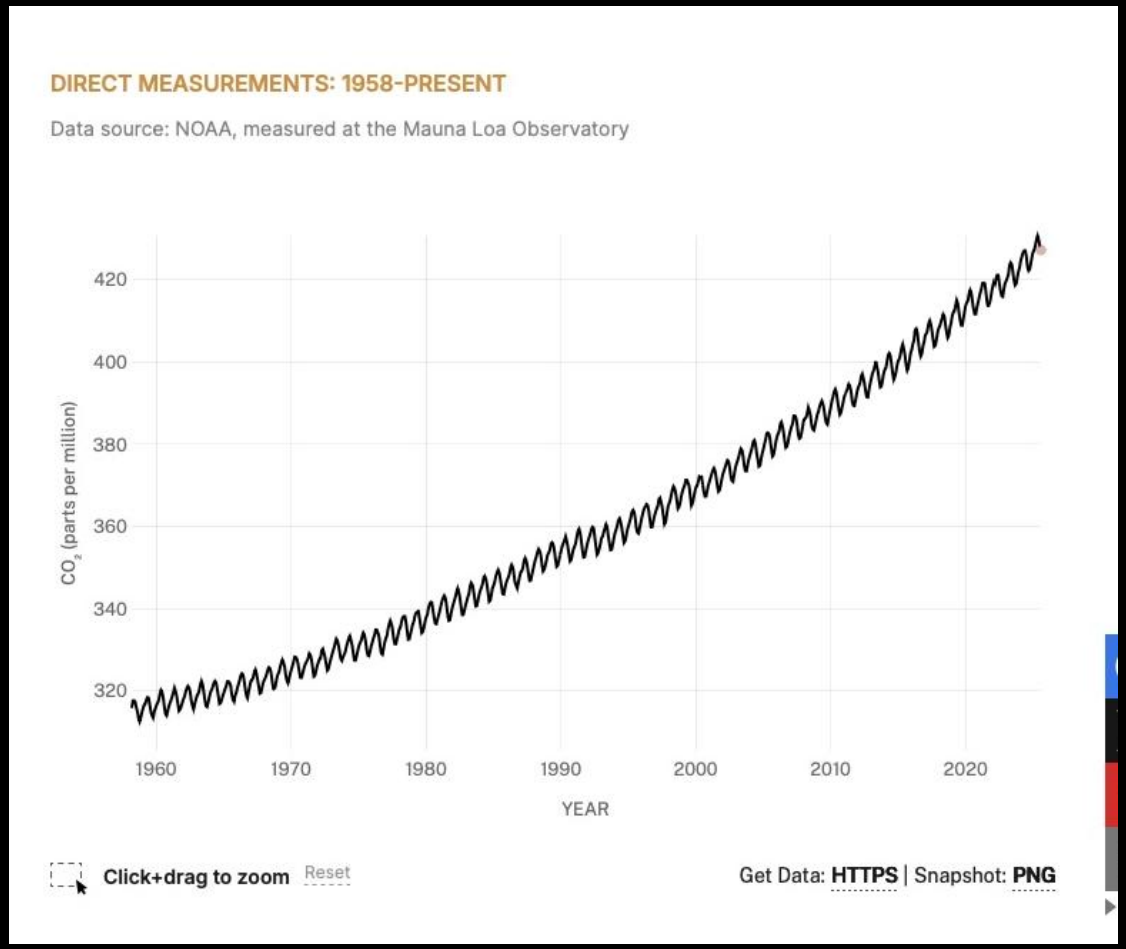
Science of Climate Change:
Personal Journey from Human Impacts into Human Resilience

Grande Médaille Lecture
The Institut de France
Paris; Sept 09, 2025

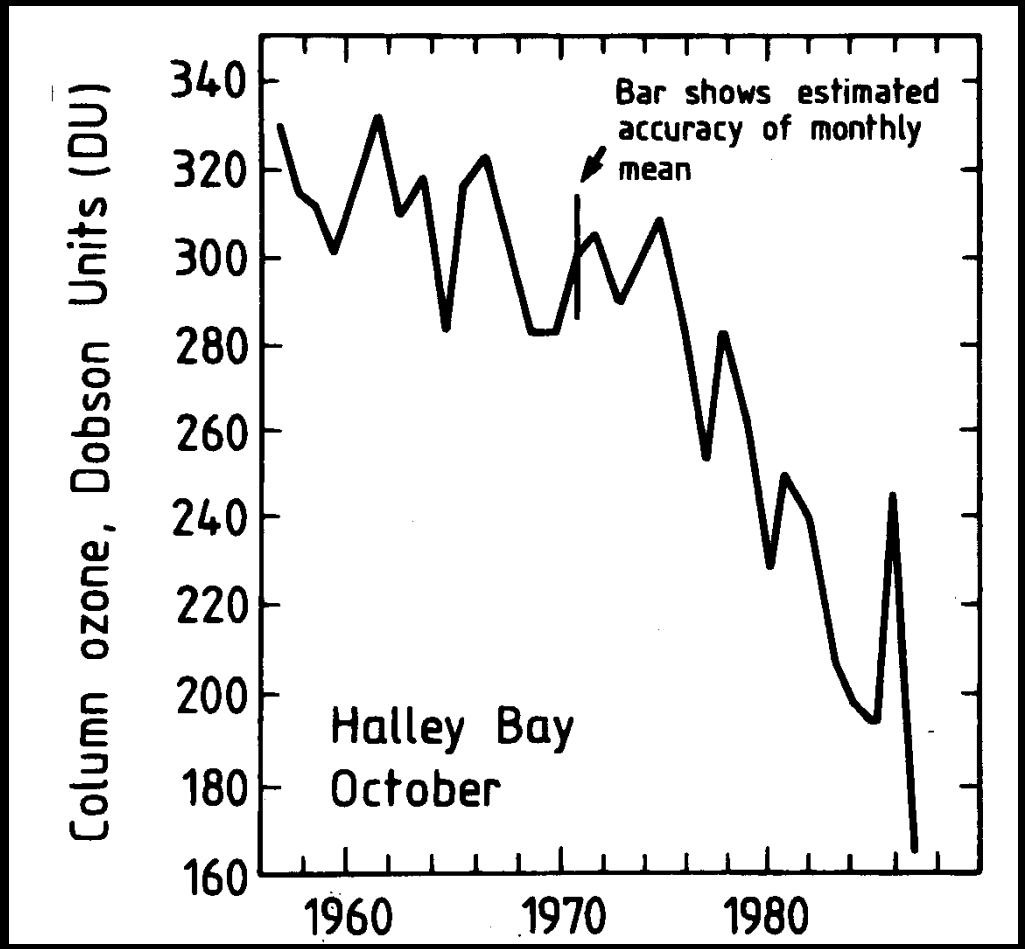
Veerabhadran Ramanathan
Scripps Institution of Oceanography, University of California at San Diego
& College of Agriculture and Life Sciences, Cornell University.

Icons of Human Impacts

Carbon Dioxide: Keeling Curve



Antarctic Ozone: Farman



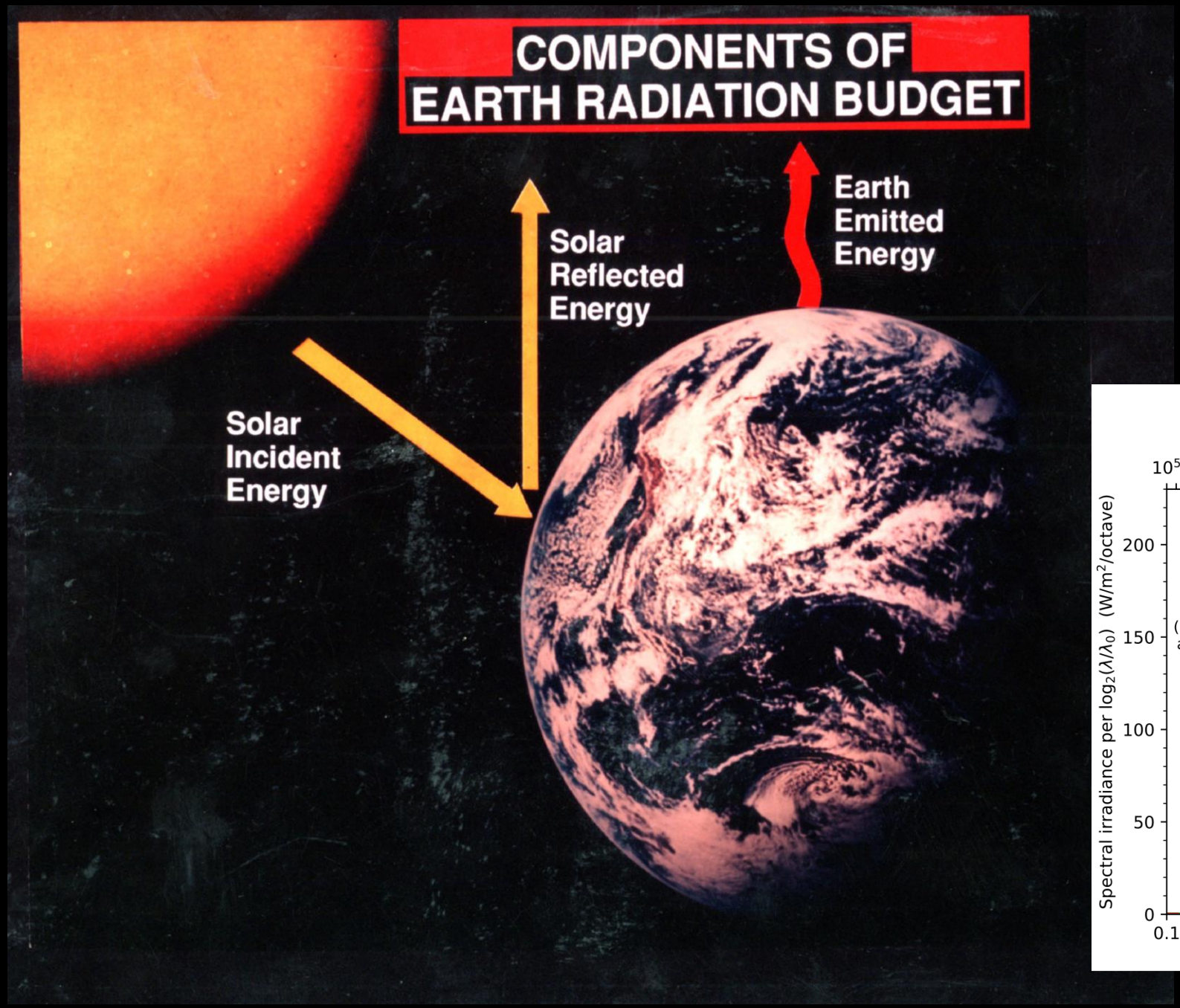
The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment

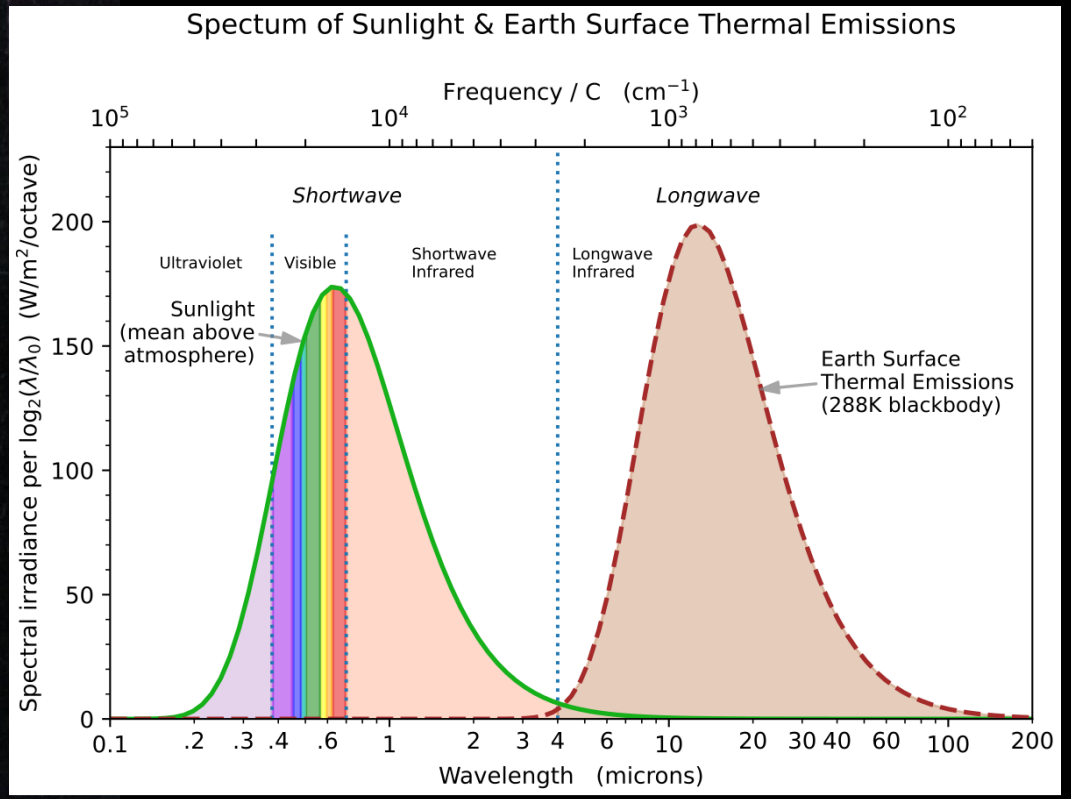
V. RAMANATHAN

1988
Science
AAAS

IN 1827, THE PHYSICIST-MATHEMATICIAN JEAN-BAPTISTE Fourier (*1*, p. 569) stated aptly: "The question of global temperatures, one of the most important and most difficult in all natural philosophy, is composed of rather diverse elements which should be considered under one general viewpoint" (translation

predicted changes, during the next few decades, could far exceed natural climate variations in historical times.

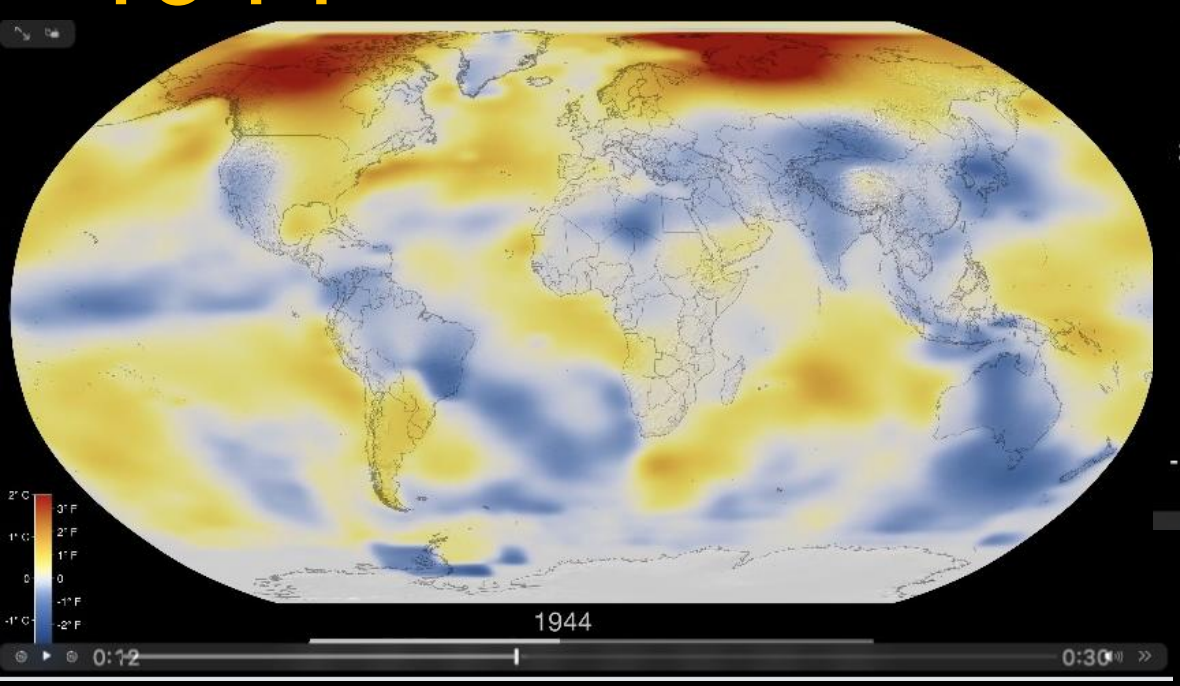

COMPONENTS OF
EARTH RADIATION BUDGET
Earth
Emitted
Energy
Solar
Reflected
Energy
Solar
Incident
Energy


Spectum of Sunlight & Earth Surface Thermal Emissions
Frequency / C (cm^{-1})
10^5
10^4
10^3
10^2
Shortwave
Longwave
Ultraviolet
Visible
Shortwave
Infrared
Longwave
Infrared
Sunlight
(mean above
atmosphere)
Earth Surface
Thermal Emissions
(288K blackbody)
Spectral irradiance per log$_2$(λ/λ_0) (W/m^2/octave)
0
50
100
150
200
0.1
.2
.3
.4
.6
1
2
3
4
6
10
20
30
40
60
100
200
Wavelength (microns)

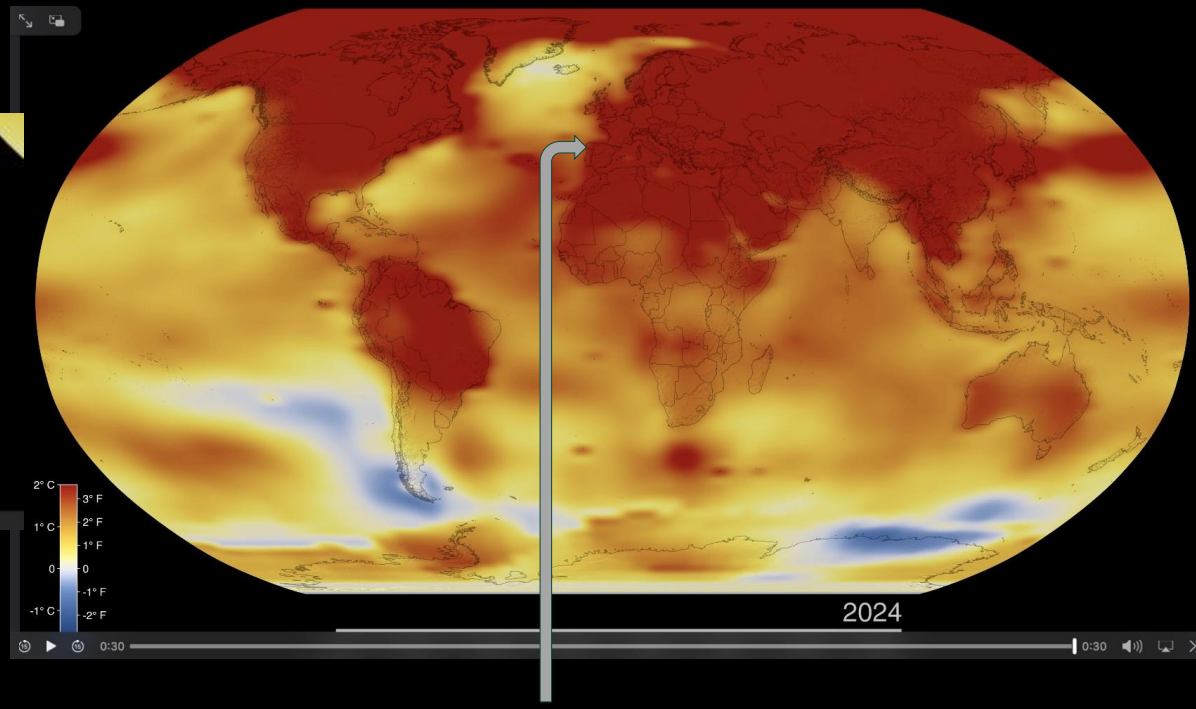
What is Happening?

