A Quantitative Definition of Global Warming Hiatus and 50-Year Prediction of Global-Mean Surface Temperature*

MENG WEI

College of Physical and Environment Oceanography, Ocean University of China, and Key Laboratory of Marine Science and Numerical Modeling, and First Institute of Oceanography, State Oceanic Administration, and Meteorology Bureau of Jiaozhou, Qingdao, China

FANGLI QIAO AND JIA DENG

Key Laboratory of Marine Science and Numerical Modeling, and First Institute of Oceanography, State Oceanic Administration, Qingdao, China

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ABSTRACT

Recent global warming hiatus has received much attention; however, a robust and quantitative definition for the hiatus is still lacking. Recent studies by Scafetta, Wu et al., and Tung and Zhou showed that multidecadal variability (MDV) is responsible for the multidecadal accelerated warming and hiatuses in historical global-mean surface temperature (GMST) records, though MDV itself has not received sufficient attention thus far. Here, the authors introduce four key episodes in GMST evolution, according to different phases of the MDV extracted by the ensemble empirical-mode decomposition method from the ensemble HadCRUT4 monthly GMST time series. The “warming (cooling) hiatus” and “typical warming (cooling)” periods are defined as the 95% confidence intervals for the locations of local MDV maxima (minima) and of their derivatives, respectively. Since 1850, the warming hiatuses, cooling hiatuses, and typical warming have already occurred three times and the typical cooling has occurred twice. At present, the MDV is in its third warming-hiatus period, which started in 2012 and would last until 2017, followed by a 30-yr cooling episode, while the trend will sustain the current steady growth in the next 50 years. Their superposition presents steplike rising since 1850. It is currently ascending a new height and will stay there until the next warming phase of the MDV carries it higher.

1. Introduction

After a rapid increase over the last quarter of the twentieth century, the globally averaged surface temperature grounded to a halt in the last decade (Easterling and Wehner 2009; Knight et al. 2009; Foster and Rahmstorf 2011). This did not match the sustaining

increase of anthropogenic greenhouse gases and triggered intense debates. Various hypotheses have been put forward to interpret this warming hiatus, which primarily falls into the following two categories (Met Office Hadley Centre 2013). One explains the heating pause with reduction of net amount of incoming energy into the climate system, which may be caused by the low solar irradiance as a result of weak solar activity (Lean and Rind 2009; Stauning 2014) or by negative irradiative forcing due to the recent decrease of stratospheric water vapor concentration (Solomon et al. 2010) or the increase of aerosol concentrations in the stratosphere (Solomon et al. 2011) and the troposphere respectively produced by volcanic eruptions (Neely et al. 2013; Santer et al. 2014) and human activities (Kaufmann et al. 2011). The other attributes the recent absence of surface warming to redistribution of energy within the climate system, mainly in the form of energy transfer from the

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Corresponding author address: Fangli Qiao, Professor of Physical Oceanography, First Institute of Oceanography, State Oceanic Administration, 6 Xian-Xia-Ling Road, Qingdao 266061, China.
E-mail: qiaofl@fio.org.cn

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upper ocean to deep ocean (Trenberth and Fasullo 2010; Balmaseda et al. 2013; Guemas et al. 2013; Drijfhout et al. 2014), generally associated with natural climate variations like El Niño–Southern Oscillation (ENSO) (Kosaka and Xie 2013; Banholzer and Donner 2014), the Pacific decadal oscillation (PDO) (Meehl et al. 2011; Trenberth and Fasullo 2013; England et al. 2014), the Atlantic multidecadal oscillation (AMO) (Knight et al. 2005; Zhang et al. 2007; Wu et al. 2011; Zhou and Tung 2013), or other ocean dynamics (Latif et al. 2013; Watanabe et al. 2013; Chen and Tung 2014).

