The Legacies of Fourier and Arrhenius: Greenhouse Effect and Global Warming

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credits

- James Fleming
  - *Historical Perspectives on Climate Change (1998)*
  - *The Callendar Effect (2007)*
- Spencer Weart
  - *The Discovery of Global Warming (2003)*

- The Enlightenment Era
  - early climate ideas and their ultimate rejection
- The Greenhouse Effect and Global Warming
  - Fourier, Tyndall, Arrhenius and Callendar
- Cloud Greenhouse and Albedo Effects
  - 21st century measurements
- The Modern Era
  - current climate ideas
    - ultimately to be rejected or accepted?

The Enlightenment Era

- 18th Century Europe
- a time of philosophers and writers
- modest religious emancipation
- origin of theories of government
- pre Scientific Method
- qualitative rather than quantitative reasoning

Enlightenment Era and Climate

- Abbé du Bos
  - French (1670–1742)

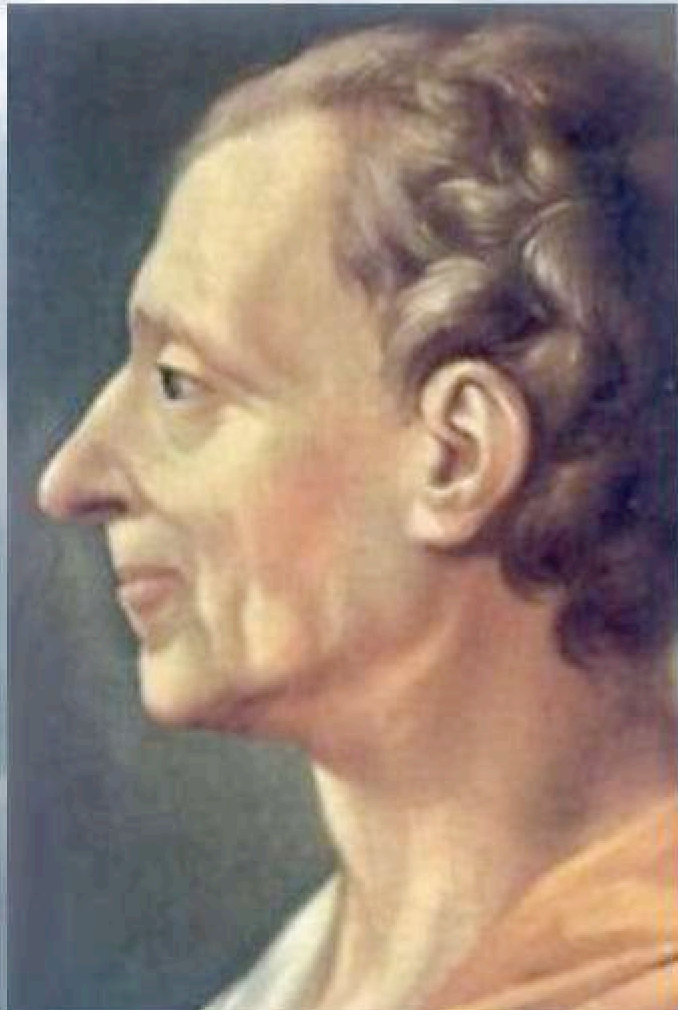
  … geniuses are not born in every climate

Enlightenment Era and Climate

- David Hume
  - Scottish (1711–1776)

  … Europe became warmer because of cultivation

Enlightenment Era and Climate



- Montesquieu
  - French (1689-1755)
  - Charles Louis de Secondat, Baron de la Brède et de Montesquieu
  - climate … the first of all the empires

Enlightenment Era: key climate ideas

- Climate shapes culture
- European climate had warmed
  - that was good, and to be encouraged
- Warming was due to deforestation and cultivation
  - cutting down trees lets in more light and heat
- Cultivation of the New World would therefore improve its climate and ultimately its culture
  - the rain follows the plough

Authors accepting cultivation argument

1634	William Wood	*New England's Prospect*
1664	John Evelyn	*Silva*
1695	John Woodward	*Natural History of the Earth*
1719	Abbé Du Bos	*Réflexions critiques sur la poésie et sur la peinture*
1721	Cotton Mather	*Christian Philosopher*
1750	David Hume	*Populousness of Ancient Nations*
1771	Hugh Williamson	*Attempt to Account for the Changes of Climate*
1785	Thomas Jefferson	*Notes on the State of Virginia*
1786	Benjamin Rush	*Cause of the Increase of Fevers*
1793	Edward Holyoke	*Heat and Cold of the American Atmosphere*
1794	Samuel Williams	*Natural and Civil History of Vermont*
1804	Constantine-François Volney	*Soil and Climate of the United States*
1809	David Ramsey	*History of South Carolina*
1812	Baron Cuvier	*Discours préliminaire sur les revolutions de la surface du globe*
1830	Charles Lyell	*Principles of Geology*
1837	Heinrich Wilhelm Dove	*Meteorologische Untersuchungen*

Authors rejecting cultivation argument

1780	J. D. Schoepf	*Climate and Diseases of America*
1799	Noah Webster	*Change in the Temperature of Winter*
1808	David Brewster	*New Edinburgh Encyclopedia*
1820	Luke Howard	*Climate of London*
1844	Samuel Forry	*Distribution of Heat over the Globe*
1850	Alexander von Humboldt	*Views of Nature*
1857	Lorin Blodget	*Climatology of the United States*
1866	Elias Loomis	*Mean Temperature at New Haven*
1876	Charles Schott	*Variations of the Atmospheric Temperature*
1889	Cleveland Abbe	*Is our Climate Changing?*

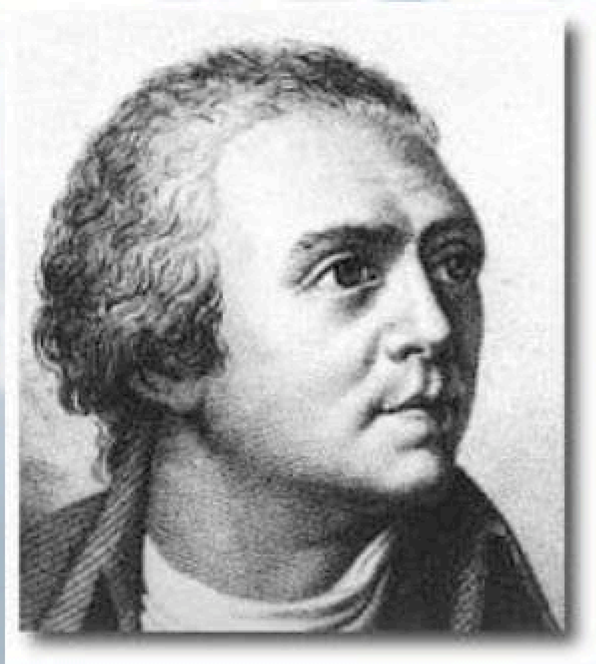
Jean-Baptiste Joseph Fourier

- french, 1768–1830
  - orphaned by age 10
- mathematician
  - instead of a priest
- physicist
  - the 'Newton' of heat
- friend of Napoleon
  - Governor of Egypt
  - imprisoned (twice)
  - Baron
- never married
- died of heat

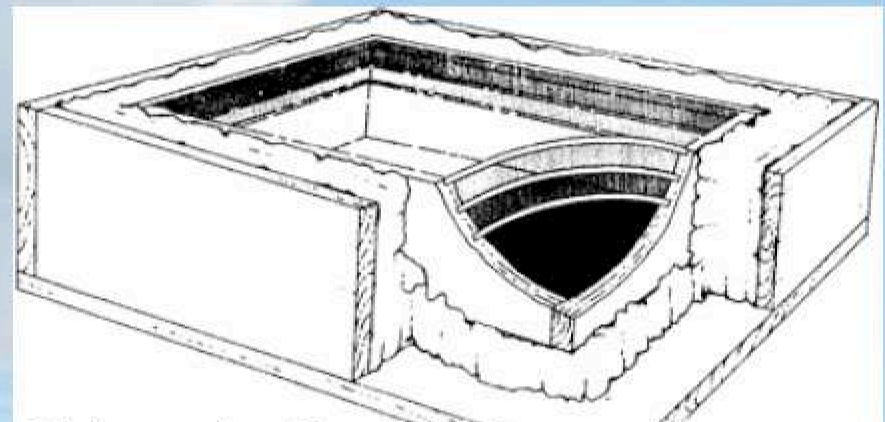
Jean-Baptiste Joseph Fourier

- "General remarks on the temperatures of the Earth and space" (in french, 1824)
- recognized heat from interior was negligible
- correctly understood thermal inertia
  - day/night and seasonal
- got polar temperatures completely wrong
  - thought they were heated from space
- atmosphere was like a giant heliothermometer
  - without actually calling it a 'greenhouse' (serre)

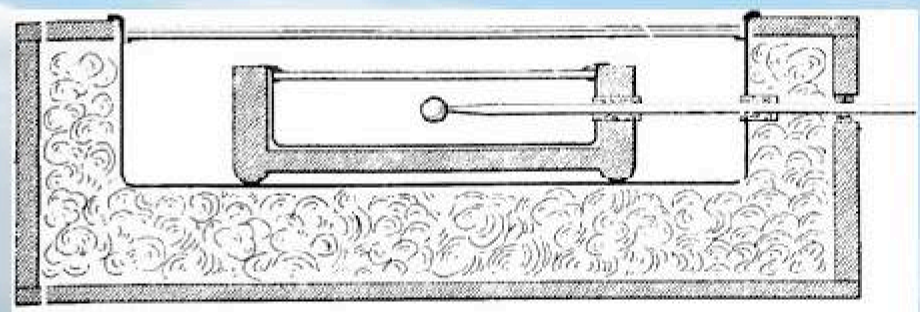
Early greenhouse effects: heliothermometers



- Horace Bénédict **de Saussure**
  - Swiss professor of physics (1740-1799)
  - heliothermometer measured 110°C (1767)
  - independent of altitude in Swiss alps



Artist's conception of de Saussure's improved hot box.

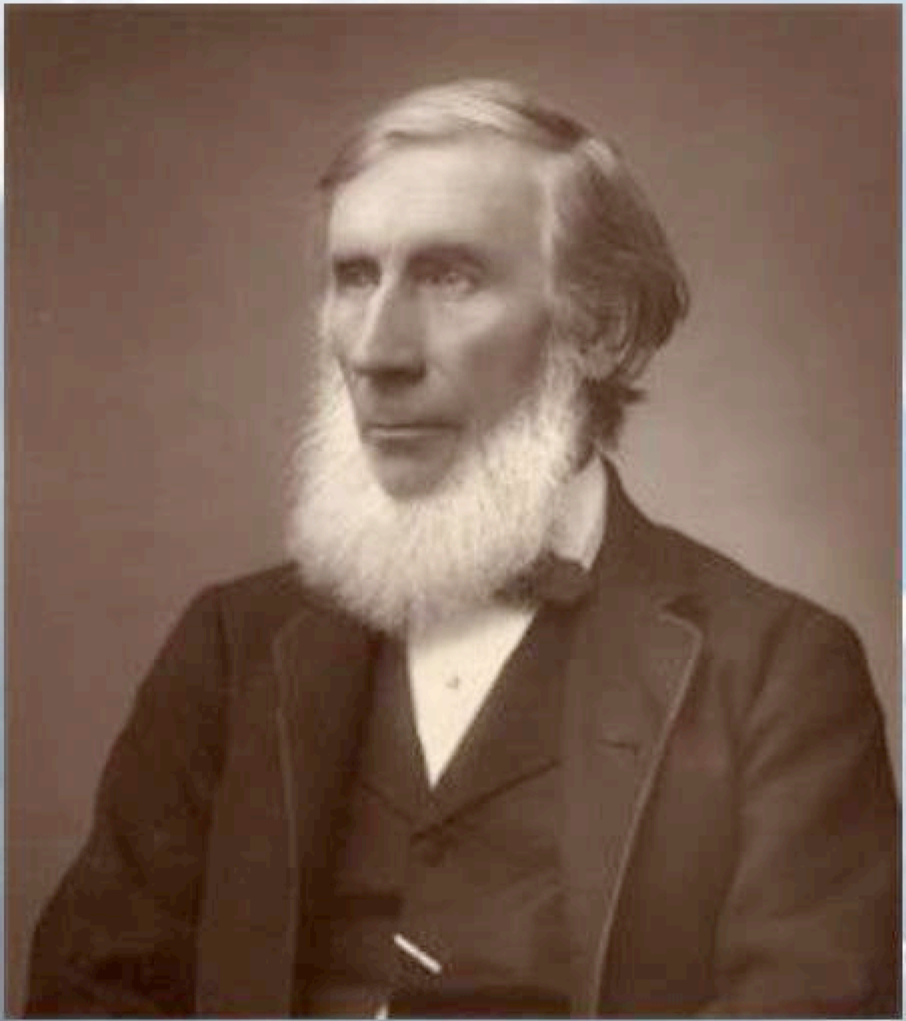


Cross-section of Langley's hot box, which was similar to de Saussure's later models. A thermomether penetrating the walls at right was used to measure the air temperature inside the inner box.

