Slowdown of Global Surface Air Temperature Increase and Acceleration of Ice Melting

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Key points:

- Our analysis of climate and ice records show a slowdown of the rate of increase in global surface air temperature and an acceleration of ice melting from 1992-2001 to 2002-2011, both statistically significant at the 5% level.
- The energies involved in both processes are of the same order of magnitude, indicating a redistribution of heat within the atmosphere-cryosphere system.

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Abstract

Although recent decades have been the warmest since 1850, and global mean temperatures during 2015 and 2016 beat all instrumental records, the rate of increase in global surface air temperature (GSAT) significantly decreased at the beginning of the 21st Century. In this context, we examine the roles of ice melting and associated increase in sea-water mass, both of which significantly increased at the same time as GSAT decreased. Specifically, we show that (1) the slowdown of the rate of increase in GSAT between the specific periods 1992-2001 and 2002-2011 exists in all three climate records analyzed and is statistically significant at the 5% level amounting between 0.029 and 0. 036 °C/yr and leaving an energy of 14.8 to 18.4 10^{19} J/yr available; (2) the increase of the atmosphere-related ice melt between these two periods amounts to 316 Gt/yr which requires 10.5 10^{19} J/yr, i.e. between 57% and 71 % of the energy left by the slowdown; and (3) the energy budget shows therefore that the heat required to melt this additional 316 Gt/yr of ice is of the same order as the energy needed to warm the atmosphere during the decade 2002-2011 as much as during the previous one, suggesting a redistribution of heat within the atmosphere-cryosphere system.

1. Introduction: The slow-down of the rate of increase in global surface air temperature

Global annual mean surface air temperature (GSAT) has increased over the last 200 years, with each of the past 3 decades being warmer than the previous ones (Stocker et al. IPCC, 2013). The IPCC attributes global warming primarily to CO_2 emissions related to fossil fuels and secondarily to net land use changes. Although the last decade is the warmest decade in the instrumental record dating back to 1850 (WMO, 2015), and CO_2 continues to rise (reaching more than 400 ppmv in 2015, Tans and Keeling, 2014), the rate of increase in GSAT has shown an apparent pause or hiatus between 2000 and 2012 (Keenlyside et al., 2008; Easterling and Wehner, 2009; Hansen et al., 2010; Yan et al., 2016). The IPCC (Stocker et al., 2013) reports a rise of GSAT of 0.26 °C per decade for the period 1984-1998 and 0.05 °C per decade for the period 1998-2012, a decrease of 0.21°C per decade. The exceptional 2015 and 2016 GSATs appear to have put an end to the hiatus (Hansen et al., 2017). There were however many discussions about whether the slowdown of the rate of increase in GSAT is real or not. A detailed analysis of the different definitions of hiatus and of different data sets (Medhaug et al., 2017) has attempted "reconciling controversies about the global warming hiatus". Nonetheless, decadal variability of the climate remains an important and as yet unresolved issue.

Several factors have been suggested as possible contributors to this slowdown of the rate of increase in GSAT. Explanations can be grouped into two categories:one dealing with reduced external forcing and the other dealing with internal variability. Among the first category, we can cite solar activity decay (Stauning, 2014), increased stratospheric aerosol optical depth due to moderate volcanic activity (Santer et al., 2014; Ridley et al., 2014) and enhanced coal burning in Asia (Neely et al., 2013), reduced stratospheric water vapor concentrations (Solomon, 2010), and lesser CFC and methane emissions (Estrada et al., 2013). In the second category, there are: a global phenomenon of unforced origin (Dieng et al., 2017a), natural variability coinciding with a lesser increase of the sum of anthropogenic and natural forcings (Kaufmann et al., 2011), and offset of anthropogenic warming by natural climate variations in the Atlantic and tropical Pacific (Keenlyside et al., 2008). Nevertheless, increased heat absorption by the oceans seems to be the favored explanation. NOAA data (Levitus et al., 2012) show slower warming of the ocean's 700 m upper layer during the first decade of the 21st century which relates to the slower atmospheric warming through the ocean atmosphere coupling. However, as global heat absorption by the ocean (mostly down to 2000 m) has not diminished significantly, heat redistribution within the ocean must explain the upper layer's slower warming, via a greater heat transfer to the deeper ocean (Yan et al., 2016). Model simulations suggest also that such an increase of deep-ocean heat uptake, related to changes in the decadal ocean circulation variability with more frequent occurrences of cold La Nina (Foster and Rahmstorf, 2011), could be at the origin of the warming slowdown (Meehl et al., 2011). Similarly, the eastern tropical Pacific surface cooling (Kosaka and Xie, 2013; Held, 2013; Trenberth and Fasullo, 2013), attributed to stronger Pacific trade winds (England et al., 2014), could have caused the slowdown through increased subsurface ocean heat uptake. In addition, the recurrent salinity anomaly in the subpolar North Atlantic (Chen and Tung, 2014) could have initiated the transport of heat to deeper layers in the Atlantic and the Southern Oceans.

It is likely that heat has been added to the deep ocean over the last decade but quantifying the amount remains difficult. Indeed, uncertainties in data processing and systematic errors within the observations do not allow sufficiently accurate measurements (Abraham et al., 2013; Dieng et al., 2015a, Yan et al., 2016). Moreover,, the ocean's thermal expansion rate has increased much less rapidly since 2003 (Dieng et al., 2015a; Llovel et al., 2014; von Schuckmann et al., 2014; Cazenave et al., 2014), in spite of a possible bias towards low values on the upper-ocean warming (Durack et al., 2014). The expansion rate was 1.6±0.25 mm/yr with a sea level rise at about 3.1±0.4 mm/yr from 1993 to 2003 (Cazenave et al., 2009), whereas from 2003 to 2012 it was down to about 1 mm/yr (Llovel et al. (2014) estimated it 0.9±0.15 mm/yr over 2005-2013) with a sea level rise at 3.3±0.4 mm/yr (Cazenave et al., 2014) and is almost stable since 2004. The mass component of the sea level rise went consequently from 1.5 mm/yr to 2.3 mm/yr. Thus, the ocean's thermal expansion is reduced by 0.6mm/yr while the mass component increases by 0.8mm/yr (pretty close to the 0.61 mm/yr of Dieng et al., 2017b), pointing to a relationship between the warming slowdown and global ice melt. Heat accumulation in the deeper ocean (below 700 m) may, however, reduce this net mass contribution increase to sea level rise to 0.4 mm/yr (this would happen if, instead of 2.3±0.4 mm/yr over the period 2003-2012, the mass increase in the ocean were 1.9±0.1 mm/yr as in Cazenave et al. (2009) for the period 2003-2008; there will even be no increase if the value of 1.5±0.4 mm/yr for 2003-2013 (Purkey et al., 2014) is used). Finally, we acknowledge that the thermal expansion depends on the temperature of the water being warmed as well as on the amount of heat added, but a very large temperature change , which is not observed, would be required to change the thermal expansion coefficient significantly.

Our examination of the rate of change of surface warming in the time spans 1992-2001 and 2002-2011 and our analysis of some components of the Earth's energy budget show that a partial energy redistribution between the atmosphere and the cryosphere has taken place. Consequently, we suggest (within acknowledged uncertainties) that the hiatus may be partly explained by a change in the partitioning of incoming energy and, importantly, that the rate of global warming (as in energy accumulation) has remained constant over the past several decades.

2. Localization of the slowdown of the rate of increase in GSAT

In an attempt to demonstrate the existence of a pause and to refine its localization, we have done regression analyses (Supporting Information S1) over different time sub-periods between 1984 and 2014 using three different data sets (Table 1 and Supporting Information S2 and Table SM1): HadCRUT4, Cowtan-Way and Karl et al.

These datasets are updated continuously. The median of the 100 ensemble member of the HadCRUT 4.3.0.0, version 2.0 of Cowtan-Way, the new analysis Karl data (ftp://ftp.ncdc.noaa.gov/pub/data/scpub201506/) and the Mean of these three data sets are used in our calculation. From all data and publications available, we can demonstrate that there is a slowdown of the rate of increase in GSAT in all data sets we analyzed (Tables 1 and SM1).

