# The Arduous Journey of TEMPO: Tracing the Path from a Nobel Prize in Chemistry that Led to Its Launch in 2023


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**St. Louis MO 63108**



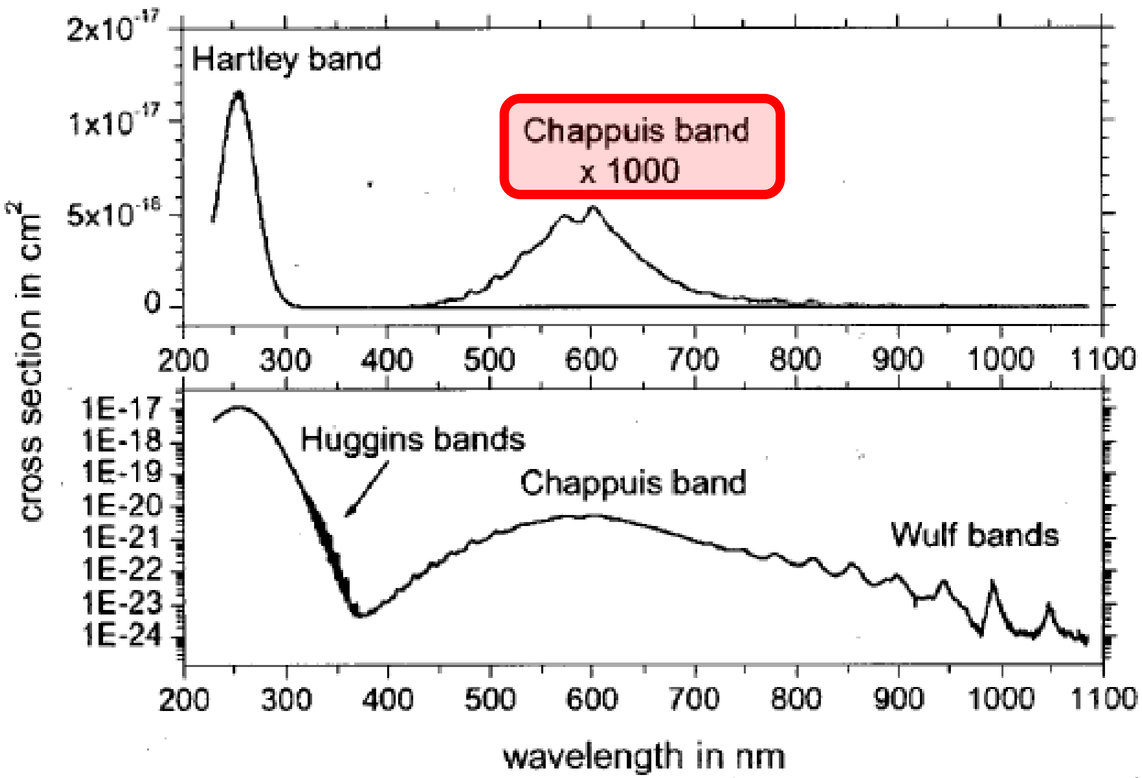
**Kelly Chance Symposium**

Cambridge, MA

August 18, 2025

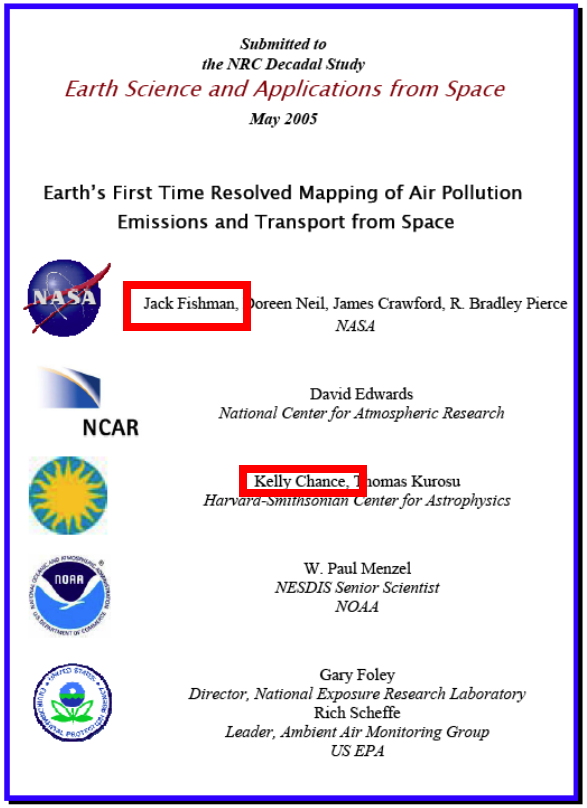
**My first recollection of Kelly:**

**"We can use Chappius Bands to get information about tropospheric ozone." (circa 1990)**



# Subsequently, Kelly and Jack Have Been an Integral Part of Studies of Using Satellite Measurements to Study Tropospheric Air Quality

**2005: Decadal Survey White Paper Written by NASA Langley**



*Submitted to*
*the NRC Decadal Study*
*Earth Science and Applications from Space*
*May 2005*

Earth's First Time Resolved Mapping of Air Pollution Emissions and Transport from Space

Jack Fishman, Doreen Neil, James Crawford, R. Bradley Pierce
*NASA*

David Edwards
*National Center for Atmospheric Research*

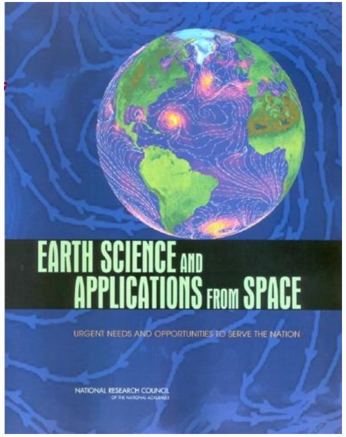
Kelly Chance, Thomas Kurosu
*Harvard-Smithsonian Center for Astrophysics*

W. Paul Menzel
*NESDIS Senior Scientist*
*NOAA*

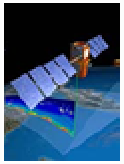
Gary Foley
*Director, National Exposure Research Laboratory*
Rich Scheffe
*Leader, Ambient Air Monitoring Group*
*US EPA*

**2006: Community Workshop Consensus Report**

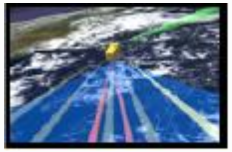
# 17 (of >100 submitted) New Missions Recommended: "Minimal Yet Robust"

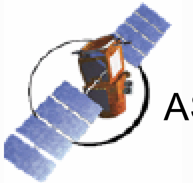



3D-Winds



ACE





ASCENDS

CLARREO

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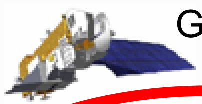