However, most existing studies primarily focused on the potential causes of the hiatus; comparatively, its definition is far from well quantified because many research results gave only qualitative descriptions. There are two ways to quantify the period of hiatus in general. One way is to calculate the least squares trend of global-mean surface temperature (GMST) or ocean heat content for recent n years, then compare it with the value for the last quarter of the twentieth century, and the recent n years are treated as the hiatus period when its trend is less than the previous trend. The other is to work out fitting least squares trends for n -yr running periods in the time series of GMST or other variables and then choose the periods with negative trends as hiatus decades and the periods with positive trends as accelerated-warming decades. However, both approaches essentially give only linear trends and may have several problems. First, the time span n is quite arbitrary which has no mathematical or physical meanings. During actual calculation, n is commonly specified as 10 or so, which is too short to rule out the influence of relatively short-period variability and results in a wide spread of probability distribution function (Easterling and Wehner 2009). Second, as a consequence of various climate variability, linear trends are sensitive to the interception (or the start and end points) of the time series (Wu et al. 2007; Stocker et al. 2013), and the time span of hiatus differs because the start date is often subjectively selected. Moreover, this short-term linear trend cannot distinguish the secular trend from a long cycle (Wu et al. 2007) and usually regards the recent warming pause as an isolated case. This does not match the fact that such cessation has appeared several times in the past 150-yr observations. Therefore, a more meaningful definition for warming hiatus is needed.

Multidecadal variability (MDV), with an approximate period of 60–70 years (Schlesinger and Ramankutty 1994), in the global climate system drew the attention of climate researchers 20 years ago. MDV may be a quasi-periodic climate variation related to the AMO, which is internally caused by the thermohaline circulation variability (Knight et al. 2009; Zhang 2010) or externally

forced by aerosols (Nagashima et al. 2006; Booth et al. 2012), or it may be a natural oscillation synchronized to the orbital periods of Jupiter and Saturn (Scafetta 2010, 2012, 2013). While there is no general agreement about the mechanism of MDV, it has been proved of great importance to the global temperature change. The multidecadal cooling and warming episodes imbedded in global temperature records is ascribed to the MDV (Scafetta 2010; Wu et al. 2011; Tung and Zhou 2013), while the long-term warming trend in response to human emission of greenhouse gases is found remarkably steady since 1910 at $0.07^{\circ}\text{--}0.08^{\circ}\text{C decade}^{-1}$ (Wu et al. 2011; Tung and Zhou 2013). The so-called accelerated warming at the end of the twentieth century was the result of concurrence of the secular warming trend and the warming phase of the MDV. As the MDV was overlooked, its contribution to global warming is wrongly attributed to the secular trend, resulting in an overestimate of anthropogenic warming rate in the second half of the twentieth century, which can lead to poor capability of climate models to predict the recent hiatus (Scafetta 2010, 2012, 2013). However, the MDV has contributed to the evolution of GMST considerably, accounting for 40% of the warming over the last half century (Tung and Zhou 2013) or 60% since 1970 (Scafetta 2010), and the warming and cooling decades were the visible manifestation of different phases of MDV. So, its significance needs to be reflected in the definition of warming hiatus.

Tung et al. (2014) described warming hiatus as a recurrent pause in the global warming rate. This motivated us to develop a method to define the global warming hiatus based on the rate of temperature change. According to the phases of MDV extracted from the ensemble GMST time series by local and adaptive ensemble empirical-mode decomposition (EEMD) method, a quantitative definition of warming hiatus is introduced. Section 2 describes the data and method used in this study. Section 3 elaborates the quantitative definition of warming hiatus and other three critical episodes in GMST multidecadal evolution. Section 4 shows 50-yr statistical predictions of MDV and secular trend. Summary and discussion are given in section 5.