About the localization of the pause, using a double linear regression, our best fit of the full data sets finds the pause period starting at the turn of the 21st century. The warming rate in HadCRUT4 is indeed respectively 0.236±0.042°C per decade in the 1984-2002 period and 0.008±0.049°C per decade in the 2002-2014 period (Table 1 and Fig. 1a). During the pause (2002-2014), the null hypothesis of a zero warming rate cannot thus be excluded. Moreover, the trend of the time series built from the difference of the two series, i.e. the series before and after 2002 is statistically different from zero at better than the 0.01 significant level. This means that the trends of the individual time series are significantly different, a result that parallels the acceleration of land ice melting as we will show. When 1998 is taken as the starting point of the pause, the result is strongly influenced by the fact that this is an exceptionally warm year (with its historically strongest El Nino) followed by two rather cool ones before the temperature rises again to reach the plateau in 2002-2003. The larger 2000-2014 trend (0.116±0.067 °C per decade) of the new analysis by Karl et al is at least partly explained by the inclusion of the cold year 2000 and the warm year 2014 in the time series. If the period 2002-2011 is indeed used, a trend of 0.018±0.078 °C per decade is found

(Table 1). In regression analyses over the periods 1984-1999 and 1999-2014 in HadCRUT4, with 1999 as a common point between the two periods, the difference between the respective trends of these two periods disappears (Fig. SM1). The same is true when 1984-2000 is compared to 2000-2014 and even more so if 2015 and 2016 are included. These, along with observed ice melt acceleration, are the reasons for us choosing 2002 rather than 1998 as the starting year of the pause period.

Finally, we selected the 2002-2011 period because it corresponds to the time span when a definite pause is observed, as compared to the 1992-2001 interval. This time frame is relevant also because the quality of observational data sets has been discussed in various publications. Moreover, the 5^{th} IPCC report shows that important changes took place in the cryosphere from one period (1992-2001) to the other (2002-2011). Accordingly, our statistical model (Supporting Information S1) shows that the rate of increase in HadCRUT4 GSAT is 0.328 ± 0.117°C/decade from 1992 to 2001 and -0.031 ± 0.095 °C/decade from 2002 to 2011; in Cowtan-Way GSAT, it is respectively 0.340 ± 0.106 and 0.0396 ± 0.134°C/decade, and in Karl, 0.305 ± 0.110 and 0.018 ± 0.078°C/decade. By way of synthesis, a similar analysis was done on the mean of the three data sets leading to a trend of 0.325 ± 0.110 °C/decade from 1992 to 2001 and of 0.0086 ± 0.089 °C/decade from 2002 to 2011 (Table 1 and Figure 1b)

3. Changes in temperature, energy and ice melting

The pause can be analyzed in a direct way by considering the observed slowdown of the rate of increase in GSAT (now given in °C/yr to fit the data on energy and on ice), i.e. 0.0359±0.0151°C per year (based on HadCRUT4), 0.0301±0.015 (based on Cowtan-Way),a minimum of 0.0288±0.0138 (based on Karl et al.), or 0.0316 ± 0.0147 (based on the Mean of the three data sets), and seeing if it might be related to the energy left available by the pause and the ice melt acceleration.

From the first law of thermodynamics and assuming that the energy would warm the atmosphere globally, the relationship between the changes in temperature ΔT and sensible heat ΔQ can be written:

$$\Delta T = \Delta Q / (C_{pa} M_a) \quad \text{with} \quad C_{pa} = 1005 Jkg^{-1}K^{-1} \quad \text{and} \quad M_a = 510x10^{16} kg$$

C_{pa} is the specific heat of the atmosphere at constant pressure and M_a the mass of the atmosphere.

The warming drop during 2002-2011 relative to 1992-2001 estimated from HadCRUT4, Cowtan-Way, Karl et al. and Mean of these data sets would therefore leave respectively 18.4±7.7, 15.4±7.7, 14.8±7.1, or 16.2 ± 7.5 10^{19} J per year available (Table 2 and Supporting Information S4 and S5). With a latent heat of fusion of ice of 334 10^3 J kg^{-1}, neglecting the energy required to warm the ice up to its melting point (the specific heat of ice is only 2.1 10^3 $Jkg^{-1}K^{-1}$), such energy could potentially melt respectively 551±231, 462±230,442±212 or 485 ± 226 Gt of ice (Table 2). Given the uncertainties, these values are 40 to 74 % larger than the difference in the atmospheric-related melted ice (316 Gt) between the period before 2002 and the period after, as shown from observations in section 4 and Table 3.

4. Observed ice melt

From literature, the total mass loss of ice during the 1992-2002 period, is estimated to be just above 500 Gt per year (Table 3). Between 2002 and 2011, it is estimated at about 1200 Gt per year (roughly 600 from continental ice and 600 from sea ice; Table 3). Assuming all this ice has melted with the ice fusion latent heat of 334 10^3 J kg^{-1}, we conclude that 39.91 10^{19} J per year or 4.43 % of the average energy gained by the Earth each year (900 10^{19} J) would have been consumed for this ice melt over the 2002-2011 period. Part of the ice melt may be due to the atmosphere, but it cannot easily be estimated.

The Greenland ice sheet mass loss has increased during the past two decades (Ice sheet Mass Balance Inter-comparison Exercise, Shepherd et al., 2012, Forsberg et al., 2017); it is estimated with high confidence at 215±58 Gt per year (Stocker et al., 2013) over the 2002-2011 period against 34±40 Gt per year over the 1992-2001 period (Table 3). Given the uncertainties, the full range of the changes from one period to the other is 181±70 Gt per year. There is good reason to attribute a similar amount of the loss to melt-runoff and to outlet glacier discharge. The energy for iceberg melting is provided essentially by the ocean and it is likely that the heat needed to melt the surface of the ice-sheet is provided by the atmosphere. Assuming that the atmosphere is at the origin of half of the mass loss (Stocker et al., 2013), the melting over the 2002-2011 pause period would amount to 107±29 Gt per year and the additional melting compared to the 1992-2001 period would be 90±35 Gt per year (Table 3). These values are rather conservative: the Greenland ice sheet could lose up to two thirds of its mass in the near future (Rignot et al., 2011; X. Fettweis, personal communication).

Because this ice melt acceleration in the 2000s could possibly be related to a change in the surface albedo, we verified whether the deposits of black carbon (soot) carried to northern high latitudes by aerosols from fossil fuel and biomass burning have increased during that period. The measurements by Doherty et al. (2010) show that black carbon deposits on the Arctic decreased between the mid-1980s and the late 2000s. No major deposit occurred in the 21st century before that of the 2012 early summer from large Siberian and north-American forest fires which resulted in a widespread surface melt of the Greenland ice sheet in July 2012 (Keegan et al., 2014). Thus black carbon deposit can be ruled out as a cause of the melting acceleration observed in the Arctic region since 2000. Dust deposits of possible mineral origin are also shown to potentially reduce the albedo in the last years according to measurements by Dumont et al. (2014). As they find that a sizeable albedo reduction occurs only after 2009, mineral dust deposits are also ruled out as a possible cause of the ice melt acceleration over our entire period of interest. However, MODIS (MODerate resolution Imaging radioSpectrometer) albedo data (Box et al., 2012) indicate a significant ice sheet areal-averaged albedo decline of -0.056±0.007 during the northern hemisphere summer over the period 2000-2011. This albedo decline is due mainly to the expansion of the ablation zone (covered by bare ice in summer) resulting from a general atmospheric circulation change in recent summers that favors an advection of warm air from the South. Surface temperature warming enhances snow grain metamorphism in the accumulation area and due to scarce snow deposit and warming induced surface melting, ponds form on the sheet (as also on sea ice) significantly decreasing its albedo and thus augmenting the melting of the ice via the well documented albedo feedback. In fact, the persistent feedback of enhanced surface melting (Box et al., 2012), below-normal summer snowfall (Box et al., 2013) and the darkening of the surface since 2009 have contributed to an acceleration of the Greenland ice sheet melt.

