

Sea Temperature Change as an Indicator of Global Change

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1. INTRODUCTION: ROLE OF OCEAN, MECHANISMS AND CORRECTION OF BIAS

The oceans play the pivotal role in Earth's climate variability and as early as 1959 it was suggested that, due to their physical properties and volume, the heat content of oceans may dominate changes in the Earth's heat balance [1]. Data collected over the last 40 a suggest that 84% of the total heating of the Earth's systems has been due to warming of the oceans [2], their heat capacity being ~ 1000 times larger than the atmosphere [3]. Therefore, as Barnett et al. [2] stated, 'if one wished to understand and explain this warming, the oceans are clearly the place to look'. Understanding the variability, and long-term changes, in the Earth's climate therefore requires an estimation of the relative contribution of different parts of the Earth system to absorbing heat over the last 50 years [1]. Over this time period, the energy content of the oceans has increased by $\sim 14.2 \times 10^{22}$ J (Fig. 1, [3]) compared with $< 1 \times 10^{22}$ J for the atmosphere and land mass, with $\sim 57\%$ of this change occurring since 1993 [3]. Assimilation of heat into the oceans will, therefore, effectively be stemming the potential build-up of heat in the atmosphere.

Two main measures of temperature of the oceans have been employed to assess changes over time: sea surface temperature (SST), taken from the

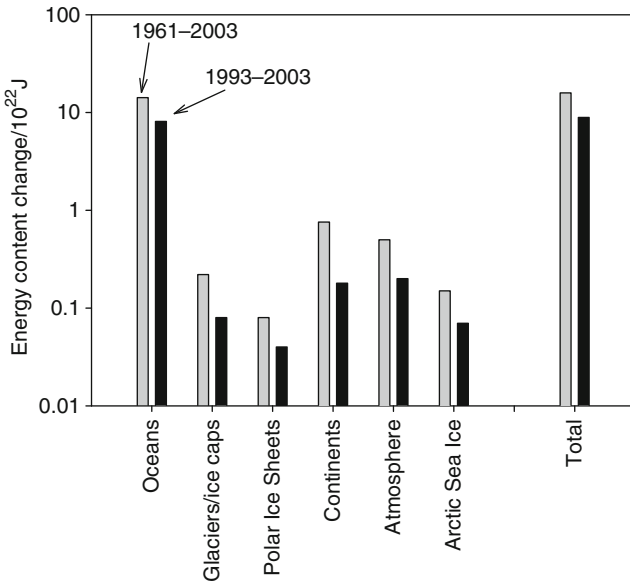


FIGURE 1 Energy content change across different parts of the Earth system. Light shaded bars are 1961–2003, dark bars 1993–2003. Data from Ref. [3] and papers therein. Values for the ocean are 14.2×10^{22} J for the 1961–2003 period and 8.11×10^{22} J for the period 1993–2003.

top few metres, and heat content, which integrates measurements from a larger depth of the water column (up to 3000 m). Traditionally, as it has been measured for decades, SST has been used as the main indicator of global ocean temperatures and thus has fed into overall trends in global surface warming. However, unlike the situation for temperature records on land, which have been relatively consistent and reliable due to a fixed network of measuring stations [4], the methodology utilised to record SST has varied over time and space [5]. Up until the 1970s, sea water temperature readings were made entirely from ships; after 1970 measurements were also taken using drifting buoys and, from the 1980s, satellites [4]. Primarily, therefore, the historical record of SST change has relied on ship-based measurement, but methods have varied over the years which affect the temperature recorded. For example, earlier in the SST time series (mainly pre-1940), temperatures were recorded from uninsulated buckets on the decks of vessels which tend to produce slightly colder temperatures due to the evaporative effect of a moving ship and standing in air [6]. A more subtle bias was introduced over time as ships generally got taller and faster and the cooling effect more enhanced [5]. After 1940, a greater proportion of temperature records were made using the ship's intake water; these records are more likely to be biased towards warmer temperatures [4]. Generally, global and regional SST values have been calculated by averaging all raw data records on the database

(e.g., International Comprehensive Ocean–Atmosphere Data Set, ICOADS [7]), so major bias problems in the record can arise when there have been temporal shifts in the main methodology, or certain practices have become dominant for a period of time. Over recent years, much effort has been targeted at correcting these biases [5,6,8–10], and thus constructing a more realistic picture of how SST have varied over the last 150 years. The result of these revisions has been to alter the original trends in raw SST data and thus alter our perception of how global ocean temperatures, and therefore overall global temperature patterns, have changed over the twentieth century.