GACM

**Missions Classified into 3 Tiers:**

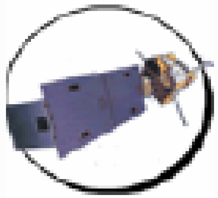
**Tier 1: 2010-2013**

**Tier 2: 2013-2016**

**Tier 3: 2016-2020**

**GEO-CAPE (Geostationary Coastal and Air Pollution Events) Classified as a Tier-2 Mission**

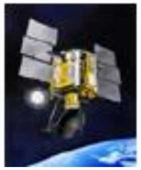
**GEO-CAPE**



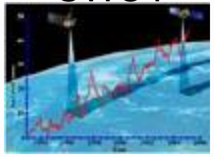
GPSRO

**NASA Created Science Working Groups for Tier-2 Missions: Assess Technical Feasibility, Cost and Implementation**

XOVRM

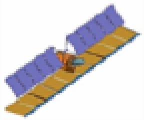


SWOT

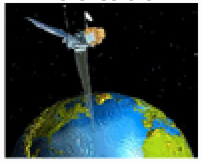


SMAP

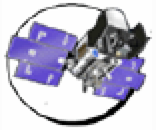
SCLP



PATH



ICESat-II

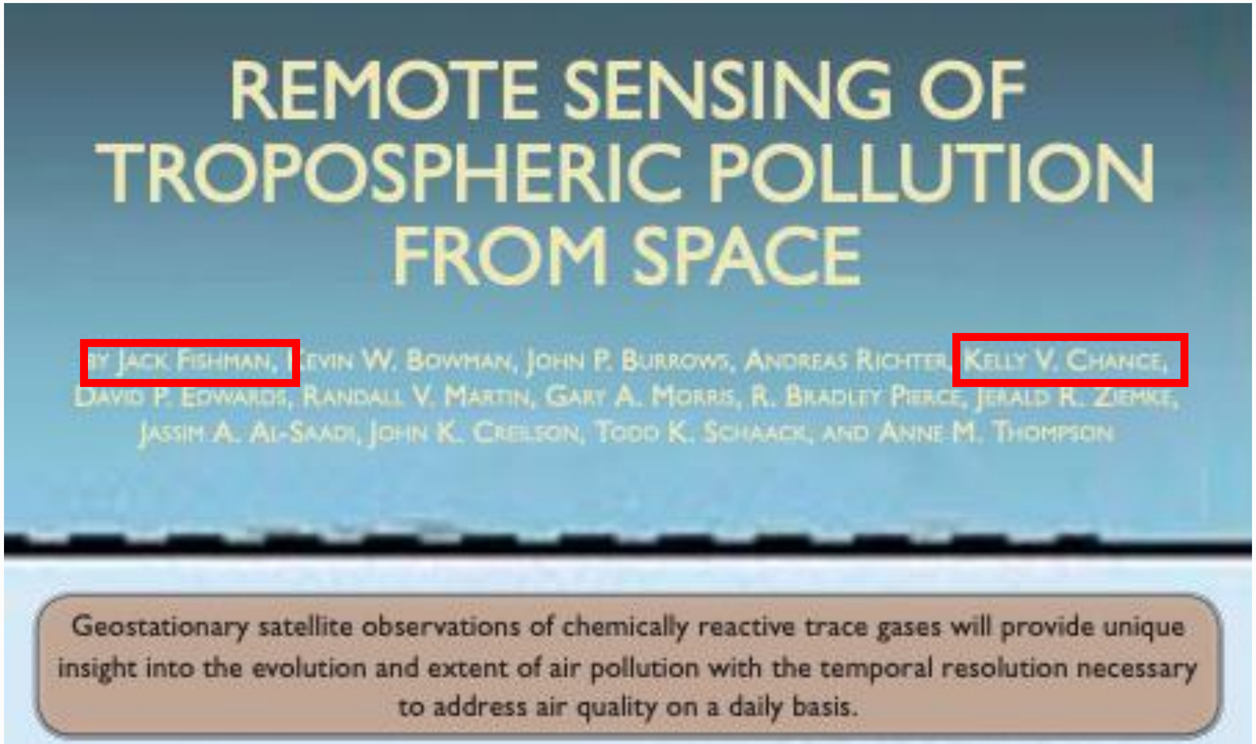


& LIST

HyspIRI

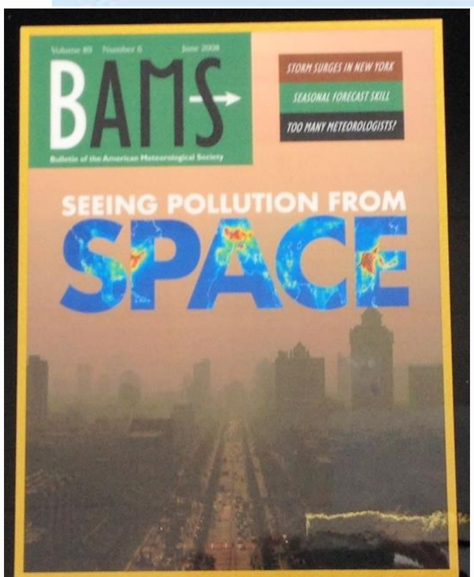
GRACE-II

***Decades of Collaboration:***


REMOTE SENSING OF TROPOSPHERIC POLLUTION FROM SPACE

BY JACK FISHMAN, KEVIN W. BOWMAN, JOHN P. BURROWS, ANDREAS RICHTER, KELLY V. CHANCE, DAVID P. EDWARDS, RANDALL V. MARTIN, GARY A. MORRIS, R. BRADLEY PIERCE, JERALD R. ZIEMKE, JASSIM A. AL-SAADI, JOHN K. CREILSON, TODD K. SCHAACK, AND ANNE M. THOMPSON

Geostationary satellite observations of chemically reactive trace gases will provide unique insight into the evolution and extent of air pollution with the temporal resolution necessary to address air quality on a daily basis.

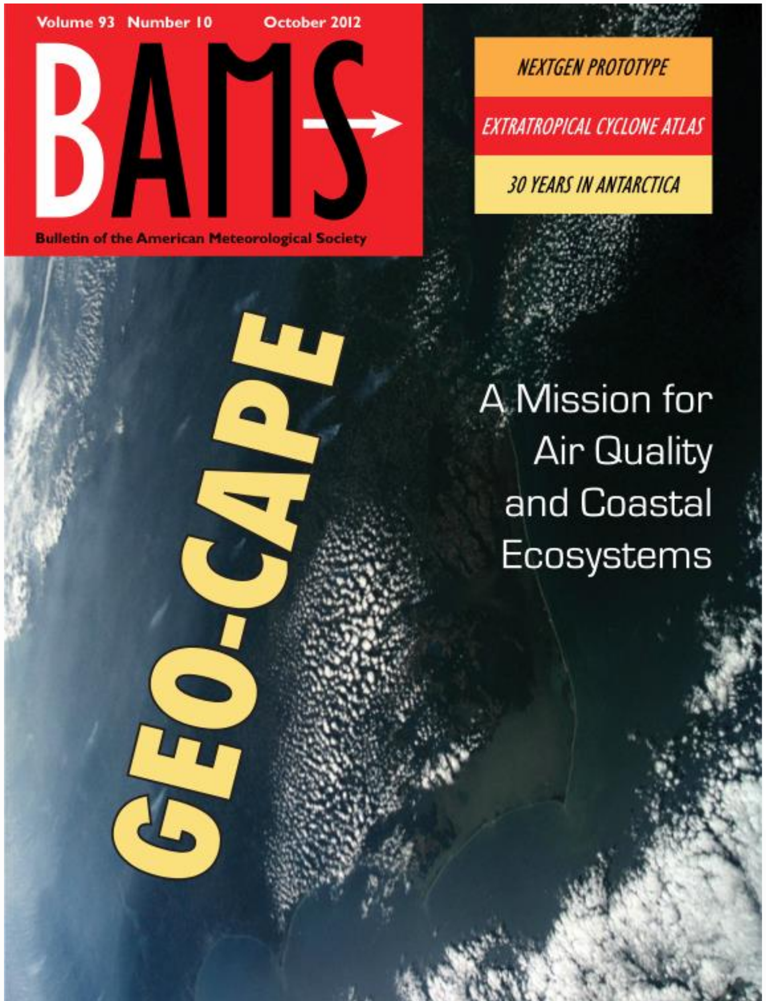



## Fishman et al. (2008):

**Summarizes Community-Wide Capabilities of Measuring Air Pollution from Satellites and Illustrates What Can be Done from a Geostationary Platform**

# Science Working Group Report Published in BAMS (2012):

# Define "Hosted Payload" Concept to Reduce Cost




## THE UNITED STATES' NEXT GENERATION OF ATMOSPHERIC COMPOSITION AND COASTAL ECOSYSTEM MEASUREMENTS

### NASA's Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission

By J. Fishman, L. T. Iraci, J. Al-Saadi, K. Chance, F. Chavez, M. Chin, P. Coble, C. Davis, P. M. DiGiacomo, D. Edwards, A. Eldering, J. Goes, J. Herman, C. Hu, D. J. Jacob, C. Jordan, S. R. Kawa, R. Key, X. Liu, S. Lohrenz, A. Mannino, V. Natraj, D. Neil, J. Neu, M. Newchurch, K. Pickering, J. Salisbury, H. Sosik, A. Subramaniam, M. Tzortziou, J. Wang, and M. Wang

GEO-CAPE will measure tropospheric trace gases and aerosols and coastal ocean phytoplankton, water quality, and biogeochemistry from geostationary orbit to benefit air quality and coastal ecosystem management.

