.e., subsurface positive temperature anomaly in tropical Pacific, is one of key factors that generate difference between 1997/98 and 2014/15/16. Those subsurface temperature anomalies correspond to positive VAT anomalies in the western tropical Pacific observed before 2013 (Figs. 3d, 4a).

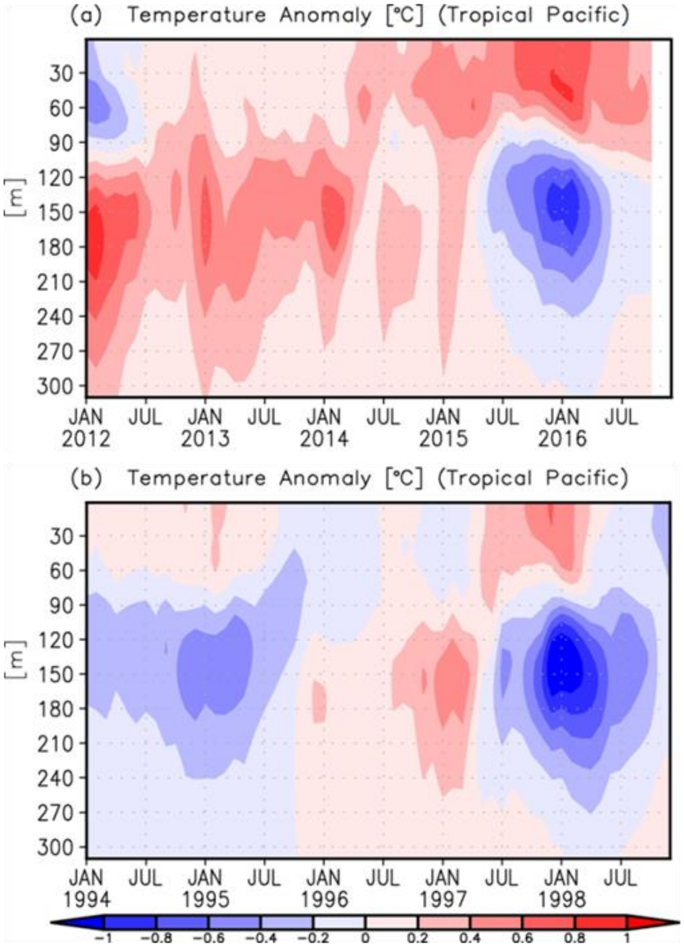

Fig. 4 (a) Time–depth diagram of temperature averaged in tropical Pacific [20° S–20° N, 100° E–100° W] for (a) 2012-2016 and (b) 1994-1998.

5. Summary and discussion

The remarkable increase in the GASST in 2014 and 2015 is generally attributed to the emergence and development of an El Niño event, and warming in the North Pacific also contributed to extreme anomaly observed in 2015/16, substantially larger than that in 1997/98 when the previous highest record was marked associated with a strong El Niño. In the tropical Pacific, positive subsurface temperature anomalies accumulated in the west, which was redistributed to the sea surface, stretching from the central to eastern part in conjunction with the development of the El Niño event. The warmed ocean surface in the tropical Pacific persisted from early 2014 to early 2016, much longer than that observed from early 1997 to mid-1998.

Recent studies indicate that La Niña-like conditions associated with decadal climate variability trigger ocean heat uptake into Pacific subsurface and play important role in weakened increase of the global surface temperature (the so-called “hiatus”; Easterling and Wehner, 2009) in the last decade (England *et al.* 2014; Liu *et al.* 2016). Urabe and Maeda (2014) indicate that positive subsurface temperature anomaly in the western tropical Pacific, especially off-equator from near Philippines to the date line (Fig. 3d), had been continuously accumulating along with the recent La Niña-like condition in decadal timescale. The temperature anomaly redistribution between subsurface and surface observed in recent years are in stark contrast with the conditions continued during the hiatus, in other words, the recent warming event is possibly accompanied by a rebound from the hiatus. Although it is difficult to show whether global warming hiatus ended around 2014/15/16, we should continue to monitor the climate system carefully in order to assess the subsequent status of global warming.

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