Figure 2 displays the trends in the raw SST data (ICOADS), highlighting a cool period early in the twentieth century, followed by warming to a peak during the 1940s. Following this peak, temperatures tended to cool again, before rising from the late 1960s – the ‘familiar’ pattern of climate change during the twentieth century. The top trace in Fig. 2 displays SST values [9] corrected for the bias associated with the uninsulated buckets prior to 1941, the correction allowing parity with the mixed methods used after WW2. This has the effect of raising temperatures prior to 1941, although the warming trend up to 1945 is still apparent. Thompson et al. [9] have, however, noted a major

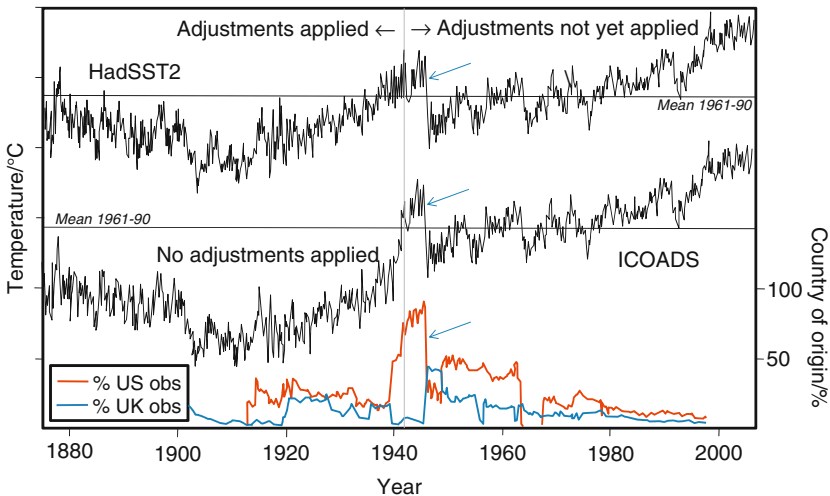


FIGURE 2 Detailed SST values since 1870s. Top, the global-mean SST time series corrected for ENSO fluctuations and pre-1941 methodological artefact (use of on-deck buckets). Middle, As in the top time series but for uncorrected data from ICOADS highlighting apparent cold period pre-1940 due to change in sampling method. Bottom, the percentage of observations which can be positively identified as coming from US (dark line) and UK (light line) ships. The vertical line denotes December 1941. All data sets show the clear discontinuity in 1945 (sharp drop in temperature) due to shift in sampling from US (engine intake) to UK (bucket) programmes. Left vertical axis shows temperature anomalies; tickmarks indicate steps of 0.5 °C. Right vertical axis shows percentage of observations. Figure redrawn with permission from Macmillan Publishers Ltd [Nature] from Thompson et al. [9].

discontinuity in the data in 1945, where temperatures cooled dramatically, resulting in peak temperatures during the early 1940s (Fig. 2, top). As would be expected, the number of SST measurements achieved plummeted during both world wars (see Fig. 1 in Ref. [4]); during WW2, around 80% of measurements were from ships of US origin, these vessels relying mainly on engine room intake measurements. Following 1945, the United Kingdom restarted their monitoring programme, but continued to use uninsulated buckets at this time; between 1945 and 1949 ~50% of observations are from the United Kingdom and only 30% of US origin [9] (Fig. 2, bottom). Therefore, the WW2 records were dominated by a methodology that was warm biased and the sudden drop in SST during 1945 is consistent with an uncorrected change from engine room to bucket measurements [9] rather than the early 1940s being exceptionally warm, but this feature of the record persists in all patterns of twentieth century climate that include SST data. It is interesting to note that this early 1940s warm period, due to the dominance of warm biased engine room data, was the only one to lie above the Intergovernmental Panel on Climate Change (IPCC's) model predictions [11] and was not apparent when only land measurements were utilised. Current reassessment of the data is underway to correct for these biases, but it is likely that the 1942–1945 records will be corrected downwards by perhaps 0.3 °C [4] whilst upwards adjustment to the data immediately after 1945 and, to a lesser extent, up to the 1960s is also necessary [9]. A further adjustment may be necessary since 2001 to accommodate a shift from ship-based to buoy-based SST measurement as the latter tend to be cool-biased (~0.1 °C). This could increase the century long trends by raising recent SST values [9]. The Met Office Hadley Centre (United Kingdom) is currently assessing adjustments to the dataset to accommodate this range of bias corrections [9]. Overall, this will not change the general pattern of increased warming through the twentieth century, in particular the last three decades, but it is more likely to smooth, or even remove, the current peak in 1940s temperatures.