It is likely that the Antarctica average rate of ice loss has increased during the last two decades. It was 147±75 Gt per year with a low confidence level (Stocker et al., 2013) during the 2002-2011 period (Table 3), and it was due to ocean heat flux. Compared to 30±67 Gt per year from 1992 to 2001, this represents an increase of 117±101 Gt per year. There is a very high confidence that these losses are mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica, and a high confidence that they result from the acceleration of outlet glaciers, surface melting being currently negligible in Antarctica (Stocker et al., 2013). Moreover, because of the importance of the ocean heat flux on the changes of floating ice shelves, surface melting associated to the atmosphere over the pause period is finally considered to be only 20±17 Gt per year and its change from 1992-2001 to 2002-2011 to be only 10±8 Gt per year (Table 3).

Note that the values of ice loss in Greenland and Antarctica used here are similar to those estimated by others. In Rignot et al. (2011), the acceleration of ice loss between 1992 and 2009 amounts to 21.9 ± 1 Gt/yr^2 for Greenland, 14.5 ± 2 Gt/yr^2 for Antarctica, and 36.3 ± 2 Gt/yr^2 for the combined total whereas our values are respectively 18±7, 12±10 and 30±12 Gt/yr^2. In Shepherd et al. (2012), the total mass loss for Greenland and Antarctica amounts to 100±92 Gt/yr from 1992 to 2000, 298±58 from 2000 to 2011 and 213±72 for the whole period 1992-2011. This compares well with our values (64±68, 362±95 and 213±123 Gt/yr), although our uncertainty is larger than in Rignot et al. and in Shepherd et al. (note also that the time intervals are not strictly the same).

Global glacier decline is unprecedented in the early 21st century (Zemp et al., 2015). From an interpolation of the data given in IPCC and the update of Marzeion et al. (2012 and 2017), the total mass loss from all glaciers (excluding those on the periphery of ice sheets) is estimated at 240±34 Gt per year over the 2002-2011 period. This is an increase of 67 Gt per year relative to 173±43 Gt per year of the period 1992 to 2001. Following Marzeion (personal communications), we will consider that the totality of these melts is induced by the energy transferred from the atmosphere (Table 3).

Ice melt is one of the most important feedback mechanisms that characterize the climate system response to radiative forcing, sea-ice extent changes, in particular, changing the Earth's surface albedo significantly. There is very high confidence that the Arctic sea ice extent decreased over the 1979-2012 period (Comiso and Hall, 2014) (Fig. 2 where September sea ice is taken only as an example) while the annual Antarctic sea ice extent increased over the 1979-2012 period (Stocker et al., 2013). Over the 1979-2010 period, the Arctic sea-ice extent decreased by 52 10^3 km^2/yr, three times more than the Antarctic sea ice extent increase (17 10^3 km^2/yr). Meanwhile, the Arctic sea ice volume decreased by 275 km^3/yr (PIOMAS, 2016), one order of magnitude more than the Antarctic sea ice volume gain of 30 km^3/yr (Holland et al., 2014), this gain being compatible with the natural variability of the climate system (Zunz et al., 2013).

The 5th IPCC report notes that the decadal extent of annual Arctic sea ice has decreased not only in the summer and autumn, but in every season, and in every successive decade since 1979 (high confidence). Moreover, the extent of Arctic perennial and multiyear ice decreased with very high confidence between 1979 and 2012. As we did when attempting to locate the global warming slowdown (see above), we used a regression strategy to trace the acceleration of Arctic sea-ice vanishing. As illustrated by the sea-ice extent in September (Fig. 2), 1998 appears to be a significant bifurcation point in also the annual trend with 40,300 km^2 per year of sea-ice vanishing before 1998 and 154,600 km^2 after. Data from Fetterer et al. (2014) (and NSIDC, 2016a) show such a decrease in the Arctic sea ice area (extent) in September, from 4.26 (6.62) 10^6 km^2 in 1998 to 2.16 (3.63) 10^6 km^2 in 2012 (September is used only to better illustrate the change in Arctic sea ice). 2001 is characterized by an anomalously large ice area (extent) of 4.56 (6.78) 10^6 km^2 but is followed by an area (extent) of 4 (6) 10^6 km^2 in 2002. From then, the decline starts to be steadier at least up to 2012 (in 2013, 2014, 2015, the ice extent is respectively 5.35, 5.29 and 4.68 10^6 km^2 indicating a slower acceleration of the Arctic sea ice melt). Figure 2, illustrates clearly that the September Arctic sea ice extent started to decline more rapidly at the turn of the 20th century (i.e. between 1998 and 2002). This coincides with the beginning of the pause.

Not only is the surface covered by ice decreasing, but the Arctic sea-ice is becoming continuously younger, i.e. thinner and melting more easily each summer. The thinning of the sea-ice cover and its disappearance considerably change the energy budget exchange between the ocean, the ice and the atmosphere and could therefore have played an important role in the acceleration of the Arctic sea-ice melting and possibly in the existence of the pause. Modelling experiments (Holland et al., 2006) show that "ice retreat accelerates as thinning increases the open water formation efficiency for a given melt rate and the ice albedo feedback increases short wave absorption". As at long time scale, the total sea ice area is approximately linearly related to Arctic surface air temperature (Mahlstein and Knutti, 2012), it is likely that there is an air temperature threshold for the acceleration of September sea ice disappearance. Melt-pond formation (Polashenski et al., 2012; Schröder et al., 2014; Lecomte et al., 2014) and the related albedo feedback could be another factor at the origin of faster Arctic sea ice melting at the beginning of the 21st century.

Sea-ice volume evaluations in the Arctic are less precise than those of sea-ice extent because of uncertainties in the ice thickness (Zygmuntowska et al., 2014). However, calculations based on the data available (Massonnet et al., 2012, 2013; Fetterer et al., 2014; PIOMAS, 2016) show that sea-ice volume loss started to accelerate around 1998 with 152 km^3 per year total disappearance rate during the 1979-1998 period compared to 545 km^3 per year during the 1999-2011 period. Concurrently, it can be shown that the Arctic lost 620 ± 60 km^3 per year during the 2002-2011 period as compared to 296 ± 66 from 1992 to 2001. With an ice density of 920 kg/m^3, this leads to a total sea-ice mass loss of 272 ± 60 and 570 ± 55 Gt per year respectively. In the Arctic, it is reasonable to assume that 50% of the annual sea ice melt is due to heat transferred from the atmosphere. Indeed, observations (Perovich et al., 2014) and modeling (Lecomte et al., 2013) show an Arctic surface melt about equal on average to the bottom melt. Over the pause period the total atmosphere-related Arctic ice melt would thus have amounted to 285 ± 28 Gt per year, which represents a 149 ± 41 Gt increase as compared to the period before 2002 (the contribution of Antarctica sea ice melt is assumed to be negligible).

In summary (Table 3), over the 2002-2011 period, 1172±115 Gt of ice vanished each year on average, i.e. 663 Gt more than the 509±107 Gt per year of the 1992-2001 period. Considering that this ice vanishing is caused in roughly equal amounts by the atmosphere and by the oceans, the additional atmosphere-related melting is 316±77 Gt of ice per year (Table 3).

The amount of energy left available in the atmosphere from the slowdown of the rate of increase in GSATwhich is $18.4 \pm 7.7\ 10^{19}$ J per year (HadCRUT4 data), $15.4 \pm 7.7\ 10^{19}$ J per year (Cowtan-Way data), $14.8 \pm 7.1\ 10^{19}$ J per year (Karl et al data) and $16.2 \pm 7.5\ 10^{19}$ J per year (Mean of the three data sets) (Table 2) is comparable to the $10.5 \pm 2.5\ 10^{19}$ J per year needed for the additional melting of 316±77 Gt of ice per year. The energy associated to the global surface warming slowdown during the 2002-2011 period as compared to the 1992-2001 period could thus be related, at least partly, to the concomitant ice melt acceleration, the remnant missing energy being transferred to ocean.