Jean-Baptiste Joseph Fourier

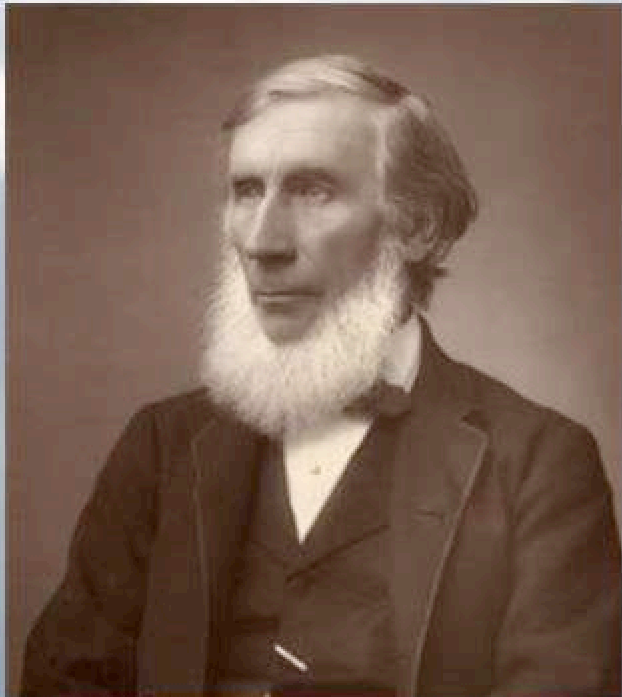
- **first correct statement on radiative-convective equilibrium**
  - ... heat finds fewer obstacles in penetrating the air when it is "chaleur lumineuse" (solar energy), than in repassing when converted into "chaleur obscure" (longwave radiant energy)
  - The mobility of the air which moves rapidly in all directions and which rises when heated ... would diminish the intensity of the effects which would take place under an transparent and solid atmosphere, but would not entirely remove these effects.

John Tyndall



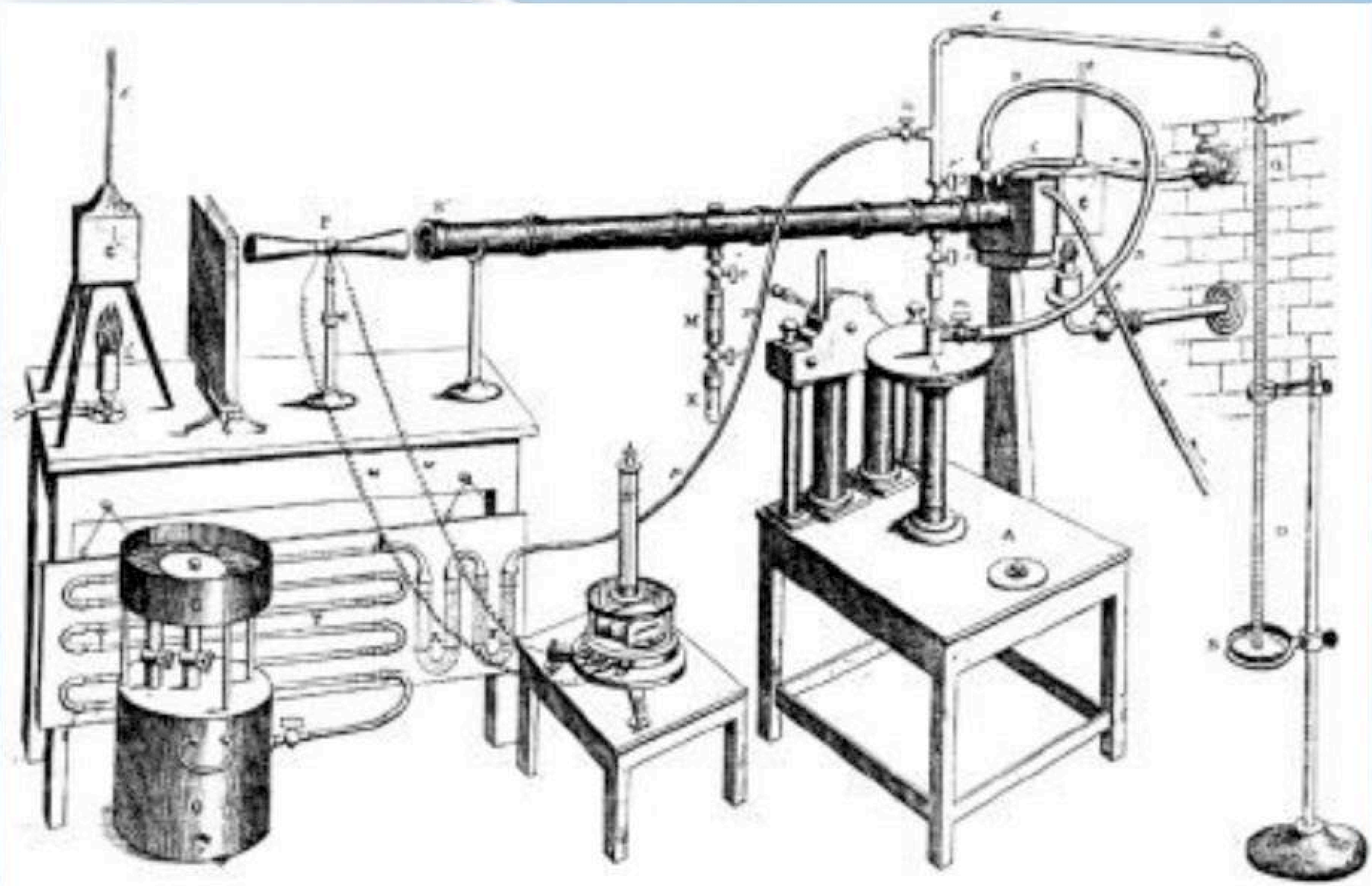
- 1820–1893
- Irish physicist, educator and mountaineer
- influential public speaker, with many scientific accomplishments
- denounced (by the Church) as a 'materialist and atheist'
- married when 56
- killed (accidentally) by his wife

John Tyndall



- discovered that most of the atmosphere (oxygen and nitrogen) did not absorb longwave radiation
  - invented a ratio spectrophotometer
- discovered CO_2 and water vapour were greenhouse gases (1859-71)
  - water vapour was far stronger than CO_2
- first to consider ice ages could be explained by changes in CO_2 and water vapour

Tyndall's ratio spectrophotometer



Svante August Arrhenius

- 1859–1927
- Swedish physicist, chemist and ‘cosmic’ scientist
- Nobel prize in Chemistry (1903)
- married his first female research assistant (1894-6)

Svante August Arrhenius

- "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground." (1896 in english)
  - derived a greenhouse law for CO_2
    - influence goes as logarithm of CO_2 concentration
  - doubled CO_2 gives 5-6°C rise
  - included changes in water vapour
  - noted greater effect on winter temperatures, and higher at the poles

Svante August Arrhenius

- motivation (like Tyndall) was to explain the ice ages
  - considered these could be triggered by carbon dioxide
- but also noted that anthropogenic carbon dioxide emissions would prevent ice ages
  - saw this as very positive, also promoting plant growth
  - might take 3000 years to see an effect

Reactions to Arrhenius

- calculations were soon shown to be in error by Ångström, overestimating the effect
- Arrhenius vehemently rejected such criticisms
- absorption data were a major limitation
  - Arrhenius had no information beyond 3 µm!
  - by 1910 CO_2 bands were known to saturate
  - and to overlap with water vapour absorption
- much debate whether CO_2 could even change a lot
- Arrhenius' climate system was too simple
  - no changes in clouds, or circulation patterns
- Chamberlain initially supportive, then recanted
  - "I greatly regret that I was among the early victims of Arrhenius' error" (1913)
- Arrhenius' paper not cited again until end of 1980s.

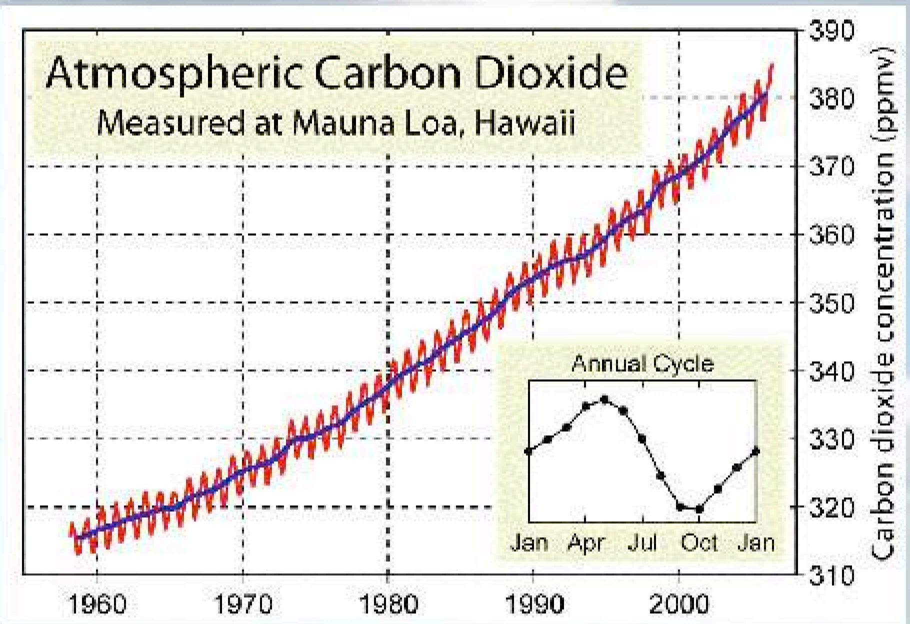
Guy Stewart Callendar

- English engineer (1898-1964)
  - quiet, non-controversial family man
- son of Hugh Callendar
  - physics prof at McGill and Imperial College
  - platinum resistance thermometer
  - Callendar Steam Tables
- British civil servant
  - war office, ministry of supply
  - FIDO (fog dispersal)
  - steam research
  - space heating, flamethrowers

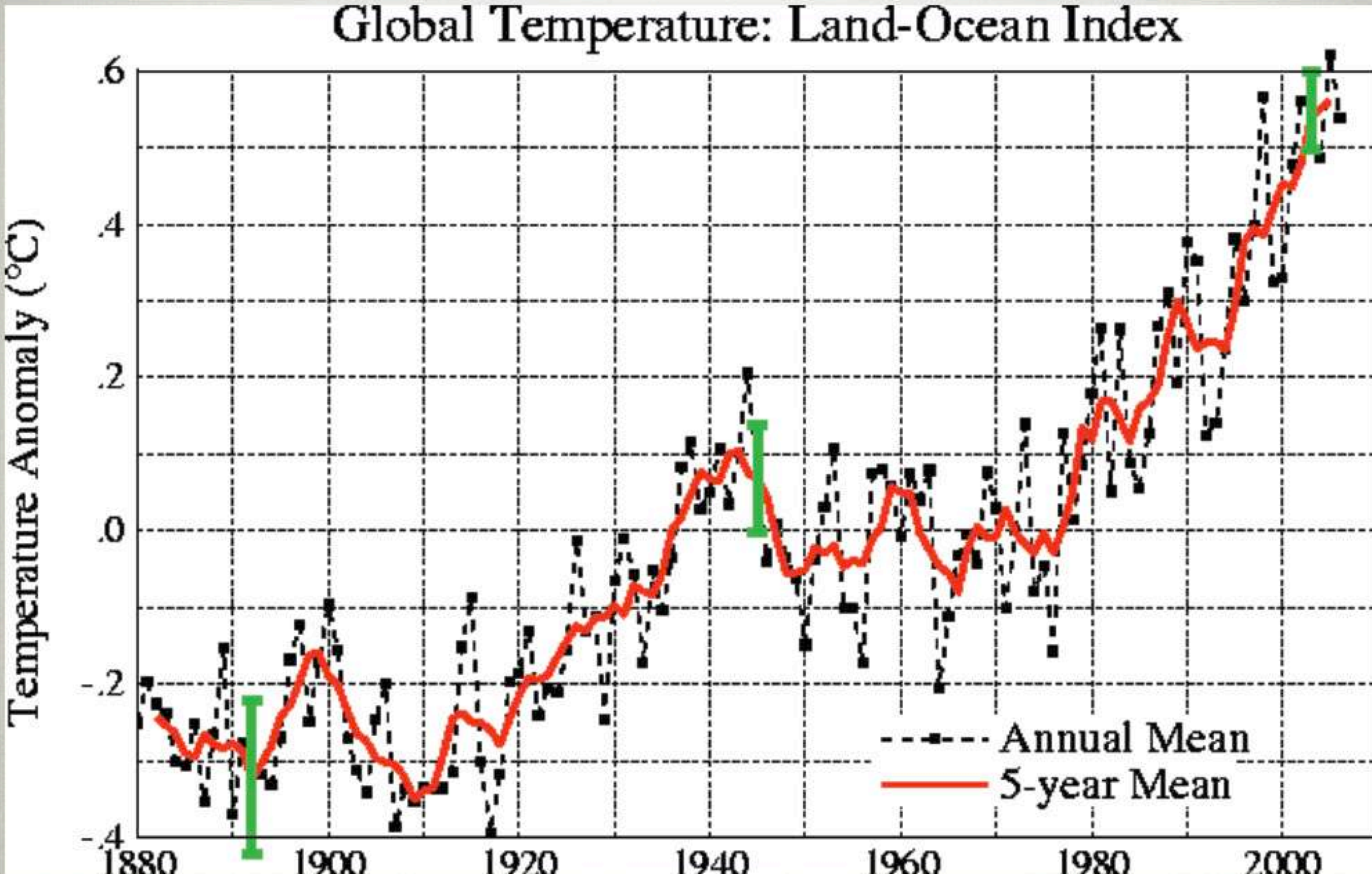
The Callendar Effect

- the first to propose global climate change due to an enhanced greenhouse effect
  - The artificial production of carbon dioxide and its influence on temperature (QJRMS 1938).
    - noted that CO_2 and temperature were both rising
    - calculated absorption due to CO_2 far more accurately, accounting for band structure
    - got 2°C warming for doubled CO_2 based on radiative equilibrium
    - predicted measurable warming within 20 years
  - Published many other papers on atmospheric radiation, temperature change and CO_2 change
    - clarified pressure broadening effects, and distinct absorption spectra of water vapour and other greenhouse gases

reaction to Callendar



- much debate on whether the CO_2 increase would amount to much
  - Callendar was vindicated by Keeling curve
- But, temperatures went down, not up, for next 40 years
  - and the Callendar Effect was largely forgotten