2. Data and methods

a. Data

The monthly global surface temperature data during 1850–2014 from HadCRUT4 are anomalies relative to the baseline period 1961–90 (Morice et al. 2012). HadCRUT4 is derived from a combination of land air temperature and sea surface temperature data from the CRUTEM4

FIG. 1. (a) EEMD decompositions of monthly HadCRUT4 GMST records from January 1850 to December 2014 (ensemble mean in dark blue and members in light blue), with c8 and c9 representing the MDV and the trend, respectively. All the IMFs were plotted on the same scale. (b) MDV and GMST series. The upper portion highlights c8 (i.e., MDV); the bottom portion shows original GMST series (ensemble mean in gray and members in yellow) and the reconstructed series by superimposing the MDV on the secular trend (ensemble mean in red and members in orange).

and HadSST3 datasets, respectively, and is provided as an ensemble of 100 dataset realizations. All the 100 realizations of ensemble global-mean time series are used to determine the time span of crucial episodes and confidence intervals (CIs).

b. Ensemble empirical-mode decomposition

To eliminate the interference of high frequency and the secular trend from the GMST time series, we use the EEMD method, which is especially powerful in extracting low-frequency oscillation and determining the intrinsic trend from data.

Empirical-mode decomposition (EMD) is an adaptive and temporal local analysis method for nonlinear and nonstationary time series. It can decompose any complicated dataset into a small number of intrinsic-mode functions (IMFs) without using a priori-determined basis functions (Huang et al. 1998). It has been widely used in many scientific and engineering studies. However, mode mixing, frequently occurring as a consequence of signal intermittency, could result in unstable decompositions and difficulty in making the IMFs meaningful.

To overcome this problem, Wu and Huang (2009) developed EEMD. They added different white-noise time series to the targeted data to form an ensemble of noise-added signals, then decomposed each noise-added time series and treated the ensemble mean of obtained IMFs as the true IMFs. The addition of white noise helps the ensemble exhaust all possible solutions and makes the signals with similar scales settle on one IMF. The true and physically meaningful IMFs rise before our eyes when the added white noises cancel each other out after taking an average over enough trials. It is a truly noise-assisted data analysis method and improves the original EMD.

3. A quantitative definition of four critical episodes

From the GMST records for January 1850–December 2014 (lower portion of Fig. 1b; gray and yellow curves), the rates of GMST change were far from uniform and exhibited multiple time-scale variations. On a century time scale, the temperature evolution is characterized by a low-frequency fluctuation superimposed on a secular trend. The dramatic warming in the late period of the

twentieth century and the recent warming pause appeared, respectively, in the warming phase and the transition to the cooling phase of this fluctuation. So, this long-term oscillation is considered to be responsible for the different change rates in different decades (Wu et al. 2011; Tung and Zhou 2012, 2013). To extract this embedded quasi-periodic fluctuation and the meaningful secular trend from the GMST records, the EEMD method is employed. The decomposition is displayed in Fig. 1a. Each time series of HadCRUT4 ensemble is decomposed into eight IMFs (c1–c8) and a remainder (c9); each component time series from different ensemble members look very similar, especially the low-frequency ones from c5 to c9. The remainder (c9) represents the intrinsic and adaptive trend, while c8, with a cycle of roughly 68 ± 4 years, is the internal MDV that we expected. For the secular trend (Fig. 1a, c9), after the initial plateau the temperature almost linearly increased with a warming rate of $0.08^{\circ}\text{--}0.11^{\circ}\text{C decade}^{-1}$ since the middle of the last century, agreeing with the results of Wu et al. (2011).

