Temperature

Global Warming Science, EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/
Global-mean surface warming

**Figure 2.20** | Annual global mean surface temperature (GMST) anomalies relative to a 1961–1990 climatology from the latest version of the three combined land-surface air temperature (LSAT) and sea surface temperature (SST) data sets (HadCRUT4, GISS and NCDC MLOST). Published data set uncertainties are not included for reasons discussed in Box 2.1.
Main issues for today

- Polar amplification
Main issues for today

- Polar amplification
- “Hiatus” periods
Main issues for today

- Polar amplification
- “Hiatus” periods
- Equilibrium climate sensitivity
Main issues for today

- Polar amplification
- “Hiatus” periods
- Equilibrium climate sensitivity
- Delaying effect of ocean heat capacity (transient sensitivity)
Main issues for today

- Polar amplification
- “Hiatus” periods
- Equilibrium climate sensitivity
- Delaying effect of ocean heat capacity (transient sensitivity)
- Stratospheric cooling
Figure 2.14 | Global annual average land-surface air temperature (LSAT) anomalies relative to a 1961–1990 climatology from the latest versions of four different data sets (Berkeley, CRUTEM, GHCN and GISS).
Sea-surface warming

**Figure 2.18** | Global annual average sea surface temperature (SST) and Night Marine Air Temperature (NMAT) relative to a 1961–1990 climatology from state of the art data sets. Spatially interpolated products are shown by solid lines; non-interpolated products by dashed lines.
Figure 2.19 | Decadal global mean surface temperature (GMST) anomalies (white vertical lines in grey blocks) and their uncertainties (90% confidence intervals as grey blocks) based upon the land-surface air temperature (LSAT) and sea surface temperature (SST) combined HadCRUT4 (v4.1.1.0) ensemble (Morice et al., 2012). Anomalies are relative to a 1961–1990 climatology. 1850s indicates the period 1850-1859, and so on. NCDC MLOST and GISS data set best-estimates are also shown.
Workshop 1 a, b, c
characterizing the warming in space and time, historical and future projections
Surface warming 1901-2012

**Figure 2.21** | Trends in surface temperature from the three data sets of Figure 2.20 for 1901–2012. White areas indicate incomplete or missing data. Trends have been calculated only for those grid boxes with greater than 70% complete records and more than 20% data availability in first and last decile of the period. Black plus signs (+) indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90% confidence interval). Differences in coverage primarily reflect the degree of interpolation to account for data void regions undertaken by the data set providers ranging from none beyond grid box averaging (HadCRUT4) to substantial (GISS). Differences in coverage primarily reflect the degree of interpolation to account for data void regions undertaken by the data set providers ranging from none beyond grid box averaging (HadCRUT4) to substantial (GISS).

(IPCC AR5, 2013)
global warming hiatus
global warming hiatus

global warming hiatus

Is the government tinkering with global warming data?

The hottest topic in climate research is the observation that global average surface temperature, as well as satellite observations of temperatures in the atmosphere, has shown little or no warming during the 21st century.

Is the government tinkering with global warming data?

The hottest topic in climate research is the observation that global average surface temperature, as well as satellite observations of temperatures in the atmosphere, has shown little or no warming during the 21st century.

Warming trend per decade: Hiatus during 1950-1980

**Figure 2.22** Trends in surface temperature from NCDC MLOST for three non-consecutive shorter periods (1911–1940; 1951–1980; 1981–2012). White areas indicate incomplete or missing data. Trends and significance have been calculated as in Figure 2.21.
workshop 2
global warming “hiatus” periods
global warming hiatus

By Fjalnes - wikipedia

“Hiatuses”

Global Average Temperature

By Fjalnes - wikipedia

Global Warming Science 101, Temperature, Eli Tziperman
global warming hiatus

By Fjalnes - wikipedia

Global Average Temperature

"Hiatuses"
global warming hiatus

By Fjalnes - wikipedia

Global Average Temperature

- Annual mean
- Five-year smoothing

“Hiatuses”

wikipedia
global warming hiatus: a presidential perspective

Variations of the Earth's surface temperature for:

(a) the past 140 years

(b) the past 1000 years

Data from thermometers (red) and from tree rings, corals, ice cores and historical records (blue).
global warming hiatus: a presidential perspective

Variations of the Earth's surface temperature for:

(a) the past 140 years

(b) the past 1000 years

Data from thermometers (red) and from tree rings, corals, ice cores and historical records (blue).
The President
The White House
Washington, D.C.