Source: NASA

1944



2024



https://svs.gsfc.nasa.gov/5450/

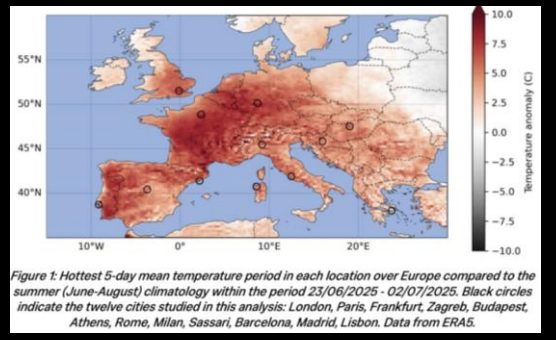


Figure 1: Hottest 5-day mean temperature period in each location over Europe compared to the summer (June-August) climatology within the period 23/06/2025 - 02/07/2025. Black circles indicate the twelve cities studied in this analysis: London, Paris, Frankfurt, Zagreb, Budapest, Athens, Rome, Milan, Sassari, Barcelona, Madrid, Lisbon. Data from ERA5.

2025 summer Extremes

Grantham Inst, 2025

My personal journey Began in a S. Indian Village

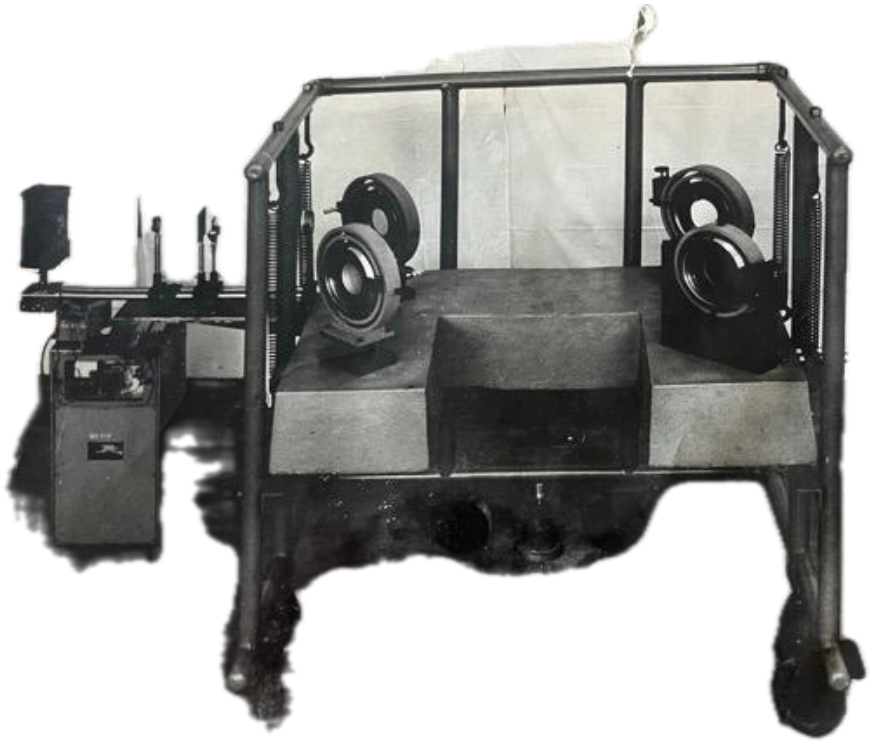
Next to Grandfather's Home, Eraharam, South India:
Photo: 2004; Ramanathan

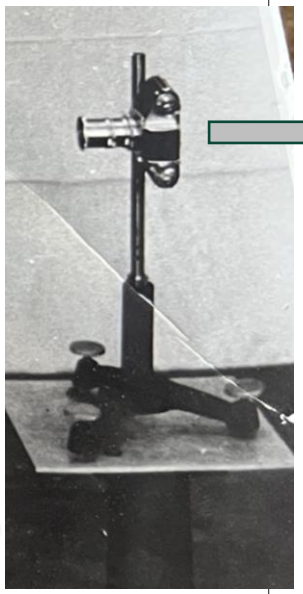
DESIGN AND DEVELOPMENT OF A
MACH-ZEHNDER INTERFEROMETER AND ITS USE
IN THE STUDY OF OSCILLATORY CONVECTIVE HEAT TRANSFER

By
V. RAMANATHAN

Department of Mechanical Engineering
Indian Institute of Science
Bangalore
September 1969

Interferograms: Transition from free and forced convection to Turbulent Flows





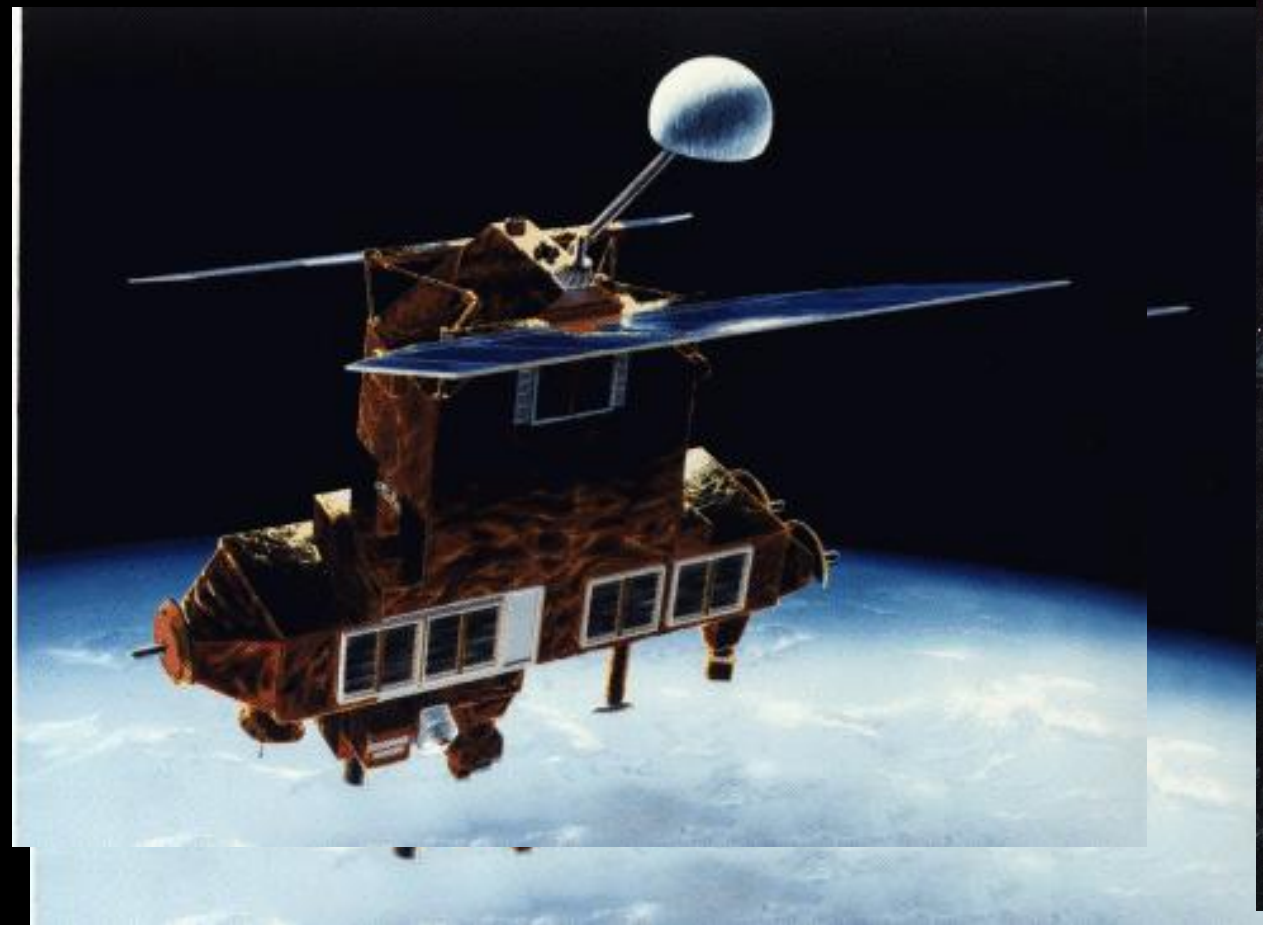
Onset of Turbulence

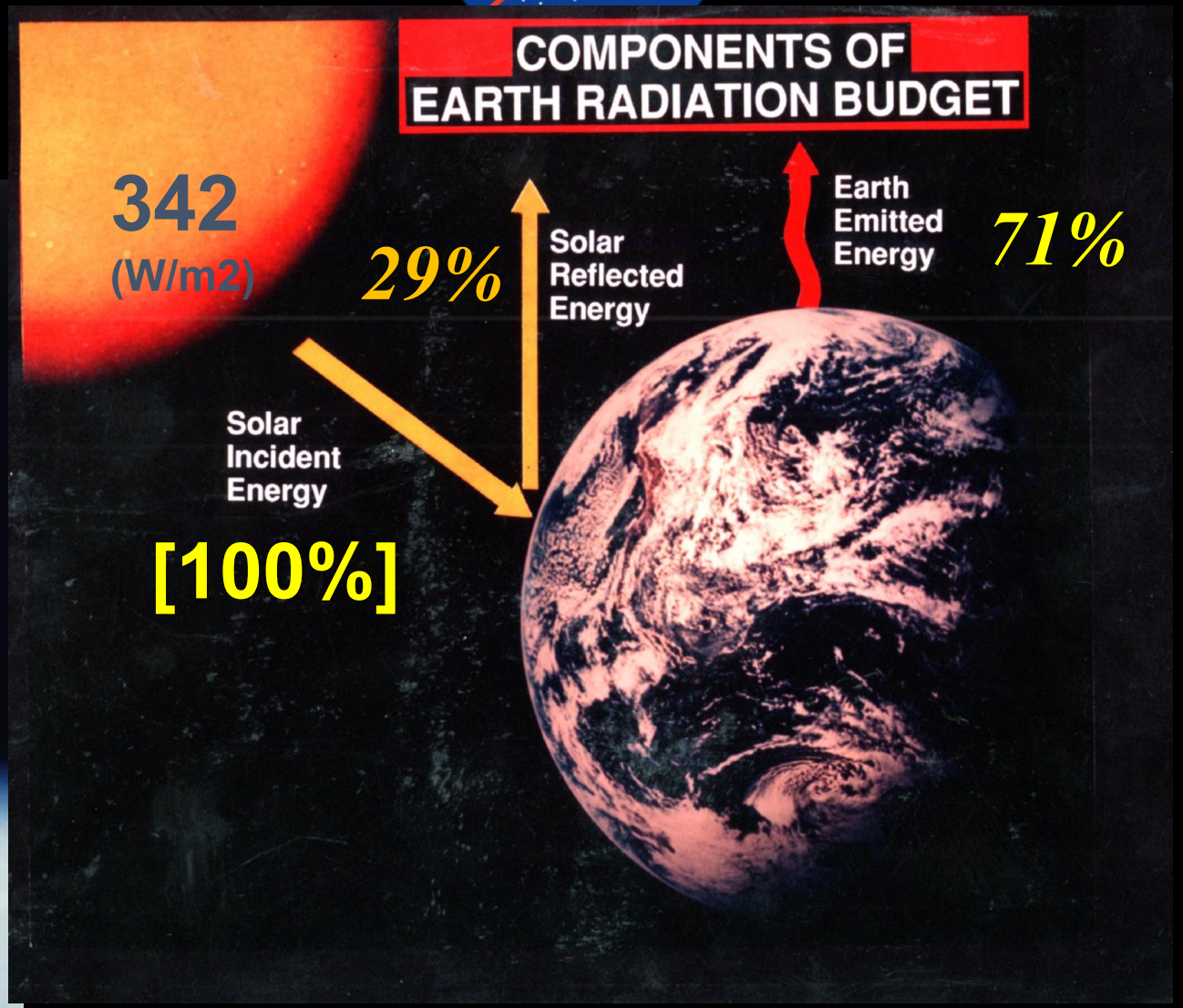
Laminar

1967 to 1969

Climate journey began in 1974 at NASA

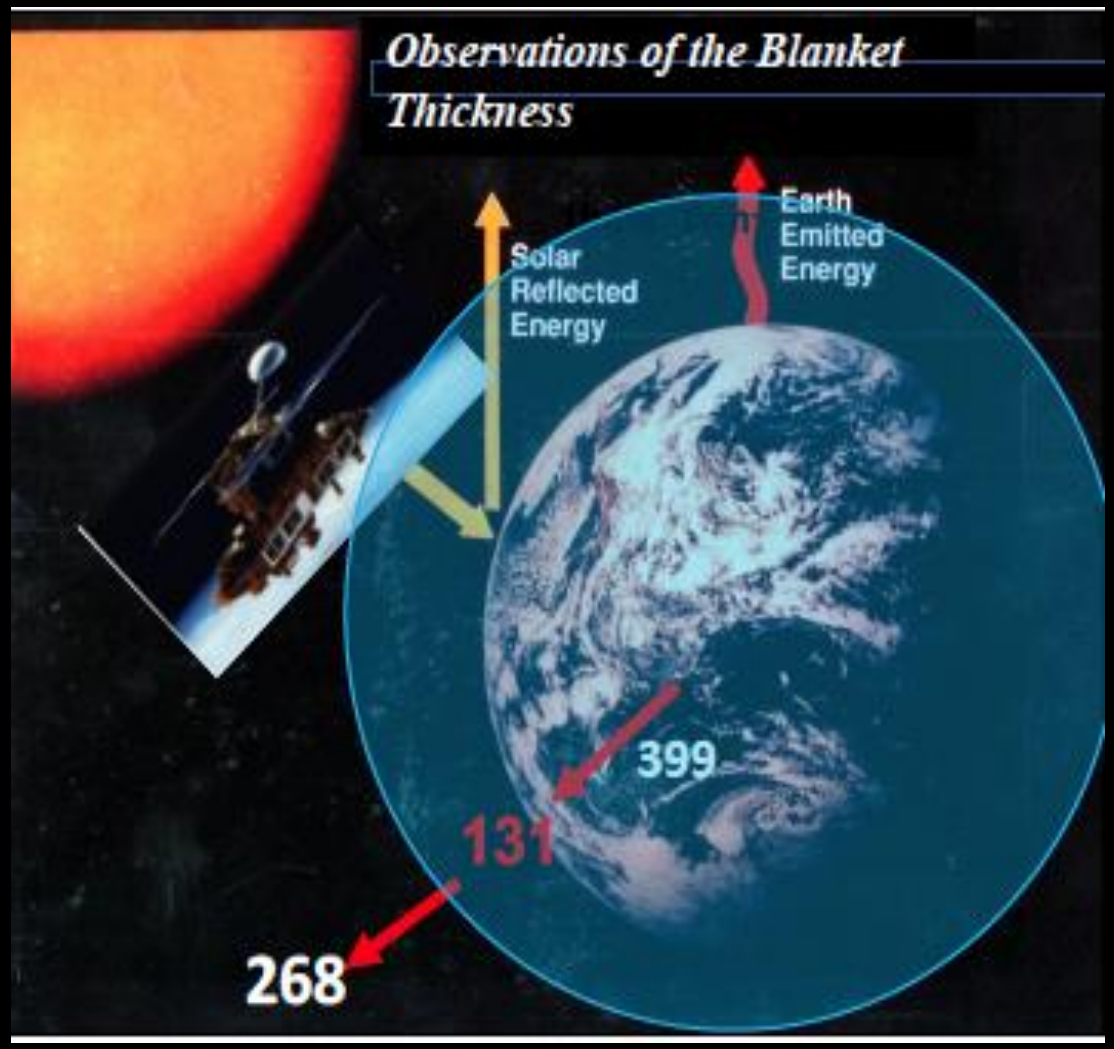
Earth Radiation Budget Experiment:
Ramanathan, Barkstrom & Harrison,
1974-1989





Directly Measuring the blanket thickness

Raval & Ramanathan, Nature, 1990



What is Happening?