5. No pause in the total of atmospheric warming plus ice melting

The beginning of the 21st century has witnessed four, almost simultaneous phenomena: acceleration of the arctic sea ice disappearance (including a shrinking of its annual maximum), increase of the rate of ice sheet and glacier melting (Zemp et al., 2015), increase of sea level rise (Cazenave et al., 2014; Cazenave and Remy, 2011) and the appearance of a slump in the warming trend of the atmosphere. These are the reasons why, in order to obtain a proper idea of the heat gain by the atmosphere, we suggest adding the heat necessary to melt ice sheets, high altitude glaciers as well as sea ice, to the heat content increase due to the atmosphere's temperature increase. Figure 3 illustrates the energy redistribution between the atmosphere and the cryosphere, showing that, while the heat content of the atmosphere alone looks stable after the turn of the 21st century, no such behavior is observed when the ice melting heat is added. When compared to the slope of the atmospheric heat, it appears that the ice melt increase compensates the pause in the atmosphere's temperature rise and restores a quasi linear behavior for the total energy involved in the atmosphere-cryosphere system. As shown in Figure 3, the trend of the energy curves is a steady increase from 7.8 to 24.4 10^{19} J per year, with a relative uncertainty that decreases markedly from 13 to 4 % and the variance increases significantly from 76 to 96 %.

6. Discussion and Conclusions

From statistical analysis of the data from HadCRUT4, Cowtan-Way, Karl et al. and Mean of these data sets, we have shown that there is definitely a slowdown of the rate of increase in their GSAT which is significant at better than the 0.1 level of significance. For example, this slowdown in the Mean data set amounts 0.316 ± 0.147 °C per decade which is significant at the 0.06 level.

According to our calculations (Table SM2), the heat gained by the Earth since the beginning of the 21st century (assumed to be 9 10^{21} J per year from Stocker et al. (2013) over the period 2002 to 2011; Supporting Information S4 and S5) is redistributed as follows (unlike the IPCC distribution characterizing the 1971-2010 period with a heat gain of 6.85 10^{21} J per year):

- Instead of 1% of the total energy gained by the Earth (9 10^{19} J per year) being used to warm the atmosphere, observations between 2002 and 2011 give 0.28 % for the 0.05 °C per decade of IPCC, 0.21% for the 0.0396°C per decade of Cowtan-Way, 0.1% for the 0.018°C per decade of Karl et al. and only 0.04% for the 0.0086°C per decade of the Mean data set.
- If the atmosphere had continued to warm between 2002 and 2011 as it did between 1992 and 2001, it would have needed respectively 2.0 %, or 1.7 % or 1.64 % or 1.8 % of the total energy gaind by the Earth more than it was actually used, depending whether HadCRUT4, or Cowtan-Way or Karl et al. or the Mean data set is used..
- Instead of 3% for the ice melt, it is 4.34 % (39.1 10^{19} J per year) that must be available to melt 1172 Gt of ice per year between 2002 and 2011. If the melting had continued as it was between 1992 and 2001 (509 Gt of ice per year), it would have required only 1.9 % (17 10^{19} J per year) of the total energy gained by the Earth, i.e. 2.44 % (22.1 10^{19} J per year) less than the amount effectively required to melt the observed ice loss of 1172 Gt .
- Assuming that the melting of 652 Gt of ice per year during the time span 2002-2011, roughly half of the total annual 1172 Gt ice melt during this period, is atmosphere related, the energy taken from the atmosphere would be 2.41 % (21.7 10^{19} J per year), not very different from the energy required to melt the additional 663 Gt of ice per year (2.44 %) resulting from the ice melt acceleration.
- The energy associated to the global warming slowdown during the 2002-2011 period as compared to the 1992-2001 period when expressed as a percentage of the total energy gained by the Earth is respectively from HadCRUT4 (2.04 %), Cowtan-Way (1.7 %) , Karl et al. (1.6 %) and the Mean data set (1.8 %). These are actually comparable to the 1.17 % (10.5 10^{19} J per year) energy required to melt 316 Gt of ice per year, an estimate of what the atmosphere may do.
- Accordingly, the share of the ocean and the continents together is barely modified.

Given the remaining uncertainties in the data used, the problem of the pause-hiatus is not totally solved and several explanations remain possible. Among these, it is our conjecture that the acceleration of the arctic sea ice melt can have played an important role in the initiation of the pause. Accordingly, the exceptional warming observed for 2014, 2015 and 2016 (Hansen and Sato, 2016) seems be concomitant with a sea ice melt slow down since 2013, except for the unprecedented sea ice extent low anomaly of the autumn 2016 and winter 2017 months (NSIDC, 2016b).

In IPCC (Stocker et al., 2013), scenario RCP8.5 leads to a vanishing of the Northern Hemisphere September sea ice by about 2060 while the extrapolation of today's Arctic sea ice melting makes it vanish within the next 30 years, as our estimate also shows (Table 3 and Overland and Wang, 2013). This is why, in addition to missing estimates of external influences on the climate in model simulations claimed by Schmidt et al. (2014), we recommend that careful attention be paid to the acceleration of the ice melting from the period before the beginning of the 21st century to after, in particular concerning the Arctic sea ice (volume), Greenland and the high altitude glaciers. To improve our understanding, the El Niño contribution to the exceptional warming of 2015-2016 must be properly estimated. Indeed, according to the Met Office (2017), the particularly strong El Niño event contributed about 0.2°C to the annual average for 2016, which was about 0.77 ± 0.1 °C above the average of the 1961-1990 period. Without El Niño, 2016 would then have been like 2014 and within the errors of the last 15 years. Thus, it is hard to claim that the pause has ended, it might simply have been interrupted by a strong El Niño and could soon resume.

We propose that the “global warming hiatus” is a redistribution of the heat taken up by the Earth, a redistribution which counts ice melting among the beneficiaries. However, it does not prevent other causes to be also considered to explain the decrease of the warming rate over the first decade of the 21st century, e.g. an increase of the transfer of heat from the upper oceanic layer to the deep ocean even if a signature in the deep ocean heat uptake is difficult to find (Dieng et al., 2015b), and/or a missing or incorrect radiative forcing (an increase of volcanic activity, a decrease of solar activity), and/or the natural variability of the Earth system at the decadal to secular time scales (Dieng et al., 2016).

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References

Abraham J.P., M. Baringer, N. L. Bindoff, T. Boyer, L. J. Cheng, J. A. Church, J. L. Conroy, C. M. Domingues, J. T. Fasullo, J. Gilson, G. Goni, S. A. Good, J. M. Gorman, V. Gouretski, M. Ishii, G. C. Johnson, S. Kizu,J. M. Lyman, A. M. Macdonald, W. J. Minkowycz, S. E. Moffitt, M. D. Palmer, A. R. Piola, F. Reseghetti,K. Schuckmann, K. E. Trenberth, I. Velicogna, and J. K. Willis, 2013. A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. Review of Geophysics, 51 (3), 450-483.

Box J.E., Cappelen J., Chen C., Decker D., Fettweis X., Mote T., Tedesco M., van de Wal R.S.W., and Wahr J., 2013. In Arctic Repord Card: Update for 2012, http://www.arctic.noaa.gov/report12/greenland_ice_sheet.html.

Box, J. E., Fettweis X., Stroeve J. C., Tedesco M., Hall D. K., and Steffen K., 2012. Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. The Cryosphere, 6, 821-839, doi:10.5194/tc-6-821-2012.

Cazenave A. and Chen J., 2010. Time-variable gravity from space and present-day mass redistribution in the Earth system. Earth and Planetary Science Letters 298, 263-274.

Cazenave A., Dominh K., Guinehut S., Berthier E., Llovel W., Ramillien G., Ablain M., Larnicol G., 2009. Sea-level budget over 2003-2008: a revaluation from GRACE space gravimetry satellite altimetry and Argo. Global and Planetary Change, 65, 83-88.

Cazenave Anny, Dieng Habib-Boubacar, Meyssignac Benoit, von Schuckmann Karina, Decharme Bertrand and Berthier Etienne, 2014. The rate of sea-level rise. Nature Climate Change 4, 358-361.

Cazenave, A. and Remy, F., 2011. Sea level and climate: measurements and causes of changes, Wiley Interdisciplinary Reviews. Climate Change 2, 647–662.

Chen, X. and Tung, K. K., 2014. Varying planetary heat sink led to global-warming slowdown and acceleration. Science 345, 897-903.

Comiso J. C. and Hall D. K., 2014. Climate trends in the Arctic as observed from space. WIREs Clim Change 5, 389–409.

Cowtan, K., & Way, R. G., 2014. Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. Q.J.R. Meteorol. Soc. 140, 1935–1944.