Dear Mr. President:

Aware of your deep concern with the future of the world, we feel obliged to inform you on the results of the scientific conference held here recently. The conference dealt with the past and future changes of climate and was attended by 42 top American and European investigators. We enclose the summary report published in Science and further publications are forthcoming in Quaternary Research.

The main conclusion of the meeting was that a global deterioration of climate, by order of magnitude larger than any hitherto experienced by civilized mankind, is a very real possibility and indeed may be due very soon. The cooling has natural cause and falls within the rank of processes which produced the last ice age. This is a surprising result based largely on recent studies of deep sea sediments.
Dear Mr. President:

Aware of your deep concern with the future of the world, we feel obliged to inform you on the results of the scientific conference held here recently. The conference dealt with the past and future changes of climate and was attended by 42 top American and European investigators. We enclose the summary report published in Science and further publications are forthcoming in Quaternary Research.

The main conclusion of the meeting was that a global deterioration of climate, by order of magnitude larger than any hitherto experienced by civilized mankind, is a very real possibility and indeed may be due very soon. The cooling has natural cause and falls within the rank of processes which produced the last ice age. This is a surprising result based largely on recent studies of deep sea sediments.

Existing data still do not allow forecast of the precise timing of the predicted development, nor the assessment of the man's interference with the natural trends. It could not be excluded however that the cooling now under way in the Northern Hemisphere is the start of the expected shift. The present rate of the cooling seems fast enough to bring glacial temperatures in about a century, if continuing at the present pace.
global warming hiatus

December 3, 1972

Dear Mr. President:

Aware of your deep concern with the future of the world, we feel obliged to inform you on the results of the scientific conference held here recently. The conference dealt with the past and future changes of climate and was attended by 42 top American and European investigators. We enclose the summary report published in Science and further publications are forthcoming in Quaternary Research.

The main conclusion of the meeting was that a global deterioration of climate, by order of magnitude larger than any hitherto experienced by civilized mankind, is a very real possibility and indeed may be due very soon. The cooling has natural cause and falls within the range of processes which produced the last ice age. This is a surprising result based largely on recent studies of deep sea sediments.

Existing data still do not allow forecast of the precise timing of the predicted development, nor the assessment of the man's interference with the natural trends. It could not be excluded however that the cooling now under way in the Northern Hemisphere is the start of the expected shift. The present rate of the cooling seems fast enough to bring glacial temperatures in about a century, if continuing at the present pace.

The practical consequences which might be brought by such developments to existing social institutions are among others:

1) Substantially lowered food production due to the shorter growing seasons and changed rain distribution in the main grain producing belts of the world, with Eastern Europe and Central Asia to be first affected.

2) Increased frequency and amplitude of extreme weather anomalies such as those bringing floods, snowstorms, killing frosts etc.
global warming hiatus

Mr. President

- 2 -

December 3, 1972

With the efficient help of the world leaders, the research could be effectively organized and could possibly find the answers to the menace. We hope that your Administration will take decisive steps in this direction as it did with other serious international problems in the past. Meantime however it seems reasonable to prepare the agriculture and industry for possible alternatives and to form reserves.
Mr. President

December 3, 1972

With the efficient help of the world leaders, the research could be effectively organized and could possibly find the answers to the menace. We hope that your Administration will take decisive steps in this direction as it did with other serious international problems in the past. Meantime however it seems reasonable to prepare the agriculture and industry for possible alternatives and to form reserves.

It might also be useful for Administration to take into account that the Soviet Union, with large scientific teams monitoring the climate change in Arctic and Siberia, may already be considering these aspects in its international moves.

With best regards,
The ocean is absorbing all that heat, what would have happened otherwise?
The ocean is absorbing all that heat, what would have happened otherwise?