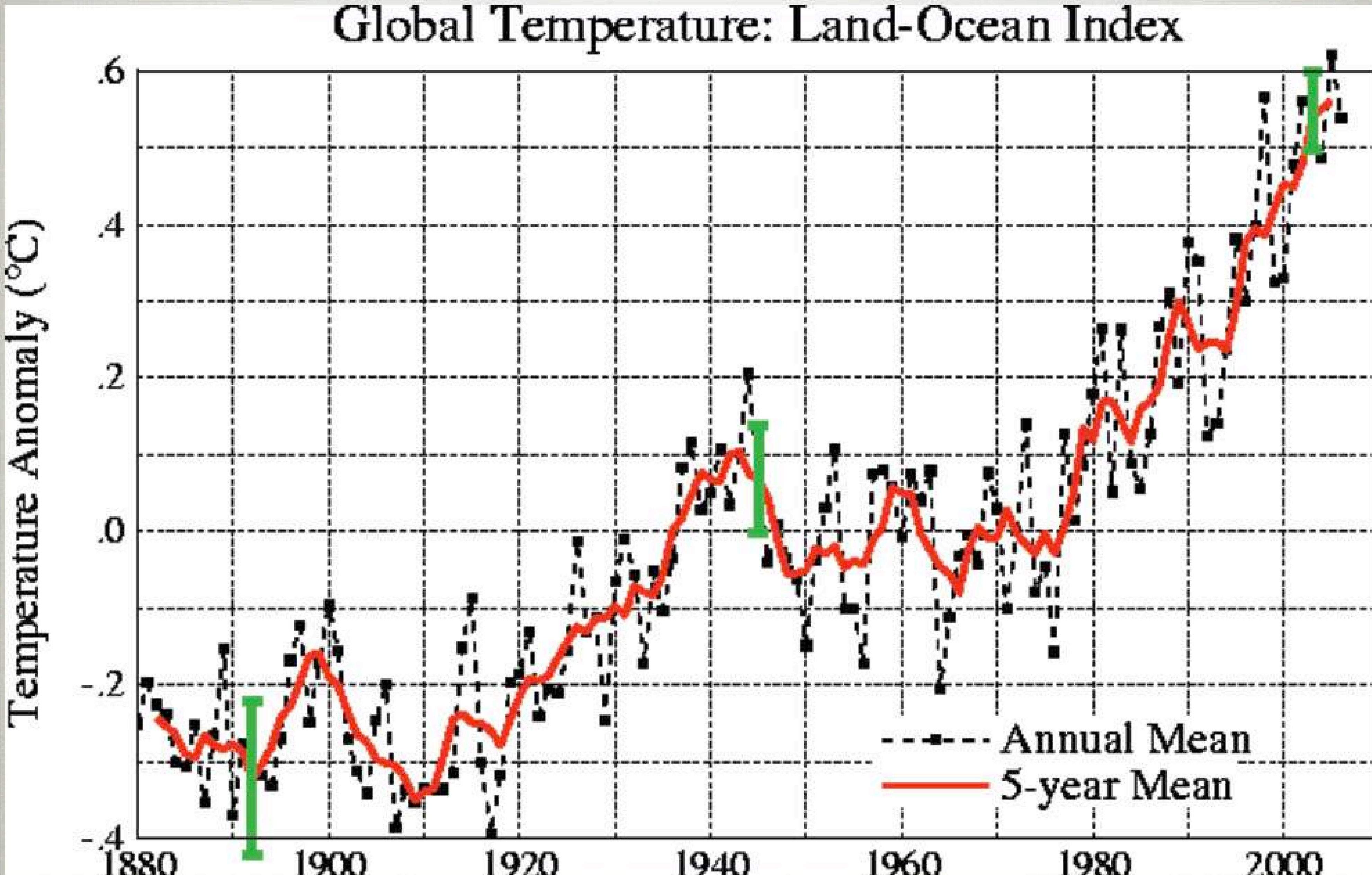
Credit: Goddard Institute of Space Studies

synopsis to date

- Fourier: introduced concept of radiative-convective equilibrium
- Tyndall: discovered existence of greenhouse gases
- Arrhenius: first calculations of warming not too far off, *but only by chance*
- Callendar: first serious calculation of enhanced greenhouse effect

1940–1976

- not much public debate on climate change until the 60s, when the cooler temperatures became recognized
- Bryson: 'human volcano'
  - ice age imminent due to too much air pollution
- Ice age models were in vogue and made good progress
- Carbon dioxide not seriously revisited until 1976
- the correlation between the *reaction* to climate change theories and temperature seemed stronger than the correlation between CO_2 and temperature



Credit: Goddard Institute of Space Studies

scientific critique

- Callendar's approach led directly to one class of climate models (radiative-convective)
  - more up-to-date radiation (very little net difference)
  - much better convection (some difference)
  - similar result (≈2°C rise for doubled CO_2)
- Most other climate models focus on atmospheric (+ some ocean) circulation (more feedback possibilities) but with less sophisticated radiation
  - larger temperature rise (≈2–4.5°C)
- So, are we there yet?
  - is the physics now complete?

One problem to consider …

… what to do about clouds?

The problem with clouds

- Clouds were mentioned only once by Fourier
  - 'the presence of clouds … tempers the cold of the nights'
- Tyndall completely ignored cloud absorption
- Arrhenius and Callendar included fixed clouds
  - both ignored cloud response to longwave radiation
- Most clouds are completely opaque to longwave radiation at all relevant wavelengths
- 65% of the Earth is cloud covered

relative trapping of longwave emission from the surface

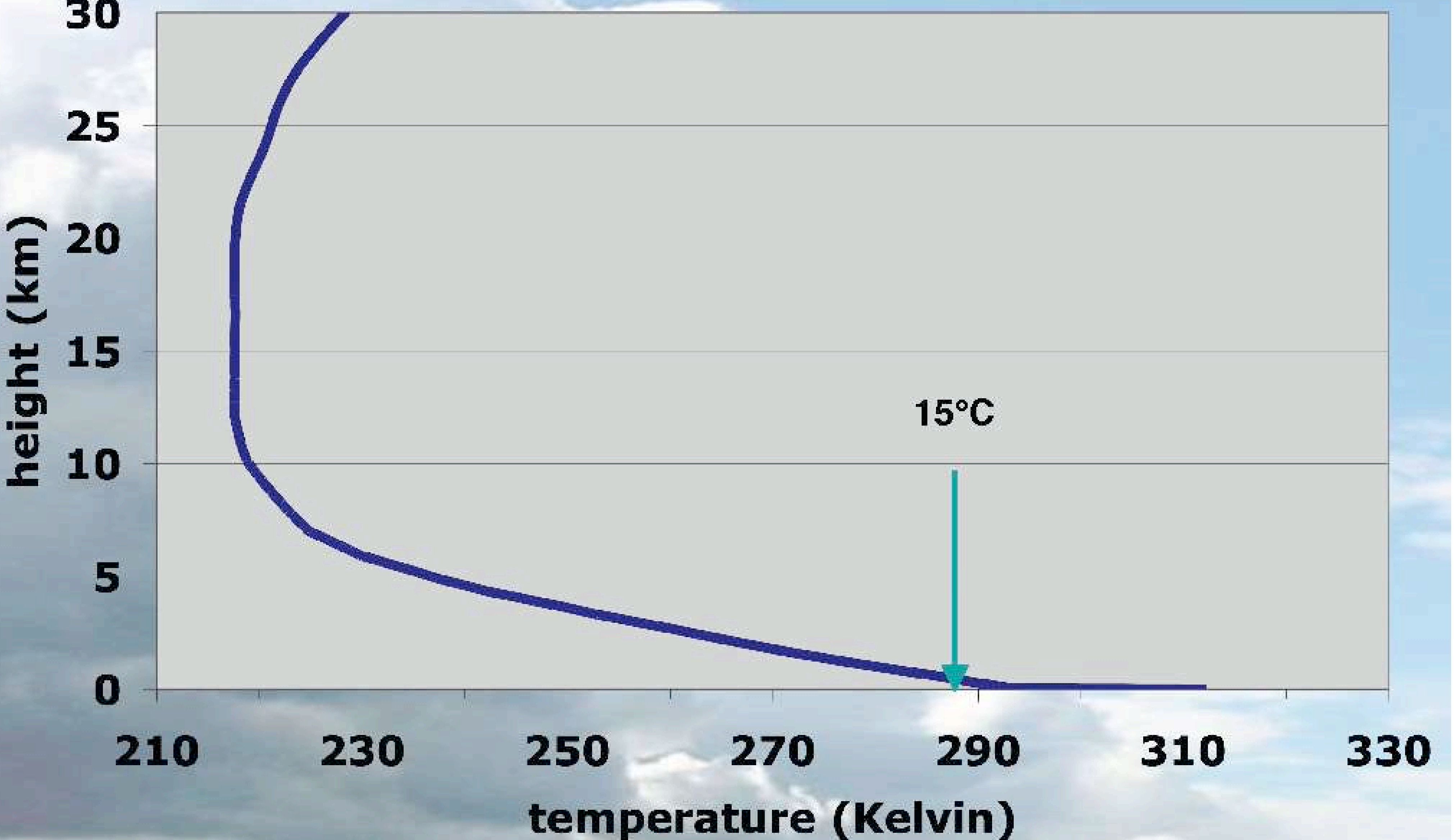
(adapted from Kiehl and Trenberth)