The upper portion of Fig. 1b highlights the MDV. When compared with the original GMST time series (lower portion of Fig. 1b; gray and yellow curves), the phase synchronism in the evolution on a multidecadal scale can be seen clearly. The warming and cooling episodes of the original time series are consistent with ascending and descending stages of MDV, respectively, while the warming- and cooling-hiatus decades correspond to phase-transition periods. When we superimpose the MDV on the secular trend to reconstruct the original time series and compare the reconstructed time series (lower portion of Fig. 1b; red and orange curves) with the original records, the phase synchronism becomes more evident. Similar analysis of the observed regional mean surface temperature records in the Southern Ocean is shown in Fig. S1, which illustrates the robustness to the synchronization between MDV and long-term temperature change. The MDV in the Southern Ocean has a roughly one-century cycle. From the late 1970s, it entered the cooling phase and continued to the present. Even if the warming trend is taken into account, the superposition time series still presents a slow cooling tendency. This may be one explanation for why satellite record of Antarctic sea ice extent has shown a slight increase in a rapidly warming world since 1979. The above results suggest that the long-term change of the surface temperature is dominated by MDV and a secular trend, at least for the global average and Southern Ocean regional mean. Because the globally averaged secular trend has been steady since the midtwentieth century, the behavior of MDV becomes the strongest predictor for climate system's multidecadal behaviors tendency.

FIG. 2. MDVs (ensemble mean in dark blue and members in light blue) and their derivatives (ensemble mean in red and members in orange). On the MDV curves, the horizontal error bars (red) indicate 95% CIs of the locations of MDV local extremes, while the vertical error bars (blue) show the extreme values. The horizontal and vertical error bars on the derivative curves respectively represent the 95% CIs of the locations and values of the local extremes of the derivatives (cyan and magenta).

Most previous studies defined global warming hiatus by making a comparison of the surface temperature change rates between recent decades and the last quarter of the twentieth century, just as they defined the accelerated warming by comparing the growth during the mid-1970s and the late 1990s with the rate of several decades before that. As a result, the warming hiatus and acceleration were usually treated as isolated events. Such comparisons are inadequate, with the MDV neglected and usually confused with the secular trend. Because the rapid warming (cooling) appeared in conjunction with the rising (falling) of MDV while the warming (cooling) hiatus corresponded to the peak (trough) of MDV (Fig. 1b), it is really not adequate to compare a peak or trough with a rising period of a wave. We intend to provide a more reasonable definition derived from MDV to describe the multidecadal evolution of GMST and to project the GMST change based on the behaviors of MDV and secular trend.

We will single out several key points and periods by exploring evolution characteristics of MDV and its derivative. Figure 2 shows ensemble MDVs and their derivatives. The blue curves show there were 2.5 regular waves of MDV since 1850. The ensemble-mean time series suggests the period being around 68 years. The span from the first trough to the second is 51 years and the span from the second to the third is 67 years. The span from the first peak to the second is 63 years and the span from the second to the third is 74 years. The three trough-to-peak amplitudes (peak value minus previous

TABLE 1. Time spans of crucial phases. The periods in italics are predicted by ARMA. The fourth cooling hiatus period is *Nov 2046–Oct 2054*.

Phase	Cooling hiatus	Typical warming	Warming hiatus	Typical cooling
First	Oct 1852–Feb 1862	Mar 1868–Mar 1871	Nov 1876–Jul 1880	Jul 1887–Oct 1902
Second	Nov 1907–Feb 1910	Nov 1916–Jan 1928	Jun 1939–Dec 1942	Jun 1951–Jul 1961
Third	Jul 1973–Jun 1977	Sep 1989–Mar 1994	<i>May 2012–Aug 2017</i>	<i>Jul 2029–Nov 2035</i>

trough value) were 0.08° , 0.22° , and 0.25°C , respectively. Both the cycle and amplitude show an increase tendency. From the red and orange curves, the derivatives also have 2.5 waves, lagging the MDVs by a quarter cycle. The rate of temperature change varied from -0.01° to -0.12° to 0.06° to $0.10^{\circ}\text{C decade}^{-1}$. When the rate equals zero, the change of temperature halts, and the MDV reaches its peak or trough. There are two kinds of temperature-change pauses: a warming hiatus and a cooling hiatus, corresponding respectively to the zero down- and up-crossing points of the derivative and also to the peak and trough of MDV. It appears that we have just entered the third warming hiatus as the warming rate was falling to zero in recent years.