Oceans Are Absorbing Almost All of the Globe’s Excess Heat

Heat Accumulates in the Oceans: “Since 1955, more than 90 percent of the excess heat retained by the Earth as a result of increased greenhouse gases has been absorbed by the oceans, leaving ocean scientists … at the National Oceanic and Atmospheric Administration feeling that 90 percent of the climate change story is being ignored.”
The ocean is absorbing all that heat, what would have happened otherwise?

Marine Species Are at Risk
Warmer temperatures are threatening some marine animal and plant species, like these bleached coral on the Great Barrier Reef. Scientists also predict that some birds, like the black-legged kittiwakes in Norway, may soon die off in warmer waters.

Habitats Are Changing
The warmer conditions have allowed some jellyfish, like the comb jellyfish, pictured above, in Narragansett Bay, to have longer seasons. Others have expanded their territory. In some cases, United States fisheries have shifted north to cooler waters.
notes section 3.1.1
Equilibrium climate sensitivity
Observations since 1970 suggest strong bottom water warming did not occur until about 1991. Conditions induced by the 1970s Weddell Sea Polynya likely contributed to the warming. Global scale abyssal warming on relatively short multi-decadal time scales, such as the period from 1992 to 2005, is evident towards the north (Figure 3.3b), where the AABW influence weakens. The warming is particularly in recently formed Antarctic Bottom Water (AABW). South of the Sub-Antarctic Front (Figure 3.3b), much of the water column warmed from 1992 to 2005, especially in the upper 75 m, decreasing to about 0.015°C per decade between 1992 and 2005.

Below 700 m data coverage is too sparse to produce annual global heat content trends, but there is evidence of continuous warming below 3000 m from about 1992–2005. Based on the limited information available, it is likely that the global ocean heat content trend from 1957 to 2009 continues unabated since 2003 (Figure 3.2b); as a result, ocean heat content from 0 to 2000 m shows less slowing after 2003 than does 0 to 1500 m the global ocean warmed from 1955–2010 and 0 to 1500 m the global ocean warmed at a rate of 0.02°C per decade (IPCC AR5, 2013).

Conclusions 2.4.2) from satellites and subsurface temperature measurements described here; (2) SST data that the surface intensification of the warming is concurrent with a slowing of the increase global mean surface temperature, as discussed in Box 9.2, this is also a time period when the deep North Atlantic north of 20°N from 2000 m to the ocean floor increased slightly greater than zero from 3000 m to 700 m heat content that is about 30% of that for 0 to 2000 m over the length of the record. 

Below 3000 m, the warming rate is 0.11 [0.09 to 0.13]°C per decade (Figures 3.2b and 3.3a; Kouketsu et al., 2010). Globally, deep ocean temperature increases are virtually certain with strong warming in the Southern Ocean.

Figures 3.3 | (a) Areal mean warming rates (°C per decade) versus depth (thick lines) with 5 to 95% confidence limits (shading), both global (orange) and south of the Sub-Antarctic Front (purple), centred on 1992–2005. Stippled basin warming rates are not significantly different from zero at 95% confidence. The positions of the Sub-Antarctic Front (purple line) and the repeat oceanographic transects from which these warming rates are estimated (thick black lines) also shown. (Data from Purkey and Johnson, 2010.)