Dieng H. B., Cazenave A., von Schuckmann K., Ablain M., and Meyssignac B., 2015a. Sea level budget over 2005-2013: missing contribution and data errors. Ocean Sci. Discuss 11, 1–34.

Dieng H. B., Hindumathi Palanisamy, Anny Cazenave, 2015b. The sea level budget since 2003, inference on the deep ocean heat content. Surveys in Geophysics 36, 209–229.

Dieng H.B., Cazenave A., Meyssignac B., von Schuckmann K., Palanisamy H., 2017a. Sea and land surface temperatures, ocean heat content, Earth's energy imbalance and net radiative forcing over the recent years. Int J. of Climatol, doi:10.1002/joc.4996

Dieng H.B., A.Cazenave, MeyssignacB., Ablain M., 2017b. New estimate of the current rate of sea level rise from a sea level budget approach. Geophys. Res. Lett., 44. Doi 10.1002/2017GL073308

Doherty, S. J., Warren S. G., Grenfell T. C., Clarke A. D., and Brandt R. E., 2010. Light-absorbing impurities in Arctic snow. Atmos. Chem. Phys. 10, 11647-11680.

Dumont, M., Brun E., Picard G., Michou M., Libois Q., Petit J. R., Geyer M., Morin S., and Josse B., 2014: Contribution of light-absorbing impurities in snow to Greenland's darkening since 2009. Nature Geoscience, 7, 509-512, doi:10.1038/ngeo2180.

Durack Paul J.,Gleckler Peter J., Landerer Felix W. and Taylor Karl E., 2014. Quantifying underestimates of long-term upper-ocean warming. Nature Climate Change 4, 999-1005.

Easterling, D. R., & Wehner, M. F., 2009. Is the climate warming or cooling? Geophys. Res. Lett. 36, L08706.

England Matthew H., McGregor Shayne, Spence Paul, Meehl Gerald A., Timmermann Axel, Cai Wenju, Gupta Alex Sen, McPhaden Michael J., Purich Ariaan and & Santoso Agus., 2014. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. Nature Climate Change 4, 222-227.

Estrada, F., Perron, P., and Martinez-Lopez, B., 2013. Statistically derived contributions of diverse human influences to twentieth-century temperature changes. Nature geoscience 6, 1050–1055.

Fetterer, F., Knowles Kenneth, Meier Walt, Savoie Matthew, 2014. Sea Ice Index. Boulder, Colorado USA: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N5QJ7F7W (2002, updated daily).

ftp://sidads.colorado.edu/pub/DATASETS/nsidc0192_seaice_trends_climo/total-ice-area-extent/nasateam/

Forsberg R., Sorensen L., Simonsen S., 2017.Greenland and Antarctica ice sheet mass changes and effects on global sea level. Surv. Geophys. ,38, 89-104. Doi 10.1007/s10712-016-9398-7.

Foster G. and Rahmstorf S., 2011. Global temperature evolution 1979-2010. Environmental Research Letters 6, 044022 (8 pages)

Fyfe J.C., Meehl G.A., England M.H., Mann M.E., Santer B., Flato G.M., Hawkins E., Gillett N.P., Xie S-P, Kosaka Y., Swart N.C., 2016. Making sense of the early-2000s warming slowdown. Nature Climate Change, 6, 224-228.

Hansen J., sato M., Ruedy R., Schmidt G.A., Lo K., Persin A., 2017. Global temperature 2016. https://data.giss.nasa.gov/gistemp/

Hansen J. and Sato M., 2016. A better graph. http://www.columbia.edu/~jeh1/mailings/2016/20160926_BetterGraph.pdf

Hansen J., Sato M., Kharecha P., and von Schuckmann K., 2011. Earth's energy imbalance and implications. Atmos. Chem. Phys. 11, 13421-13449.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010. Global surface temperature change. Rev. Geophys. 48, RG4004.

Held, I. M., 2013. The cause of the pause. Nature 501, 318–319.

Holland M.M., Bitz C.M. Treblay B., 2006. Future abrupt reductions in the summer Arctic sea ice. Geophysical Resaerch Letters, 33, L23503, doi:10.1029/2006GL028024.

Holland P.R., Enright C, Losch M., Kurtz N.T., Kwok R., 2014. Modeled trends in Antarctica sea ice thickness. J. Climate, DOI: http://dx.doi.org/10.1175/JCLI-D-13-00301.1

Karl Thomas R., Arguez Anthony, Huang Boyin, Lawrimore Jay H., McMahon James R., Menne Matthew J., Peterson Thomas C., Vose Russell S., Zhang Huai-Min, 2015. Possible artifacts of data biases in the recent global surface warming hiatus. Science 348, 1469–1472.

Kaufmann Robert K., Kauppi Heikki, Mann Michael L., and Stock James H., 2011. Reconciling anthropogenic climate change with observed temperature 1998–2008. PNAS, 108(29): 11790–11793, doi: 10.1073/pnas.1102467108 http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1102467108/-/DCSupplemental.

Keegan, K. M., Albert M. R., McConnell J., Baker, I., 2014. Climate change and forest fires synergistically drive widespread melt events of the Greenland Ice Sheet. Proceedings of the National Academy of Sciences, 111(22):7964-7. www.pnas.org/cgi/doi/10.1073/pnas.1405397111

Keenlyside N. S., Latif M., Jungclaus J., Kornblueh L. & Roeckner E., 2008. Advancing decadal-scale climate prediction in the North Atlantic sector. Nature 453, 84–88.

Kosaka, Y. and Xie, S. P., 2013. Recent global warming hiatus tied to equatorial Pacific surface cooling. Nature 501, 403–407.

Lecomte O., Fichefet Th., Vancoppenaolle M., Domine F., Massonnet F., Mathiot P., Morin S., Barriat P.Y., 2013. On the formulation of snow therml conductivity in large-scale sea ice models. J. Adv. Model arth Syst., 5, doi: 10.1002/jame.20039.

Lecomte, O. Fichefet Thierry, Flocco Daniela, Schroeder David, Vancoppenolle Martin, 2014. Interactions between wind-blown snow redistribution and melt ponds in a coupled ocean–sea ice model. Ocean Modelling, 87, 67–80.

Levitus S., Antonov J.I., Boyer T.P., Baranova O.K., Garcia H.E., Locamini R.A., Mishonov A.V., Reagan J.R., Seidov D., Yarosh E.S., Zweng M.M., 2012. World ocean hea content and thermosteric o sea level change (0-2000m), 1955-2010. Geophysical Research Letters, 39(10) (5 pages).

Llovel W., Willis J. K., Landerer F. W. and Fukumori I., 2014. Deep-ocean contribution to sea level and energy budget not detectable over the past decade. Nature Climate Change 4(11): 1031-1035.

Mahlstein I. and Knutti R., 2012. September Arctic sea ice predicted to disappear near 2°C global warming above present. J. Geophys Res, 117, D06104, doi: 10.1029/2011JD016709.

Marzeion B., Jarosch A. H. and Hofer M., 2012. Past and future sea-level change from the surface mass balance of glaciers, The Cryosphere 6, 1295–1322.

Marzeion B., Champollion N., Haeberli W., Langley K., Leclercq P., Paul F., 2017. Observations-based estimates of global glacier mass change and its contribution to sea-level change. Surv. Geophys., 38, 105-130. DOI 10.1007/s10712-016-9394-y

Massonnet, F. Fichefet, T., Goosse, H., Bitz, C., Philippon-Berthier, G., Barriat, P., 2012. Constraining projections of summer Arctic sea ice, The Cryosphere 6, 1383-1394.

Massonnet, F., Pierre Mathiot, Thierry Fichefet, Hugues Goosse, Christof König Beatty, Martin Vancoppenolle, Thomas Lavergne, 2013. A model reconstruction of the Antarctic sea ice thickness and volume over 1980-2008 using data assimilation. Ocean Modelling 64, 67-75.

Medaugh I., Stolpe M.B., Fisher E.M., Knutti R., 2017. Reconciling controversies about the 'global warming hiatus'. Nature, 545, 41-47. Doi 10.1038/nature22315.

Meehl Gerald A., Arblaster Julie M., Fasullo John T., Hu A. and Trenberth Kevin E., 2011. Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. Nature Climate Change 1, 360–364.

