The Satellite Record of the Pale Blue Dot: The Late 1970s to Now

Compton Tucker
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771
Almost a billion Galaxies are known but only 1 planet is known to have life.
Earth Perspective by Carl Sagan
The Pale Blue Dot

Valentine’s Day 1990 -- from 6,000,000,000 km
The Pale Blue Dot from Voyager-1

Valentine’s Day 1990 -- from 6,000,000,000 km
The Global Biosphere from SeaWiFS
Definitions

Without proper definitions, logical discourse is impossible. Without logical discourse, nothing can be accomplished.

Confucius
Geophysical Measurements

1. RADAR

\[ P_R = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R^4} \]

where,

- \( P_R \): Received echo power [W]
- \( P_T \): Transmit signal power [W]
- \( G_T \): Transmit antenna gain [dB]
- \( G_R \): Receive antenna gain [dB]
- \( \lambda \): Radar wavelength [m]
- \( \sigma \): Radar cross-section of the target surface [m²]
- \( R \): Range to target [m]

\[ R_{max} = 4 \sqrt{\frac{P_T G^2 \lambda^2 \sigma}{P_R (4\pi)^3}} \]

2. Gravity

\[ F_g = G( m_1 \times m_2 )/r^2 \]

3. Temperature

Planck’s Law

\[ B(\lambda, T) = \frac{2hc^2}{\lambda^5} \left( \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \right) \]

Temperature (K) = °C + 273
The Earth is Warming!

- Sea Level rising
- Sun no change
- Ocean temperatures increasing
- Surface thermometers increasing
- Atmospheric temp. increasing
- Glaciers melting
- Arctic sea ice
Fundamental discovery: TSI is $\sim 1361 \text{ W m}^{-2}$, not $1366 \text{ W m}^{-2}$
In the satellite record, total solar irradiance varied by ~one part in 500.

$\Delta T \sim 0.1 ^\circ C$, nearly all associated with the ~11-year solar cycle.
In the satellite record, total solar irradiance varied by ~one part in 500. 

$\Delta T \sim 0.1^\circ C$, nearly all associated with the ~11-year solar cycle.
Battle of Britain—RADAR

August-1940
Pearl Harbor—Ignored Geophysical Variables

7-Dec-1941
Pearl Harbor—Ignored Geophysical Variables
Sea level can be very accurately measured by satellites using C band (5.3 GHz) & Ku band (13.6 GHz), with corrections at +18, 21, & 37 GHz. The rise in sea level is estimated to be between 0.3-0.4 cm/yr.
Global Warming /Cooling
Earth warms, sea level rises; Earth cools, sea level falls

~50% thermal expansion  ~50% glacial melt
Thermal Expansion of Sea Water

\[ V = V_0 (1 - \beta \Delta T) \]
Nature’s best thermometer, perhaps its most sensitive and unambiguous indicator of climate change, is ice.

“Ice asks no questions, presents no arguments, reads no newspapers listens to no debates. It is not burdened by ideology and carries no political baggage as it changes from solid to liquid. It just melts.”

From A World Without Ice by Henry Pollack, 2009
Gravity Recovery &
Climate Experiment

500 km orbit
220 km separation
Distance accuracy ±0.001 mm

\[ F_g = \frac{G(m_1 m_2)}{r^2} \]
Estimating time-variable gravity with GRACE/GRACE-FO

1. Satellites are far from mass anomaly: no effect

2. Approaching mass anomaly: separation increases

3. Flying over mass anomaly: maximum separation

4. Leaving mass anomaly: → original separation
GRACE & GRACE-FO Observations Greenland Ice Mass $\Delta$

Data source: NASA GSFC mascons (Loomis et al., 2019)

Average Annual Greenland Ice Loss (gigatons water equivalent/year)

Average Mass Loss: 273 Gigatons/year
GRACE & GRACE-FO Observations of Antarctic Ice Mass $\Delta$

Data Source: NASA GSFC mascons (Loomis et al., 2019)

Average Annual Antarctic Ice Loss (gigatons water equivalent/year)

Average Mass Loss: 121 Gigatons/year
East Antarctica is above sea level while much of West Antarctica is not (image: V.R. Barletta)
Satellite Detection of Sea Ice

Higher rate of microwave emission from sea ice than from open water. Emissivity indicated is for wavelength of 1.55 cm/19 GHz. 22 GHz & 37 GHz are used for water vapor corrections.
Arctic Sea Ice
Arctic Sea Ice Extent

Average Monthly Arctic Sea Ice Extent
December 1978 - 2020

Frequencies: 19 GHz, 22 GHz, & 37 GHz
Arctic Sea Ice Extent in August

Reference period 1981-2000

August Trend:
-72 thousand km²/year
-9.1%/decade

Graph was plotted 01/09/2019 10:35 UTC
Source: EUMETSAT OSI SAF (http://osisaf.met.no)
Antarctic Sea Ice Minima Extent