A wave can be separated into four periods: peak, trough, ascending, and descending. We select four crucial points from a cycle to represent the above four periods, at which the MDV gets the local maxima and minima and the fastest rising and falling. The corresponding points in the derivatives are the zero down- and up-crossing points and the local maxima and minima points. The location of fastest rising and falling points can be easily determined by the local extreme of the derivative. Peak and trough can be located by calculating both the zero crossing point of derivative and the local extreme of MDV. Considering the data are discrete records, it is hard to find a point where derivative is strictly equal to zero but is easy to identify the extremes; so, the latter approach is used to determine the positions of the peak and trough. Between the results of the two methods, there are only a few monthly differences for a several members, and their ensemble-mean values are equal. In this way, for each MDV time series, “the warming (cooling) hiatus” and “the typical warming (cooling)” points are respectively defined as the points where MDV and its derivative reach their local maxima (minima). This calculation is applied to all the members of MDV ensemble. For one crucial point, we obtain a collection of 100 positions, which allows us to calculate the ensemble-mean position and standard deviation (STD) and to obtain the CIs of its locations. Based on these, “the warming (cooling) hiatus period” and “the typical warming (cooling) period” are defined as the 95% CI of the locations of local maxima (minima) of MDV and of its derivative, respectively. The horizontal

error bars in Fig. 2 indicate the durations of crucial episodes, while the vertical error bars represent the 95% CIs of extreme values of MDV or its derivative. To clearly show the most dramatic rate of temperature change, the error bars for typical warming and cooling are marked on the derivative curves.

The time spans of four crucial episodes are given in Table 1. To make them more visible, they are also marked on the reconstructed time series in Fig. 3, along with original ensemble-mean GMST time series and secular trend. From Table 1 and Fig. 3, each of the warming hiatus, cooling hiatus, and typical warming occurred three times since 1850, and the typical cooling appeared twice. These episodes generally last for years, but the third warming hiatus had an extremely short duration. This is due to the limitation of the length of the record; the third peak cannot be exactly located until now. Next, we will predict future MDV and the secular trend and show where the GMST may be.

4. 50-yr prediction of MDV and the secular trend

Here, we give statistical prediction of MDV and the secular trend without any consideration of dynamical mechanism. The MDV is predicted using an autoregression

FIG. 3. The ensemble-mean GMST series (gray), secular trend (light blue), and reconstructed series (black). Horizontal error bars are time spans of four crucial phases for the MDV (peak in red, trough in blue, typical warming in magenta, and typical cooling in cyan).

moving-average (ARMA) method. The autoregression order p and moving-average order q are redetermined at each point according to the Akaike information criterion (AIC), which means each prediction is obtained by a specific ARMA (p, q) model and hence this method is adaptive. Here, p ranges from 5 to 10, with a mean of 7.8, and q is between 0 and 10 with an average of 7.4. Based on MDV time series from January 1850 to December 2004, we extend the MDV for another 60 years (720 months, from January 2005 to December 2064) into the future. Similarly, we can get a 60-yr prediction of the secular trend but using a cubic spline interpolation function. The superposition of the MDV and secular trend is regarded as the prediction for the low-frequency portion of the GMST. Since the observation is an ensemble of 100 time series, the prediction is also an ensemble. The ensemble mean and STD of the predictions can be worked out, and so can the CIs.

The 60-yr projection of the MDV, secular trend, and reconstruct series are shown in Fig. 4. The blue curves denote the observations, the orange and red curves denote predictions, and the gray dotted lines indicate the 95% CIs of the predictions. Note that since the historical MDV and trend from January 2005 to December 2014 are not used when we do the forecasting, they are used to verify the prediction ability for these 10 years of ARMA and cubic spline interpolation. The next 50-yr (from January 2015 to December 2064) forecast is the real prediction about the future. As shown in Fig. 4, the forecasts (in orange) almost coincide with the historical records (in blue) between 2005 and 2014. The differences between observations and predictions are quite modest, which indicates that the first 10-yr predictions are sound. This increases our confidence in the forecasts of the later years.