Met Office, 2017. 2016: one of the two warmest years. http://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html

Morice, C.P., Kennedy, J.J., Rayner, N.A. and Jones, P.D., 2012. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, J. Geophys. Res. 117, D08101.

Neely III R. R., Toon O. B., Solomon S., Vernier J.-P., Alvarez C., English J. M., Rosenlof K. H., Mills M. J., Bardeen C. G., Daniel J. S., Thayer J. P., 2013. Recent anthropogenic increases in SO_2 from Asia have minimal impact on stratospheric aerosol. Geophysical research Letters 40 (5), 999–1004.

NSIDC, 2016a. Monthly sea-ice extent. ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/

NSIDC,2016b. Sea ice hits record lows. https://nsidc.org/arcticseaicenews/2016/12/arctic-and-antarctic-at-record-low-levels/

Overland, J. E. and Wang, M., 2013. When will the summer Arctic be nearly sea ice free? Geophysical Research Letters 40, 2097–2101.

Perovich D., Richter-Menge J., Polashenski Ch, Elder B., Arbetter t., Brennick O., 2014. Sea ice mass balance observations from the North Pole Environmental Observatory. Geophys Res. Lett., 41, 2019-2025, doi: 10.1002/2014GL059356.

PIOMAS, 2016. http://psc.apl.washington.edu/wordpress/wp-content/uploads/schweiger/ice_volume/PIOMAS.2sst.monthly.Current.v2.1.txt

Polashenski, C., Perovich, D. and Courville, Z., 2012. The mechanisms of sea ice melt pond formation and evolution. Journal of Geophysical Research 117, DOI: 10.1029/2011JC007231.

Purkey S.G., Johnson C.G. and Chambers Q.P., 2014. Relative contributions of ocean mass and deep steric changes to sea level rise between 1993 and 2013. J. Geophys. Res. Oceans, 119, 7509-7522. Doi:10.1002/2014JC010180.

Ridley D.A. et aL., 2014. Total volcanic stratospheric aerosol optical depths and implications for global climate change. Geophys. Res. Lett., 41, 7763-7769. Doi:10.1002/2014GL061541.

Rignot E., Velicogna I., van den Broeke M. R., Monaghan A., Lenaerts J. T. M., 2011. Acceleration of the contribution of the Greenland and Antarctic ice. Geophys. Res. Lett. 38, L05503.

Santer B.D., Bonfils C., Painter J.F., Zelinka M.D., Meras C., Solomon S., Schmidt G.A., Fyfe J.C., Cole J.N.S., Nazarenko L., Taylor K.E., Wentz F.J., 2014. Volcanic contribution to decadal changes intropospheric temperature. Nature Geoscience, 7, 185-189. Doi:10.1038/NGEO2098.

Schmidt, G. A., Shindell, D. T. and Tsigaridis, K., 2014. Reconciling warming trends. Nature Geosciences 7, 158–160.

Schröder David, Feltham Daniel L., Flocco Daniela, Tsamados Michel, 2014. September Arctic sea-ice minimum predicted by spring melt-pond fraction. Nature Climate Change, 4, 353–357.

Shepherd A, Ivins E.R., A G, Barletta V.R., Bentley M.J., Bettadpur S., Briggs K.H., Bromwich D.H., Forsberg R., Galin N., Horwath M., Jacobs S., Joughin I., King M.A., Lenaerts J.T., Li J., Ligtenberg S.R., Luckman A., Luthcke S.B., McMillan M., Meister R., Milne G., Mouginot J., Muir A., Nicolas J.P., Paden J., Payne A.J., Pritchard H., Rignot E., Rott H., Sørensen L.S., Scambos T.A., Scheuchl B., Schrama E.J., Smith B., Sundal A.V., van Angelen J.H., van de Berg W.J., van den Broeke M.R., Vaughan D.G., Velicogna I., Wahr J., Whitehouse P.L., Wingham D.J., Yi D., Young D., Zwally H.J., 2012. A reconciled estimate of ice-sheet mass balance. Science 38, 1183-1189.

Solomon, S., 2010. Contributions of stratospheric water vapor to decadal changes in the rate of global warming. Science 327, 11219–1223.

Stauning, P., 2014. Reduced solar activity disguises global temperature rise. Atmosphere and climate Sciences 4, 60–63.

Stocker Th. F., Qin Dahe, Plattner G-K., Tignor M. M. B., Allen S. K., Boschung J., Nauels A., Xia Yu, Bex V., Midgley P.M., 2013: Climate Change 2013, The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge, 2013.1533 p.

Tans, P. NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and R. Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/), (2014).

Trenberth, K. E. and Fasullo, J. T., 2013. An apparent hiatus in global warming? Earth's Future 1, 19–32.

Trenberth K.E., Fasullo J.T., Balmaseda M.A., 2014. Earth's energy imbalance. J. Clim. 27, 3129-3144.

Trenberth K.E., Fasullo J.T., von Schuckmann K., Cheng L., 2016. Highlights into Earth's energy imbalance from multiple sources. J. Clim., vol. 29, 7495-7505.

von Schuckmann K., Sallée J.-B., Chambers D., Le Traon P.-Y., Cabanes C., Gaillard F., Speich S., and Hamon M., 2014. Consistency of the current global ocean observing systems from an Argo perspective. Ocean Sci. 10, 547–557.

von Schuckmann K., Palmer M.D., Trenberth K.E., Cazenave A., Chambers D., Champollion N., Hansen J., Josey S.A., Loeb N., Mathieu P-P., Meyssignac B., Wild M., 2016. An imperative to monitor Earth's energy imbalance. Nature Climatic Change, vol. 6, 138-144.

WMO, WMO statement on the status of the global climate in 2014. WMO n°1152, World Meteorological Organization, Geneva, (2015).

Yan, X.-H., T. Boyer, K. Trenberth, T.R. Karl, S.-P. Xie, V. Nieves, K.-K. Tung and D. Roemmich (2016). The global warming hiatus: Slowdown or redistribution? , Earth's Future, 4, 472-482, doi:10.1002/2016EF000417

Zemp, Michael; Frey, Holger; Gärtner-Roer, Isabelle; Nussbaumer, Samuel U.; Hoelzle, Martin; Paul, Frank; Haeberli, Wilfried; Denzinger, Florian; Ahlstrøm, Andreas P.; Anderson, Brian; Bajracharya, Samjwal; Baroni, Carlo; Braun, Ludwig N.; Cáceres, Bolívar E.; Casassa, Gino; Cobos, Guillermo; Dávila, Luzmila R.; Delgado Granados, Hugo; Demuth, Michael N.; Espizua, Lydia; Fischer, Andrea; Fujita, Koji; Gadek, Bogdan; Ghazanfar, Ali; Hagen, Jon Ove; Holmlund, Per; Karimi, Neamat; Li, Zhongqin; Pelto, Mauri; Pitte, Pierre; Popovnin, Victor V.; Portocarrero, Cesar A.; Prinz, Rainer; Sangewar, Chandrashekhar V.; Severskiy, Igor; Sigurðsson, Oddur; Soruco, Alvaro; Usubaliev, Ryskul; Vincent, Christian, 2015. Historically unprecedented global glacier decline in the early 21st century. J. of Glaciology 61 (228), 745-762.

Zunz V., Goosse H., and Massonnet F., 2013. How does the internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? The Cryosphere, 7, 451-468. Doi: 10.5194/tc-7-451-2013.

Zygmuntowska M., Rampal P., Ivanova N., and Smedsrud L. H., 2014. Uncerainties in Arctic sea ice thickness and volume: new estimates and amplification for trends. The Cryosphere 8, 705-720.