Blanket Thickness = 131 Wm $^{-2}$
Gases only

Water Vapor + CO2; (95%)
Ozone (5%)- From Models

Increase in thickness due to human-added gases*: 3.6 Wm^{-2}

** Drefus, Xu, Shindell, Zaelke and Ramanathan, 2022*

How thick is the human-made CO_2 blanket?

CFCs, methane and other Non-CO_2 gases trap another **800 terrawatts**

Emitted 2,400,000,000,000 tons of CO_2. 1850-2019
Yes: 2.4 Trillion Tons

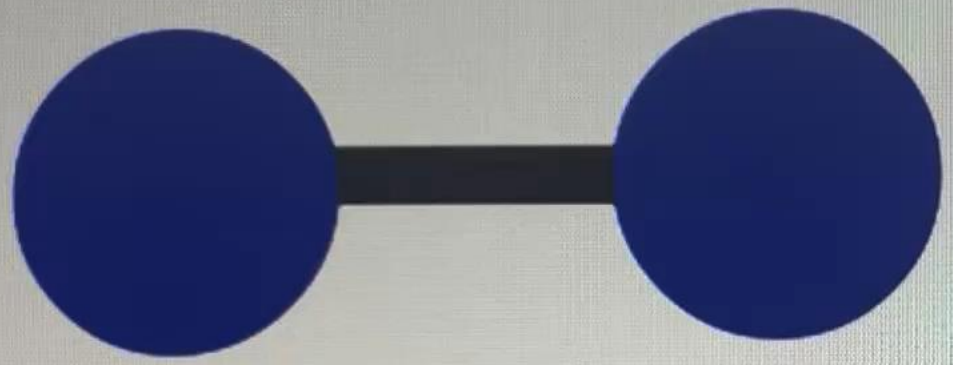
Estimated from IPCC-AR6-2021;

Drefus, Xu, Shindell, Zaelke & Ramanathan, 2022

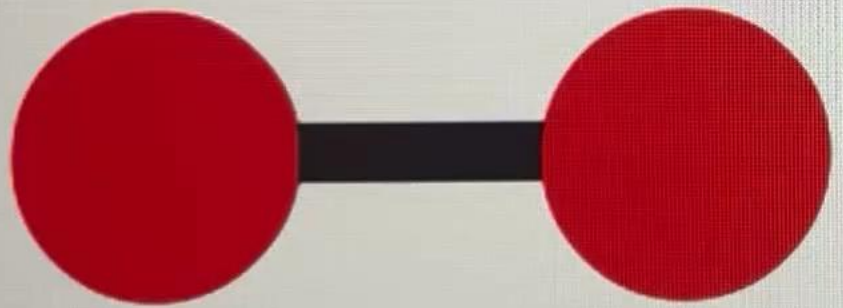
Climate Change Science

- Quantum Mechanics
- Radiative Transfer- Integral Equations
- Thermodynamics of Energy Transfer:
  Radiant to latent/sensible/potential
- Newtonian Dynamics- Differential Equations
- Turbulence (Who Understands Turbulence?)

Motions of Atoms within a Molecule



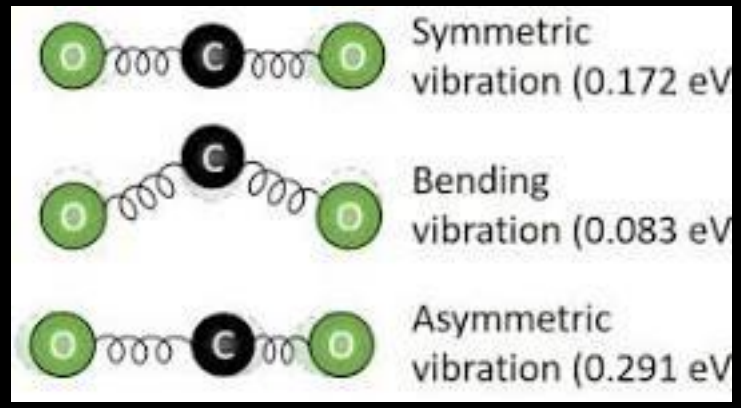
Nitrogen



Oxygen

Quantum Mechanics of Energy-Trapping by CO_2 Molecule

1977



A Radiative-Convective Model Study of the CO_2 Climate Problem

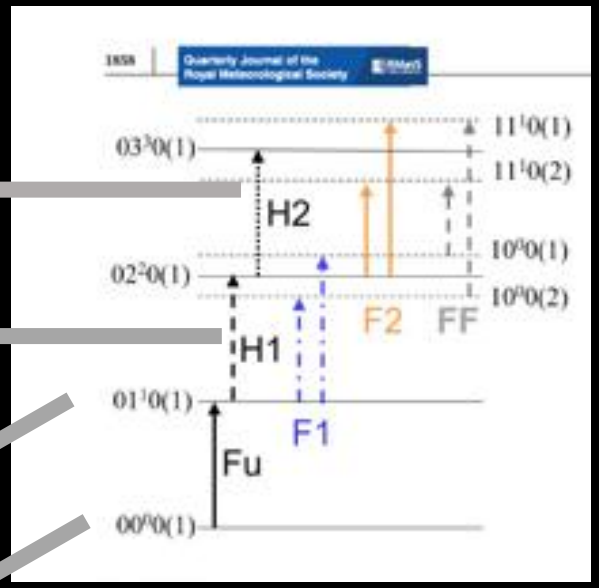
T. Augustsson

George Washington University, NASA-Langley Research Center, Hampton, Va. 23665

V. Ramanathan

National Center for Atmospheric Research,[1] Boulder, Colo. 80307

Vibrational Energy Levels



Shine and Perry, QJRMS, 2023

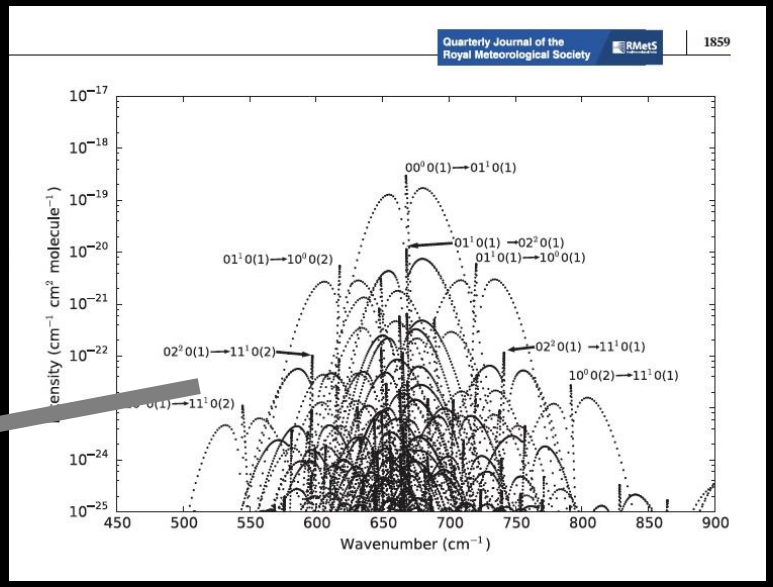
Second Hot Band

First Hot Band

First Excited State

Ground State

Energy Absorption in Bands



Fermi Resonance Bands

My Entry into Climate- Change Science

Greenhouse Effect Due to Chlorofluorocarbons:
Climatic Implications

V. Ramanathan

1975
Science
AAAS

1975 discovery of Halocarbons as Super-greenhouse gases puts Non-CO_2 greenhouse gases on par with CO_2

"All the News That's Fit to Print"

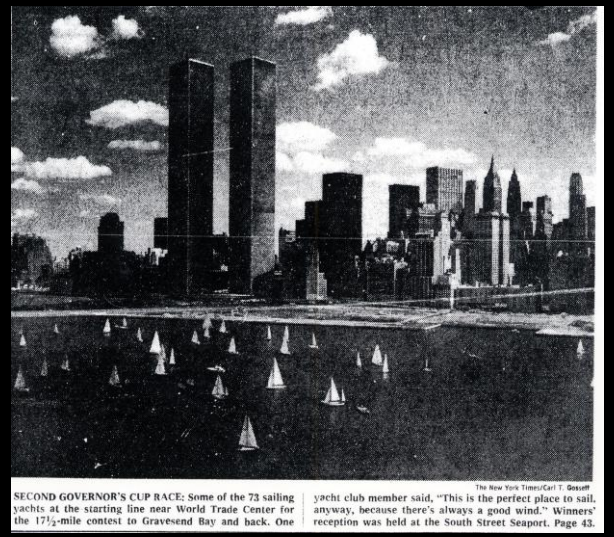
The New York Times

LATE CITY EDITION
Weather: Sunny, pleasant today; clear tonight. Sunny tomorrow. Temperature range: today 51-72; Saturday 52-71. Details on Page 53.

SECTION ONE

VOL. CXXIV . No. 42,967 © 1975 The New York Times Company NEW YORK, SUNDAY, SEPTEMBER 14, 1975 $1.00 beyond 50-mile zone from New York City, except Long Island, Hudson and out-of-town delivery cities. 60 CENTS

1975



SECOND GOVERNOR'S CUP RACE: Some of the 73 sailing yachts at the starting line near World Trade Center for the 17½-mile contest to Gravesend Bay and back. One yacht club member said, "This is the perfect place to sail, anyway, because there's always a good wind." Winners' reception was held at the South Street Seaport. Page 43.

The New York Times/Carl T. Gossett

U.S. PUTS OFF CUT IN SUPPORT FORCE IN WEST GERMANY

Concern Over a Weakening of Combat Power Brings Shift on Trimming 'Fat'

By JOHN W. FINNEY

Special to The New York Times

WASHINGTON, Sept. 13 — The Defense Department has deferred a planned 8,000-man reduction in support troops in West Germany because of concern that the combat strength of the United States Army in Europe would be weakened too much.

The decision, disclosed by a high-ranking Army officer, represents the first reversal of a much publicized Pentagon policy of recent years to getting rid of "fat" in the military services through elimination of support troops and headquarters staffs.

The policy has been a key component in the budget strategy of Defense Secretary James

U.F.T. Weighs Board Plan To Trim Class Schedules

Reduction of Two Periods Each Week Linked to Dropping of Two Periods of Preparation Time for Teachers

By LEE DEMBART

The striking United Federation of Teachers is "seriously considering" a proposal by the Board of Education that would involve cutting two preparation periods a week from some teachers' schedules and shortening the school day by two periods a week, for a total saving of $48-million a year.

If accepted, the proposal would result in freeing enough teachers from covering other teachers' free periods to enable the board to hold down class sizes.

Union negotiators held "staff-level meetings" with the Board of Education until 9 P.M. last night at the Plaza Hotel, and each side then caucused separately. Earlier the union negotiators had caucused at the U.F.T. headquarters without the union's president, Albert

Continued on Page 38, Column 3

Shanker, who was said to be exhausted and at his home upstate. It was thought that no settlement in the week-long strike could be made final until Mr. Shanker returned.

Full-dress negotiations involving Mr. Shanker and Dr. Christen are to resume today. The union is under some pressure to reach a contract agreement before tomorrow because Mr. Shanker must appear in court Tuesday morning under a threat of being jailed for violating the state's Taylor Law, which bars strikes by public employes.

The union had neither accepted nor rejected the board's proposal, and it was learned that the U.F.T. had a number of questions about how the plan

M.A.C. ARRANGES $100-MILLION SALE OF BOND PACKAGE

Buyers Are Savings Banks and Insurance Companies —Deal Crucial for City

PURCHASERS NOT NAMED

Three in Congress Challenge Constitutionality of New Fiscal Control Board

By STEVEN R. WEISMAN

The Municipal Assistance Corporation has arranged to place $100-million of its bonds in the portfolios of savings banks and insurance companies here, a step that nearly completes the $2.3-billion in financing to tide the city over to December.

"We're home — for three months, anyway," said one of the corporation officials who had been working on the $2.3-billion package

Climatic Changes by Aerosols in Atmosphere Feared

By WALTER SULLIVAN

Although attention in the debate regarding the role of fluorocarbon aerosol sprays has hitherto focused on public health questions, it has now been proposed that they could alter world climates.

According to calculations by Dr. Veerabhadran Ramanathan of the National Aeronautics and Space Administration's Langley Research Center in Hampton, Va., fluorocarbons in the atmosphere could have a "greenhouse effect" similar to that caused by carbon dioxide.

Such an effect occurs when a gas, acting like the glass in a greenhouse, permits sunlight to pass freely, but inhibits the escape of heat in the form of infrared radiation. The result is a warming of the lower atmosphere and the earth.

It is an extreme greenhouse effect that is believed to account for the oven-hot temperature of Venus, whose atmosphere consists of a heavy blanket of carbon dioxide.

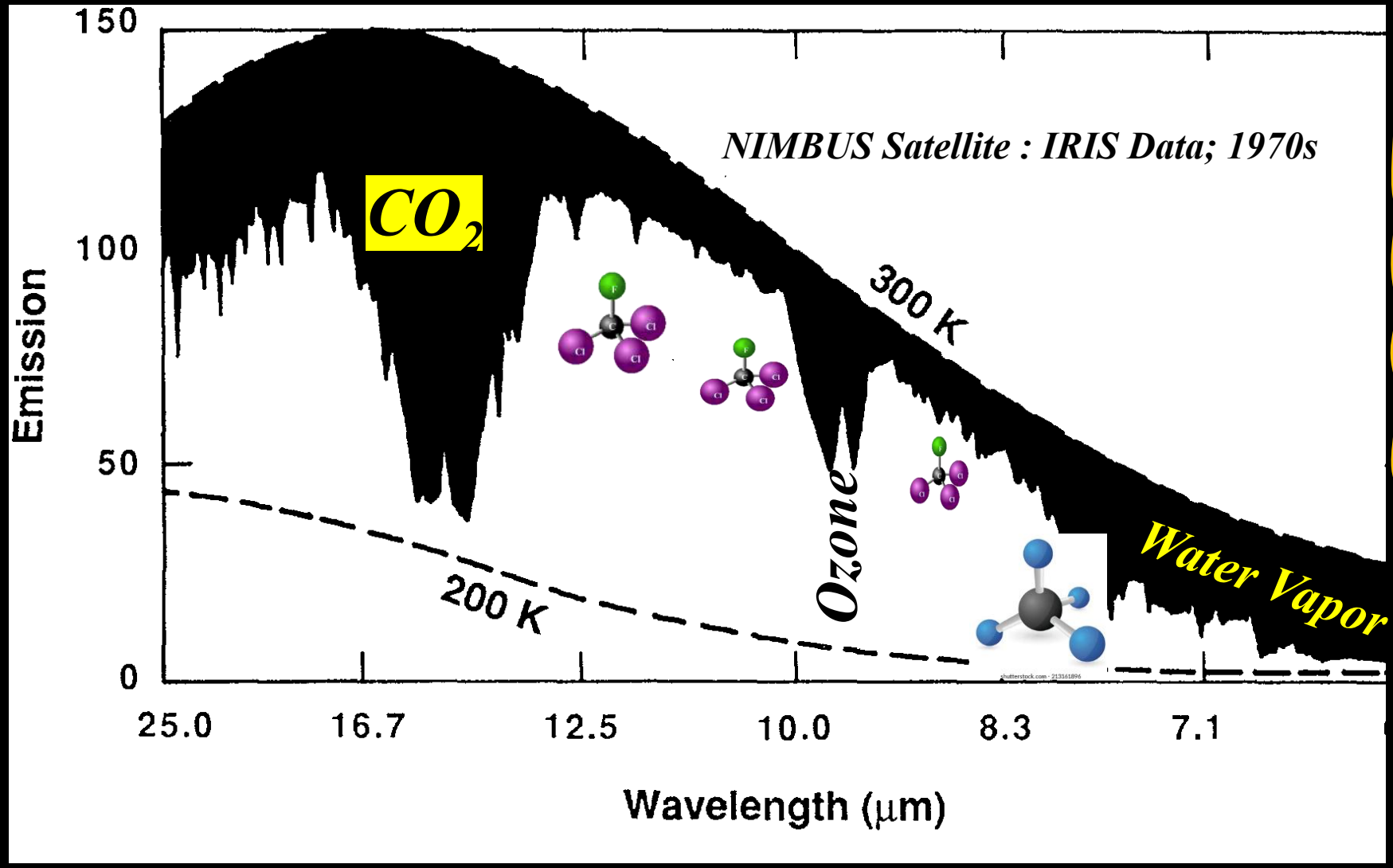
Dr. Ramanathan's warning, based on calculations to be published shortly in the journal Science, coincides with a growing number of stratospheric observations that bear on the controversy.