With the predictions of MDV, now we can discuss the features of the third peak. This peak is between May 2012 and August 2017, corresponding to the maximum value range of $0.092^\circ \pm 0.037^\circ\text{C}$. So, we are going through the third warming-hiatus period, which may continue for a few more years until the following cooling phase pulls it down and brings us to a cooling episode. The cooling period will last for around 30 years, and then the fourth cooling-hiatus period will come between 2046 and 2054 with a minimum value of $-0.088^\circ \pm 0.049^\circ\text{C}$; after that, the MDV will turn to a new warming phase. However, global warming will not be prevented by the negative phase of MDV, because the trend will continue its steady growth at the current warming rate in the next five decades. In Fig. 4c, the behaviors of superposition time series can be clearly identified after we grafted the 60-yr predictions onto the historical records. Reconstructed time series presents a step-type pattern with a gradually

FIG. 4. (a) The 165-yr observations from 1850 to 2014 and 60-yr predictions from 2005 to 2064 for the MDV. (b) As in (a), but for the trend. (c) Reconstructed series by superimposing MDV on the secular trend. The blue curves show the observations (ensemble mean in dark blue and members in light blue) while the orange and red curves show the predictions (ensemble mean in red and members in orange). Gray dotted lines denote the 95% CIs of the predictions.

rising trend since 1850, and right now we are climbing up the third step, which could extend to the 2040s with a low rate of temperature change and then be followed by a rapidly warming era like our experience in the last quarter of the twentieth century.

Similar results were reported by other scientists. Scafetta (2010) employed a phenomenological model based on the 20- and 60-yr astronomical oscillations and made a forecast for the global surface temperature, suggesting that the temperature would likely remain almost steady or cool until 2030–40. Fu et al. (2011) statistically extrapolated the multidecadal oscillation and the secular trend for 40 years by respectively using a fifth-order polynomial function and a cubic spline fitting; they expected the global average temperature to remain

flat until the 2040s. [Tung and Zhou \(2012\)](#) established a multiple linear regression model on a linear trend and a sinusoidal “AMO” and extended it to 2013–52. Their results indicated the current low rate of warming could continue for several more years then turn slightly negative and reach a maximum cooling in 2040. Although these predictions by different approaches may show different temperature-change rates, they all agree that the temperature will not significantly increase until the 2040s, which is consistent with our projection.

However, we should keep in mind that the amplitude and frequency of MDV vary with time. With the only 2.5 historical waves, the predicted phases and amplitudes may be inaccurate. Moreover, considering that the future change of greenhouse gas and aerosol emissions can influence the radiative forcing, the current steady trend may be disturbed further. So, there is a huge uncertainty in the 50-yr projections in our reconstructed time series. This paper gives only the future trend of GMST’s evolution on a century scale.

5. Summary and discussion

The MDV and the secular trend dominate the variation of GMST at the centennial time scale. Both the recent warming hiatus and previous rapid warming are closely associated with both the MDV and the secular trend. As the trend has been steady since the early twentieth century, the MDV becomes a strong predictor for climate multidecadal change and it deserves more attention. Based on the four critical episodes of MDV, a quantitative definition for GMST multidecadal evolution is presented. We first separate an MDV cycle into four periods—peak, trough, ascending, and descending—and select four crucial points to represent them. At these points, the MDV gets the local maxima and minima and the most rapid rising and declining. We then define “the warming (cooling) hiatus period” and “the typical warming (cooling) period” as the 95% CIs of the location of local maxima (minima) of the MDV and of the derivatives, respectively. According to the above definition, time spans of those crucial periods are calculated. There have been three warming hiatuses, cooling hiatuses, and typical warming episodes and two typical cooling episodes since 1850. We also provide 60-yr statistical predictions of the MDV and the secular trend. The MDV is predicted using an adaptive ARMA model based on historical records from January 1850 to December 2004. The trend is obtained by cubic spline interpolation. The predictions show a reasonably good agreement with the last 10 years of historical records (which are used to validate our predictions). For the MDV, we are now in the warming hiatus period that