Southern Hemisphere Extent Anomalies Jun 1979 - 2019

1981-2010 mean = 13.4 million sq km

slope = 0.9 ± 1.2 % per decade
Arctic & Antarctic Sea Ice Extents

Sea Ice Extent at Yearly Minima

source: James Hansen, data from NSIDC
Arctic Ocean is Surrounded by Continents
Antarctica is Surrounded by Ocean
Jan-2021: 415.3 ppm
Jan-2020: 413.4 ppm

Atmospheric CO2 Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory

Eunice Foote  Arrhenius  Keeling

Year

parts per million (ppm)


November 2020
Plate Tectonics & the Carbon Cycle

Beerling & Royer 2011

Atmos. CO₂ (ppm)

Temp. (°C)

Time (millions of years ago)


- stomata
- plankton
- palaeosols
- liverwarts
- boron
- B/Ca
- Nahcolite--trona

Plate Tectonics & the Carbon Cycle
Plate Tectonics & Carbon Cycle

Global Surface Temperature ($T_s$)

- Paleocene
- Eocene
- Oligocene
- Miocene
- Pliocene
- Present

$T_s$ (°C)

- CO$_2$ = 1500 ± 500 ppm
- India collides with Asia

$T_s$ = 25°C, 20°C, 15°C, 10°C

NOW 14.5°C

Antarctic Ice Sheet @ <450 ppm CO$_2$

Greenland Ice Sheet @ 400 ppm CO$_2$

Hominins

Zachos et al. 2001 O16/O18
Atmospheric CO2 Mauna Loa Observatory

Jan-2021: 415.3 ppm
Jan-2020: 413.4 ppm

Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory

Eunice Foote
Arrhenius
Keeling

Antarctic Ice Sheet @ <450 ppm CO₂
Greenland Ice Sheet @ 400 ppm CO₂
Carbon Cycle—back to the Cretaceous

rate = 0.02 °C/yr

rate = -0.0000003 °C/yr

Zachos et al. 2001 O16/O18
Cretaceous & Modern Earth

Cretaceous Period
(110 million years ago)
1,000 ppm CO2
No ice on planet
Sea level 300 feet higher
80° F Average Surface Temperature

Present Day
415 ppm CO2
Glaciers, Sea Ice, Ice Sheets
Present Sea Level
59° F Average Surface Temperature
Night Comes to The Cretaceous
Nuclear Winter/Astroidal Impact

K-T Impact: >100,000,000 Nuclear Bombs
10 – 15 km diameter @ 20 km/second
Night Comes to The Cretaceous
Super Nuclear Winter
K-T Impact—Super Nuclear Winter

- Massive fires
- No Photosynthesis for 1 year
- Cooler continents by 20°-30° C
- Oceans cooler by 10° C

Kring (2000)

H₂O and CO₂ greenhouse warming?
K-T Impact—Super Nuclear Winter & Microwave Summer

- Massive fires
- No Photosynthesis for 1 year
- Microwave Summer
- Cooler continents by 20°-30° C
- Oceans cooler by 10° C

Temperature (°C)

Time (→)

Hours Days Weeks Months Years Decades

Dust loading
Soot NOx SO2

H2O and CO2 greenhouse warming?

Kring (2000)
Rise of the Mammals
here we come, ready or not!
What do we do?

Tables Are Turning for Carbon Capture and Storage

Previously thought to be a hopeless money pit, carbon capture and storage (CCS) is seeing a revival thanks to policy incentives and private sector efforts to mitigate climate change.
What do we do?
Why NASA?

NASA uses space for exploration & scientific discovery:

Looking up, looking down, & looking forward!
GRACE measures surface mass change

Range-rate (nm/s²)

Range-rate (µm/s)

Range (µm)

Distance (km)

10 cm x 4° x 4° water block
Western Europe last glacial maxima 20,000 BC

Stockholm 2,500 m of ice

X
In areas that were covered by ice, the land has rebounded after glacial ice mass loss.
Surface temperature comparisons
Same data, different interpolations & reference years

95% confidence interval shown for Berkeley Earth
Temperature anomalies relative to 1981-2010 average
SURFACE TEMPERATURE RECONSTRUCTIONS FOR THE LAST 2,000 YEARS

- Borehole temperatures (Huang et al. 2000)
- Multiproxy (Mann and Jones 2003)
- Multiproxy (Hegerl et al. 2006)
- Instrumental record (HadCRUT2v)
- Glacier lengths (Oerlemans et al. 2005)
- Multiproxy (Moberg et al. 2005)
- Tree rings (Esper et al. 2002)
Cretaceous & Modern Earth

Cretaceous Period
(110 million years ago)
1,000 ppm CO2
No ice on planet
Sea level 300 feet higher
80°F Average Surface Temperature

Present Day
410 ppm CO2
Glaciers, Sea Ice, Ice Sheets
Present Sea Level
59°F Average Surface Temperature
Greenland ice sheet & bedrock
Gravity: \( F_g = \frac{G(m_1 m_2)}{r^2} \)
Atmospheric CO$_2$ Concentrations

Earth’s Magnetic Field
Mars’ Lack of a Strong Magnetic Field:
No Atmosphere & -81° F
Thanks to Earth’s Magnetic Field!!