clouds	45%
water vapour	33%
carbon dioxide	15%
others	7%

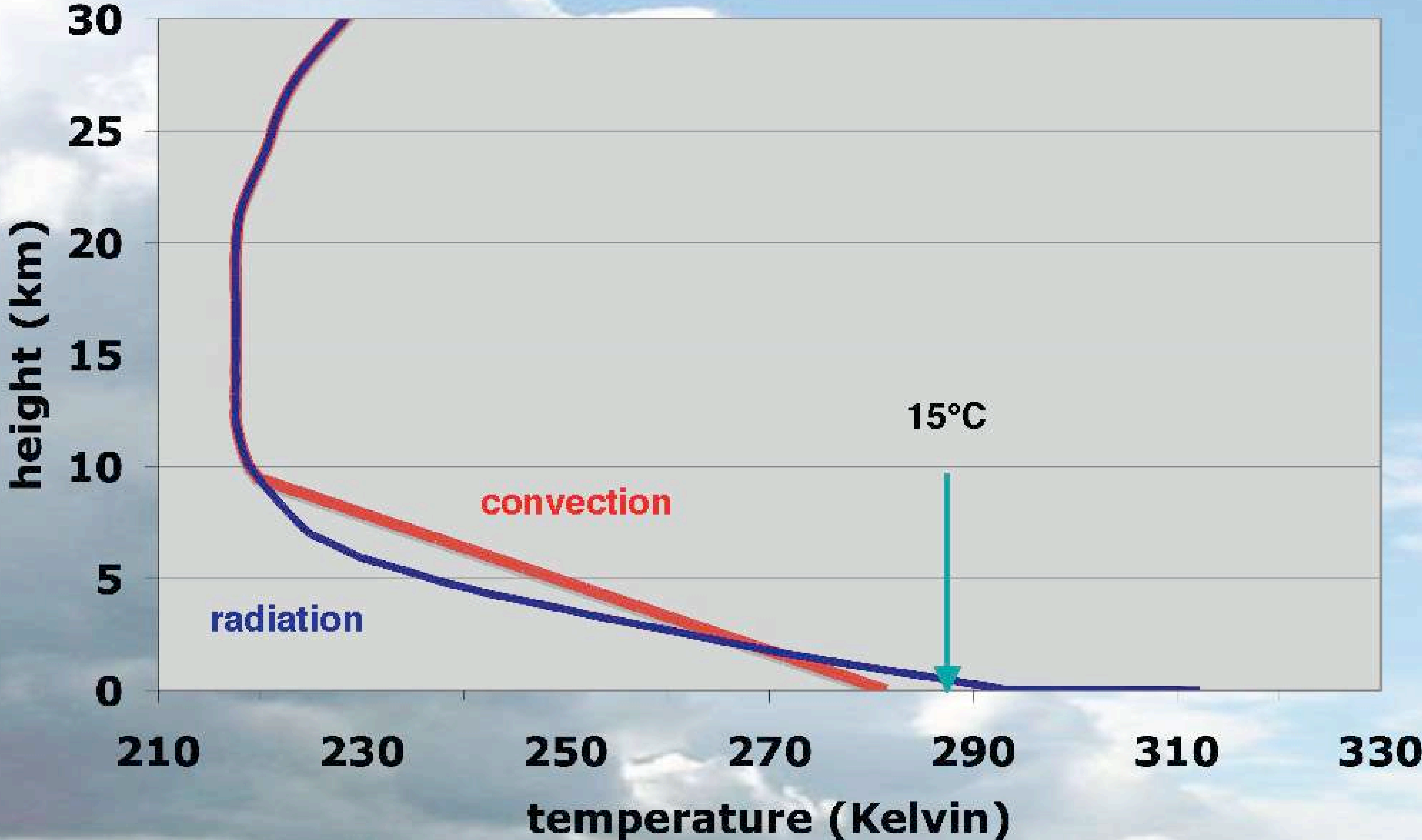
The Cloud Greenhouse Effect

- results from a simplified radiative-convective equilibrium model
- credit: Claire Radley, physics student