Corrections have been applied to more recent data, however, to account for biases due to the method of temperature measurement, in this case data on heat content of the ocean [8,12], allowing improved estimates of oceanic warming. Data for the upper-ocean since 1950 have been obtained using a range of methods [12], such as reversing thermometers (whole period), expendable bathythermographs (XBTs since the 1960s), conductivity-temperature-depth probes from ships (since 1980s) and, since 2001, Argo floats. The biggest differential between these methods is between XBTs and CTDs [8], with XBTs having a warm bias of 0.2–0.4 °C; XBTs comprise the largest proportion of the dataset. Rates for the 1990s in particular have a positive bias due to instrumental errors [12], so adjusted temperatures to account for the range of these recent biases has resulted in a heat-content trend showing a continual upwards progression since the 1950s (Fig. 3). Domingues et al. [12] suggest that actual ocean warming

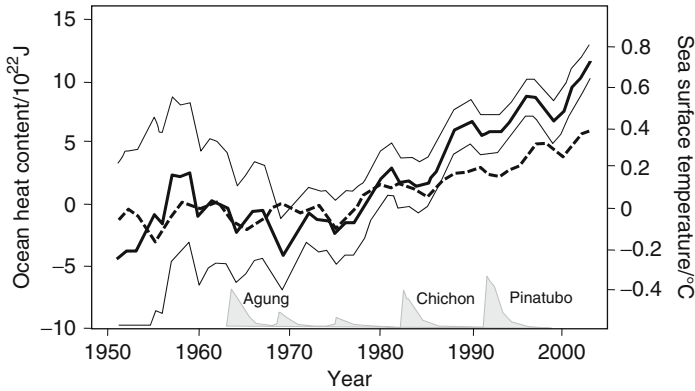


FIGURE 3 Improved estimates of upper-ocean warming since 1950 as presented by Domingues et al. [12] and redrawn from that source with permission from Macmillan Publishers Ltd [Nature]. Thick black line is upper-ocean heat content (thin lines 1SD) following application of recent methodological corrections (see text). Broken line is sea surface temperature. All time series were smoothed with a three-year running average and are relative to 1961.

trends from 1950 to 2003 are 50% larger than earlier estimates, but the 1993–2003 trend is about 40% smaller (so will impact Fig. 1). It is notable (Fig. 3) that the ocean heat content warming trend for the upper 700 m is increasing faster than the equivalent for SST.

2. LONG-TERM TRENDS IN SEA TEMPERATURE: THE HISTORICAL CONTEXT

A variety of proxies enables the reconstruction of ocean temperatures through geological time and thus assessment of global climate trends. In particular, the oxygen isotope ratio ($\delta^{18}\text{O}$) of calcite depends on the ambient water temperature from which it has been precipitated [13], so analysing the shells of fossil calcareous planktonic organisms (such as Foraminifera and coccolithophores) allows estimation of past surface ocean temperatures. For much of earth's long-term history, the oceans (and the global climate) have been warmer than today [14] and have been gradually declining at the millions-of-years scale since the Cretaceous [15]. This is particularly marked for the deep-ocean which has seen a general near-linear drop in temperature of at least 12 °C over the last 70 Ma [16]. Over the last 5 Ma, a general downwards trend has also been apparent ([17], Fig. 4, top) from a warm Pliocene [18], although there has been increased variability with time due to the Milankovitch cycles and onset of ice ages ~ 2.75 Ma ago; recent inter-glacial temperature peaks almost match the warm temperatures evident >3 Ma ago (Fig. 4, top).