According to the experimenters, these suggest—but do not prove—that fluorocarbons in the stratosphere have been broken down into chlorine, which can then act to deplete the ozone of that region. The public health concern relates to the role of ozone in absorbing wavelengths of ultraviolet sunlight that otherwise cause skin cancer and other injury to earth-borne life. Dr. Ramanathan's calculations suggest the possibility of climatic effects far less dramatic than those on Venus, but nevertheless of major importance to mankind. If, he suggests, fluorocarbons reach a level of two parts per billion in the atmosphere, as predicted for the end of this century if present usage continues, global

Continued on Page 36, Column 4

One molecule, each of CFC-11 and CFC-12 have the same warming effect as about 10000 molecules of CO_2

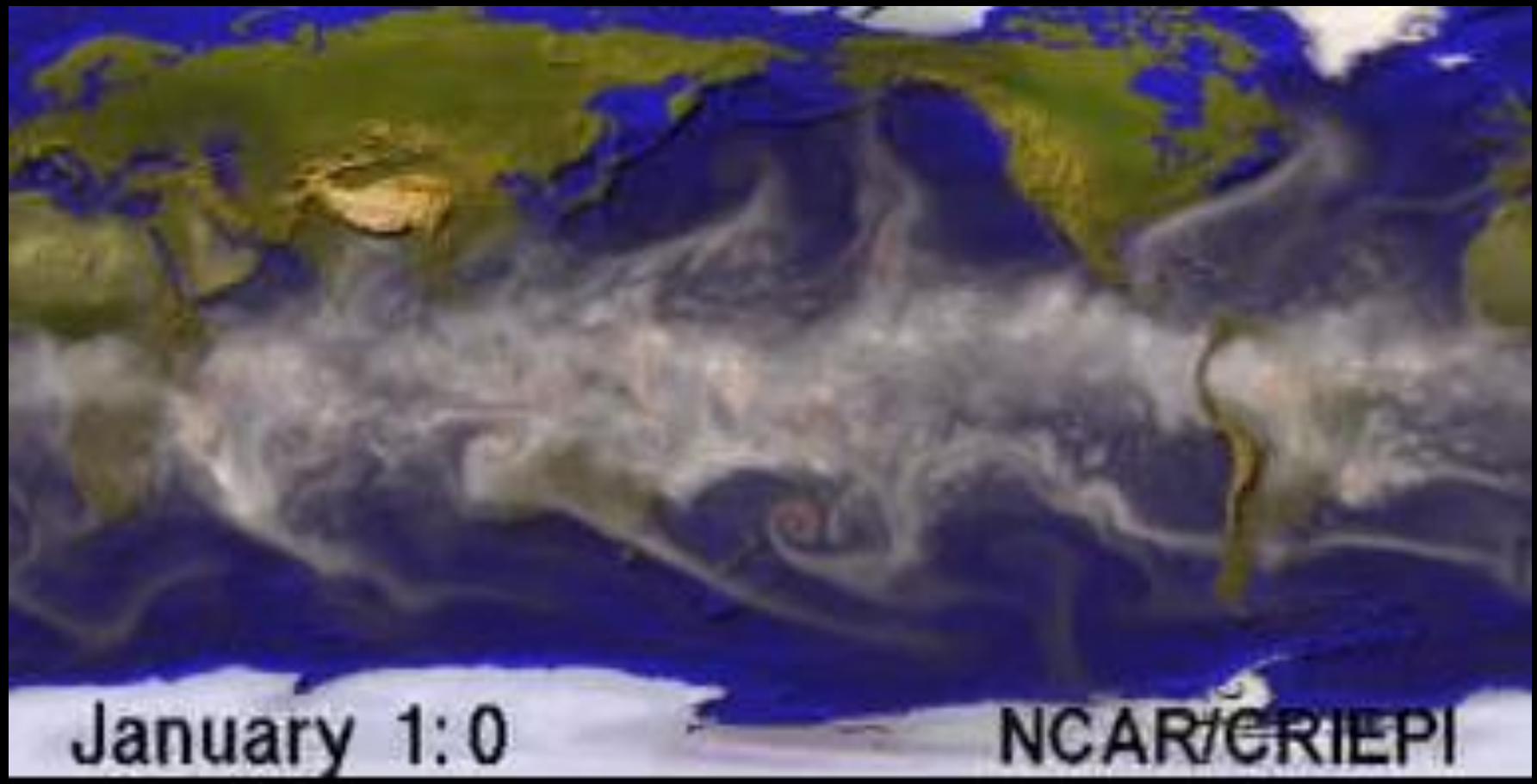
CFCs and Short -Lived Climate Pollutant gases (Methane; HFCs & Ozone) trap heat in Atmospheric Window



❖Super pollutants are creating a dirty Window

Three-Dimensional Community Climate Model of NCAR:

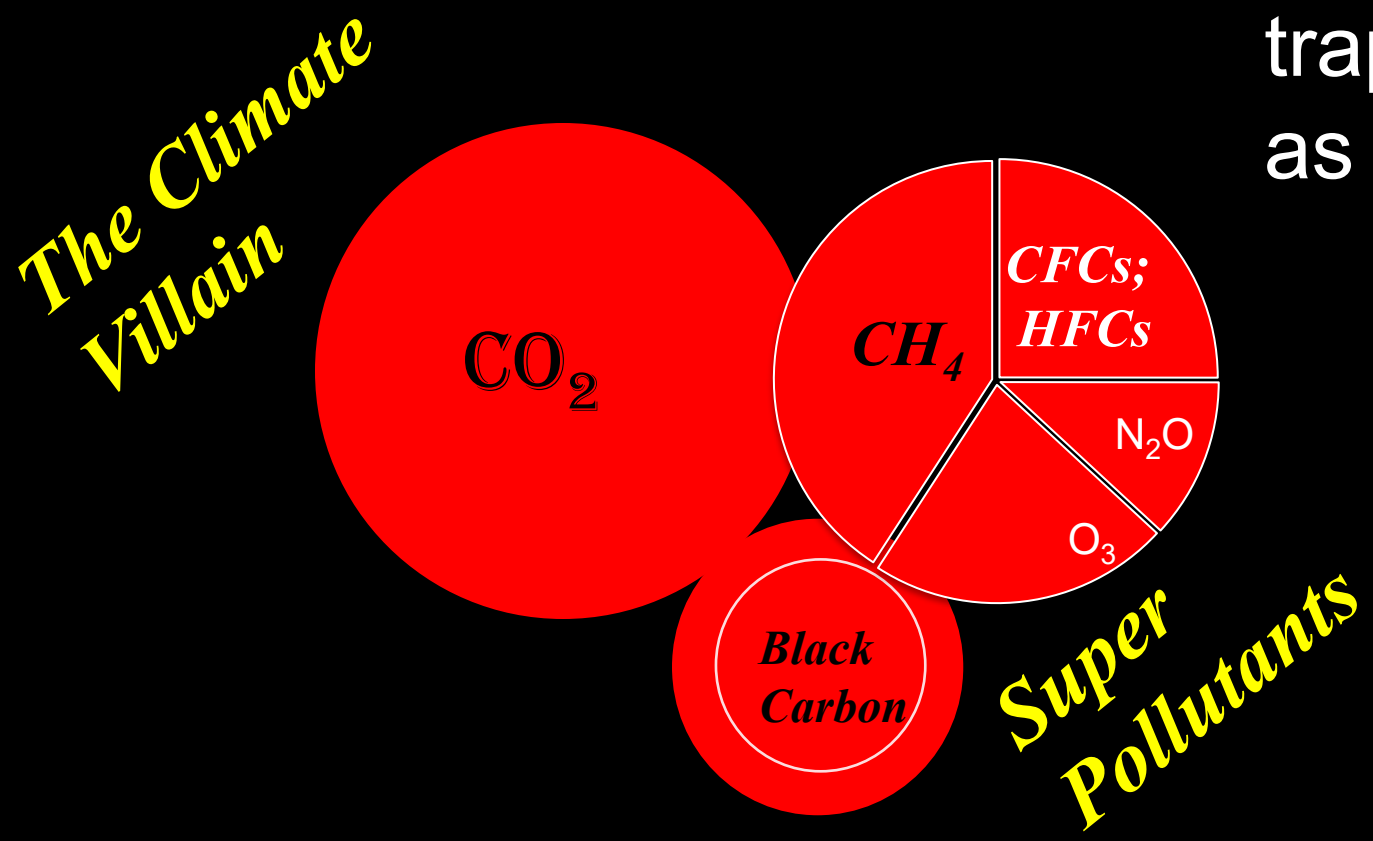
Pitcher, Malone, Ramanathan, Blackmon, Puri and Bourke, 1983
Ramanathan, Pitcher, Malone and Blackmon, 1983



Emission anywhere is surface warming everywhere

Movement of water vapor in the atmosphere (around 5 kilometers)

Heat Trapping Pollutants



Total energy trapped is about 4 Wm^{-2} as of 2019.

Ramanathan et al, WMO-Report, 1985; IPCC 2001 and 2007; Ramanathan and Feng, 2008; Ram and Xu, 2010; Dreyfus, Xu, Shindell, Zaelke & Ramanathan, 2022

JUDGING A THEORY BY ITS PREDICTIONS

Science
AAAS
15 AUGUST 1980

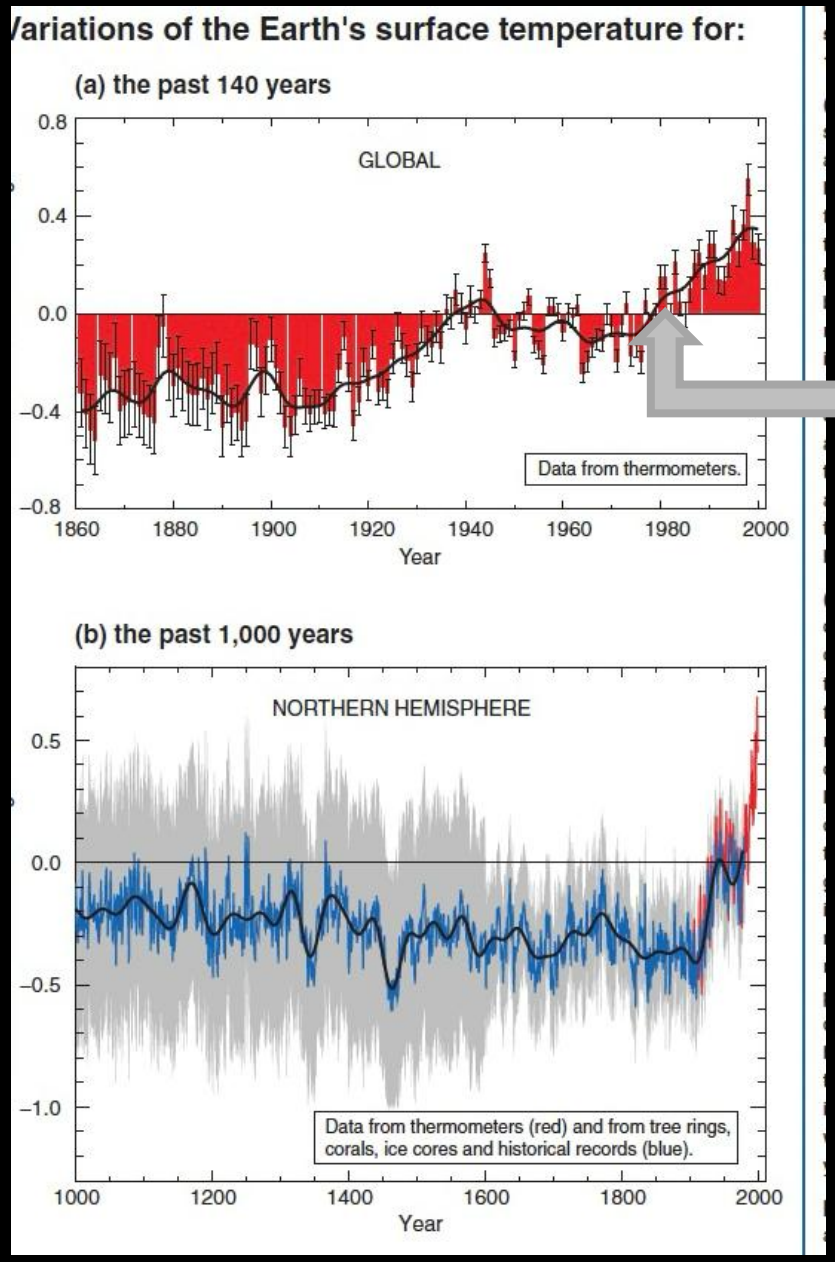
Detecting Climate Change due to Increasing Carbon Dioxide

Roland A. Madden and V. Ramanathan

Prediction

Warming Due To CO_2 Should Be Detectable By Year 2000

IPCC-TAR-2001



Madden & Ram, 1980

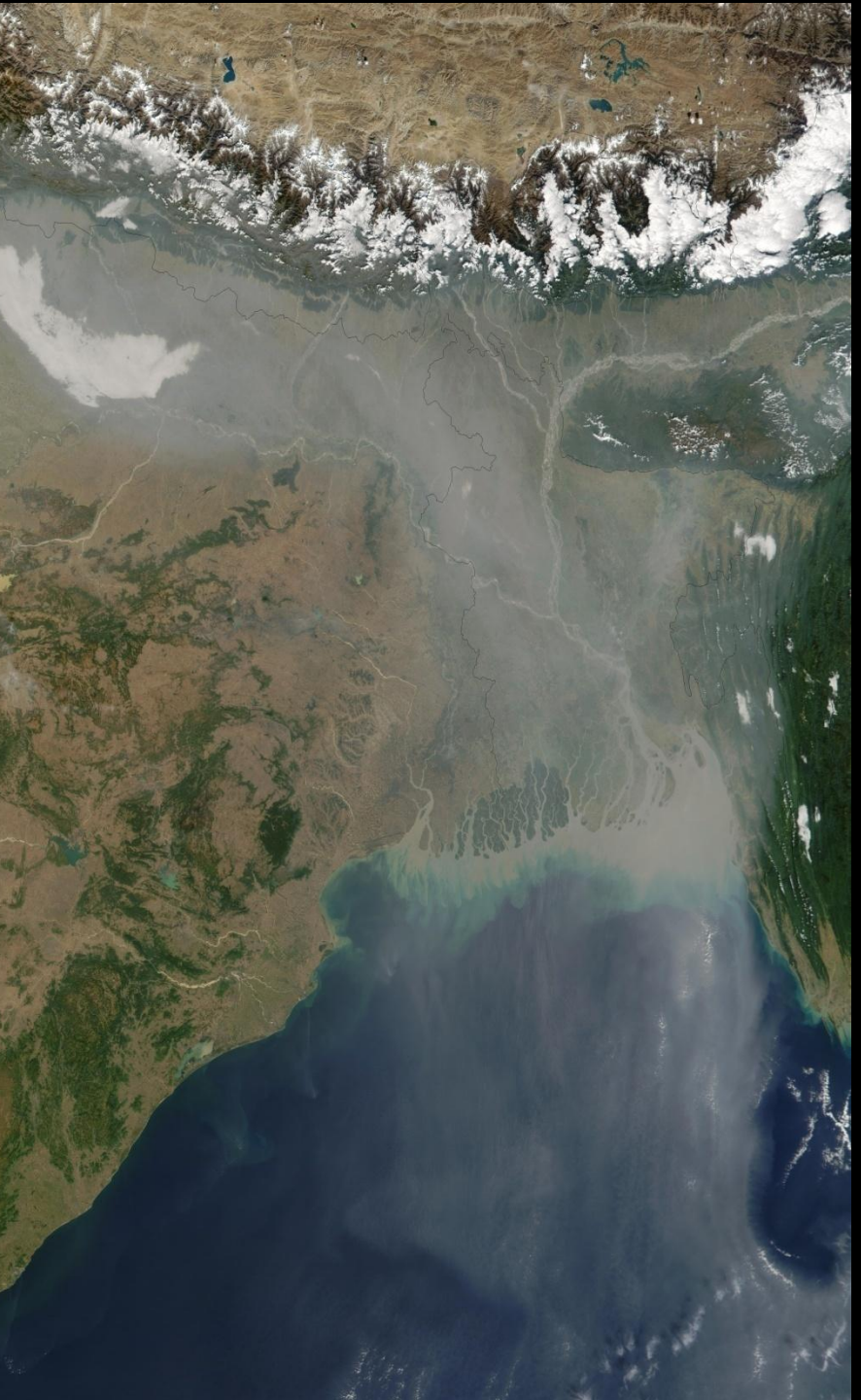
IPCC Conclusion: 2001

There is new and stronger evidence that most of the warming observed over the last 50 years is attrib-utable to human activities.

But there was a major discrepancy in the magnitude of the warming: The warming, although significant, was only about half of what we expected!

Masking of Global Warming By Atmospheric Brown Clouds (aka particles in Air pollution)

Source: Ramanathan 2005

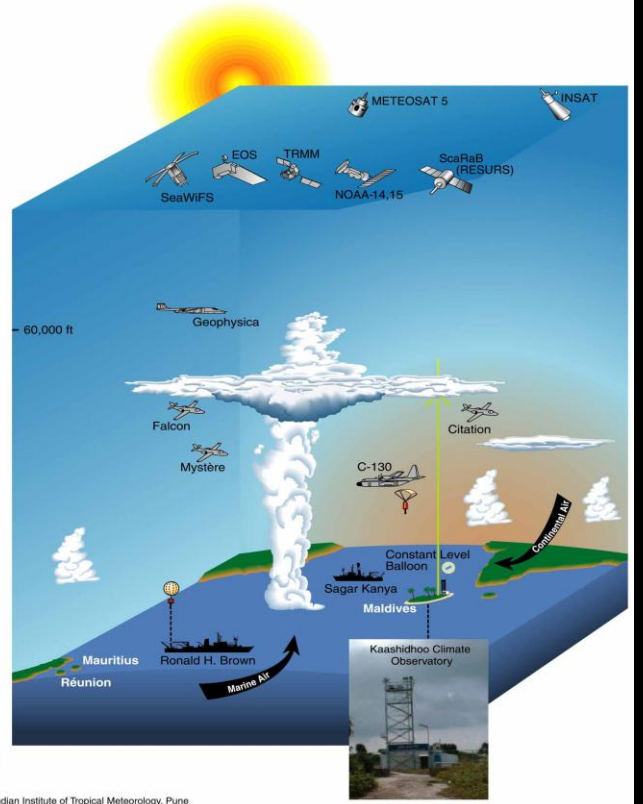


Indian Ocean Experiment (1997 to 1999)

PIs: Ramanathan,Crutzen, Mitra & Lelieveld.