# The ***Clandestine*** Birth of

# A Concept…

***<u>An Illegitimate Meeting to Discuss a Concept during a government shutdown:</u>***

# Arlin Krueger and P.K. Bhartia Invited to NASA Langley by Doreen Neil to Discuss Placing Geostationary Versions of TOMS and MAPS on a Communications Satellite




**Because of Government Shutdown, Group Forced to Meet (illegally) at Pizza Restaurant and Fishman's House in Poquoson**

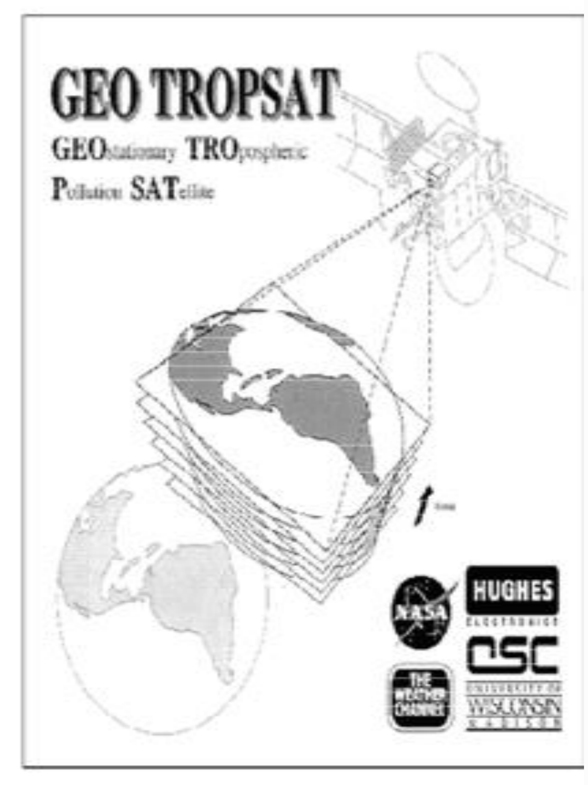
***The NASA Meeting in Poquoson was not the only Clandestine Activity Taking Place during the Government Shutdown***


**Monica Lewinsky and Bill Clinton Were Meeting at the White House**

# GEO TROPSAT (1996) proposed to ESSP-1:

**Rated “outstanding science” and invited to submit Step-2 proposal**

Step-2 proposal rated “non-compliant” because spacecraft and launch vehicle could not be identified




GEO-TROPSAT CONCEPT formally published: “Remote sensing from geostationary orbit (GEO-TROPSAT), a new concept atmospheric remote sensing,” Alan D. Little, Doreen O. Neil, Glen W. Sachse, Jack Fishman and Arlin Krueger, *Proc. SPIE 3221,* 480 (1997)

# The Scientific Evolution of TEMPO:

## Which Scientific Discipline Hatched This Mission?

### Aeronomy?

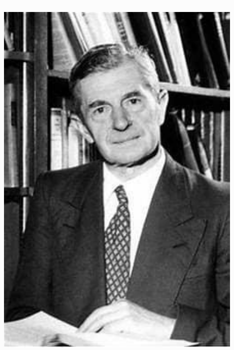
AER*ON*O*MY \A(E)R-'AN-O-ME\N [FR. GK AERO-] A BRANCH OF SCIENCE THAT DEALS WITH THE ATMOSPHERE OF THE EARTH AND THE OTHER PLANETS WITH REFERENCE TO THEIR CHEMICAL COMPOSITION, PHYSICAL PROPERTIES, RELATIVE MOTION, AND RESPONSES TO RADIATION FROM SPACE.


### Atmospheric (Air) Chemistry?

IUGG

IAGA International Association of Geomagnetism and Aeronomy

IO3C International Ozone Commission



**Sydney Chapman**

Described the chemical mechanism that explains the existence of the stratospheric ozone layer

"Chapman" Chemistry

1888-1970

iCACGP

IGAC

**Chris Junge**

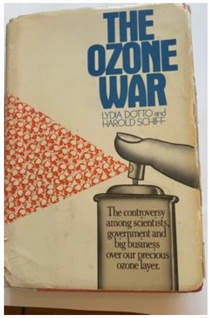
Recognized as the "Father of Atmospheric Chemistry": Studied Chemical Cycles of CO, $O_3$, $CH_4$, $H_2$, others

"Junge" Layer

1912-1996

# What did the Science Look Like Before there were Satellites?

Opening remarks
IAGA Meeting
Kyoto, Japan (1973)




***The Ozone War***
Lydia Dotto and Harold Schiff
Doubleday (New York) 1978

1921-2003

Once upon a time there lived in the land of IAGA, in the kingdom of ***Aeronomy***, strange creatures called ***aeronomers***. Little was known about these creatures because they lived most of their lives in the remote areas of the kingdom, more than 60 kiloleagues from Earth.

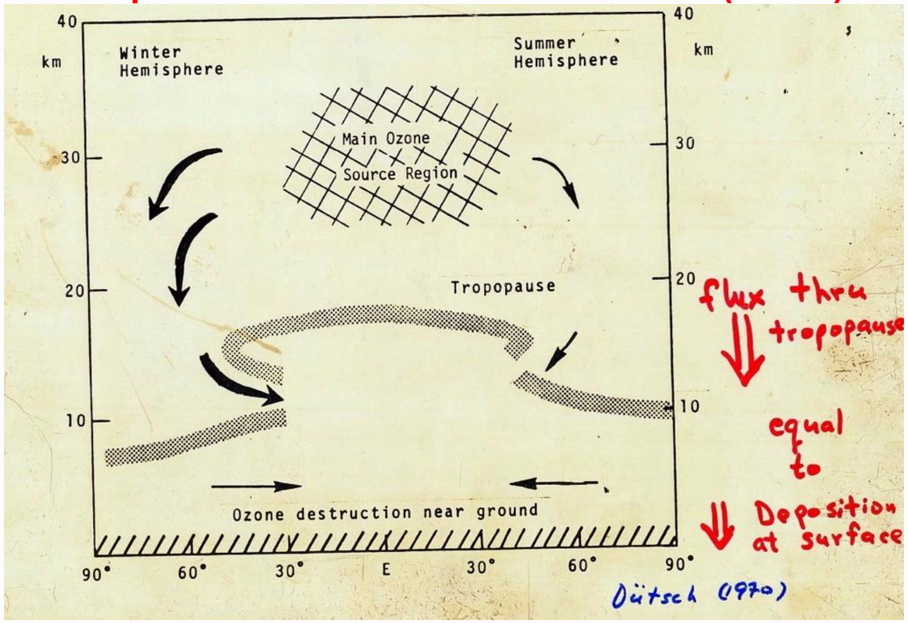
Not so long ago, a part of their kingdom, known as ***Stratos***, was threatened by the invasion of a flock of big birds who make noises that sound something like—sst. Some of the creatures of ***Aeronomy*** rushed to ***Stratos*** to try to discover what these birds might be doing to their kingdom. Some came because they heard that these birds could also lay golden eggs.

We soon learned that there are three kinds of ***aeronomers***. There is group of high priests called ***modelers***. They never go outside their temples where they try to prophesy what the big bird will do by examining the entrails of large animals called ***computers***. Another group, who appear to be the worker drones called ***experimenters***, spend most of their time in noisy smelly rooms called ***laboratories*** playing with little boxes whose purpose seems to be the generation of random numbers called ***data***. A strange relationship exists between the ***modeler*** priests and the ***experimenters***. The priests feed the ***data*** to the ***computer*** animals and then they study their entrails. They then tell the ***experimenters*** what kind of new ***data*** the animals need and the ***experimenters*** rush back to their ***laboratories*** and make more black boxes.

The third group is called ***observers***. They also make black boxes but they throw their boxes into the sky. Most of the time the black boxes break. Sometimes they too give ***data*** which the high priests also give to their animals. However, the animals sometimes get sick if they eat this ***data*** and may even die if too many different kinds of ***data*** are fed to them at the same time. However, the high priests become very clever at getting their animals to accept almost anything.

The diet of these animals seem to lack one essential nutrient called ***transport data***. Unfortunately, these *data* are grown mostly by ***dynamicists*** who live in the land of ***Tropos***. Only recently have the borders between ***Tropos*** and ***Stratos*** been opened to allow ***dynamicists*** and ***aeronomers*** to talk to each other.

