What regulates global temperature?

Heat Balance:

Energy in = Energy out

Energy in = (Solar output)\((\pi r^2)(1-A)/(4\pi R^2)\)

Energy out = \((4\pi r^2)\sigma T^4\)

\(r\) = Earth radius  
\(R\) = Earth sun dist.  
\(A\) = Albedo  
\(T\) = °K
Black Body Temperature Depends on:

Energy in = Energy out

\[ \sigma T^4 = \frac{(\text{Solar output})(1-A)}{(16\pi R^2)} \]

For \( A = 0.30 \), \( T = 255 ^\circ K = -18 ^\circ C \)

Critical Factors:
1. Solar output - varies over long term. Short term variation?
2. Earth-sun distance (R) - average is constant, orbit shape changes.
3. Albedo (A) - ice cover, dust, cloud cover can change
5. Efficiency of heat transport to poles dictates uniformity of T - can vary with mountains, continent position, location of deep water production.
Grand Canyon: Why the great unconformity?
Snowball Earth

Late Proterozoic had glaciation to low latitudes. Continents and perhaps oceans were mostly ice covered (high albedo!!)

How can Earth escape?
In extreme cases CO2 might provide negative feedback. Why? CO2 is added from volcanism related to subduction. Today CO2 is removed by weathering rocks:

\[ \text{CO}_2 + \text{CaSiO}_3 = \text{CaCO}_3 + \text{SiO}_2 \]

Without liquid water this will not happen efficiently! Plate tectonics saves the Earth from permanent ice!
Some Major Changes in Climate

Known amplitude of changes (low latitude changes poorly known)
Cenozoic: High latitude drops from 12°C to <0°C particularly thorough Miocene. Eocene had 20°C at 60° lat.
Pleistocene: High latitudes oscillate on 20-100 ky times by 5-10°C
Shorter time scales are also recognized (decades-millenia)
Shells of marine plankton

(a) Coccolithophore

(b) Foraminifera (foram)

(c) Diatom

(d)
Forams grow shells of CaCO3

\[ \text{Ca}^{+2} + \text{CO}_3^{-2} \rightarrow \text{CaCO}_3 \]

ions \hspace{1cm} \text{shell}

Forams put on heavy coats because:

1. Ice sheets are light, so oceans are heavy
   \( \text{(H}_2\text{O molecules exchange oxygen with CO}_3^{-2}) \)

2. At lower temperatures, forams prefer to take
   \( \text{CO}_3^{-2} \) molecules with heavy isotopes
Heat Transport

Oceans:
   Sensible heat
   Currents depend on continent configuration

Atmosphere:
   Sensible heat
   Latent heat (water vapor & condensation)
Cenozoic Cooling

Effect of Continental configuration and Mountains on heat transport through atmosphere and oceans:

Some cooling began about 40 my ago: Response to uplift of Himalayas?

More cooling in Miocene, about 20 my: Open Drake Passage and isolate Antarctic?

Pliocene/Pleistocene ice ages, last 3 my: Closure of Isthmus of Panama?
Areas Covered by Ice Sheets 20,000 years ago
Broecker (1992)
Heat transport by ocean. Can it change?

An example from the Younger-Dryas time.

A cold snap lasting 1000 years!

It came in a decade or so, in Europe.
Younger-Dryas: Cold climate 11-12 ky ago.
Conveyor shut down due to melt water discharge from St. Lawrence River.
Record of oxygen isotopes in Foram shells.

Note that major ice sheets wax and wane with 100 ky period. Smaller oscillations have 20 ky period.
Milankovitch Curve
(N. Hem. Solar radiation)

Parameters:
precession (22 ky)
tilt (41 ky)
ellipticity (100 ky)

During Pleistocene, major ice ages come and go with 100 ky period, with smaller cycles matching precession.

Timing fits well, although amplitude does not

Relative radiation (N. hem.) <-warm cold->
Milankovitch Cycle Pattern

Ice volume, temperature, atmospheric CO2 all have cycles with same periodicity (especially 100 ky and 20 ky)

Seasonality appears to provide timing, but changes in radiation seem too small to explain large climate variations

Perhaps ice cover or CO2 amplify (positive feedback) Milankovitch effects of seasonality

But why does CO2 change so much with climate change? Partly solubility. Rest is hotly debated!!!!
Ice Core Record

CO2 from gas bubbles (cold when low CO2)

Temperature from isotopes

Methane from gas bubbles (high = wet, when warm)
Atmospheric CO2 Concentrations

Last glacial maximum (20 ky ago)  200 ppm
1700 AD (pre-industrial)        280 ppm
2003 AD (today)                375 ppm

Atmospheric CO2 may be an amplifier of climate cycles. Warming should cause it to increase, showing that it provides positive feedback.
Mechanisms to Make Climate Vary

1. Change in solar output
2. Change Earth-sun distance. Milankovitch cycles cause change in seasonality: precession (22 ky), tilt (41 ky), eccentricity (100 ky)
3. Change in albedo: clouds, ice, stratospheric particles
4. Change in atmosphere: H2O, CO2, CH4 (?)
5. Change efficiency of heat transport to poles: ocean and atmosphere circulation depend on continent configuration and mountains. Also, location of deep ocean water formation.