Over 200 scientists from India, Europe, USA participated

The Indian Ocean Experiment (INDOEX), an international field experiment, has been collecting data since 1996, featuring an intensive field campaign conducted in Spring 1999. For details, see *http://www-indoex.ucsd.edu.*



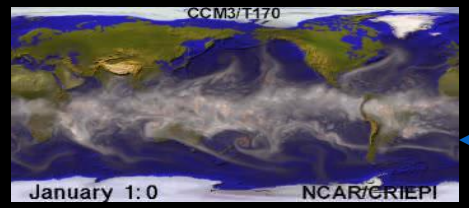
INDOEX
INDIAN OCEAN EXPERIMENT

Participating Institutions

Austria
Universität Innsbruck
Canada
York University, Toronto
Europe
Airborne Platform for Earth Observation (Geophysica, Falcon)
European Organisation for the Exploitation of Meteorological Satellites (Meteosat-5)
France
Laboratoire d'Optique Atmosphérique
Laboratoire de Météorologie Dynamique du CNRS
Laboratoire de Météorologie Physique, Université Blaise Pascal
Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS
Laboratoire Interuniversitaire des Systèmes Atmosphériques
Service d'Aéronomie
Germany
Forschungszentrum Jülich
GKSS-Forschungszentrum Geesthacht
Institut für Troposphärenforschung
Max Planck Institut für Chemie
Max Planck Institut für Kernphysik
Max Planck Institut für Meteorologie
Meteorologisches Institut der Universität Hamburg
Universität Bremen
India
Antarctic Study Centre, Vasco-da-Gama
Indian Institute of Science, Bangalore
Indian Institute of Technology, New Delhi
Indian Institute of Tropical Meteorology, Pune
Indian Meteorological Department, New Delhi
Indian Space Research Organization, Bangalore
National Centre for Medium Range Weather Forecasting, New Delhi
National Institute of Oceanography, Goa
National Physical Laboratory, New Delhi
Physical Research Laboratory, Ahmedabad
Space Applications Centre, Ahmedabad
Space Physics Laboratory, Thiruvananthapuram
Israel
Tel-Aviv University
La Réunion
Université de La Réunion
Mauritius
Department of Meteorological Services, Mauritius
University of Mauritius, Reduit
Maldives
Department of Meteorology, Maldives
Ministry of Home Affairs, Housing and Environment
Netherlands
Koninklijk Nederlands Meteorologisch Instituut
Technische Universiteit Delft
Universiteit Utrecht
South Africa
University of Witwatersrand, Johannesburg
Sweden
Meteorologiska Institutionen, Stockholms Universitet
United Kingdom
Imperial College, London
United States
Center for Clouds, Chemistry and Climate
Arizona State University, Tempe
Atmospheric Research Laboratory
Colorado University, Boulder
Desert Research Institute
Florida State University, Tallahassee
NASA - Goddard Space Flight Center
National Center for Atmospheric Research
NOAA - Atlantic Oceanographic and Meteorological Laboratory
NOAA - Climate Monitoring and Diagnostics Lab
NOAA - Pacific Marine Environmental Laboratory
North Carolina State University, Raleigh
Oregon State University, Corvallis
Pennsylvania State University, University Park
Scripps Institution of Oceanography
SeaSpace Corporation
University Corporation for Atmospheric Research
University of Alaska, Fairbanks
University of California, Irvine
University of California, Riverside
University of California, San Diego
University of Hawaii, Manoa
University of Maryland, College Park
University of Miami
University of Washington, Seattle

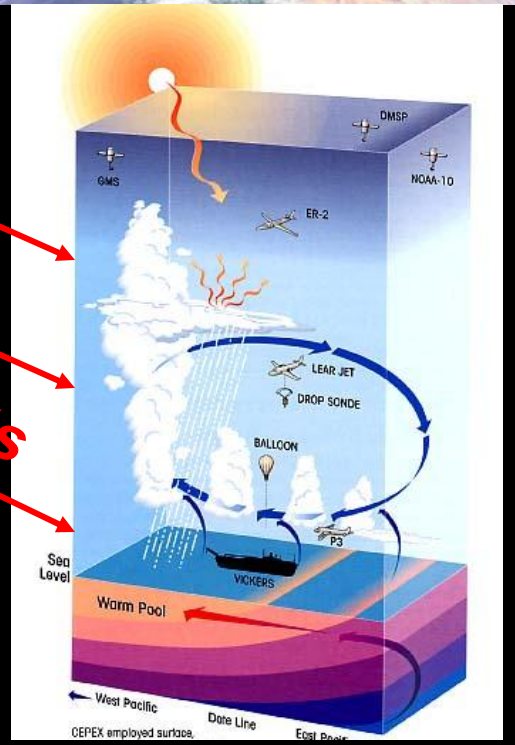
My Research Tools

Ramanathan, 2007



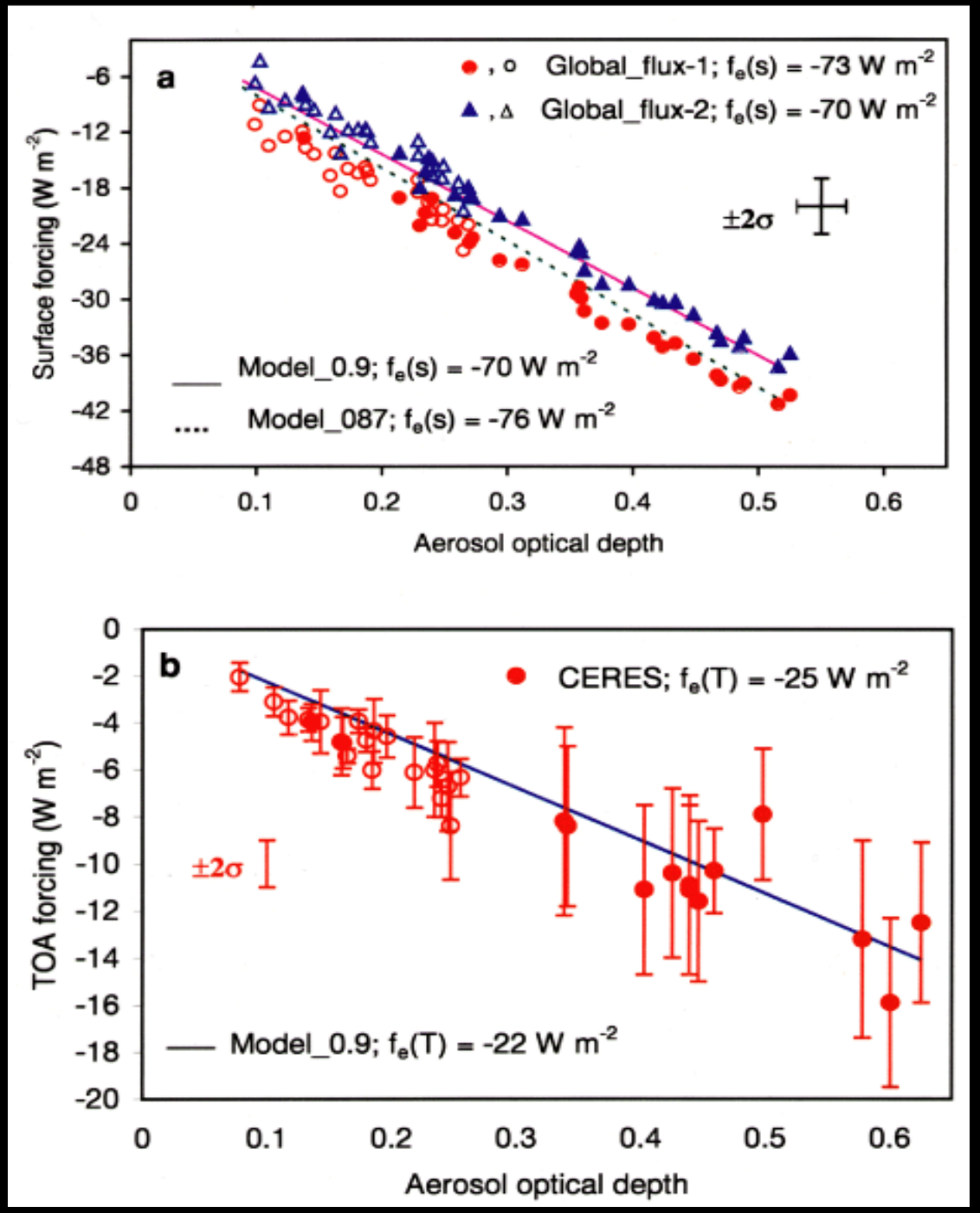
- *Satellites (1970s-)*
- *Aircraft (1990s-)*
- *Balloons*
- *Ships (1990s-)*
- *Surface Stations (1990s*
- *UAVs (2004-)*
- *Climate Models (1980s-)*

Field Experiments



Thanks: NASA, NOAA and NSF & a dedicated program director, Jay Fein of NSF and my manager Hung Nguyen of SIO, Who made it all possible by supporting and helpi

Maldives Climate Observatory

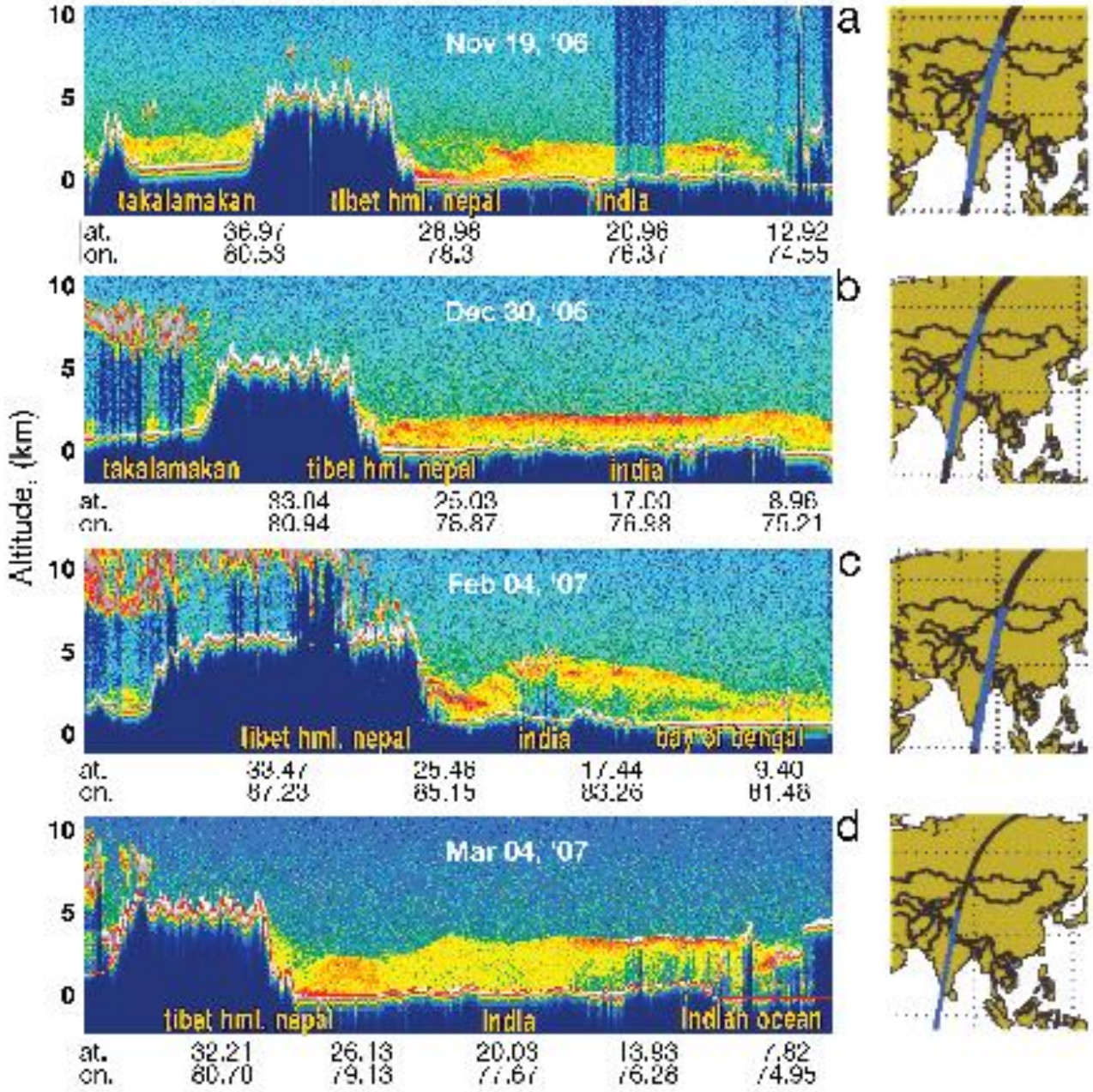


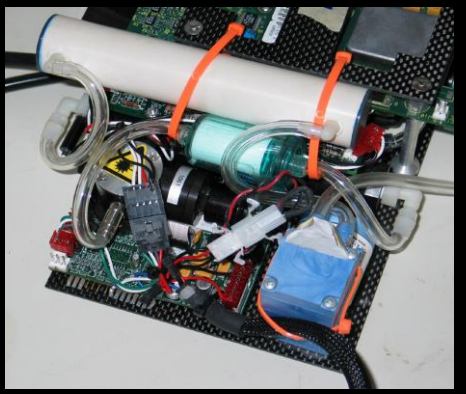
Surface Forcing

Satheesh and Ramanathan, Nature, 2000

Top-of-Atmosphere Forcing

Ramanathan, et al, 2007

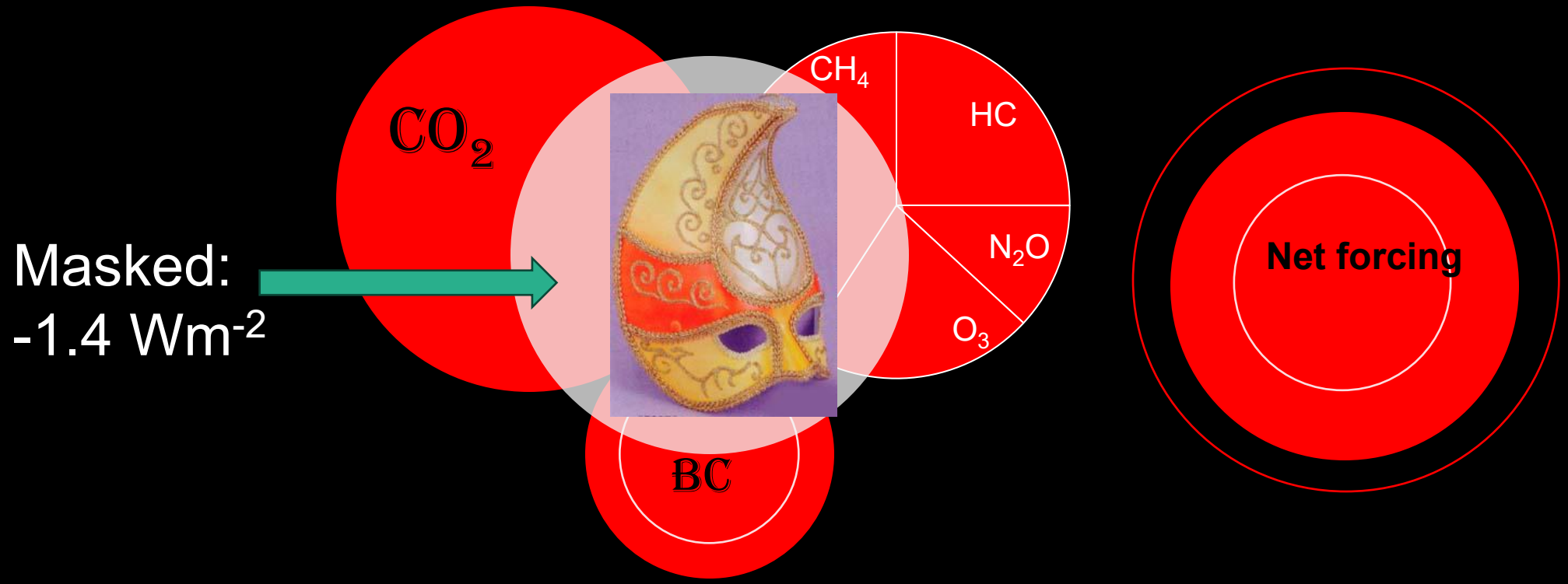




The Mask is made up of sulfates/Nitrates/Organics particles

ASKING OF GLOBAL WARMING BY AEROSOLS

Data from : IPCC 2007; Ramanathan and Feng, 2008 & Ram and Xu, 2010



Instead of thinning the GHGs blanket and the Mask, we are just thinning the mask

ARTICLES

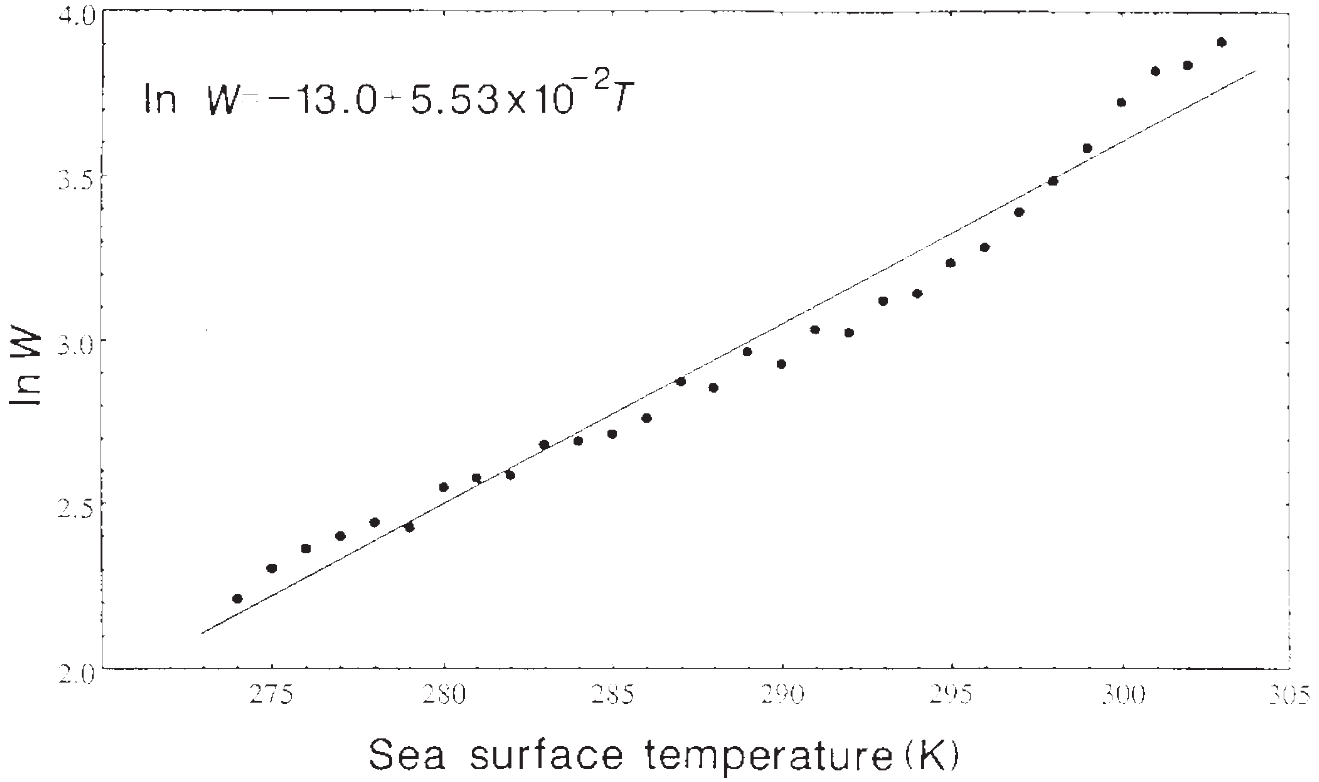
Observational determination of the greenhouse effect