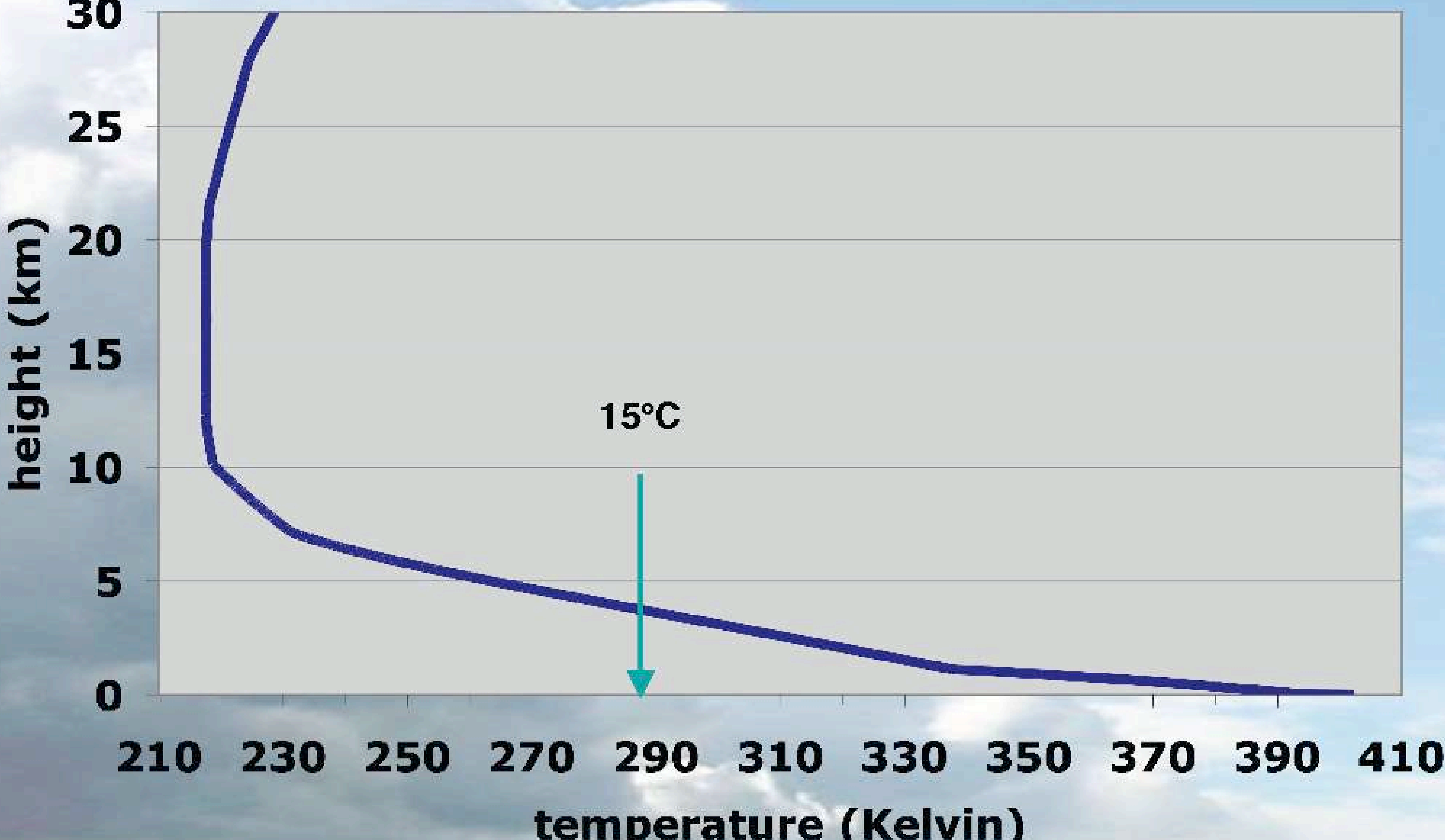
Callendar's Radiative Equilibrium



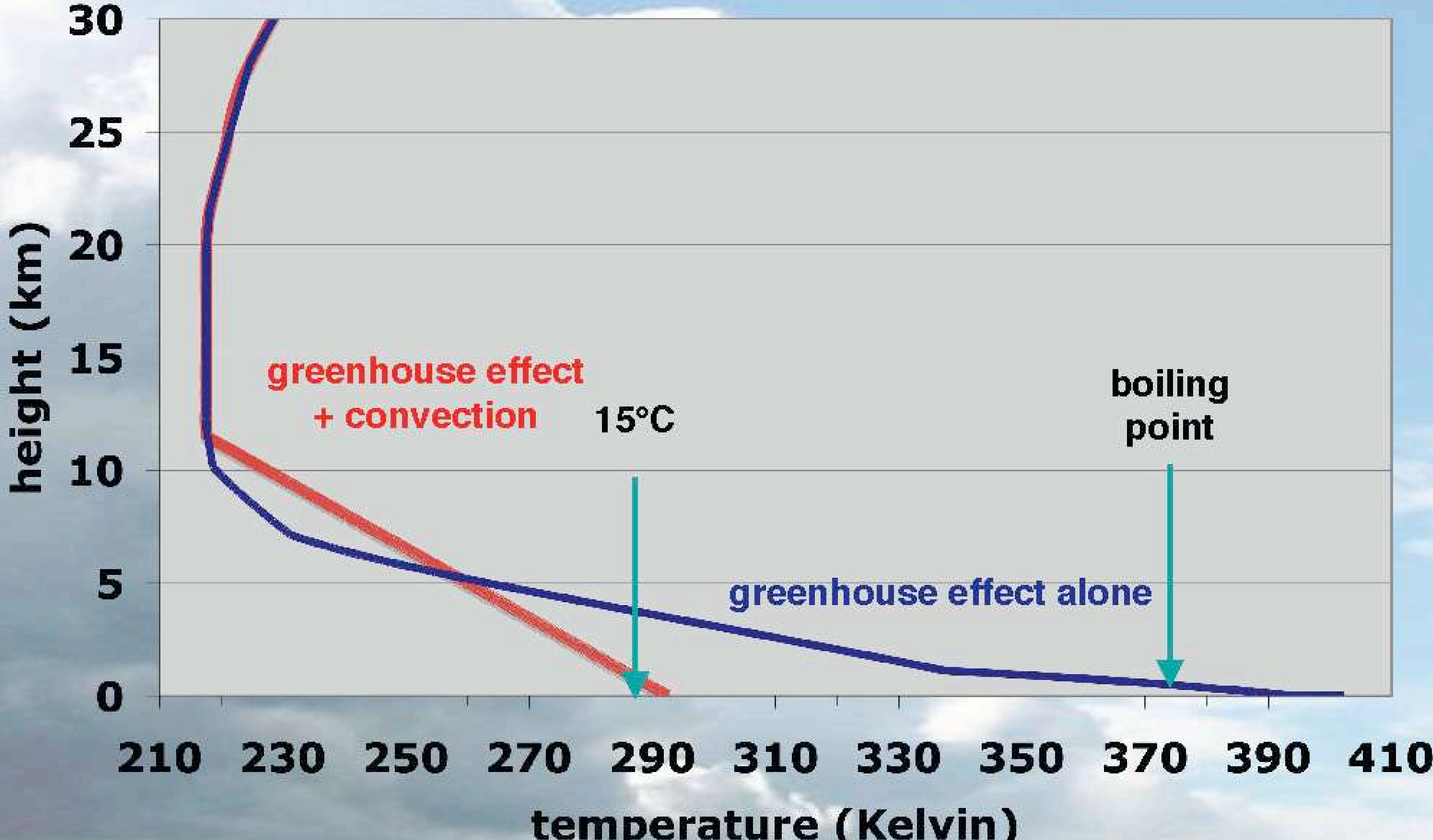
In Radiative-Convective Equilibrium



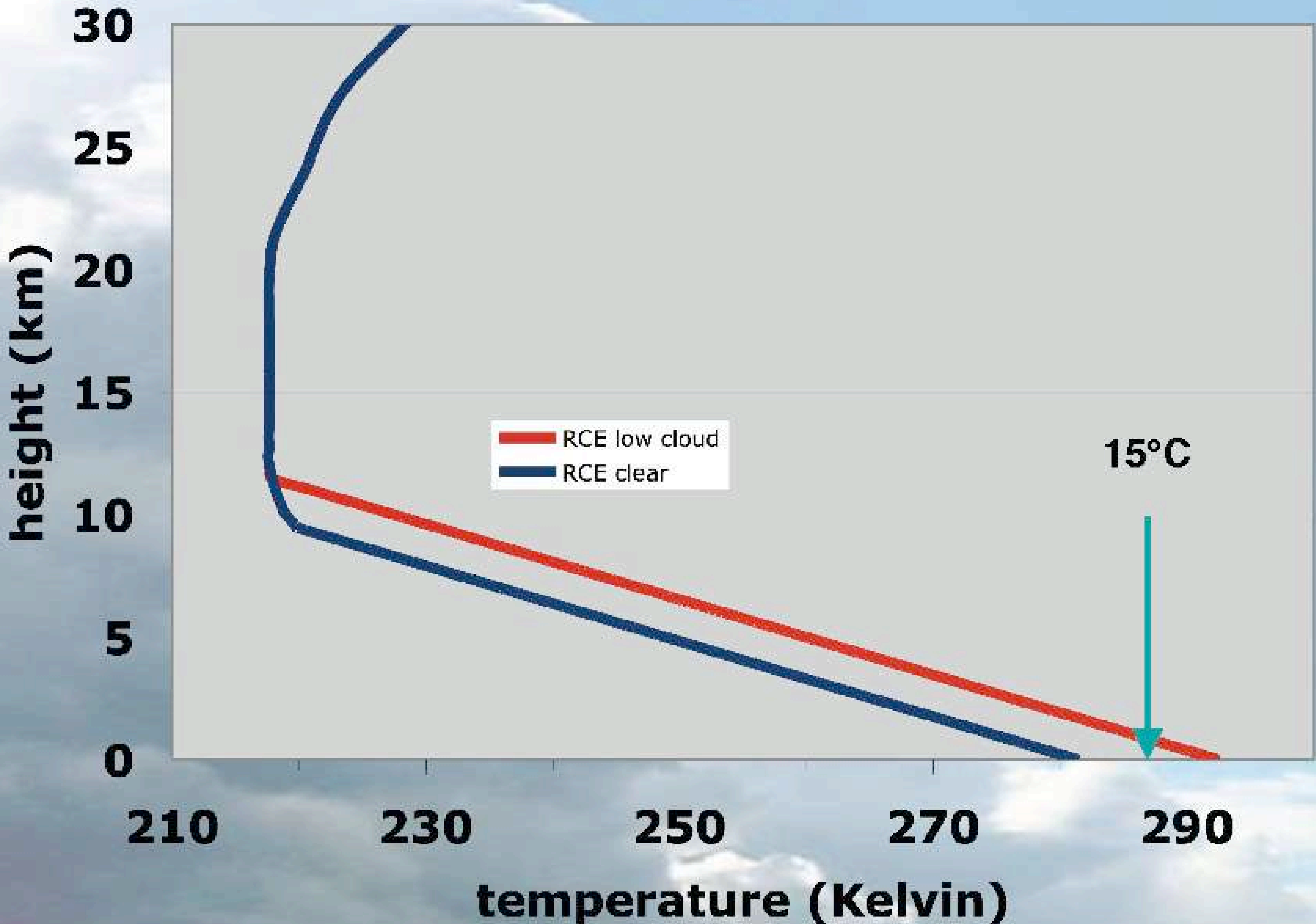
Radiative Equilibrium with Low Clouds



Radiative-Convective Equilibrium with Low Clouds



Radiative-Convective Equilibrium

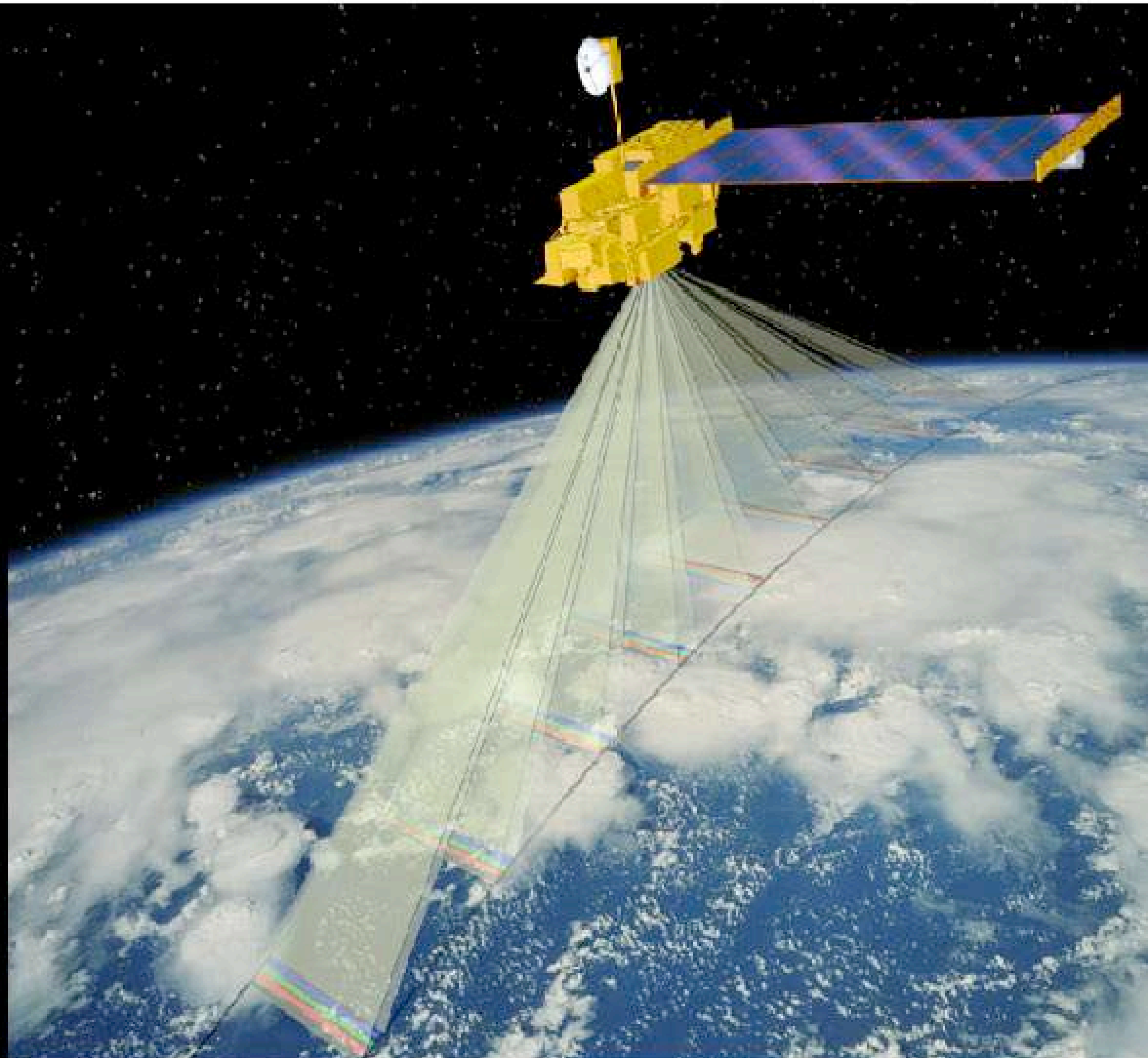


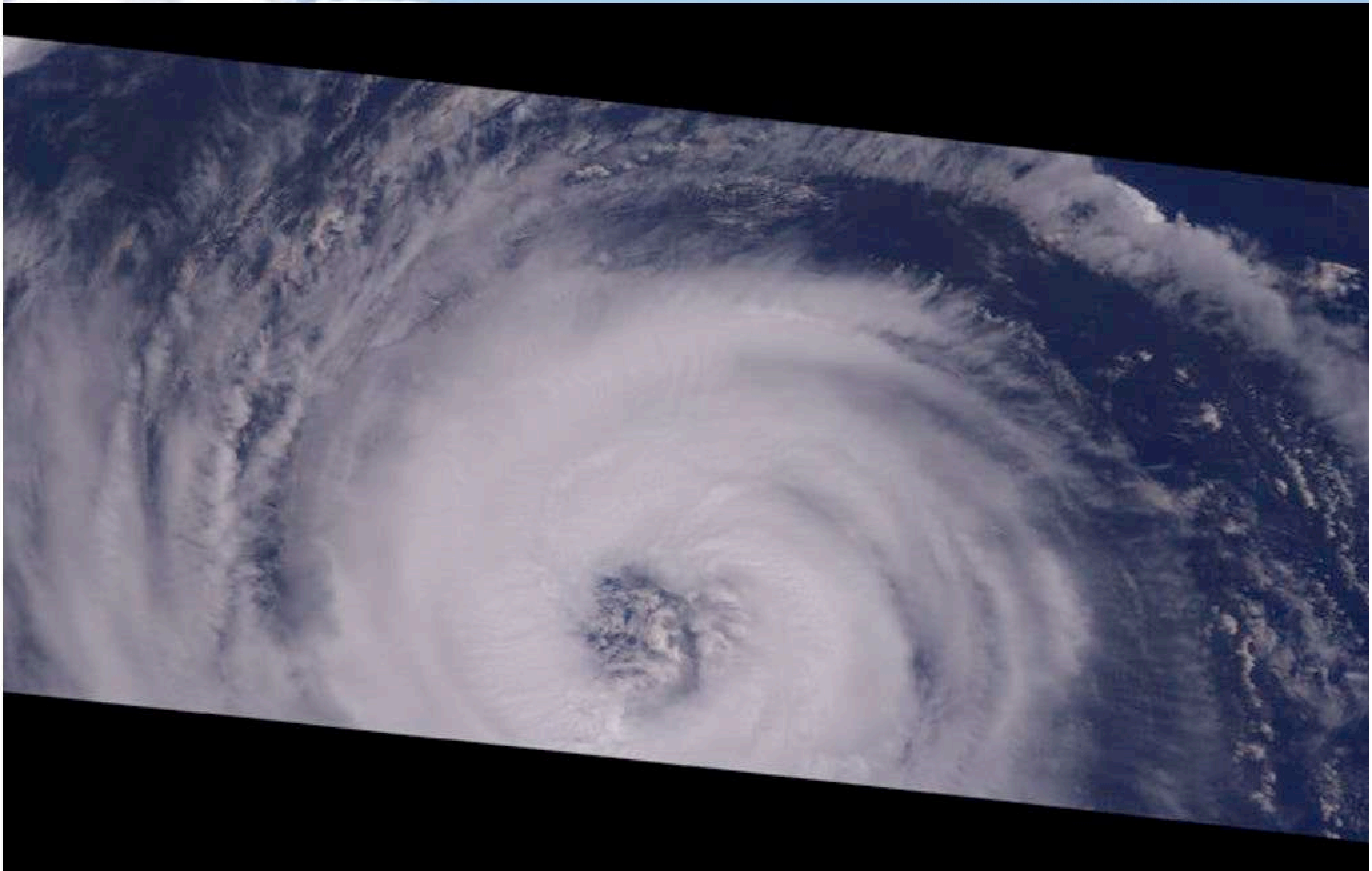
what Fourier, Tyndall, Arrhenius and Callendar did not know

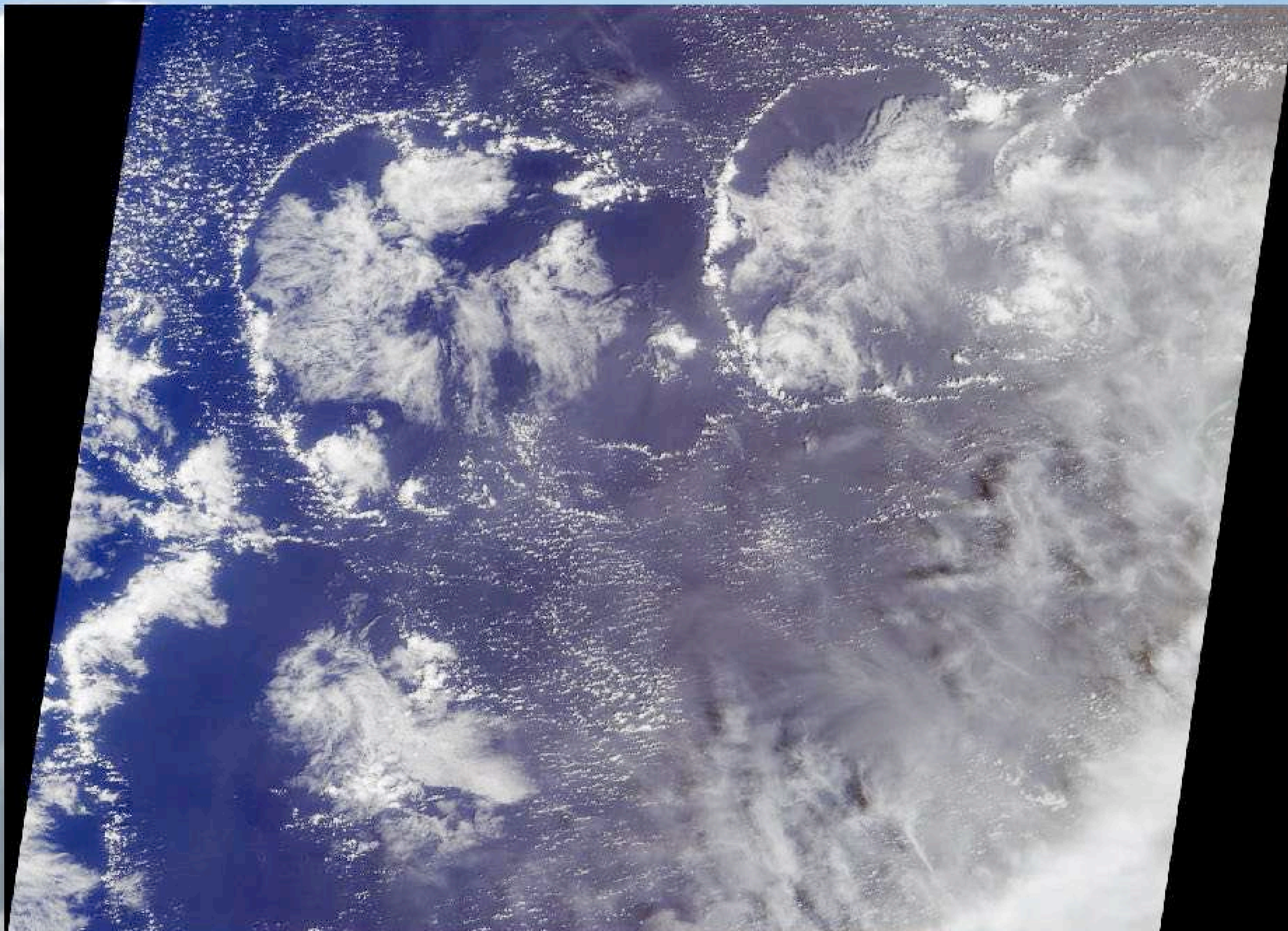
- the greenhouse effect is far more relevant at high altitudes than at low altitudes
- most clouds and water vapour occur at low altitudes, but CO_2 is well-mixed vertically
- high clouds (cirrus) and any high altitude water vapour are extremely important
- any changes in these could swamp the effect of CO_2 changes