**Simplified Schematic Picture of Ozone (~1970)**

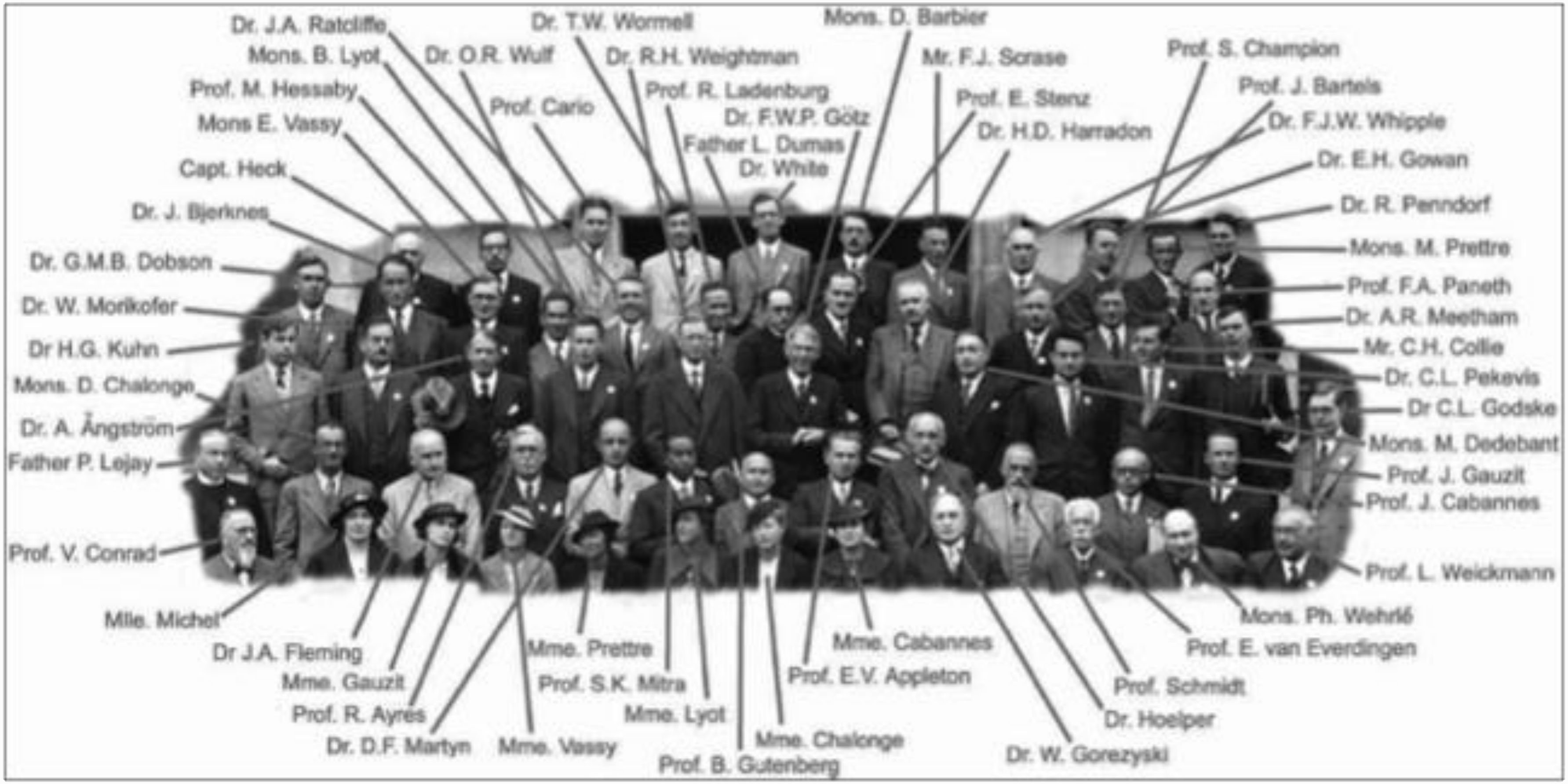


## What Did Ozone Science Look Like Before the “Ozone Hole?”

IO3C International Ozone Commission

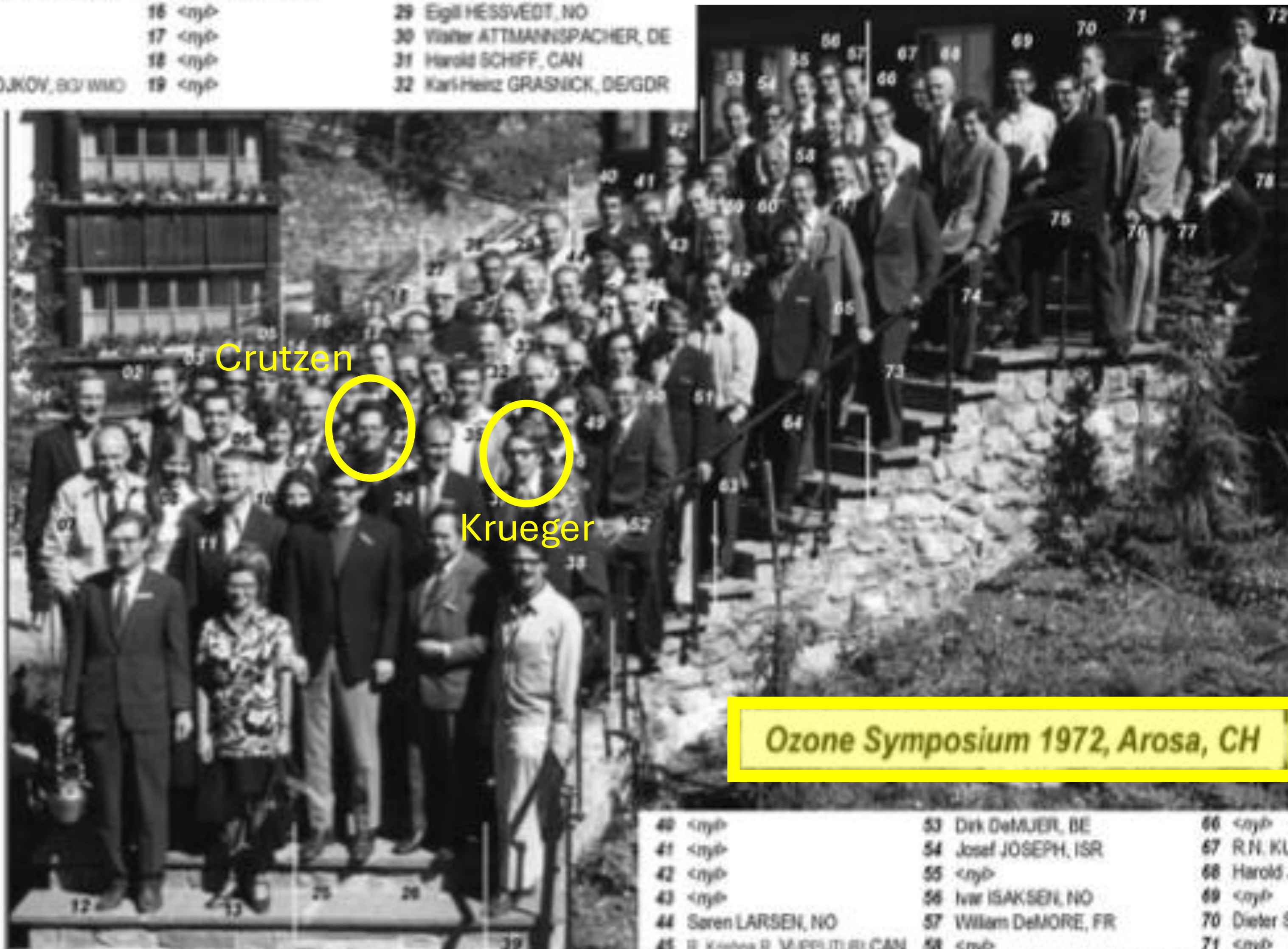
The International Ozone Commission was established in **1948** as one of the special commissions of the International Union of Geodesy and Geophysics, who represent the entire community of geophysical scientists around the world. The purpose of the IO3C is to **help organize the study of ozone around the world**, including ground-based and satellite measurement programs and analyses of the atmospheric chemistry and dynamical processes affecting ozone.