(b) Mean warming rates (°C per decade) below 4000 m (colour bar) estimated for deep ocean basins (thin black outline lines), centered on 1992–2005. Stippled basin warming rates are not significantly different from zero at 95% confidence. (IPCC AR5, 2013)
Ocean heat uptake pathways. The ocean is stratified, with the coldest, densest water in the deep ocean (upper panels: use map at top for orientation). Cold Antarctic Bottom Water (dark blue) sinks around Antarctica then spreads northward along the ocean floor into the central Pacific (upper left panel: red arrows fading to white indicate stronger warming of the bottom water most recently in contact with the ocean surface) and western Atlantic oceans (upper right panel), as well as the Indian Ocean (not shown). Less cold, hence lighter, North Atlantic Deep Water (lighter blue) sinks in the northern North Atlantic Ocean (upper right panel: red and blue arrow in the deep water indicates decadal warming and cooling), then spreads south above the Antarctic Bottom Water. Similarly, in the upper ocean (lower left panel shows Pacific Ocean detail, lower right panel the Atlantic), cool Intermediate Waters (cyan) sink in sub-polar regions (red arrows fading to white indicating warming with time), before spreading toward the equator under warmer Subtropical Waters (green), which in turn sink (red arrows fading to white indicate stronger warming of the intermediate and subtropical waters most recently in contact with the surface) and spread toward the equator under tropical waters, the warmest and lightest (orange) in all three oceans. Excess heat or cold entering at the ocean surface (top curvy red arrows) also mixes slowly downward (sub-surface wavy red arrows).
workshop problem 3
Estimating equilibrium climate sensitivity
notes section 3.1.2
Transient climate sensitivity
workshop problem 4
Transient climate sensitivity: role of ocean depth
Polar amplification
Figure 1 | Arctic amplification in CMIP5 models. a, Zonal mean surface temperature change for the last 30 years of the CMIP5 $4 \times CO_2$ experiment compared with the last 30 years of the control run. Box and whisker plots show the median (lines), 25th to 75th percentiles (boxes) and full spread (whiskers) of temperature change averaged over the tropics ($30^\circ S–30^\circ N$) and the Arctic ($60^\circ N–90^\circ N$). b, Bars show the intermodel mean warming for different seasons. Intermodel mean warming is 11.2 K in the Arctic and 4.3 K in the tropics. Arctic warming is strongest in winter (15.9 K) and weakest in summer (6.5 K). March–May, MAM; September–November, SON.
Figure 1 | Arctic amplification in CMIP5 models. a, Zonal mean surface temperature change for the last 30 years of the CMIP5 4 × CO2 experiment compared with the last 30 years of the control run. Box and whisker plots show the median (lines), 25th to 75th percentiles (boxes) and full spread (whiskers) of temperature change averaged over the tropics (30° S–30° N) and the Arctic (60° N–90° N). b, Bars show the intermodel mean warming for different seasons. Intermodel mean warming is 11.2 K in the Arctic and 4.3 K in the tropics. Arctic warming is strongest in winter (15.9 K) and weakest in summer (6.5 K). March–May, MAM; September–November, SON.
notes section 3.2
Polar amplification
(use next slides)
Arctic amplification & tropical lapse-rate feedback

[Pithan & Mauritsen 2014]: In tropics, greater warming in the upper troposphere than at surface $\Rightarrow$ Smaller increase in $T_{\text{surface}}$ required to balance CO$_2$ radiative forcing at Top Of Atmosphere (TOA) $\Rightarrow$ weaker surface warming response to CO$_2$. 

![Graph showing temperature profiles and difference](image-url)
Arctic amplification & lapse-rate “feedback”

[Pithan & Mauritsen 2014]: In tropics, greater warming in the upper troposphere than at surface → Smaller increase in $T_{\text{surface}}$ required to balance CO$_2$ radiative forcing at Top Of Atmosphere (TOA) → weaker surface warming response to CO$_2$.

---

**Arctic**

**Tropics**

Present:

- Increased CO$_2$:
  - TOA warming needed to balance $\Delta$CO$_2$
Arctic amplification & lapse-rate “feedback”

[Pithan & Mauritsen 2014]: In tropics, greater warming in the upper troposphere than at surface \( \rightarrow \) Smaller increase in \( T_{\text{surface}} \) required to balance CO\(_2\) radiative forcing at Top Of Atmosphere (TOA) \( \rightarrow \) weaker surface warming response to CO\(_2\).

\[ \rightarrow \text{Lapse-rate “feedback” is negative in tropics & positive in Arctic: same TOA warming leads to larger surface warming in Arctic} \]
workshop 5 a (leave b, c for HW)
Polar amplification
notes section 3.4
Stratospheric cooling
(use next slides)
The troposphere is warming, the stratosphere is cooling

(IPCC AR5, 2013)