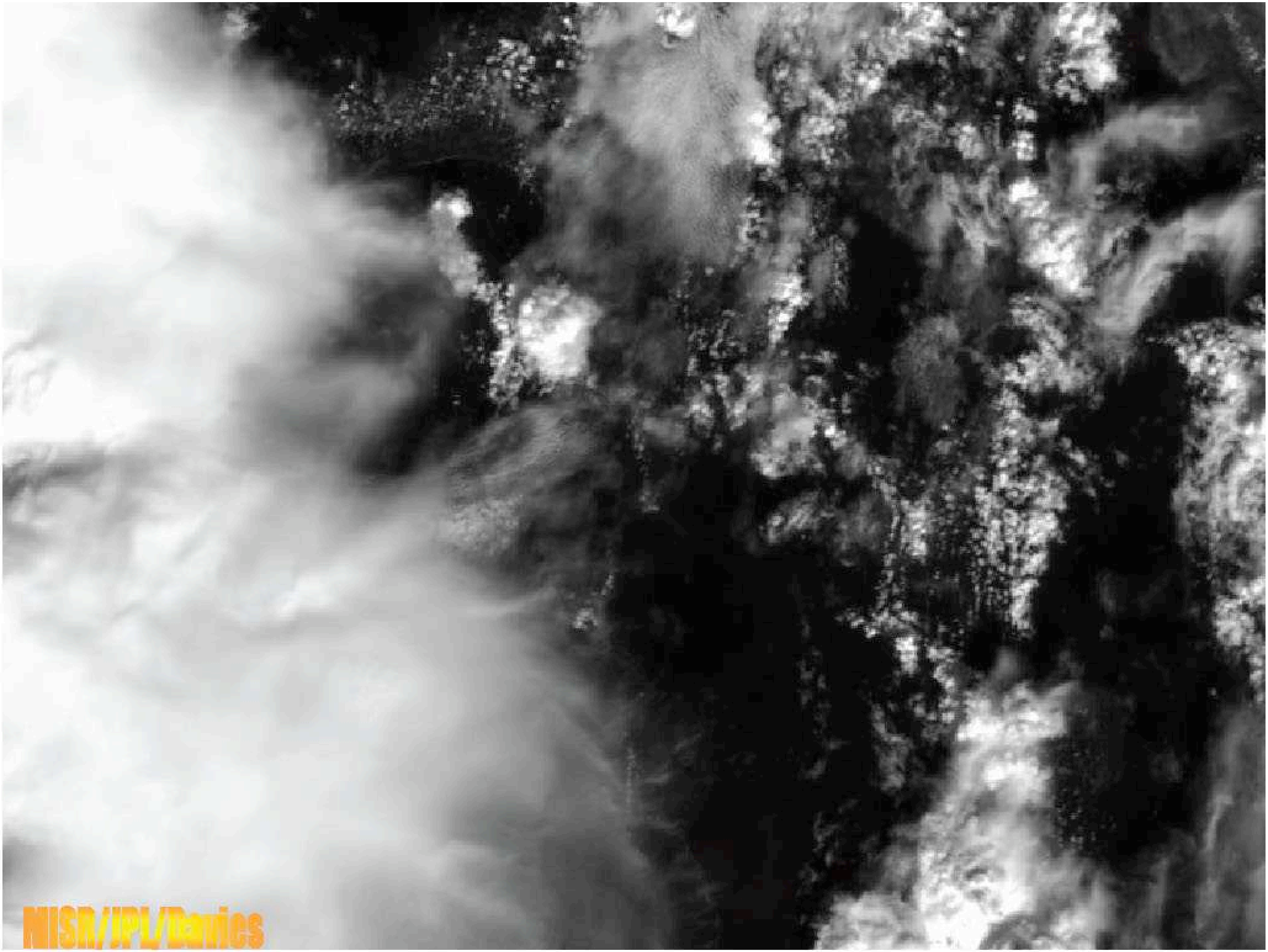
Some Recent Measurements of Clouds from Space

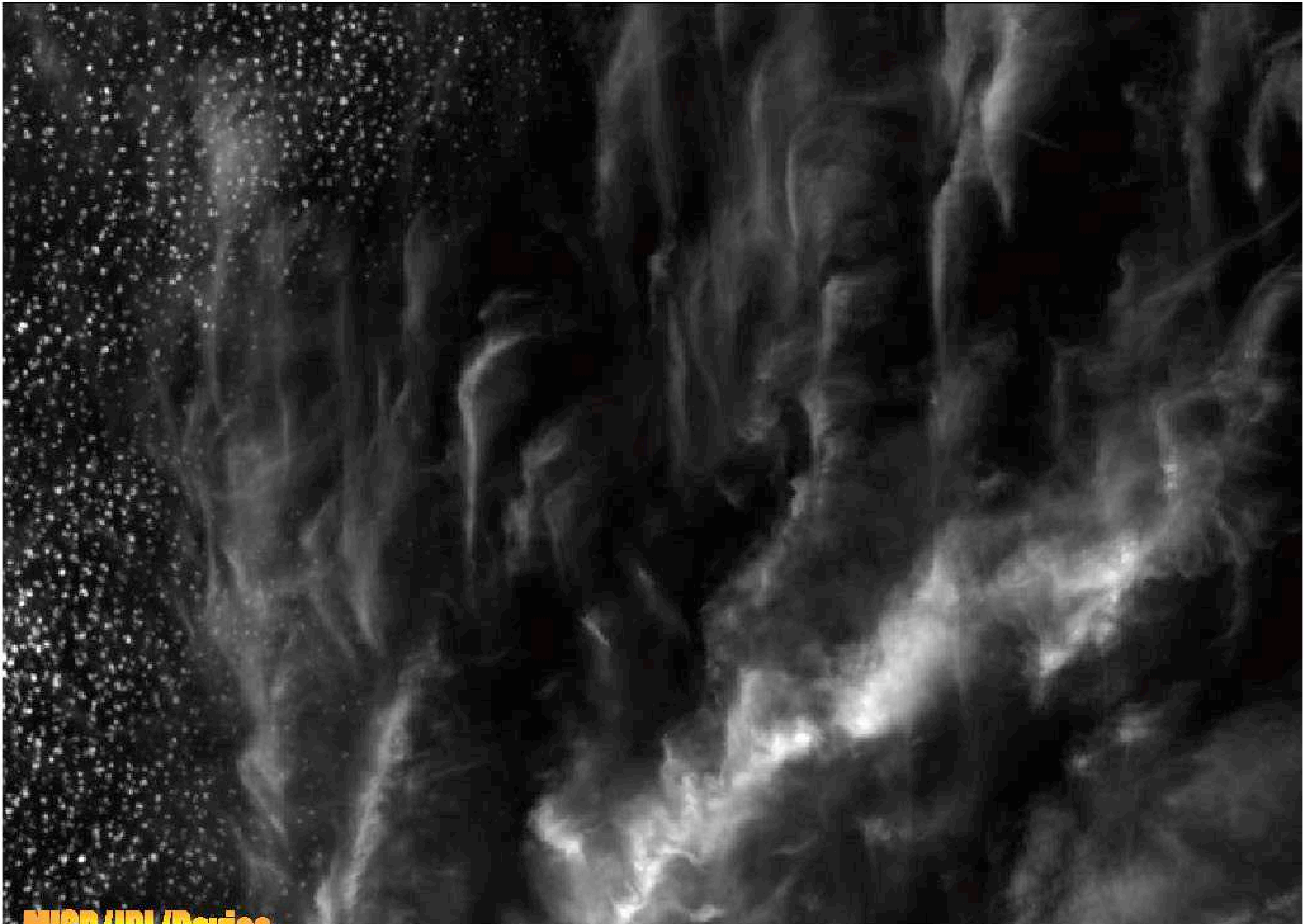
the Terra satellite carries the MISR instrument