# First Ozone Conference: 1936




*Participants of the Ozone Conference held in Oxford, 9-11 September 1936. Remarkable is the mixture of many pioneers in ozone studies with prominent figures of general meteorology and national meteorological services.* *(Courtesy: Oxford university)*

# Quadrennial Ozone Meeting Every 4 Years




01 not yet identified <nyi>
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06 Rumen BOJKOV, BG/WMO
07 Alan BREWER, UK
08 <nyi>
09 Arlette VASSY, FR
10 Anna MANI, IND
11 <nyi>
12 Hans-Ulrich DÜTSCH, CH
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15 Peter FABIAN, DE
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20 Victor REGENER, USA
21 Paul CRUTZEN, SE
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26 Hans-Karl PAETZOLDT, DE
27 Art SCHMELTEKOFF, USA
28 J.S. RANDHAWA, USA
29 Eigil HESSVEDT, NO
30 Walter ATTMANNSPACHER, DE
31 Harold SCHIFF, CAN
32 Karl-Heinz GRASNICK, DE/GDR
33 Byron BOVILLE, CAN
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35 Alistair CHRISTIE, CAN
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38 Desmond WALSHAW, UK
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62 John DeLUISI, USA
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72 Yoshiro SEKIGUCHI, JAP
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74 Marcel ACKERMAN, BE
75 <nyi>
76 Guy BRASSEUR, BE
77 Stanislas CIESLIK, BE
78 <nyi>

# Where does ozone in the troposphere come from?

## No One from the Kingdom of *Stratos* seemed to care!

## This is the question We've been trying to answer for 50+ years

**Classical** Studies Assumed Only Source of Tropospheric $O_3$ was from stratosphere (<1977)

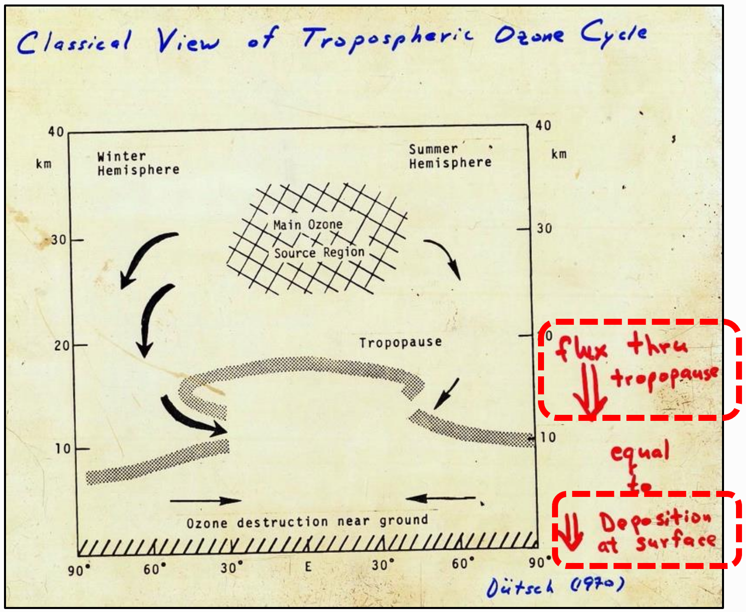



TABLE 1. Results of Studies of the Tropospheric Ozone Budget

| Estimated Ozone Flux, molecules $cm^{-2} s^{-1}$ | Domain of Interest | Reference |
|---|---|---|
| $4 \times 10^{10}$ | global average | *Paetzold* [1955] |
| $7.5 \times 10^{10}$ | global average | *Junge* [1962] |
| $6 \times 10^{10}$ | one local calculation | *Kroening and Ney* [1962] |
| $4.4–7.6 \times 10^{10}$ | northern hemisphere | *Fabian and Junge* [1970] |
| $3.7–8.2 \times 10^{10}$ | 30°–50°N | *Fabian* [1973] |
| $7.4 \times 10^{10}$ | northern hemisphere | *Fabian and Pruchneiwicz* [1976] |
| $7.95 \times 10^{10}$ | 30°–40°N | *Fabian and Pruchniewicz* [1976] |
| $4.3 \times 10^{10}$ | southern hemisphere | *Fabian and Pruchniewicz* [1976] |
| $7 \times 10^{10}$ | northern hemisphere | *Danielsen and Mohnen* [1977] |

Tropospheric Photochemical Models (<1977) Ignited Controversey in Scientific Community

- Crutzen (1973; 1974): Identified chemistry that could be significant source of $O_3$
- Chameides and Walker (1973; 1976): $CH_4$ oxidation primary source of tropospheric $O_3$
- Fishman and Crutzen (1977): One-dimensional photochemical model of tropospheric chemistry (my dissertation)

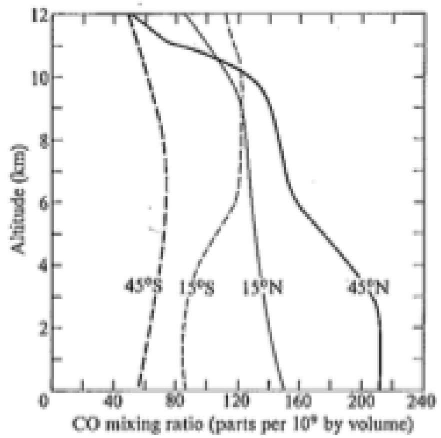
# Measurements of CO Critical for Understanding Origin of Tropospheric $O_3$ in Original Theoretical Papers

(Reprinted from Nature, Vol. 274, No. 5674, pp. 855–858, August 31, 1978)


## The origin of ozone in the troposphere

Jack Fishman
Department of Atmospheric Science, Colorado State University, Ft Collins, Colorado 80523

Paul J. Crutzen
National Center for Atmospheric Research, PO Box 3000, Boulder, Colorado 80307




Tellus (1979), 31, 432–446

## Observational and theoretical evidence in support of a significant in-situ photochemical source of tropospheric ozone

By JACK FISHMAN, Department of Atmospheric Science, Colorado State University, Ft. Collins, Colorado 80523, U.S.A., SUSAN SOLOMON, National Centre for Atmospheric Research,[1] P.O. Box 3000, Boulder, Colorado 80307, U.S.A. and Department of Chemistry, University of California, Berkeley, Berkeley, California 94720, U.S.A., and PAUL J. CRUTZEN, National Centre for Atmospheric Research,[1] P.O. Box 3000, Boulder, Colorado 80307, U.S.A.

Table 1. *Calculated photochemical destruction rates of various trace gases in the troposphere*

| | NH | SH | Global |
|---|---|---|---|
| Photochemical destruction of $O_3$ | 20.0 | 11.0 | 15.5 |
| From $O(^1D) + H_2O$ (R13) | 10.4 (52%) | 5.0 (45%) | 7.7 (50%) |
| $O_3 + HO_2$ (R14) | 8.5 (42%) | 5.2 (42%) | 6.8 (44%) |
| $O_3 + OH$ (R15) | 1.1 (6%) | 0.8 (8%) | 1.0 (6%) |
| Photochemical oxidation of CO | 28.6 | 19.3 | 23.9 |
| Photochemical oxidation of $CH_4$ | 5.2 | 6.0 | 5.6 |
| Injection of $O_3$ from the stratosphere (Fabian and Pruchniewicz, 1977) | 6.8 | 4.4 | 5.6 |

**Oxidation of CO is a significantly larger source of $O_3$ than transport from the stratosphere**

# Fishman works with Seiler in 1979 to Analyze Aircraft Measurements from 1974: Analyses published in three journal articles (1980, 1981, 1983)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. C6, PAGES 3662–3670, APRIL 20, 1983