A. Raval & V. Ramanathan

Department of Geophysical Sciences, University of Chicago, Chicago, Illinois 60637, USA

nature

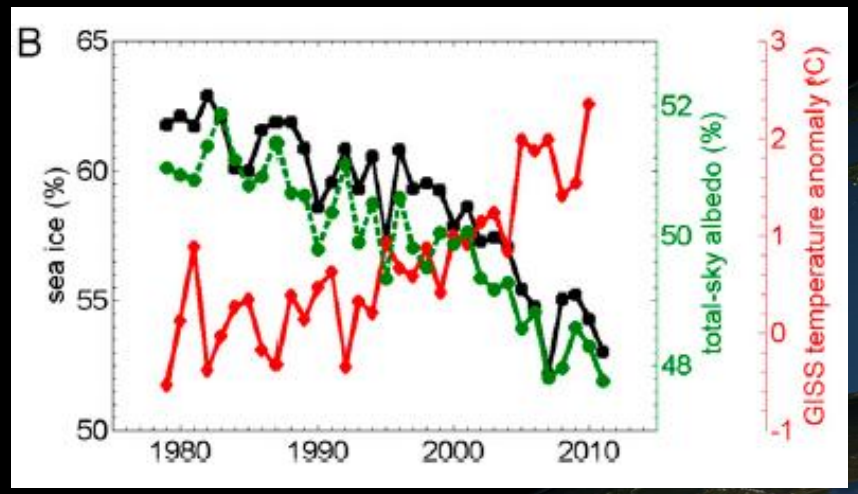
1989



$$Es \propto e\left(-\frac{5400}{T}\right)$$

Water Vapor increases by 5.5% per ^{0}C SST:

Feedbacks act as force multipliers:
Retreating Sea Ice enhances solar heating & amplifies warming



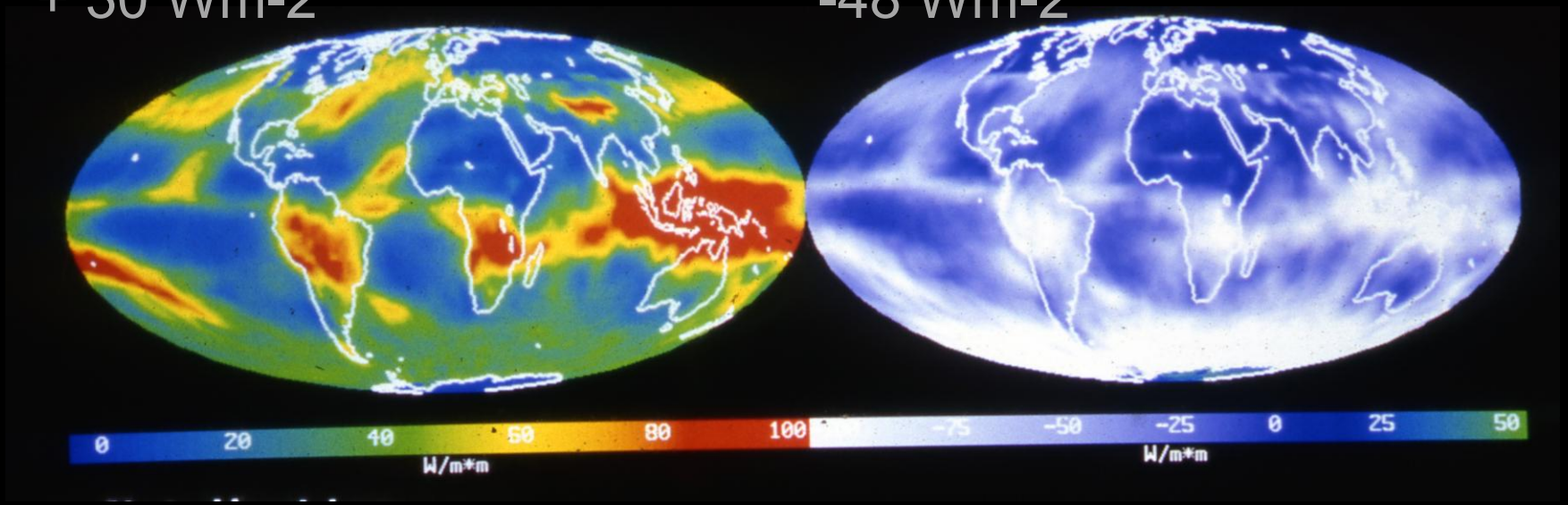
PISTONE, EISENMAN & RAMANATHAN, PNAS, 2014

Blanket- Effect Of Clouds

+ 30 Wm-2

Albedo- Effect Of Clouds

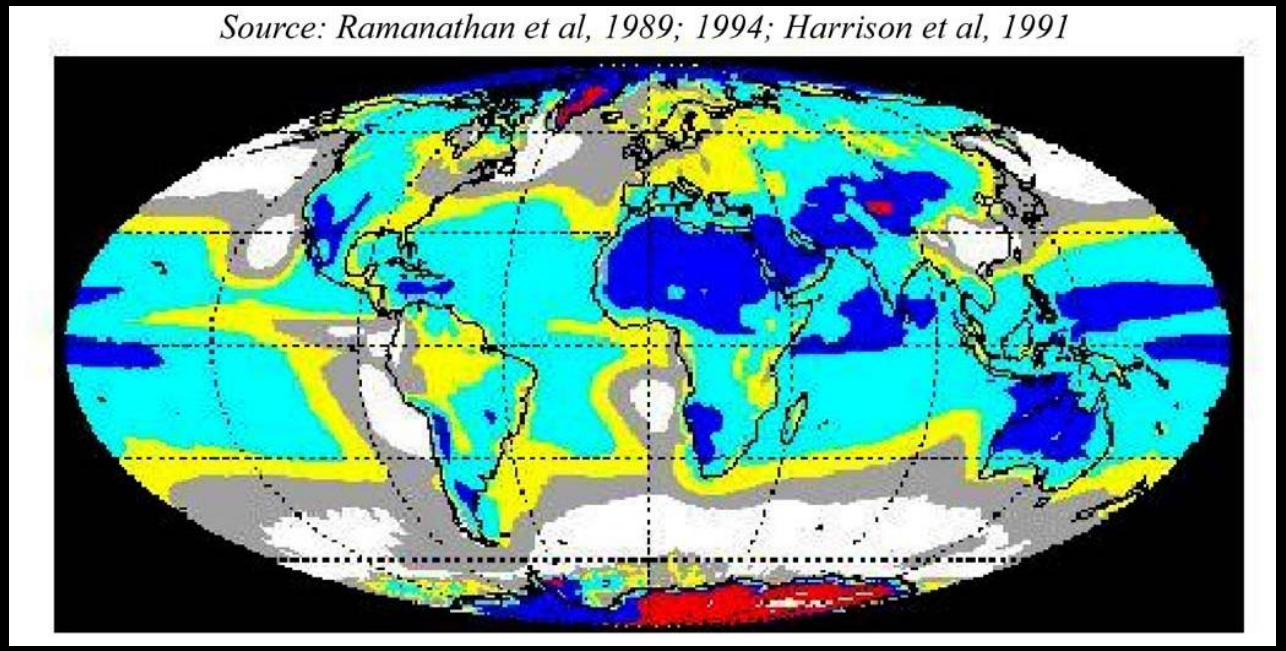
-48 Wm-2



Science
AAAS

1989

V. Ramanathan, R. D. Cess,
E.F. Harrison, P. Minnis,
B. R. Barkstrom, E. Ahmed,
D. Hartmann.



1985-1989: Net Radiative Effect

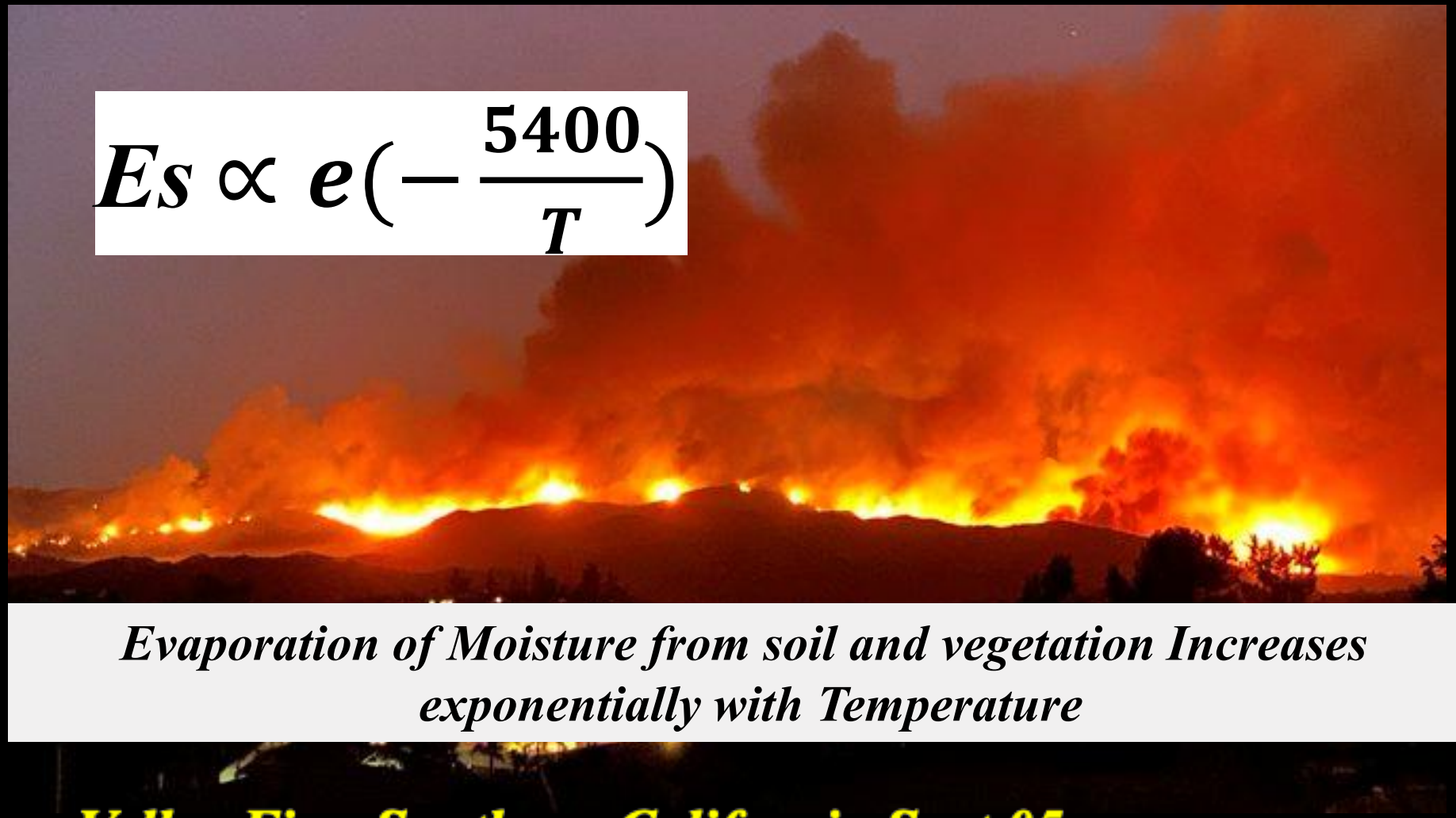
Of Clouds : - 18 Wm^{-2}

Clouds Radiatively
Cool the Planet

21st Century: Climate Change Morphed into Climate Disruption:
Low Probability High Impact Extremes: Fat Tails

- ***Hot temperature extremes frequency increased 180%***
- ***Heavy Precipitation frequency increased 30%***
- ***Agriculture & ecological droughts in drying regions increased 70%***
- ***Disaster numbers increased by 400% from 1970s to the current decade; 2.06 m deaths and $3.64 trillion loss***
- ***Reference: IPCC-2021; WMO, 2021***

Climate Change to Climate Disruption: Weather Extremes



$$Es \propto e\left(-\frac{5400}{T}\right)$$

Evaporation of Moisture from soil and vegetation Increases exponentially with Temperature

Valley Fire, Southern California Sept 05

Image Source: @Acampa Najjar; Twitter, Sept 05, 2020

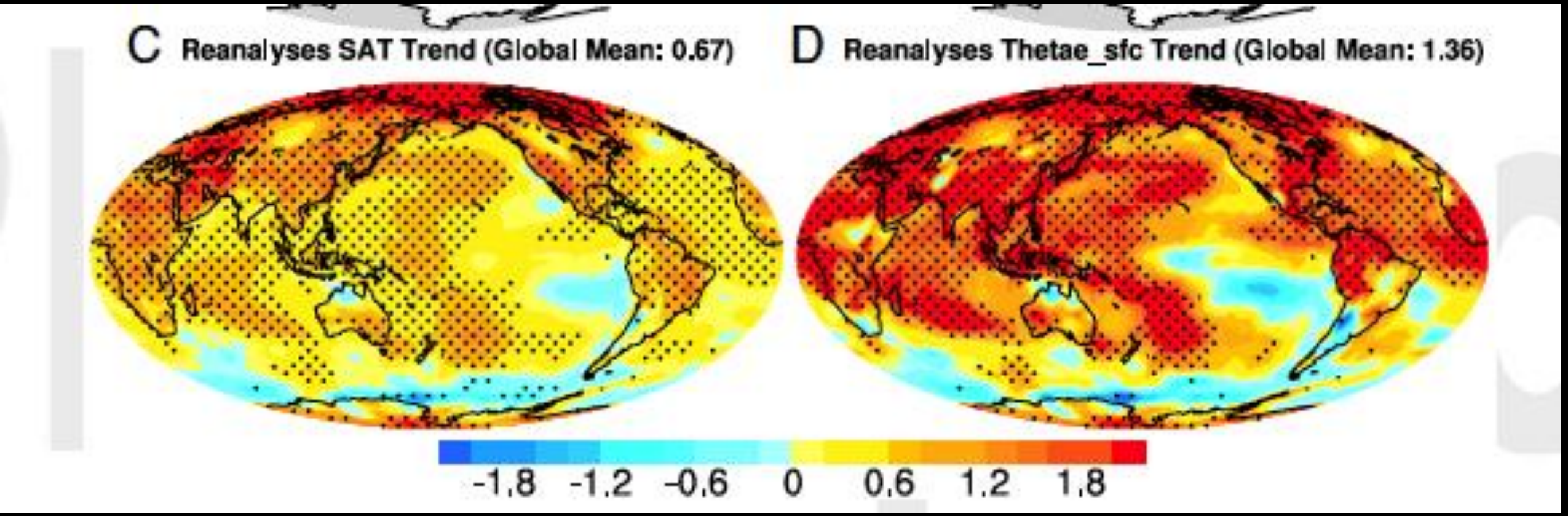
Trends in surface equivalent potential temperature: A more comprehensive metric for global warming and weather extremes

Fengfei Song[a,b,c], Guang J. Zhang[d,1], V. Ramanathan[d,1], and L. Ruby Leung[c]