**Figure 2.24** Global annual average lower stratospheric (top) and lower tropospheric (bottom) temperature anomalies relative to a 1981–2010 climatology from different data sets. STAR does not produce a lower tropospheric temperature product. Note that the y-axis resolution differs between the two panels.
The distinguishing element of the stratosphere is its warming as function of altitude, as opposed to the cooling as function of altitude in the troposphere (right panel of Fig. 3.8). This is a result of absorption of SW radiation by the ozone layer in the stratosphere. Thus, unlike the troposphere whose main source of radiative heating is LW from the surface, the stratosphere is also heated by absorbed SW radiation, and this leads to its very different response to the increase in CO\textsubscript{2} concentration. The left panel of Fig. 3.9 shows the zonally averaged warming in an RCP8.5 scenario during the 20th century as function of height and latitude, showing that while the troposphere warms, the stratosphere cools significantly. To understand the response of the stratosphere, we add a third layer to our two-level energy balance model from section 2.2.2, such that \(T_{s}\) is the surface temperature, \(T_{t}\) the tropospheric temperature, and \(T_{str}\) the newly added stratospheric temperature, as shown in the schematic Fig. 3.9.

\[
\begin{align*}
\text{(1.1)} & \quad \frac{1}{4}S_0 + e_{trop}T_4 + (1 - e_{trop})e_{str}T_4 = T_4 - T_{trop} + e_{str}T_4 = 2e_{trop}T_4.
\end{align*}
\]
Stratospheric cooling

3-layer energy balance model

\[
(1 - \beta_{str}) \frac{1}{4} S_0 + \varepsilon_{tro} \sigma T_{tro}^4 + (1 - \varepsilon_{tro}) \varepsilon_{str} \sigma T_{str}^4 = \sigma T_s^4 \\
\varepsilon_{tro} \sigma T_s^4 + \varepsilon_{tro} \varepsilon_{str} \sigma T_{str}^4 = 2 \varepsilon_{tro} \sigma T_{tro}^4 \\
\beta_{str} \frac{1}{4} S_0 + \varepsilon_{str} (1 - \varepsilon_{tro}) \sigma T_s^4 + \varepsilon_{str} \varepsilon_{tro} \sigma T_{tro}^4 = 2 \varepsilon_{str} \sigma T_{str}^4.
\]

solve by writing as a matrix equation for \( T^4 \) (Thanks Xiaoting!):

\[
\begin{pmatrix}
\sigma & -\varepsilon_{tro} \sigma & -(1 - \varepsilon_{tro}) \varepsilon_{str} \sigma \\
-\varepsilon_{tro} \sigma & 2 \varepsilon_{tro} \sigma & -\varepsilon_{tro} \varepsilon_{str} \sigma \\
-(1 - \varepsilon_{tro}) \varepsilon_{str} \sigma & -\varepsilon_{str} \varepsilon_{tro} \sigma & 2 \varepsilon_{str} \sigma
\end{pmatrix}
\begin{pmatrix}
T_s^4 \\
T_{tro}^4 \\
T_{str}^4
\end{pmatrix}
= \begin{pmatrix}
(1 - \beta_{str}) \frac{1}{4} S_0 \\
0 \\
\beta_{str} \frac{1}{4} S_0
\end{pmatrix}
\]

Discuss results, explanation.
Global-mean surface warming: not much uncertainty about magnitude of warming, or about it being unusual relative to past climate...
summary

• Global-mean surface warming: not much uncertainty about magnitude of warming, or about it being unusual relative to past climate…
• Warming as function of time over land vs ocean
summary

- Global-mean surface warming: not much uncertainty about magnitude of warming, or about it being unusual relative to past climate…
- Warming as function of time over land vs ocean
- Hiatus periods
summary

- Global-mean surface warming: not much uncertainty about magnitude of warming, or about it being unusual relative to past climate…
- Warming as function of time over land vs ocean
- Hiatus periods
- Polar amplification: Albedo, lapse-rate (tropical/Arctic), Planck feedbacks
Global-mean surface warming: not much uncertainty about magnitude of warming, or about it being unusual relative to past climate…

Warming as function of time over land vs ocean

Hiatus periods

Polar amplification: Albedo, lapse-rate (tropical/Arctic), Planck feedbacks

Climate sensitivity from present-day data w/o models
summary

- Global-mean surface warming: not much uncertainty about magnitude of warming, or about it being unusual relative to past climate...
- Warming as function of time over land vs ocean
- Hiatus periods
- Polar amplification: Albedo, lapse-rate (tropical/Arctic), Planck feedbacks
- Climate sensitivity from present-day data w/o models
- Delaying effect of ocean heat capacity (transient climate sensitivity)
summary