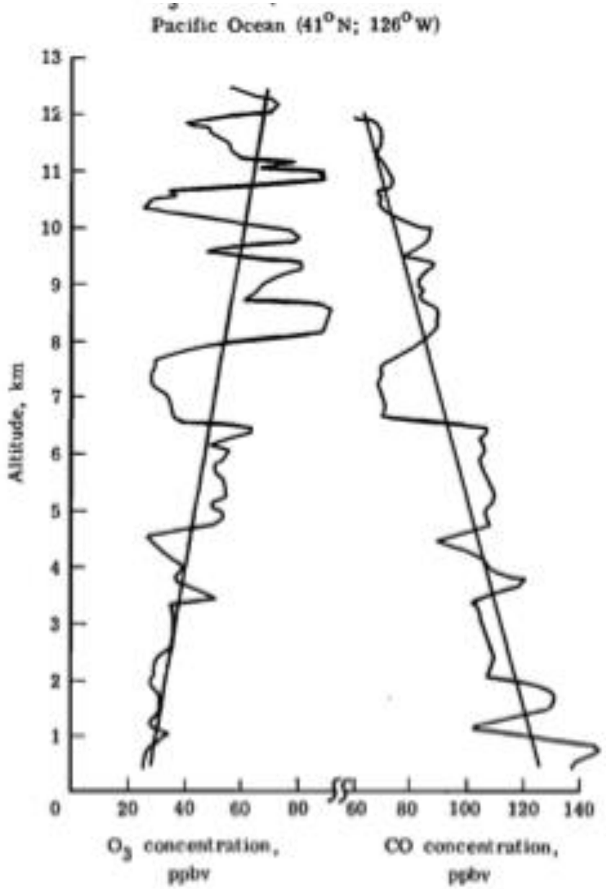
## Correlative Nature of Ozone and Carbon Monoxide in the Troposphere: Implications for the Tropospheric Ozone Budget

JACK FISHMAN

*NASA Langley Research Center, Hampton, Virginia 23665*

WOLFGANG SEILER

*Max Planck Institute for Chemistry, D-6500 Mainz, West Germany*



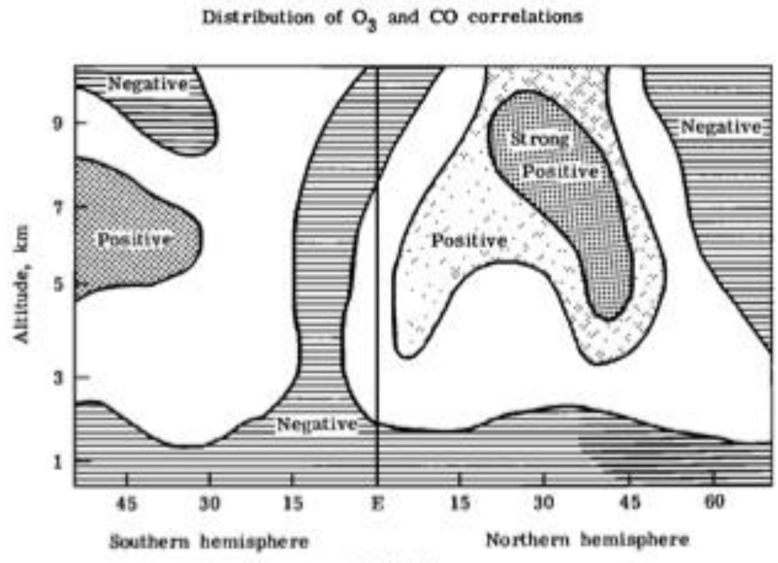
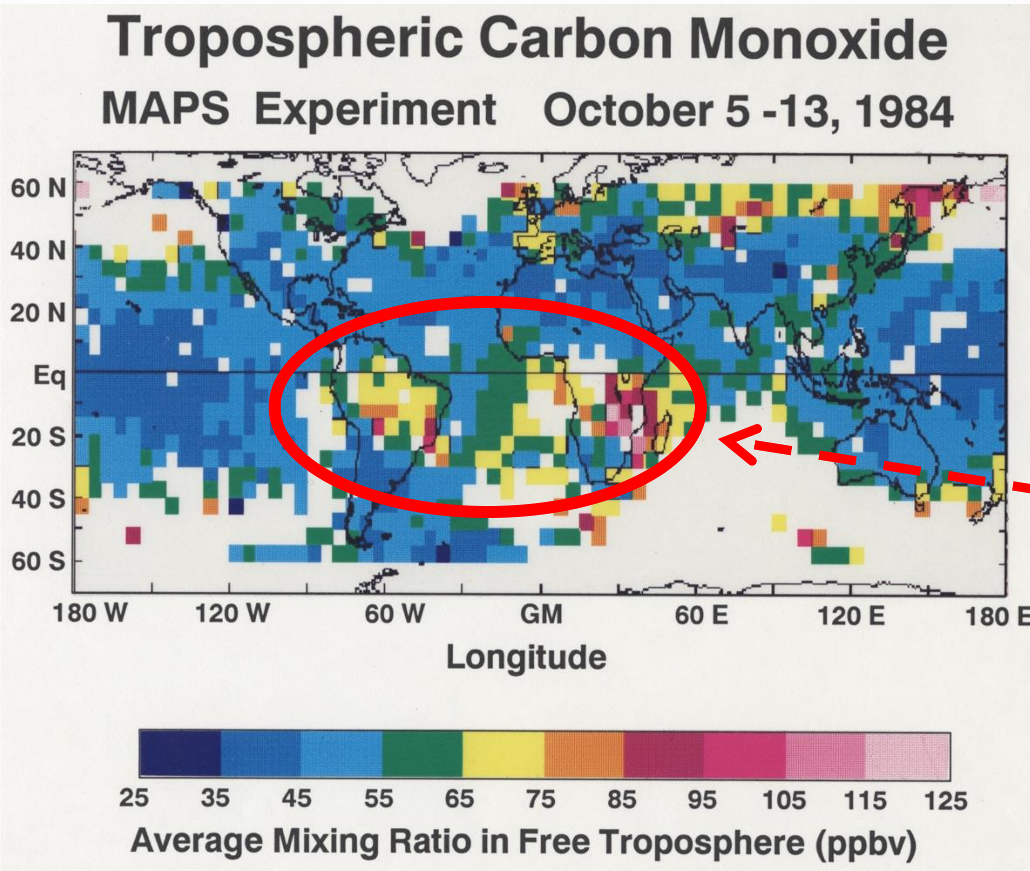
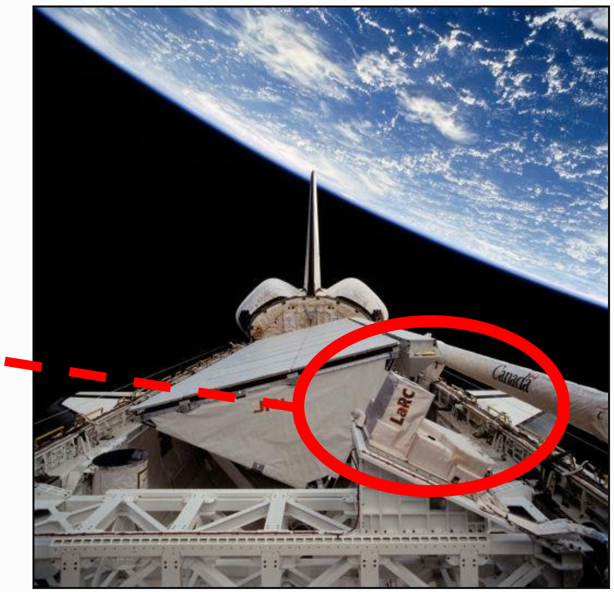




TABLE 1. Summary of $O_3$ and CO Profiles Analyzed

| | Latitude Domain | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 55°–45°S | 45°–30°S | 30°–15°S | 15°S–0° | 0°–15°N | 15°–30°N | 30°–45°N | 45°–55°N | 55°–67°N |
| Profiles analyzed | 5 | 6 | 3 | 7 | 6 | 7 | 7 | 6 | 14 |
| Correlation | | | | | | | | | |
| Significantly positive (<0.5) | 2 | 2 | 1 | 1 | 2 | 4 | 6 | 2 | 5 |
| Significantly negative (<−0.5) | 1 | 0 | 1 | 3 | 1 | 1 | 0 | 1 | 4 |
| Average concentration | | | | | | | | | |
| $O_3$, ppbv | 40 | 26 | 22 | 23 | 22 | 38 | 47 | 46 | 44 |
| CO, ppbv | 70 | 70 | 79 | 98 | 105 | 101 | 108 | 129 | 128 |