began in May 2012 and will last until August 2017; then, we would undergo a cooling episode in the following 30 years or so. The superposition time series of the MDV and the trend presents a step-type rising since 1850; now it is ascending the third step and will stay there for decades until the warming phase of MDV take it to a new height.

The quantitative definition and predictions presented in this paper are based on an intrinsic MDV decomposed by EEMD, getting rid of interference from the secular trend and high-frequency variability to show clear physical meaning. Using an ensemble of data, this definition reduces the effects of a particular dataset and also avoids arbitrary starting and ending points or a time span, making it more reliable. An ensemble of data can be generated by combination of various data from the same or different sources. However, sometimes there is only one time series. In this case, a useful method to produce ensemble results using a single sequence is available in [Huang et al. \(2003\)](#).

There is one final issue to note. Influenced by various processes, the evolution of global-mean temperature is extremely complex, with time scales ranging from several months to a century according to our decomposition ([Fig. 1](#)). The relative importance of these scales differs depending on the problem itself. As we try to present the long-term change of the GMST in its simplest form, the MDV, which has the maximum amplitude and the highest significance among all the scales, is chosen to define key stages of GMST. However, no single item can cover all the variation because higher- or lower-frequency variability will cause discrepancies between MDV and GMST.

As illustrated in [section 3](#), the multidecadal variation of global temperature can be reconstructed better by the superposition sequence of MDV and the secular trend than by the MDV alone ([Figs. 3 and 5](#)). Shifts of superimposed phases relative to MDV’s phases depend on the variation characteristics of the secular trend. The positions of the superimposed phases are primarily the same as those of the MDV in the context of a flat trend, as they did before the 1910s. But the increasing trend makes the superimposed peaks lag those of MDV while the troughs lead, like the shifts of the peak around 1945 and of the trough around 1970. In those cases with a linear increase (i.e., the derivative of trend is nearly constant), the superimposed typical warming and cooling periods do not change in terms of timing, as they did after the 1950s. With an accelerated increase (i.e., the derivative is also growing), the superimposed typical warming lags that of MDV, such as that around 1925, while the superimposed typical cooling leads.

FIG. 5. The upper portion shows the ensemble-mean IDV (red), MDV (blue), and their superposition (pink). The lower portion shows the ensemble-mean GMST series (gray), secular trend (light blue), and reconstructed series by superimposing two items (MDV and trend; black) and three items (IDV, MDV, and trend; magenta). Horizontal error bars are time spans of four crucial phases for MDV (peak in red, trough in blue, typical warming in magenta, typical cooling in cyan).

We also noticed that $c7$, the interdecadal variability (IDV) with a roughly 20-yr period and minimum amplitude (Figs. 1 and 5), reshapes the waveform of MDV significantly. As shown in Fig. 5 (pink curve), the riding IDV makes the temperature frequently fluctuate around a smooth MDV. The peaks (troughs) become sharper when the IDV and MDV reach peaks (troughs) at the same time. In particular, the IDV passed from a warming phase to a cooling phase in the early 2000s and has held it ever since, slowing the temperature growth caused by the MDV's warming phase and secular trend. The contribution of IDV to GMST change and the prediction of its future behavior will be discussed in our future research.

The superposition of the abovementioned three items nicely reconstructs the evolution of GMST from decadal to century scales. Although the definition based on MDV alone is not perfect, it offers a new approach to quantitatively define the global warming hiatus. The definition can be easily improved by replacing the MDV with superposition of the last two or three components in the above decompositions (Fig. 1) and can be applied to the study of climate change at other time scales, too.

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