PNAS

Feb 2022

1980 to 2019 Trend



Global warming will happen faster than we think

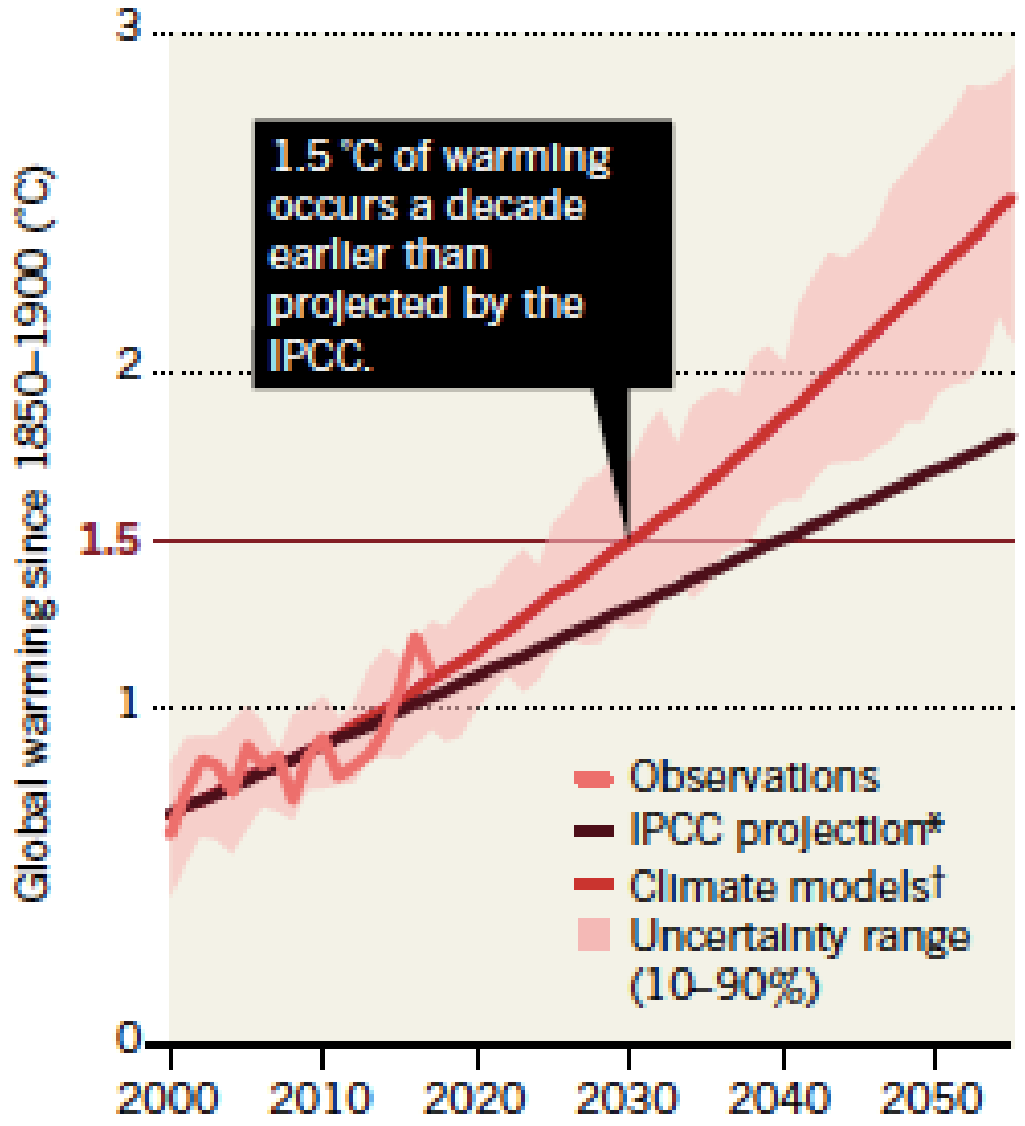
Three trends will combine to hasten it, warn Yangyang Xu, Veerabhadran Ramanathan and David G. Victor.

nature

2018

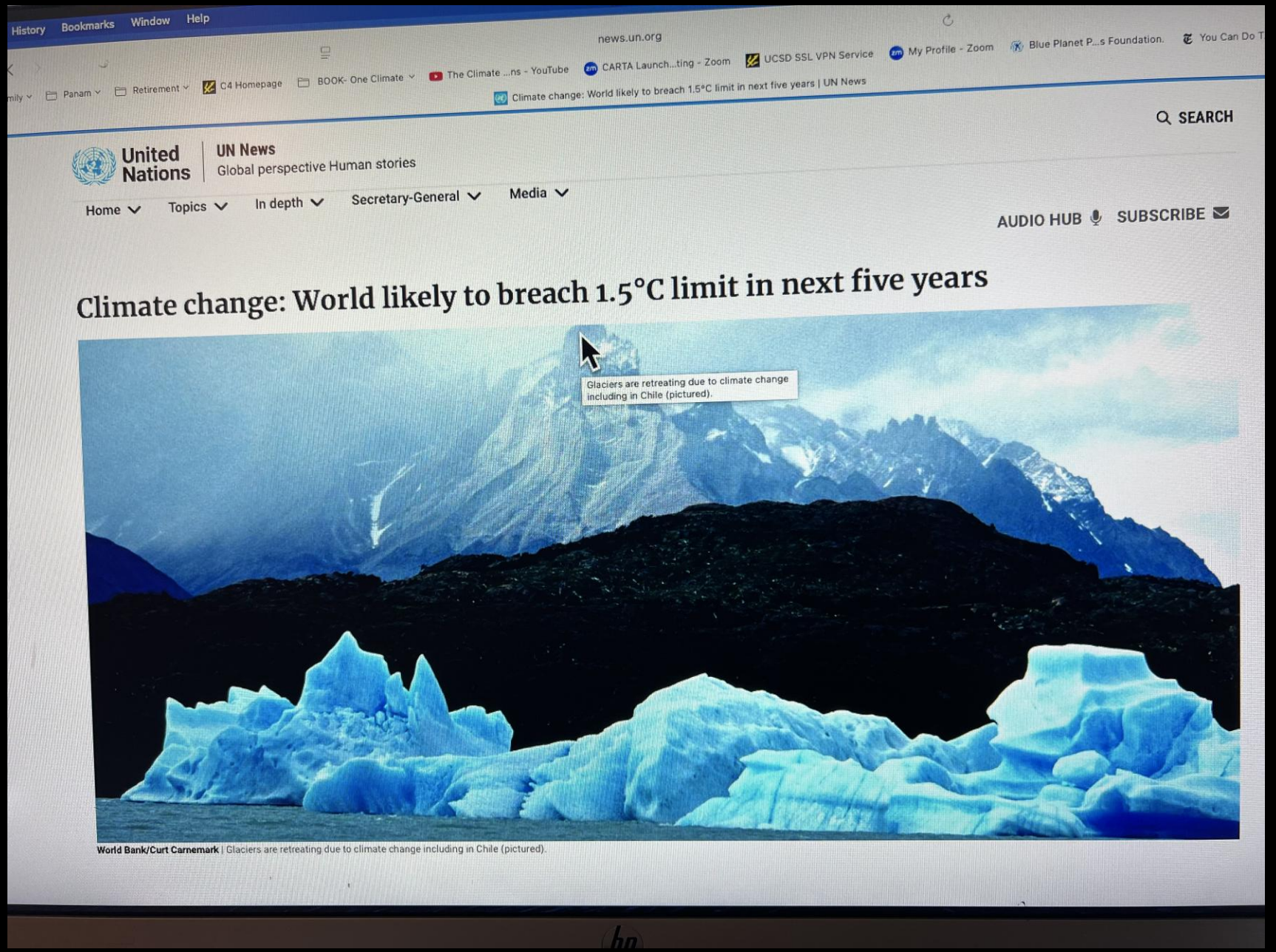
ACCELERATED WARMING

Climate simulations predict that global warming will rise exponentially if emissions go unchecked.



Climate Change will get its Ozone Hole Moment around 2030

Finally United Nations Scientists Agree with us: January 2025

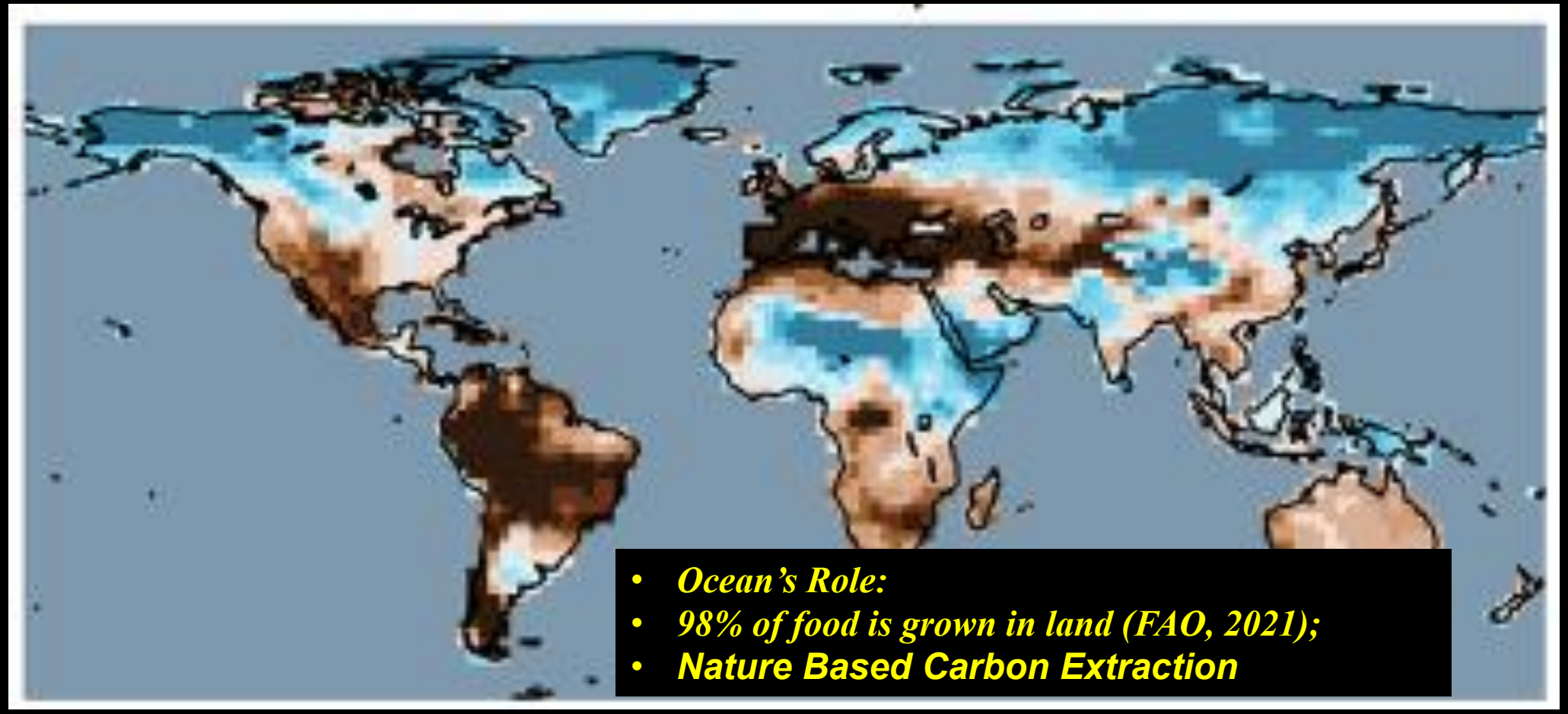


Drought Index for 2080-2099:

NOAA-Princeton Univ Model Study

[From Cook et al, 2014]

5% Probability Projection

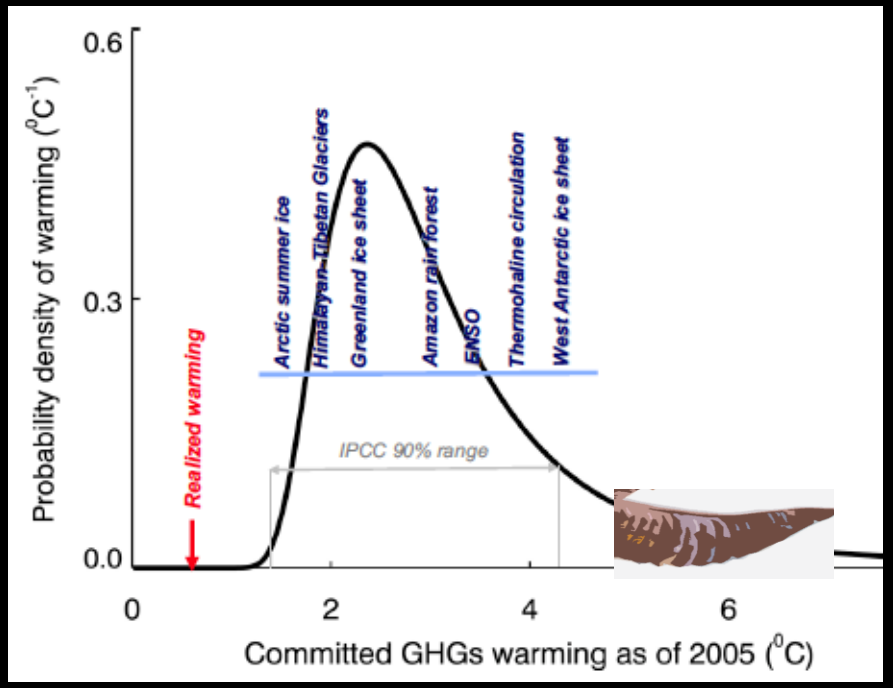


Can it get any worse? Yes, it Can:

Due to LPHIEs; Fat Tails & Black Swans

(Ramanathan, Suarez-Orozco, von-Braun and Forman, 2025)

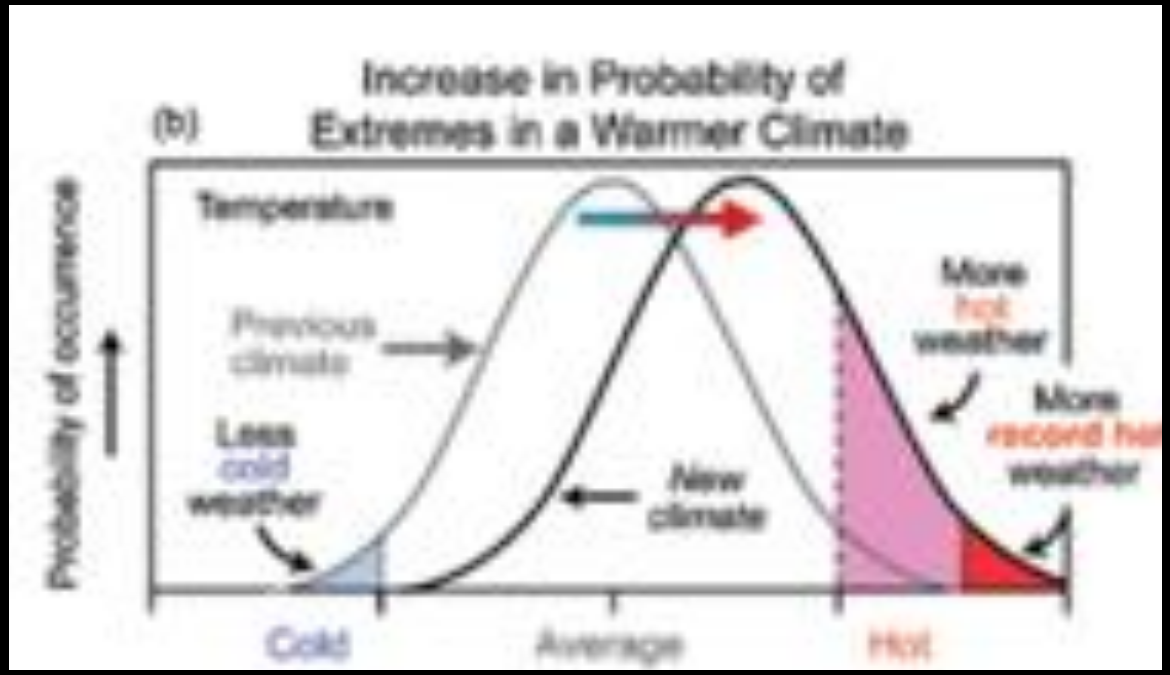
Climate Extremes



V. Ramanathan and Y. Feng;*

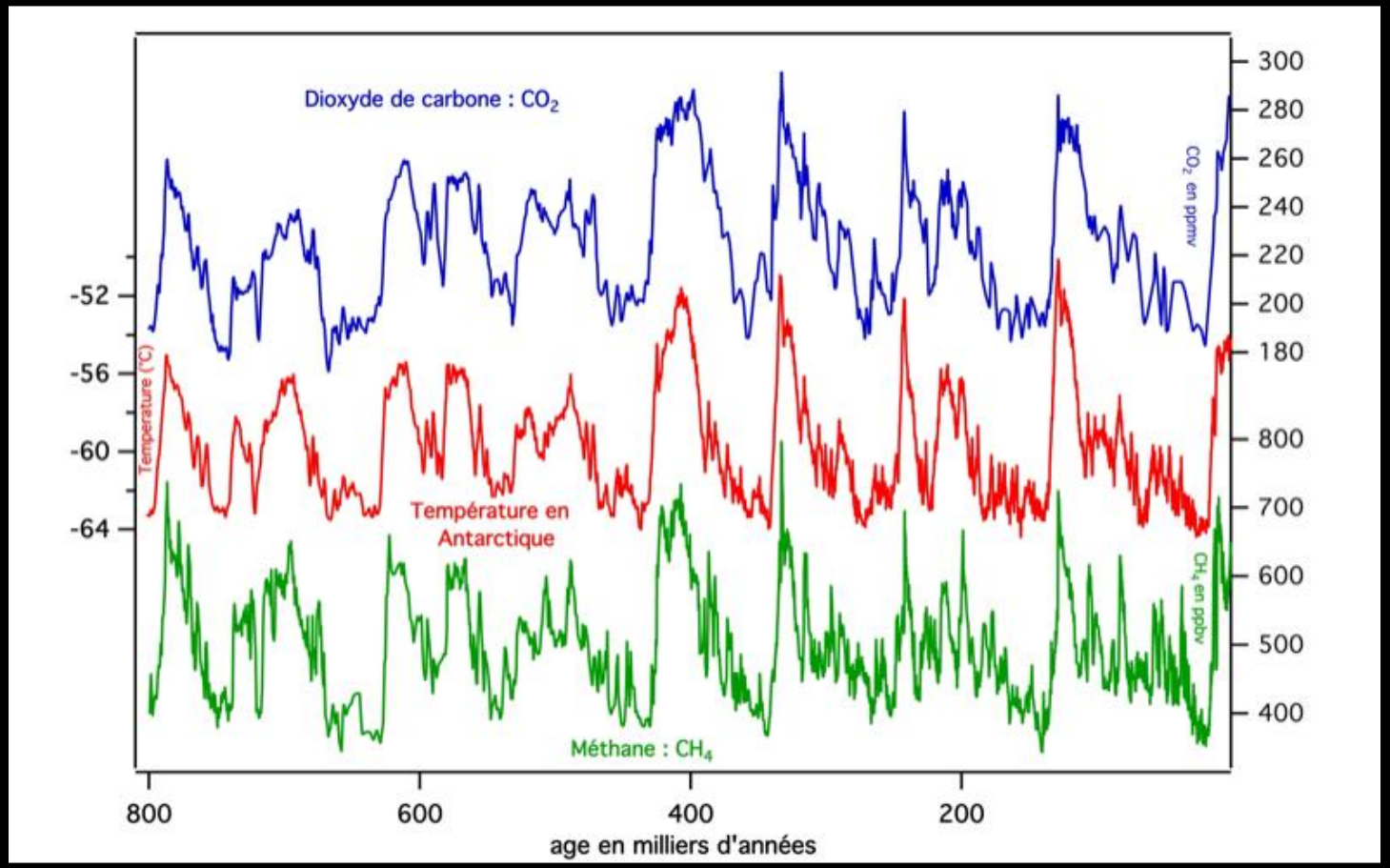
PNAS-2008

Weather Extremes



USGCRP-2008;
T Karl , Meehl, et al

Why is this good as well as Bad news?