Table 1. Different rates of warming (°C/decade) in the global annual mean surface temperature over the last 30 years. The HadCRUT4 data (Morice et al., 2012), Cowtan and Way (2014) and Karl et al. (2015) are used.

time interval	trend	s.e. trend	t ratio	time interval	trend	s.e. trend	t ratio	Slowdown (°C/decade)	s.e.	t ratio	significant level of slow down
1984-1998	0.266	0.072	3.7	**1998-2014**	0.062	0.039	1.6*	0.204	0.082	2.49	0.03
1984-2002	0.236	0.042	5.7	**2002-2014**	0.008	0.049	0.2**	0.228	0.065	3.53	0.005
1992-2001	0.328	0.117	2.8	**2002-2011**	-0.031	0.095	0.3**	0.359	0.151	2.38	0.05
1992-2001	0.340	0.106	3.2	**2002-2011x**	0.0396	0.134	0.3**	0.301	0.154	1.95	0.08
1992-2001	0.305	0.110	2.8	**2002-2011xx**	0.018	0.078	0.2**	0.288	0.138	2.08	0.07
1992-2001	0.325	0.110	2.9	**2002-2011xxx**	0.0086	0.089	0.1**	0.316	0.147	2.14	0.06

* trend different from 0 only at the 0.15 significant level.
** trend not significantly different from 0.
First 3 lines data from HadCRUT4
x data from Cowtan-Way (2014)
xx new data from Karl et al. (2015)
xxx mean of the three data sets
s.e.: standard error

Table 2. Decrease of the rate of warming between 1992-2001 and 2002-2011 and the consequences.

	HadCrut4	Cowtan-Way	Karl et al.	Mean of data sets
Rate of warming 2002-2011 (°C/yr)	-0.0031±0.0095	0.00396±0.0134	0.0018±0.0078	0.0009±0.009
Slowing down from 1992-2001 (°C/yr)	0.0359±0.015	0.0301±0.0154	0.0288±0.0138	0.0316±0.0147
Energy left (10^{19} J/yr)	18.4±7.7	15.4±7.7	14.8±7.1	16.2±7.5
Equivalent in ice melt (Gt/yr)	551±231	462±230	442±212	485±226
Equivalent in % of Accelerated ice melt (316 Gt/yr)	174	146	140	153
Energy for ice melt (10.5 10^{19} J/yr) in % of Energy left (%)	55	68	71	65

Table 3. Average ice loss and melt (Gt/yr) for the periods 1992-2001 and 2002-2011.

	Ice loss		Ice melt from atmosphere		
	1992-2001 Gt/yr	2002-2011 Gt/yr	% of ice loss	2002-2011 Gt/yr	(2002-2011)-(1992-2001) Gt/yr
Greenland (IPCC, 2013)	34±40	215±58	50	107±29	90±35
Antarctica (IPCC, 2013)	30±67	147±75	14	20±17	10±8
Glaciers (Rignot et al., 2011)	173±43	240±34	100	240±34	67±55
Sea ice Arctic (PIOMAS, 2016)	272±60	570±55	50	285±28	149±41
Total	509±107	1172±115		652±55	316±77
Energy for fusion (10^{19} J/yr)	17±3.5	39.1±3.8		21.7±1.8	10.5±2.5
Energy for fusion (Wm^{-2})	0.011	0.024		0.014	0.007
% of the Energy gained by the Earth (900 10^{19} J/yr)		4.34		2.40	1.17