The current interglacial, however, shows little sign of receding (Fig. 4, middle): despite an apparent original peak 8200 a ago [19], temperatures have recently increased again with the average SSTs for 2001–2005 being amongst the highest during the last 1.4 Ma (Fig. 4, middle; [20]).

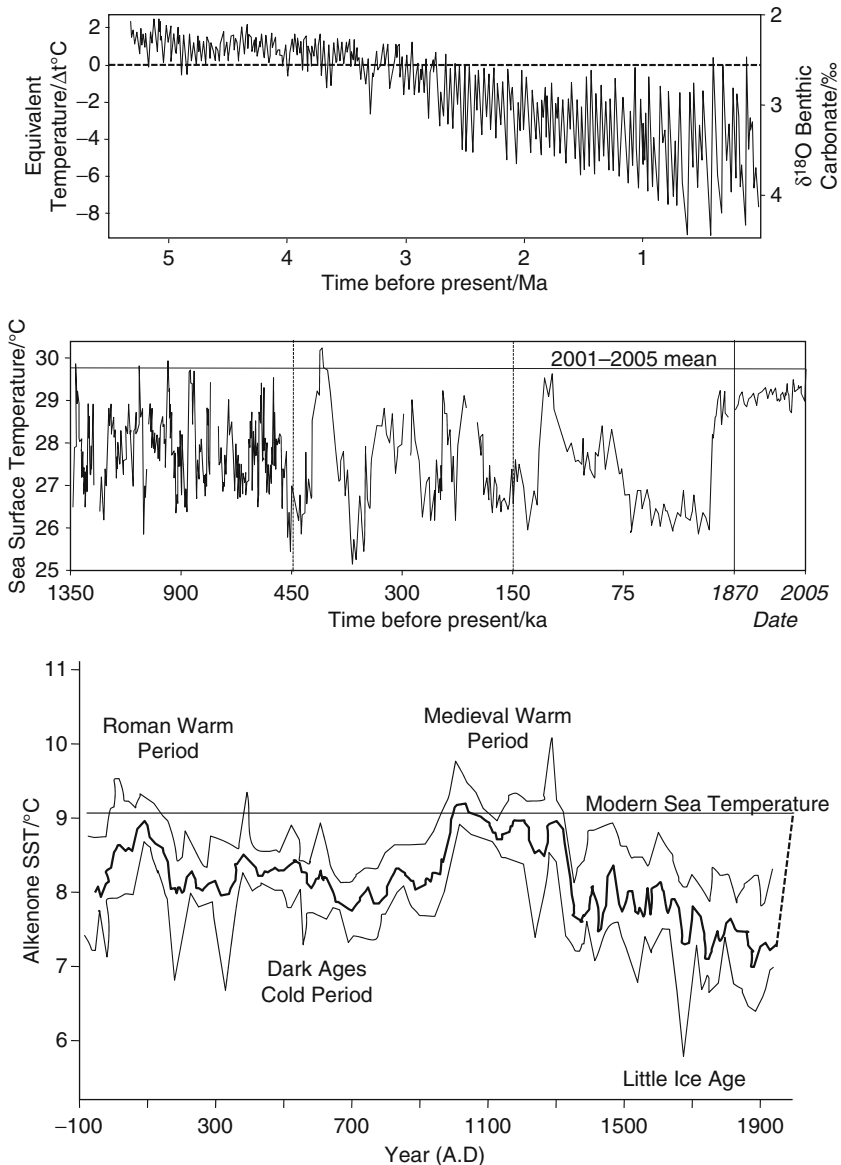


FIGURE 4 Top, climate record of Lisiecki and Raymo [17] constructed by combining measurements from 57 globally distributed deep sea sediment cores. Original figure by Robert A. Rohde of Global Warming Art from published data (http://www.globalwarmingart.com/wiki/Image:Five_Myr_Climate_Change_Rev.png). Middle, modern sea surface temperatures in the Western Equatorial Pacific compared with paleoclimate proxy data. Modern data are the 5-a running mean, while the paleoclimate data have a resolution of the order of 1000 a. Figure redrawn from Hansen et al. [20], copyright (2006) National Academy of Sciences, U.S.A. Bottom. Alkenone data from sediment cores off Iceland reconstructing temperatures over last 2000 a. Solid line is 10 point running mean, thin lines indicate range of temperature data. Redrawn from Sicre et al. [23] with permission from Elsevier.