MISR/JPL/Davies



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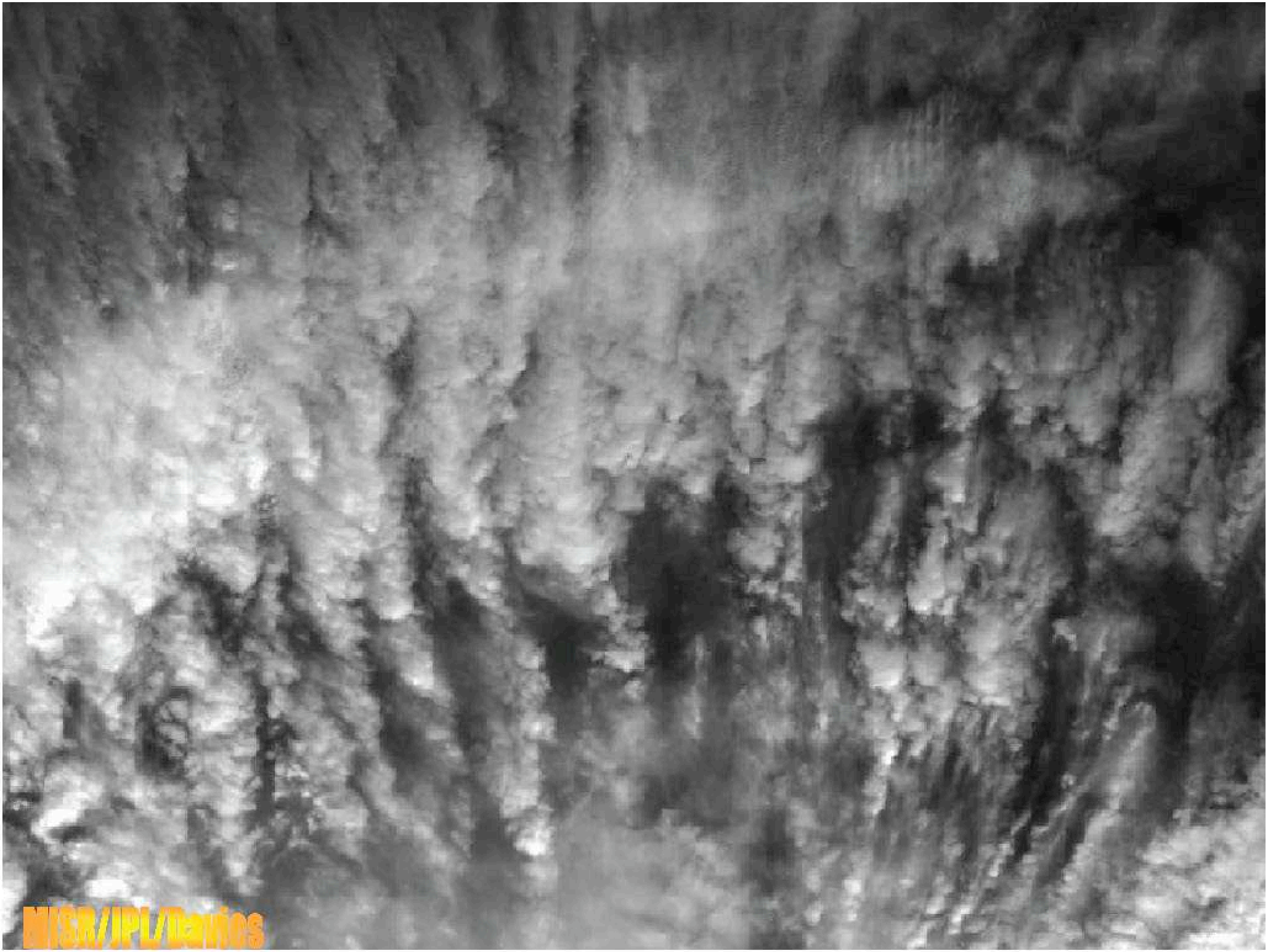
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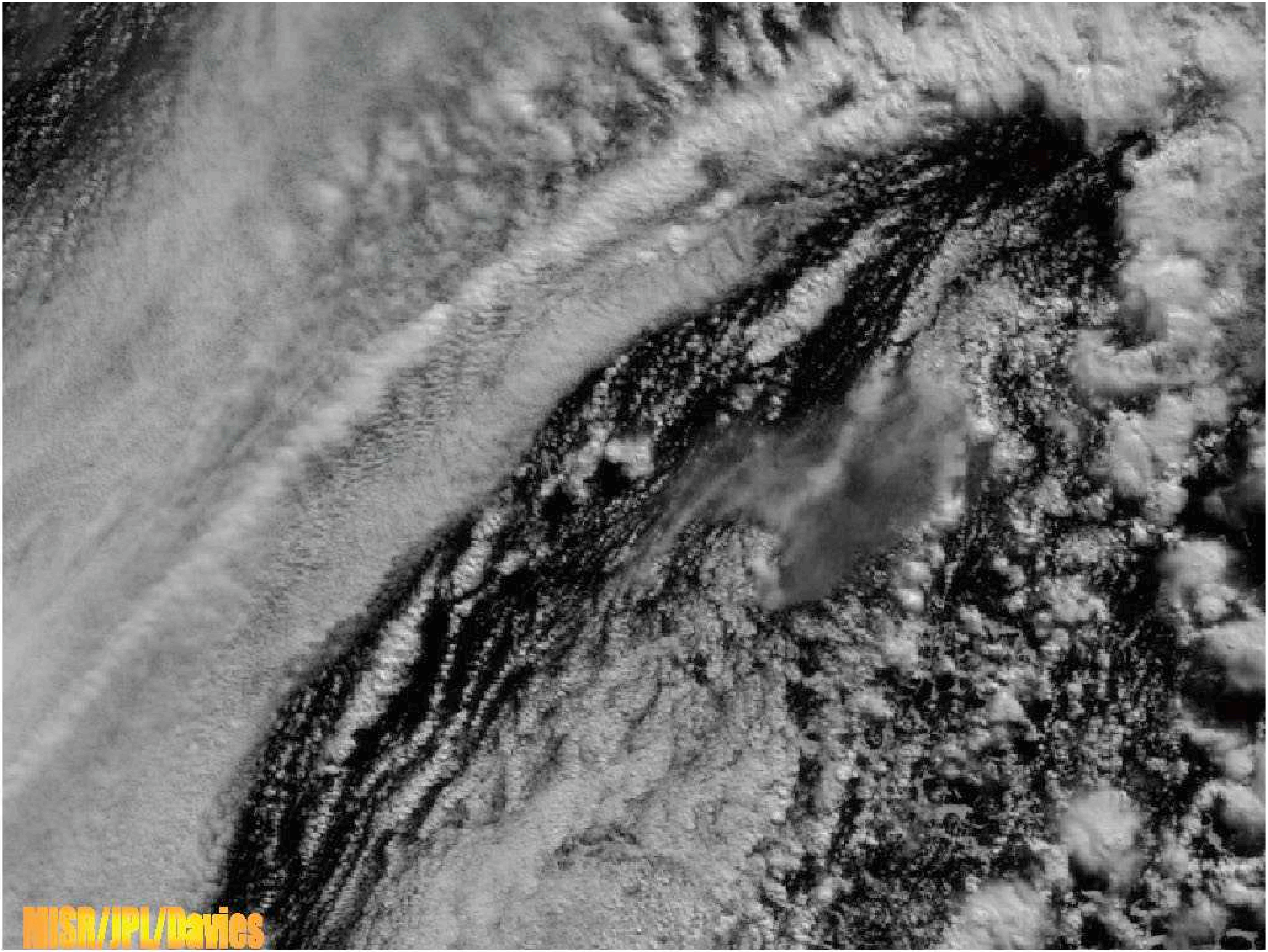
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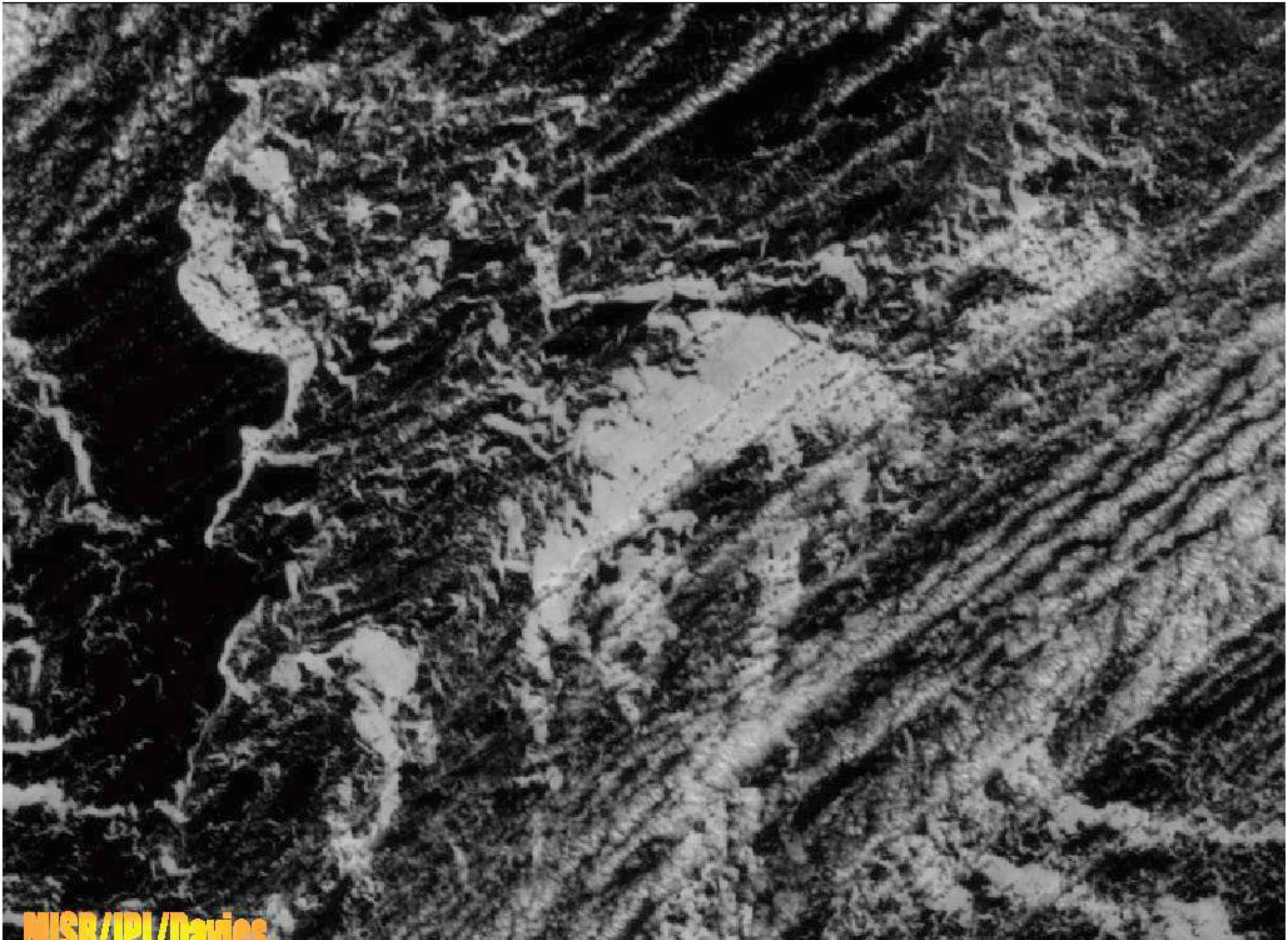
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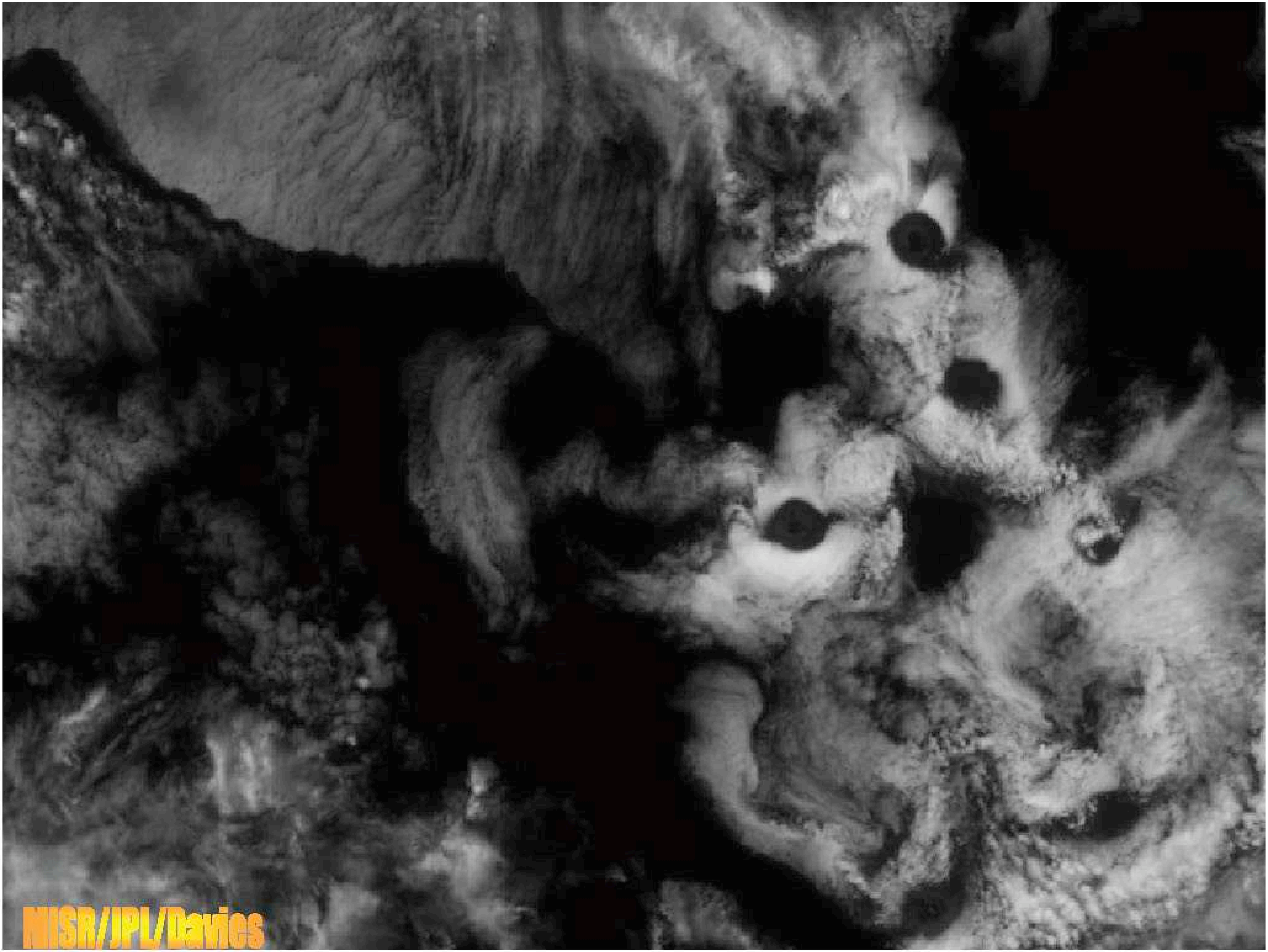
wind driven Sc (far south)