# MAPS (Measurement of Air Pollution from Satellites) flies on Space Shuttle in 1981 and 1984



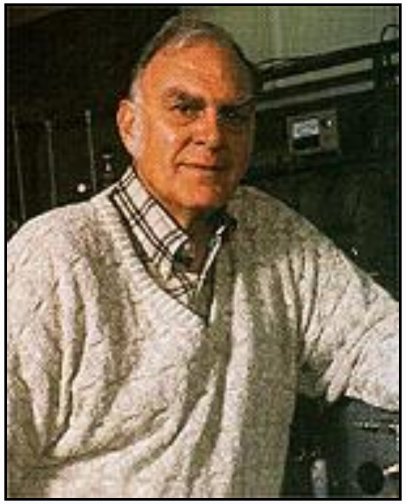
## ***Atmospheric Chemistry Achieved Unparalleled Respect in 1997:***

The Nobel Prize in Chemistry Was Not Awarded Solely for the Chemistry Related to Stratospheric Ozone Depletion

"... the Royal Swedish Academy of Sciences awarded the 1995 Nobel Prize in Chemistry to **Paul Crutzen, Mario Molina** and **F. Sherwood Rowland** for their work in atmospheric chemistry, particularly concerning **the formation** and decomposition **of ozone**."

1933-2021
Modeler/Meteorologist

1943-2020
Kineticist (Experimenter)



1927-2012
Observationalist

## ***Atmospheric Chemistry Achieved Unparalleled Respect in 1997:***

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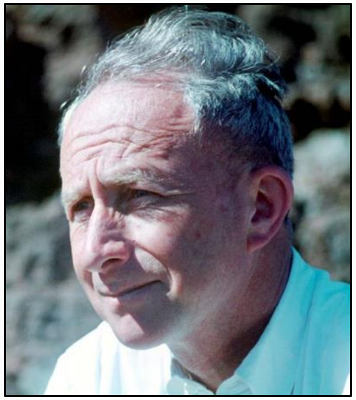
"... the Royal Swedish Academy of Sciences awarded the 1995 Nobel Prize in Chemistry to **Paul Crutzen, Mario Molina** and **F. Sherwood Rowland** for their work in atmospheric chemistry, particularly concerning **the formation** and decomposition **of ozone**"

**Subsequent to receiving to their Nobel Prize, Each Laureate's research focused on understanding an aspect of tropospheric chemistry:**

- **Crutzen – Global Tropospheric sources of Ozone and other trace gases**
- **Molina – Focus on air pollution in Mexico City (MILAGRO)**
- **Rowland – Sources of methane and other trace gases in remote regions**



# Christian Junge

1912-1996

**“father of atmospheric chemistry”**

**Junge’s Students:**
**Dieter Ehhalt ($CH_4$)**
**Wolfgang Seiler (CO)**
**Peter Fabian ($O_3$)**
**Ulrich Schmidt ($H_2$)**

THE INVENTION OF AIR CHEMISTRY - CHRISTIAN JUNGE (1912 -1996)

In 1963 the book “Air Chemistry and Radioactivity” by Christian Junge was published. The book was very well received and served for many years as a reference for trace substances and tracer studies in the atmosphere. Actually it has coined the term “Air Chemistry” or “Atmospheric Chemistry” as the name for a completely standalone science. His study was concentrated on those trace substances of the atmosphere, which many scientists of those days regarded as unavoidable dirt. However, substances like atmospheric aerosols and trace gases like methane, $N_2O$, and the chlorofluoromethanes (CFMs) might directly and indirectly influence weather, climate, and the environment. The Max Planck Society appointed Junge as director at the Max Planck Institute for Chemistry after a long search. Junge drove forward this research field so today it is a prosperous science.

# While Working at NOAA's Aeronomy Laboratory Crutzen Had Access to Latest Chemical Kinetics Research and Concluded that Sources of Several Key Trace Gases Were Missing

- New Reaction Rate for $NO + HO_2 \rightarrow NO_2 + OH$ Could have Significant Impact on Global OH Distribution

- "Diagnostic" Tropospheric Chemistry Model Implied Considerably Lower OH in Troposphere than Previously Calculated

## AVERAGE CONCENTRATIONS OF OH IN THE TROPOSPHERE, AND THE BUDGETS OF $CH_4$, CO, $H_2$ AND $CH_3CCl_3$

Abstract. An average tropospheric OH concentration in the Northern Hemisphere of about $3 \times 10^5$ $cm^{-3}$ is not in disagreement with present photokinetic information. This has important implications for the tropospheric budgets of $CH_4$, CO, $H_2$ and $CH_3CCl_3$. Present concentrations of

CO sink at the ground (Seiler, 1974), there must be additional sources of CO than considered in presently evaluated budgets.

# Consensus ~1970 was that Source from Forest Burning was not Significant (NAS Report, 1977)

TABLE 3-4 Estimated Carbon Monoxide Production Rates from Natural and Anthropogenic Sources, 1970

| Source | CO Emission Rate, $10^6$ metric tons/yr ($10^9$ kg/yr) |
| --- | --- |
| Anthropogenic | 359 |
| Methane oxidation | 2,500 |
| Forest fires | 10 |
| Terpene oxidation | 54 |
| Plant synthesis and degradation | 90 |
| Oceans | 220 |
| Total, all carbon monoxide sources | 3,233 |

CARBON MONOXIDE

*Committee on Medical and Biologic Effects of Environmental Pollutants*

DIVISION OF MEDICAL SCIENCES
ASSEMBLY OF LIFE SCIENCES
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1977

NAS-NAE

# Seminal Papers Published on Biomass Burning

SEILER* and PAUL J. CRUTZEN

r for Atmospheric Research,** P.O. Box 3000, Boulder, Colorado 80307, U.S.A.


**Abstract:** In order to estimate the production of charcoal and the atmospheric emissions of trace gases volatilized by burning we have estimated the global amounts of biomass which are affected by fires. We have roughly calculated annual gross burning rates ranging between about 5 Pg and 9 Pg (1 Pg = $10^{15}$ g) of dry matter (2–4 Pg C). In comparison, about 9–17 Pg of above-ground dry matter (4–8 Pg C) is exposed to fires, indicating a worldwide average burning efficiency of about 50%. The production of dead below-ground dry matter varies

## Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles

PAUL J. CRUTZEN AND MEINRAT O. ANDREAE

21 Dec 1990 Vol 250, Issue 4988 pp. 1669-1678

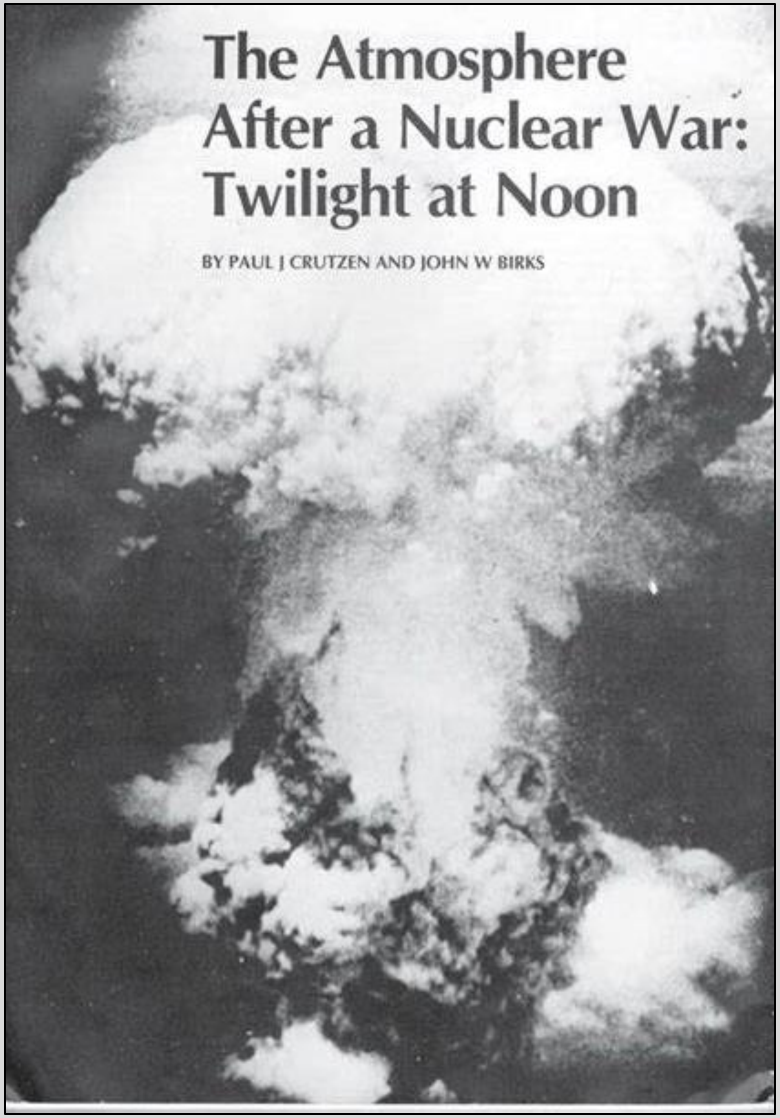
# Crutzen Invited Wolfgang Seiler to NCAR in 1978 to Re-Examine Global CO Budget