Jouzel et al, 1993;
Petit,, Jouzel et al 1999

Glacial – Interglacial Cycles for the last 800,000 Years

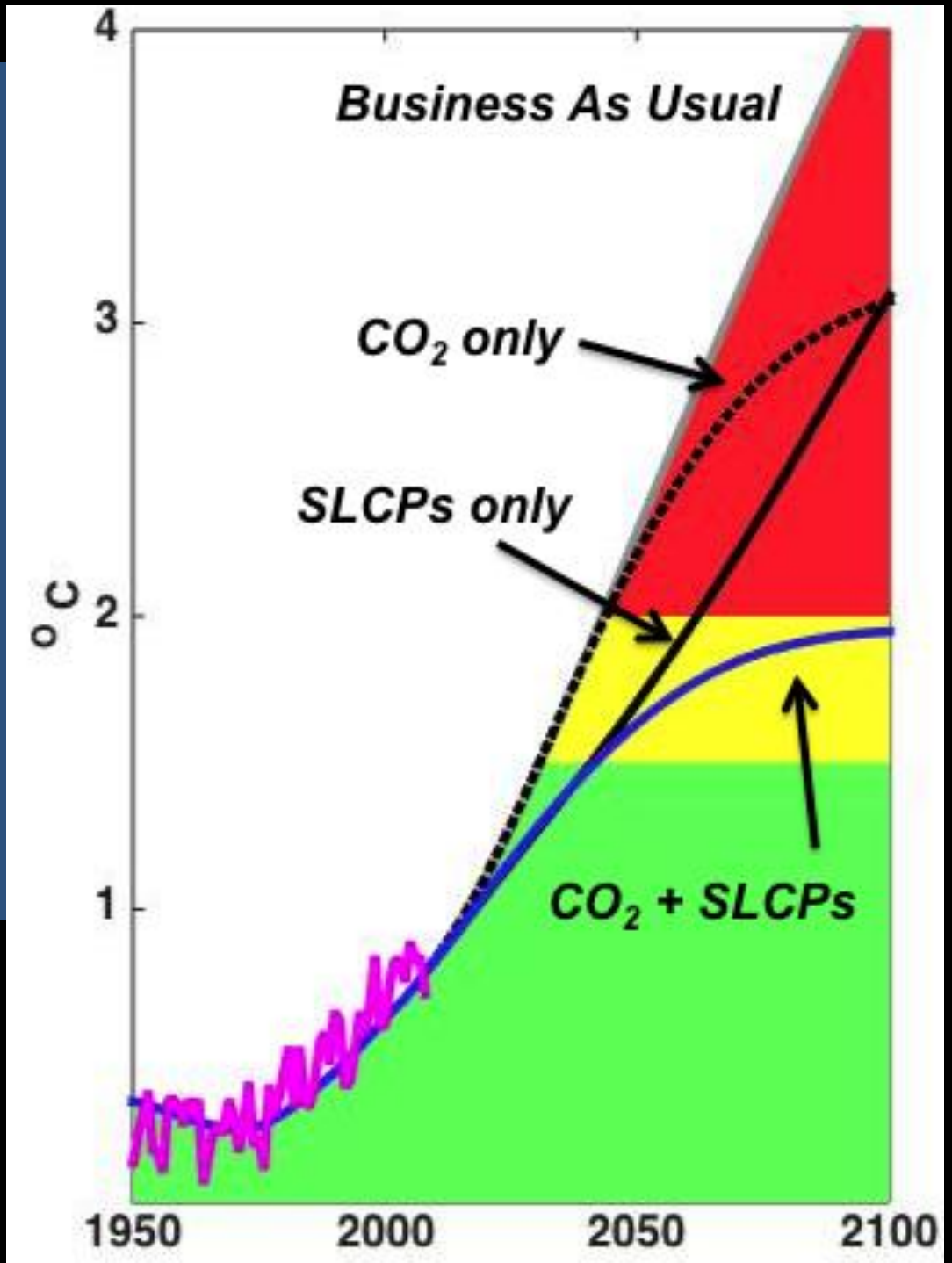
Bend the warming curve

Fast mitigation- SLCPs

Short Lived Climate Pollutants

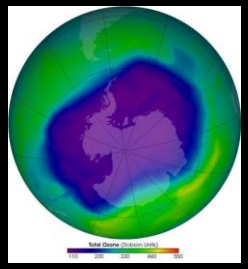
Long-Term mitigation- CO_2

Drawn by UNEP based on Ramanathan & Xu, 2010; Shindell…… Ramanathan et al, 2011



1987: Montreal Protocol Targets CFCs

1985



1974: Molina and Rowland ; 1975: Ramanathan

1997: Kyoto Protocol: Includes Non-CO2 heat trapping gases

1985: Ramanathan et al; WMO/NASA/EU Report- First Intl Report to recognize Non-CO2

2016: Kigali Amendment -phases out HFCs

2022: USA Ratified Kigali- Bi Partisan.

2009: Phasing down HFCs.. Molina, Zaelke,…… Ramanathan, …
2010: Quantifying HFCs role in climate mitigation; Ramanathan & Xu,
2013: The role of HFCs in mitigating 21st century climate change: Y. Xu[1], D. Zaelke[2], G. J. M. Velders[3], and V. Ramanathan; ACP Journal

2016: California Passes SB1383

My Prediction (The Last One)

By 2030 (with few years uncertainty), The warming will pass 1.5C (Xu, Victor and Ramanathan, 20
That will be the Ozone Hole Moment for Climate Change

2030-2035: The Climate Resilience Protocol

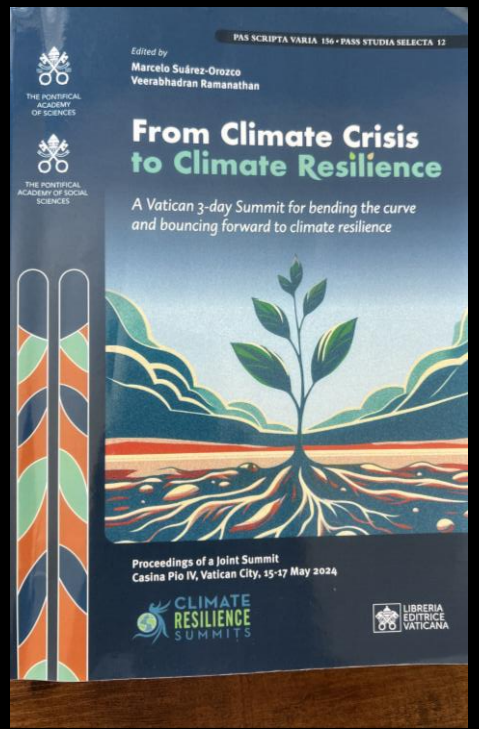
Phase out fossil fuels and SLCPs; Thin the CO2 Blanket by 300 billion tons;
Clean Energy, Water & Food for All; Biodiversity;
Chart out sustainable pathway for the next century

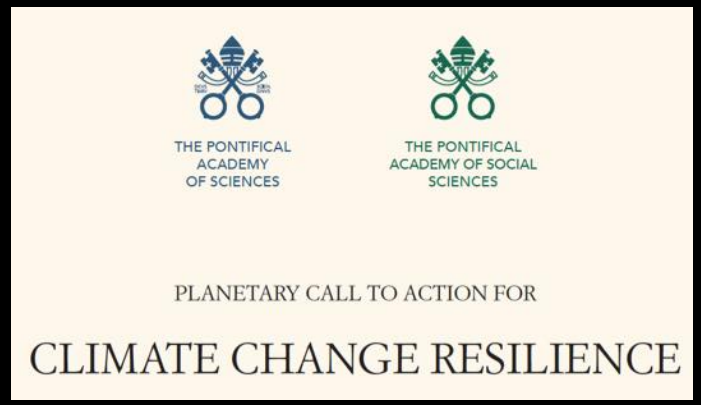
My Resilience Journey Began at the Vatican- 2004

Laudato Si, 2015

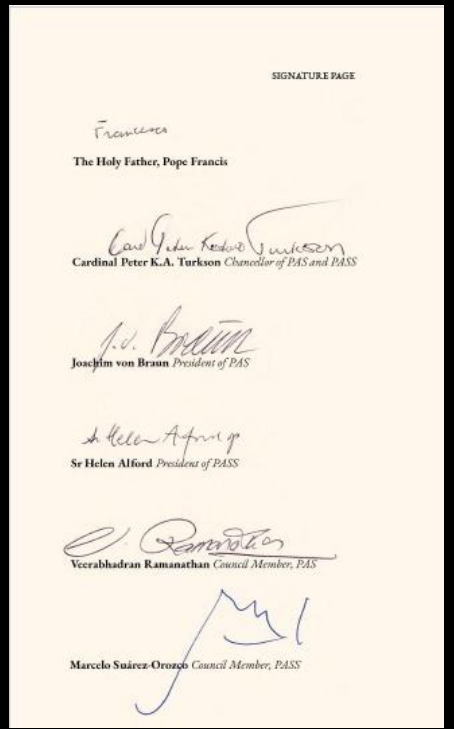
COP-Paris-2015

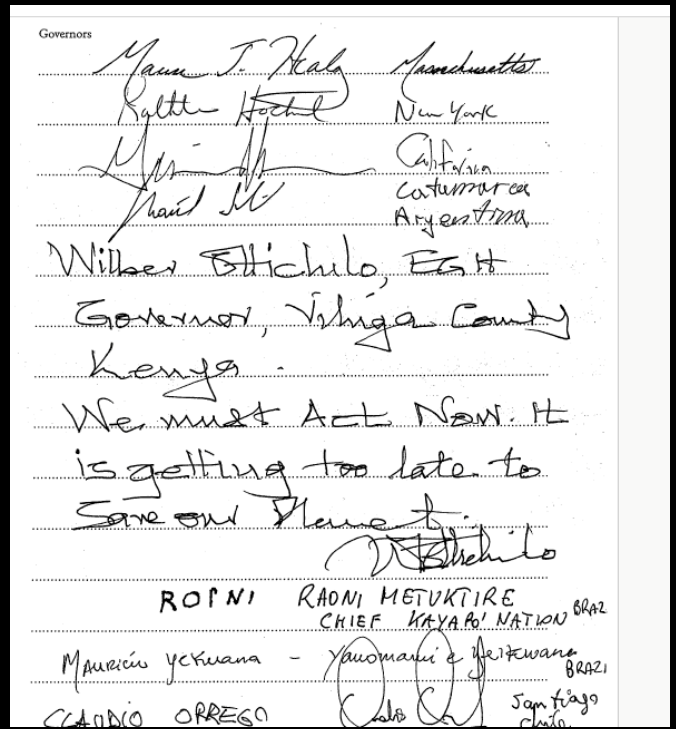
La Jolla-UCSD 2013





Authors: Ramanathan, Orozco,
Von Braun, Sr Alford,
Card Turkson, O Gustafsson, Mohamed





Vatican Climate
Climate Resilience Summit, 2024

MAST Three Pillars

Climate Resilience

SURVIVE

Thrive

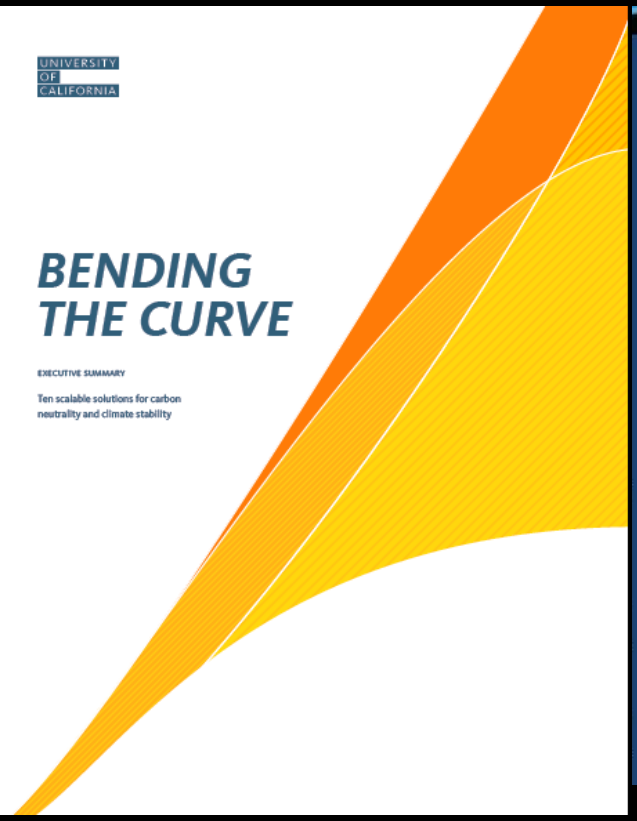
Mitigation
Reduce Emissions

Adaptation
Manage Impacts

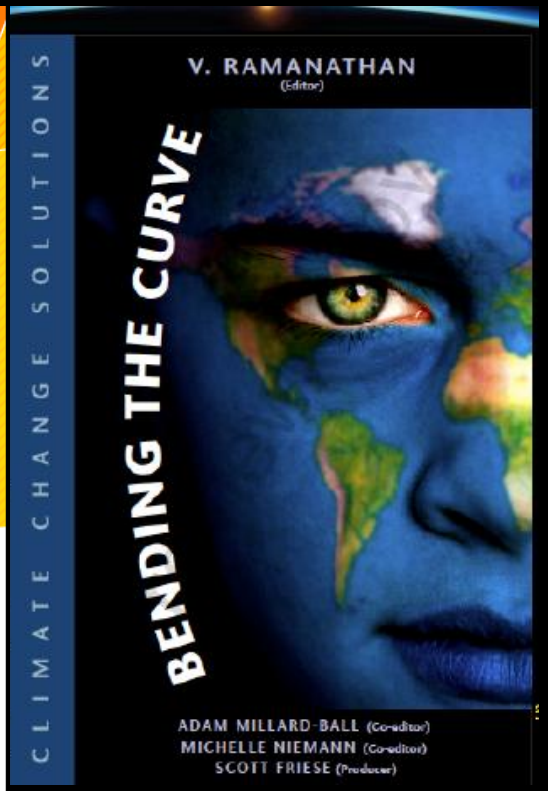
Societal Transformation
Societal Change

Ramanathan, 2022

Educating one million climate warriors



Ramanathan, Forman, Kammen & UC 50, 2014



Editors: Ramanathan, Ball, Nieman & Friese, 2016

- Digital Book
- Hybrid Course:
- UC-10 & Stockholm U
- COURSERA-4 Courses
- Business Majors

Designers/Instructors: Apel & Mishra

UC Climate Resilience Course

- **Designed to build shared learning skills**
- **process distress related to current world events in a safe space**
- **build social support and community collaboration with collective action**

Listen up Kids: Our Climate is Changing
(Self-Published Cartoon Book in Amazon)

Interconnections: Ananya Gupta (17 Yrs)
High school Climate Solutions course for all of LA County:
https://www.theintersectionsinitiative.org

project surya

Fighting Climate Change Now

Forced Draft Biomass Stove

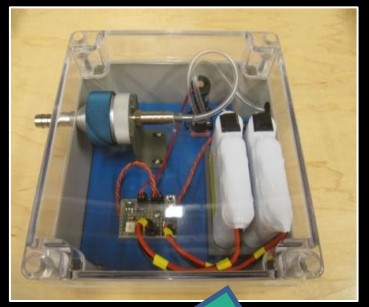
nature climate change

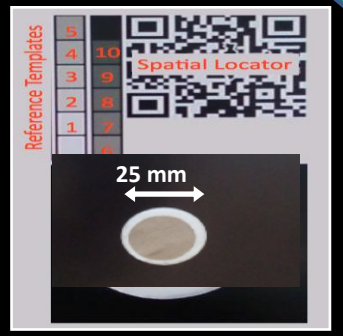
LETTERS

PUBLISHED ONLINE: 31 OCTOBER 2016 | DOI: 10.1038/NCLIMATE3141

Wireless sensors linked to climate financing for globally affordable clean cooking

Tara Ramanathan[1], Nithya Ramanathan[1]*, Jeevan Mohanty[2], Ibrahim H. Rehman[2], Eric Graham[1] and Veerabhadran Ramanathan[3]





There is time to survive and thrive the climate/weather extremes and chart a sustainable pathway.
Hundreds of solutions are available & accessible