- Global-mean surface warming: not much uncertainty about magnitude of warming, or about it being unusual relative to past climate...
- Warming as function of time over land vs ocean
- Hiatus periods
- Polar amplification: Albedo, lapse-rate (tropical/Arctic), Planck feedbacks
- Climate sensitivity from present-day data w/o models
- Delaying effect of ocean heat capacity (transient climate sensitivity)
- Stratospheric cooling as a powerful attribution tool
The End
More... time permitting
Temperature measurement techniques
Atmospheric temperature: satellites and radiosondes

Satellites carrying SST instruments

Low Orbiting Satellites, their SST Sensors and Space Agencies:
1. AQUA MODIS NASA & AMSR-E
2. ENVISAT AATSR ESA, image credit: ESA
3. METOP-A AVHRR and IASI
4. EUMETSAT, image credit: ESA-AOES MediaLab
5. NOAA-18 and NOAA-19 AVHRR
6. Terra MODIS NASA, image credit: NASA
7. Coriolis WindSat NRL, image credit: US Navy

Geostationary Satellites, their SST Sensors and Space Agencies:
8. GOES-E and GOES-W GOES
9. MSG SEVIRI EUMETSAT, image credit: ESA-DIVCIRROS
10. MTSAT-2 MTSAT JMA, image credit: JMA
Satellite observations: vertical weight functions

Satellites measure the intensity of upwelling microwave radiation from atmospheric oxygen, proportional to the temperature of broad vertical layers of the atmosphere. Different frequency bands sample a different weighted range of the atmosphere. The brightness temperature \( T_B \) measured by satellite is given by:

\[
T_B = W(0)T(0) + \int_{0}^{TOA} W(z)T(z) \, dz
\]

Figure 2.23 | Vertical weighting functions for those satellite temperature retrievals discussed in this chapter (modified from Seidel et al. (2011)). The dashed line indicates the typical maximum altitude achieved in the historical radiosonde record. The three SSU channels are denoted by the designated names 25, 26 and 27. LS (Lower Stratosphere) and MT (Mid Troposphere) are two direct MSU measures, and LT (Lower Troposphere) and *G (Global Troposphere) are derived quantities from one or more of these that attempt to remove the stratospheric component from MT.

(IPCC AR5, 2013)
Polar orbiting satellites

http://tornado.sfsu.edu/geosciences/classes/m407_707/Monteverdi/Satellite/PolarOrbiter/Polar_Orbits.html
Historically, most SST observations were obtained from moving ships. Intercomparisons of data obtained by different measurement methods, including satellite data, have resulted in better understanding of errors and biases in the record. Since AR4 the availability of metadata has increased, data completeness and a number of new SST products have been produced. AR4 concluded that 'recent' warming (since the 1950s) is strongly evident. Temporal changes in the prevalence of different measurement methods have occurred. An assessment of the potential impact of systematic errors on the SST global mean estimates: note the difference in 1850–1941 between the ICOADS and HadSST2 data sets, and the recovery of modern biases can be ascertained by considering the difference among SST data from ships, the ship SSTs are biased warm by 0.12°C on average compared to the buoy data (Kent et al., 2010). Because of the prevalence of the ERI measurements engine room intake (ERI) and hull contact sensor observations (green), moored and drifting buoys (red), and unknown (yellow). (IPCC AR5, 2013).

**Figure 2.15** Temporal changes in the prevalence of different measurement methods in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). (a) Fractional contributions of observations made by different measurement methods: bucket observations (blue), engine room intake (ERI) and hull contact sensor observations (green), moored and drifting buoys (red), and unknown (yellow). (b) Global annual average sea surface temperature (SST) anomalies based on different kinds of data: ERI and hull contact sensor (green), bucket (blue), buoy (red), and all (black). Averages are computed over all 5° × 5° grid boxes where both ERI/hull and bucket measurements, but not necessarily buoy data, were available. (Adapted from Kennedy et al., 2011a.)