Variations away from this overall pattern are evident, however, with the western tropical Pacific appearing to have generally cooled by $\sim 0.5^{\circ}\text{C}$ over the last 10 000 a [21]. Ocean temperature trends have also been reconstructed for the last 2000 a using techniques such as Mg/Ca ratios in sediment cores [22] and alkenone biomarkers from the coccolithophore *Emiliana huxleyi* [23], providing more detail on the historical context of recent trends. Most data sets demonstrate a trend of a medieval warm period around 900–1300 and a general decrease in ocean temperatures from this point in time [24] which has been markedly reversed over the last century. Chesapeake Bay records suggest anomalous recent behaviour of the climate system over a 2000 a record [22], this modern increase in temperature being much more recent (but equally marked) in records off Iceland [23] where previously ocean temperatures had been steadily falling since 1300 (Fig. 4, bottom); modern records are an equivalent temperature to the medieval warm period.

3. GLOBAL AND REGIONAL PATTERNS OF SEA TEMPERATURE OVER THE LAST 100–150 YEARS

Global trends in sea temperature since the late nineteenth century can be split into several clear periods (Fig. 2), although the magnitude and clarity of some of the decadal trends have been partly due to the sampling artefacts discussed in Section 1 [5,6,8,9,12]. The early twentieth century generally witnessed a trend of cooling SSTs to around 1910 that has now primarily been attributed to the lasting impact of aerosols from major volcanic eruptions such as Krakatoa (1883) and Santa Maria (1902) ([4,9,25,26]; see Chapter 4), with the volcanic cooling signature clearly visible in subsurface ocean temperatures into the middle part of the twentieth century [27]. Individual volcanic eruptions have resulted in several discontinuities within the ocean temperature record over the twentieth century [4,9], particularly the eruption of Mt. Pinatubo in 1991 ([25]; Fig. 3); in simulations, recovery of temperatures from this eruption was not complete by 2000, depressing the underlying warming trend [25].

Two distinct warming periods have been evident during the twentieth century [28]: the recovery of depressed temperatures from the 1920s to the 1940s and the pronounced warming from 1978 till the present. The first phase has been exaggerated over time due to the problems with the warm-biased SSTs obtained during the 1940s and cold-biased records prior to 1941 [9], although there is also evidence of increasing human-induced radiative forcing due to greenhouse gases and a particularly large realisation of the decadal ocean-climatic variability during this time [28]. These records, plus the major discontinuity in SSTs in 1945 discussed earlier [9], will also dampen the cooling trend apparent in uncorrected data from 1945 to 1970 (Fig. 2). It is, therefore, most likely that finally corrected global SST records will

demonstrate an overall gradual warming from 1920s to 1970s, followed by the modern period of accelerated warming. This last 30 a period has also seen some variability in ocean temperatures, particularly a levelling off of the warming trend since 1998 [29; Fig. 2]. In addition to required methodological adjustments for the 1990s detailed earlier [12], this trend is most likely a function of the behaviour of the El Niño Southern Oscillation (ENSO) cycle, which has a major controlling influence over the world's climate [30]; the 1997–1998 'super' El Niño part of the cycle was the most extreme on record [30] and lifted temperatures 0.2°C above the trend line [20]. The Pacific ENSO cycle more recently (late 2000s) has moved into the cooling La Niña phase, but during 2005 near-record temperatures were also recorded without the boost from El Niño [20]. Throughout the ocean temperature record, ENSO has resulted in fluctuations around any warming trend and so can be corrected for in simulations to understand the underlying trend [9]. The most modern improved estimates of ocean warming smooth out the effect of ENSO and adjust for methodological biases [12], resulting in a clear, continued upwards trend in global temperatures since 1950 (Fig. 3), with no underlying evidence of long-term cooling since 1998 [29].