complex open cells


image of the week: moguls

image of the week: small closed cells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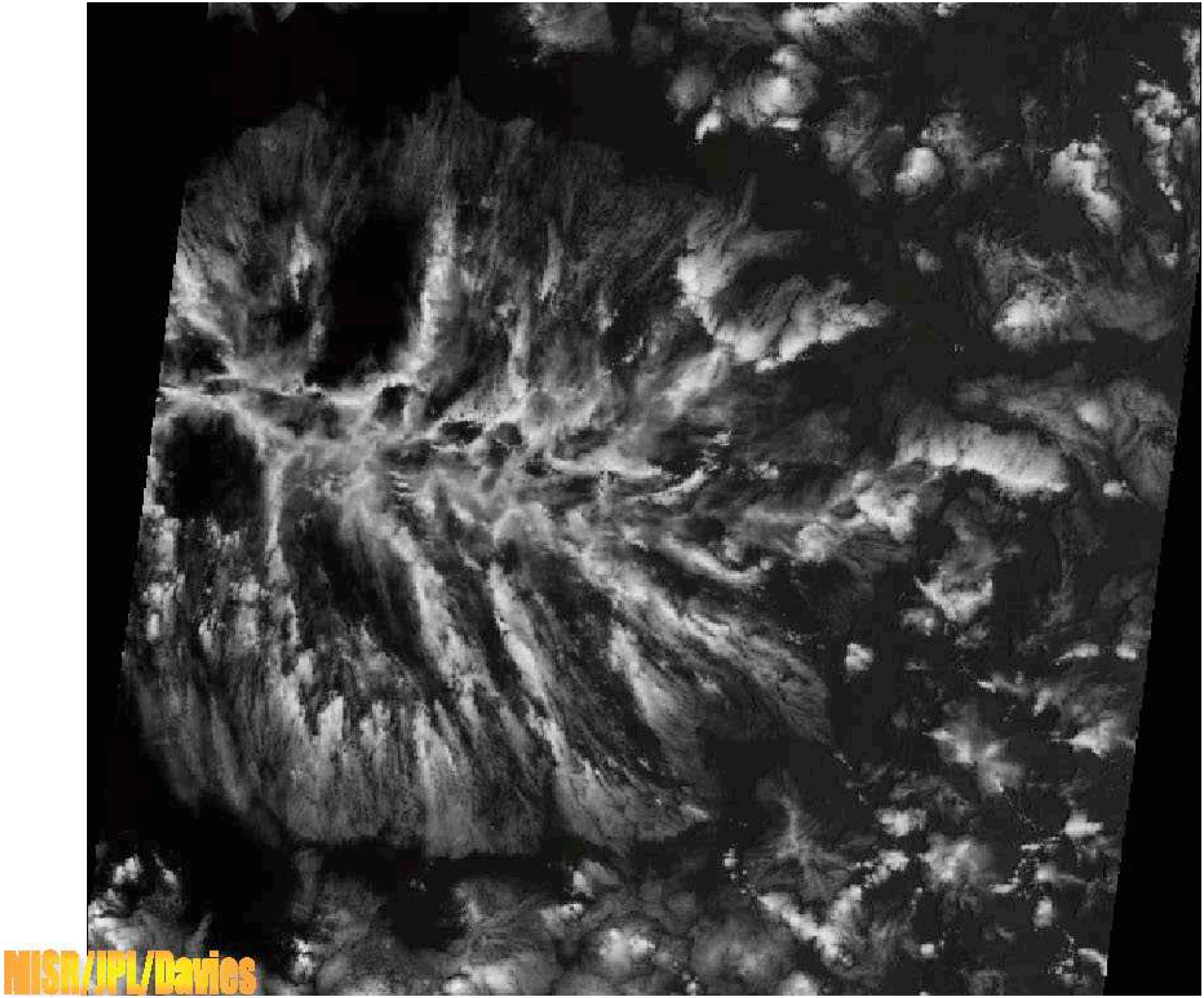
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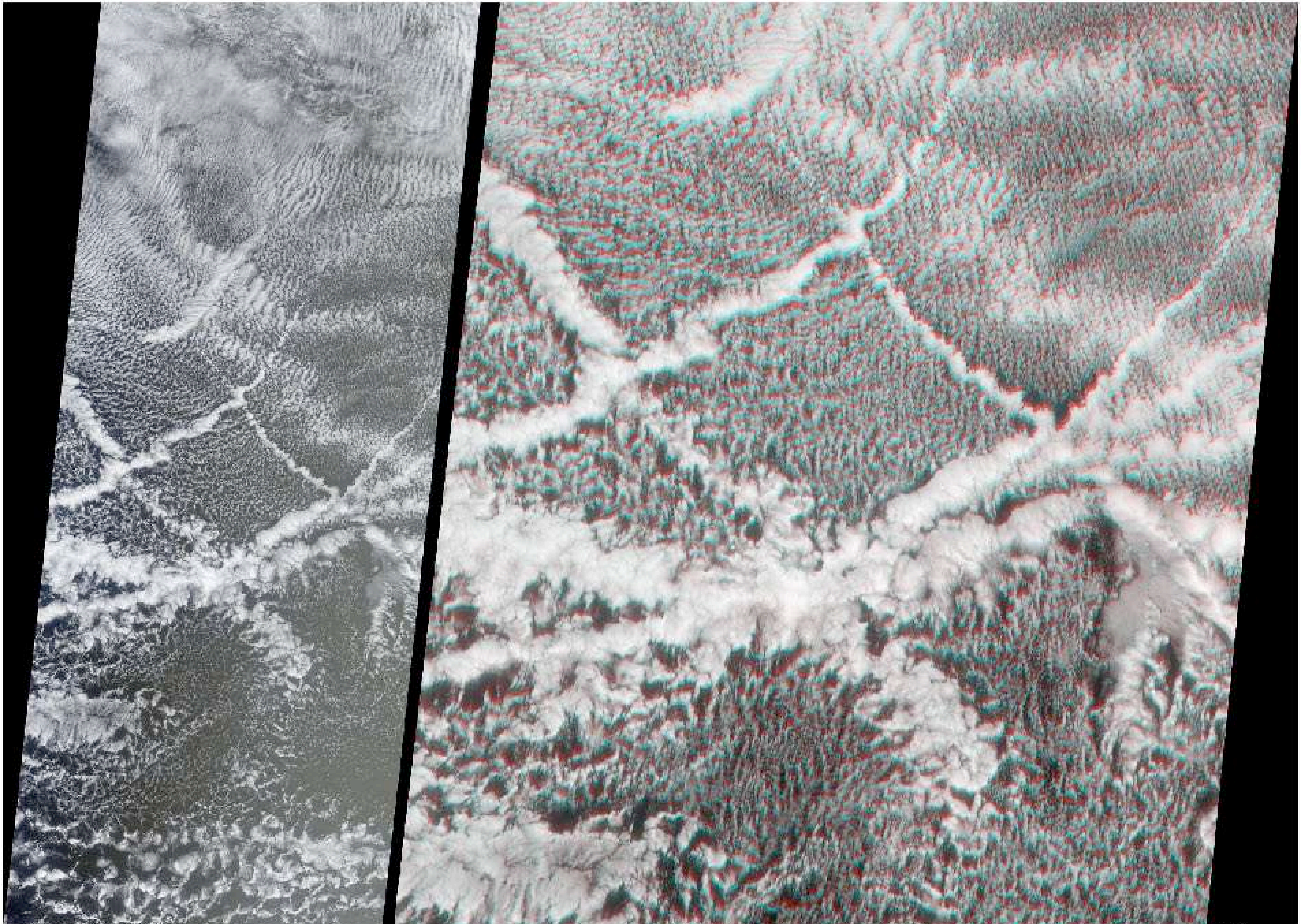
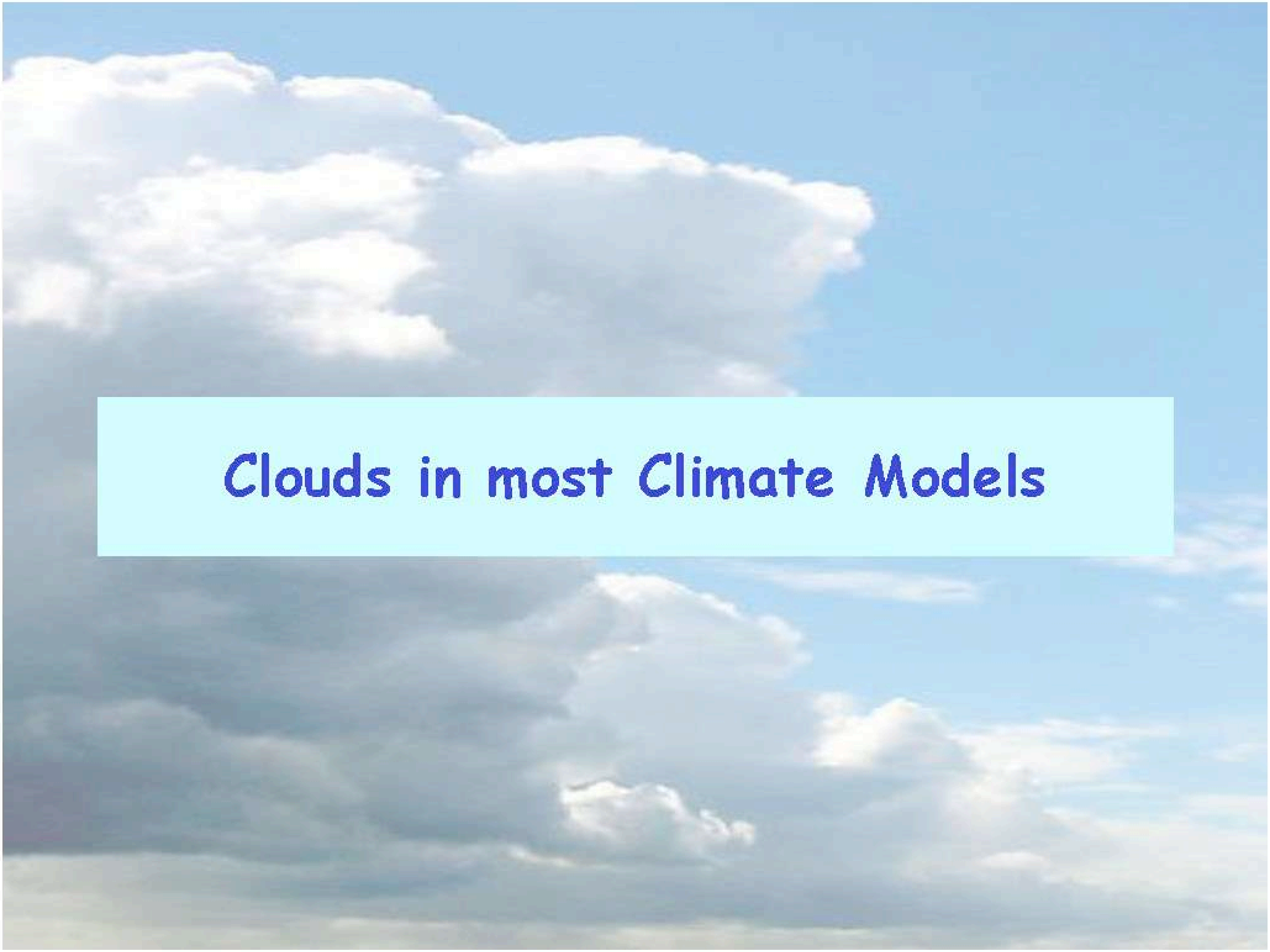
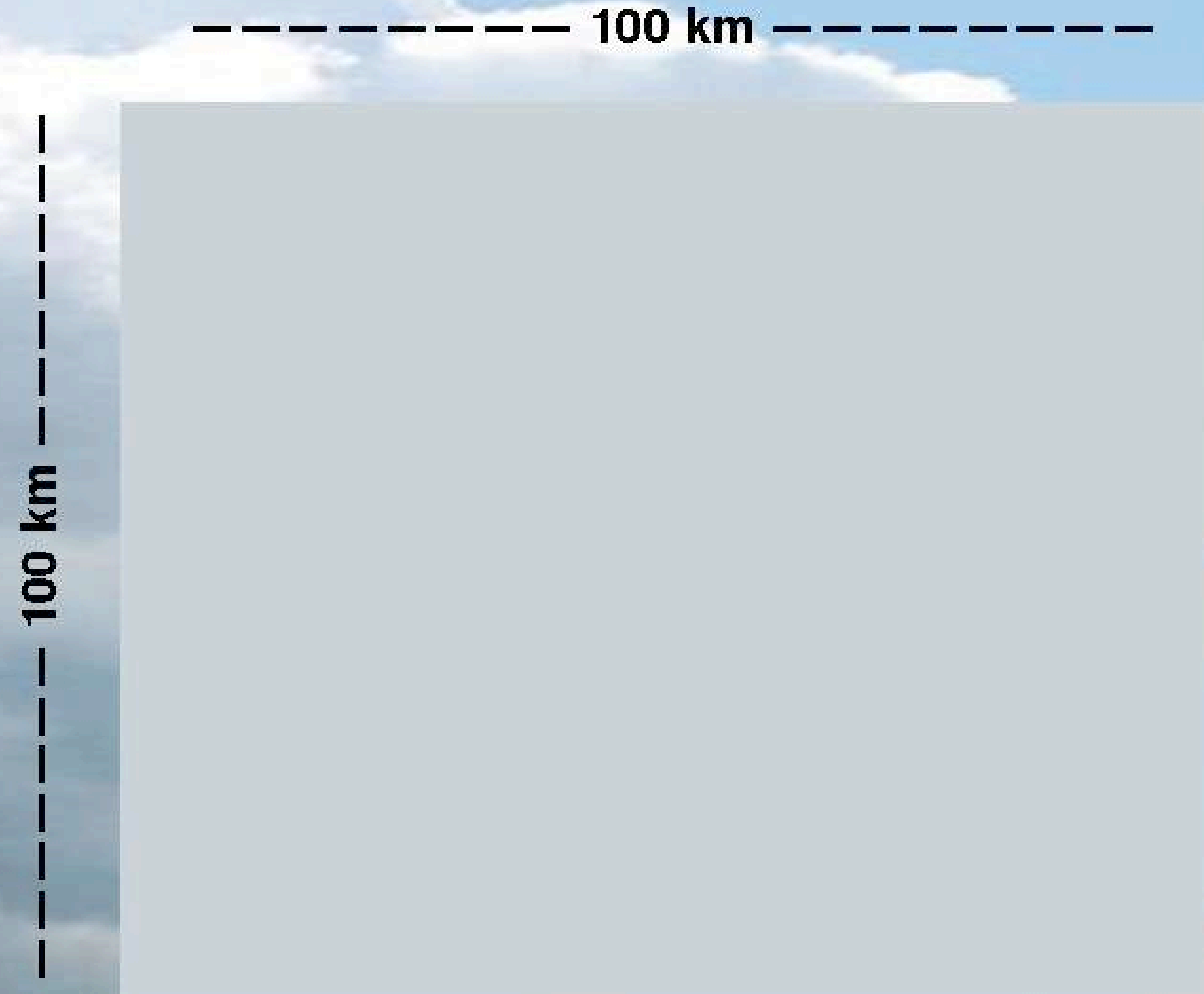



Clouds in most Climate Models

General Circulation Model Clouds



MISR's main discoveries, 2000–now

- cloud height has been lowering
  - 11 m/yr globally
  - 70 m/yr near equator
  - this is a global cooling effect equivalent to the rate of CO_2 increase
- reflectivity has decreased, but only at high Northern Hemisphere latitudes
  - consistent with reduction in Arctic ice, modified by clouds
    - big darkening in 2006, compared with 2005 and 2007
  - this is a warming effect globally equivalent to 3x the rate of CO_2 increase
- which effect will win over time?

In Summary

- we have learned a lot about the climate system from the legacy of Fourier, Tyndall, Arrhenius and Callendar
- however, we have not yet learned enough to escape the fate of the Enlightenment Era predictions
  - assuming we are constrained to the scientific method
- for example, we need to know more about cloud albedos and high altitude cloud amounts
  - what controls these?
  - how do they respond to changes in surface temperature?
- these are merely necessary conditions
  - they are not likely to be sufficient


That's all folks!