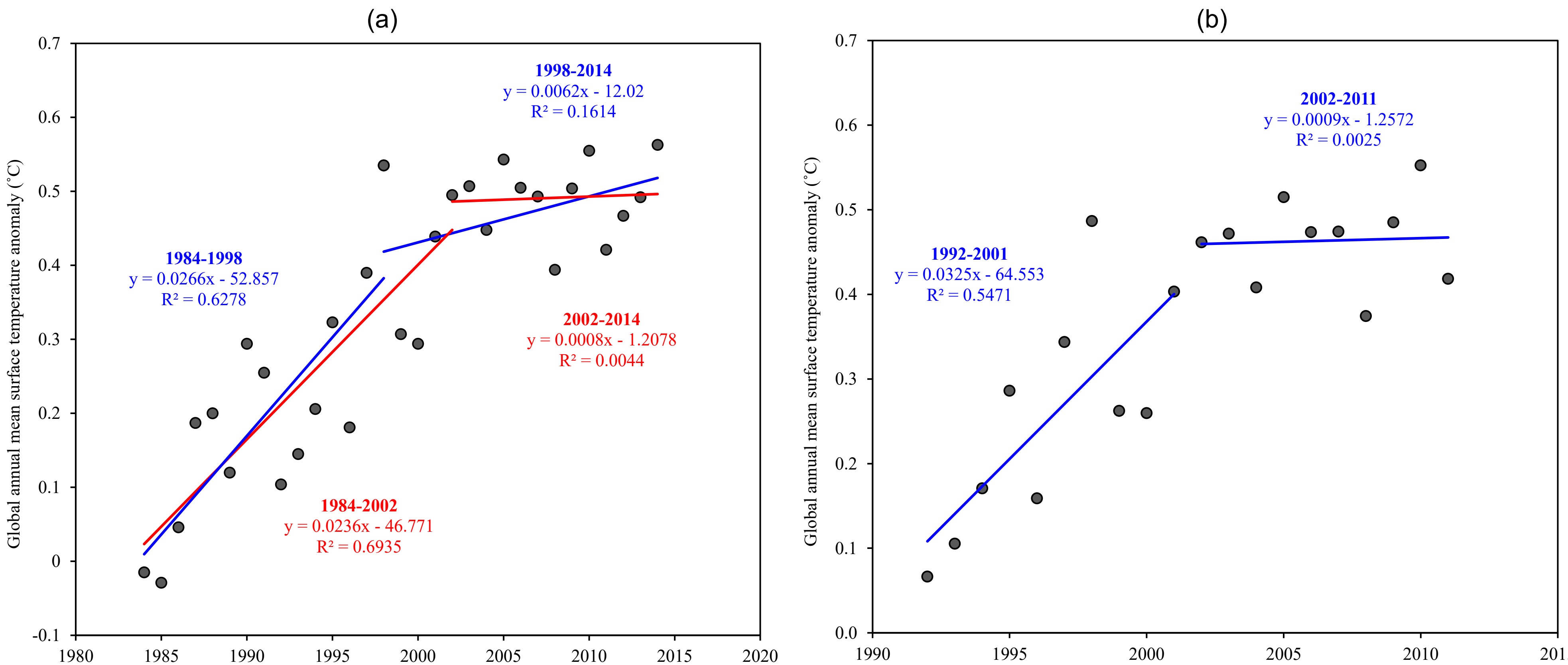
900 10^{19} J/yr = 0.56 Wm^{-2}

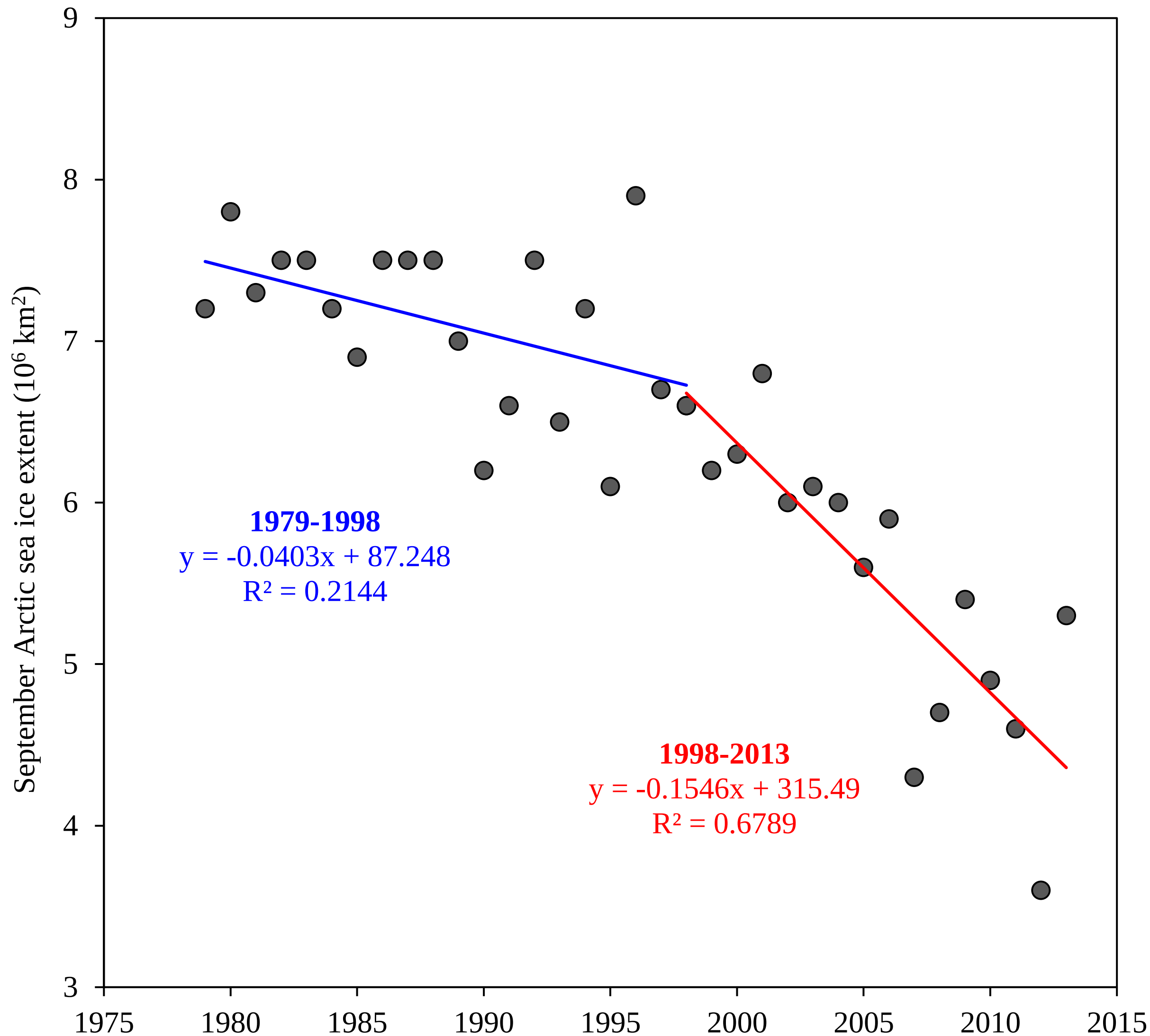
Figure Captions

Figure 1. Increase of global annual mean surface temperature (a) from 1984 to 2014 with respectively 1998 and 2002 as the turning point, the temperature anomalies being from HadCRUT4 (Morice et al., 2012); (b) from 1992 to 2001 and 2002 to 2011, the data being the Mean of HadCRUT4, Cowtan-Way and Karl et al. data sets. The linear regressions and explained variances are indicated.

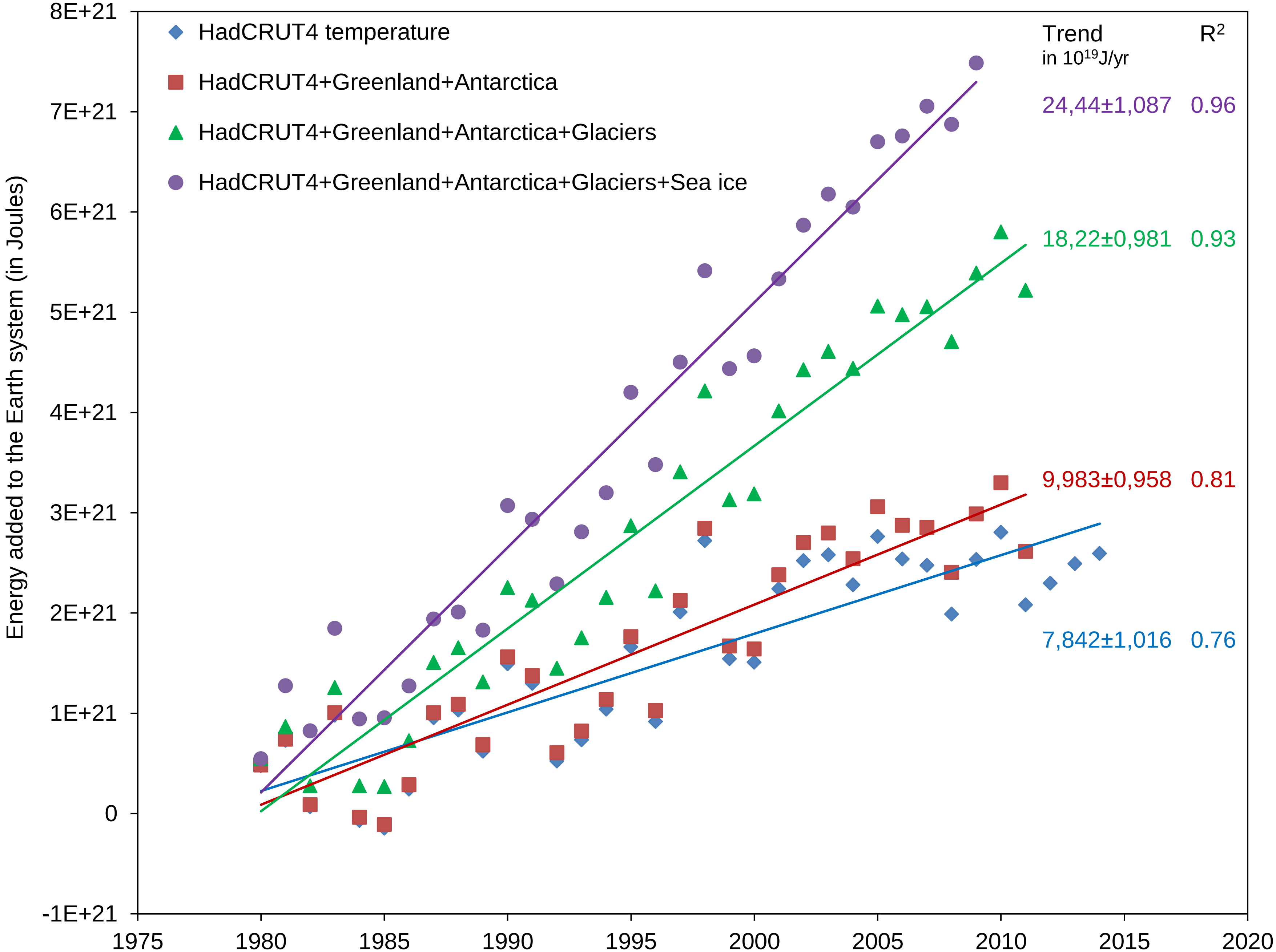
Figure 2. Decrease of September Arctic sea ice extent (Massonnet et al., 2012; Fetterer et al., 2014, NSIDC, 2016a) between 1979 and 1998 and between 1998 and 2013 with the corresponding linear regressions and the explained variances.

Figure 3. Energy added to the atmosphere and cryosphere since 1980. The energy for the atmosphere is calculated from the HadCRUT4 temperature data; the energy absorbed by the cryosphere is calculated from the loss of mass from Greenland, Antarctica, mountain glaciers and sea ice melting.


(a)
1998-2014
y = 0.0062x - 12.02
R² = 0.1614
1984-1998
y = 0.0266x - 52.857
R² = 0.6278
2002-2014
y = 0.0008x - 1.2078
R² = 0.0044
1984-2002
y = 0.0236x - 46.771
R² = 0.6935
Global annual mean surface temperature anomaly (°C)
(b)
2002-2011
y = 0.0009x - 1.2572
R² = 0.0025
1992-2001
y = 0.0325x - 64.553
R² = 0.5471
Global annual mean surface temperature anomaly (°C)



9
8
7
6
5
4
3
September Arctic sea ice extent (10⁶ km²)
1979-1998
y = -0.0403x + 87.248
R² = 0.2144
1998-2013
y = -0.1546x + 315.49
R² = 0.6789
1975
1980
1985
1990
1995
2000
2005
2010
2015



8E+21
7E+21
6E+21
5E+21
4E+21
3E+21
2E+21
1E+21
0
-1E+21
Energy added to the Earth system (in Joules)
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
HadCRUT4 temperature
HadCRUT4+Greenland+Antarctica
HadCRUT4+Greenland+Antarctica+Glaciers
HadCRUT4+Greenland+Antarctica+Glaciers+Sea ice
Trend
in 10^{19}J/yr
R^2
24,44±1,087 0.96
18,22±0,981 0.93
9,983±0,958 0.81
7,842±1,016 0.76