Global trends in ocean temperatures have not been consistent across all seas, however. Whilst most records do demonstrate upwards trajectories in temperature comparable with the global trend [5,26], northern hemisphere seas have warmed more since 1850 than those in the southern hemisphere [5]. Decadally filtered differences in SST for the Northern Hemisphere are $0.71^{\circ}\text{C} \pm 0.06$; for the Southern Hemisphere warming has been on average $0.64^{\circ}\text{C} \pm 0.07$ [5]. Such a warming trend differential is even more marked for the Arctic, where the ice–ocean system has been warming faster than the global average since 1966 [31]. A clear global anomaly in terms of SST (together with part of the North Pacific and south of Greenland [32]) is the east equatorial Pacific region where ENSO events originate and are most marked. Here long-term trends have only shown modest upwards trends in SST [5], if any [10], since 1870, due primarily to increased trade-winds and upwelling [32], but this has resulted in another trend in ocean temperatures with major global consequences. Over the course of the twentieth century, there has been an increase in the temperature gradient across the equatorial Pacific [32], the build up of such a temperature gradient being generally a precursor of El Niño events [30]. Hansen et al. [20] suggested this trend will increase the likelihood of strong El Niños. There is evidence that El Niño events are becoming more frequent and severe over recent decades [33,34], resulting in increased variability (and thus more extreme peaks) in SST in the east Pacific region [34] and thus affecting the world's climate and ocean temperatures. Such Pacific temperature distributions may have been apparent during the warm Pliocene which had a permanent El Niño-like climate: paleoceanographic data suggest Pacific SST distribution pre-Ice Ages most resembled that of the 1997–1998 El Niño [35].

4. CONCLUSION: ANTHROPOGENIC INFLUENCE

In summary, the oceans have been warming over the last century, with the latest most accurate adjusted data [5,8,9,12] that has accounted for methodological artefacts (e.g., the 1940s) suggesting this trend has been more consistent and continuous than previously thought, with a particularly marked increase in sea temperatures since the 1970s (Figs. 2 and 3). Debate about the causes of global warming has been discussed in earlier chapters (e.g., Chapters 1–6), but for the oceans there is clear evidence of an anthropogenic signal in the pattern of warming over the last 40 years [2,36]. The penetration of this human-induced warming is evident across the top 700 m and apparent in all oceans, but the signal is complex and varies widely by ocean [2]. Figure 5 displays examples of the change in sea temperature at depth since 1960 for northern parts of the three major oceans (see [2] for full set of data) and illustrates how warming at depth has varied. The North Atlantic demonstrates a strong warming pattern down to 700 m, with an increase in the rate of change from depth to the surface. However, warming in the Pacific and Indian oceans is more confined to the upper 100 m, with the North Pacific in particular actually demonstrating cooling at depth (Fig. 5, right panel). Deep convection is characteristic of the Atlantic, whereas in the Pacific the shallow meridional overturning circulation isolates the surface layer and thus confines the signal to the upper ocean [2]. In order to assess cause of the warming trend, Barnett et al. [2] have modelled the warming effect of all natural internal variability; the grey polygons in Fig. 5 display the 90% confidence limits of this natural signal strength. As can be seen, observed warming patterns bear little resemblance to what would be expected from warming due to internal variability. Observed warming also bears no resemblance to a signal forced by solar and volcanic variability (Fig. 5, open circles), but does fit closely to modelled anthropogenic forcing signal strength [2]. Evidence compiled over recent years [2,36,37], therefore, strongly demonstrates a human-induced warming signal in the ocean temperature record.

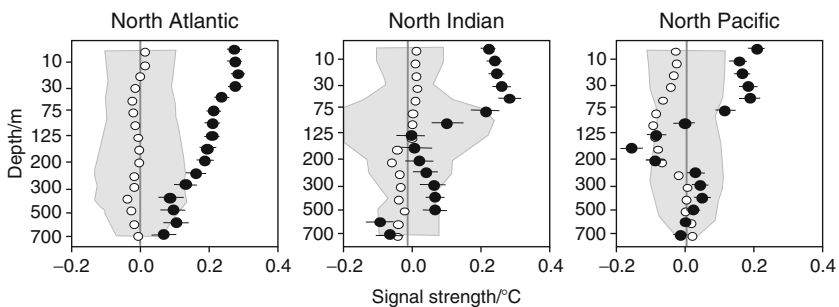


FIGURE 5 Warming signal strength since 1960 by ocean and depth (black circles, $\pm 2SD$). Grey polygons reflect the 90% probability distribution of warming signals associated with internal variability. Open circles are the warming signal forced by solar and volcanic variability. Figure redrawn from Barnett et al. [2], reprinted with permission from AAAS.

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