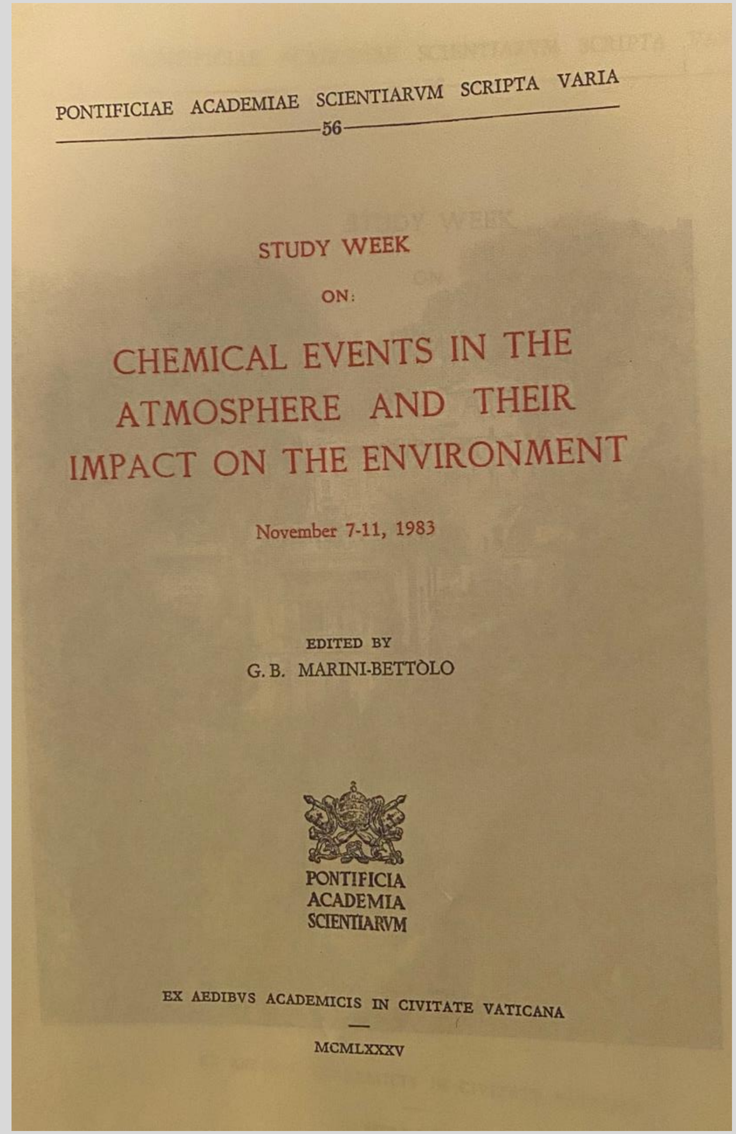
## The cycle of atmospheric CO

By WOLFGANG SEILER, *Max-Planck-Institut für Chemie (Otto-Hahn-Institut), Mainz, West Germany*

(Manuscript received June 20; revised version October 15, 1973)

Seiler's dissertation under Junge published in 1974





PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA

56

STUDY WEEK

ON:

CHEMICAL EVENTS IN THE ATMOSPHERE AND THEIR IMPACT ON THE ENVIRONMENT

November 7-11, 1983

EDITED BY

G. B. MARINI-BETTÒLO

PONTIFICIA
ACADEMIA
SCIENTIARVM

EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

MCMLXXXV


**Crutzen Honored as *Discover* Magazine's Scientist of the Year in 1985 for Introducing the World to the Concept of "Nuclear Winter"**

# Crutzen's Search for Missing CO Source Ignites Interest in Burning in the Tropics and the Science of Burning

Leads NCAR Field Mission to Brazil to Study Biomass Burning

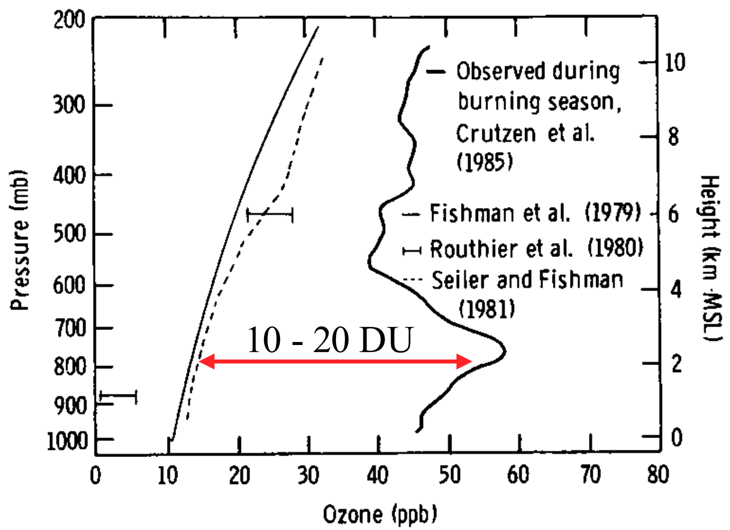
Consults with Missoula Fire Research Center to Understand Fire Science

# NASA Becomes Interested in Tropospheric Chemistry in Late 1970s

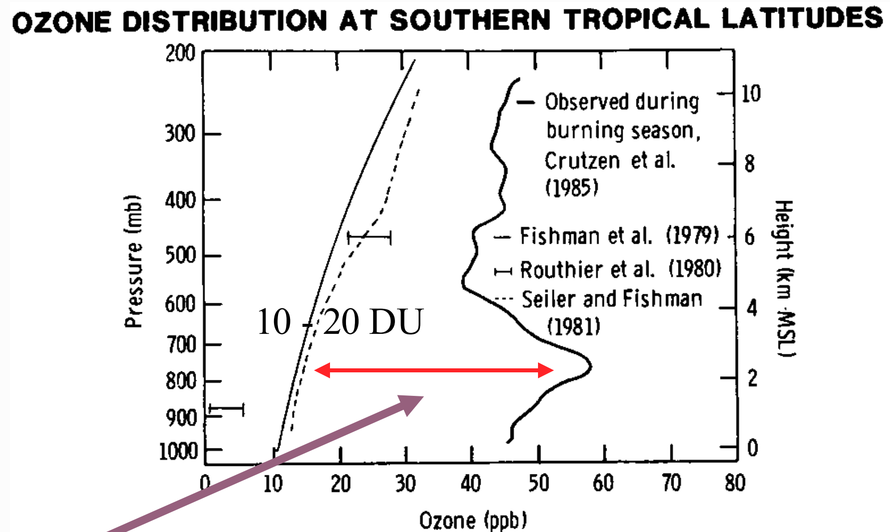
- Environmental Quality Project Office Established at Langley
- Becomes Part of AESD at NASA Langley

## Planning Meeting of Global Tropospheric Experiment (1984): Tony Delany to Showed Results from NCAR Expedition

OZONE DISTRIBUTION AT SOUTHERN TROPICAL LATITUDES



In his search for understanding the sources of ozone in the troposphere, Crutzen made the first comprehensive measurements trace gases where tropical biomass burning was occurring and found considerably higher concentrations than what had been published previously



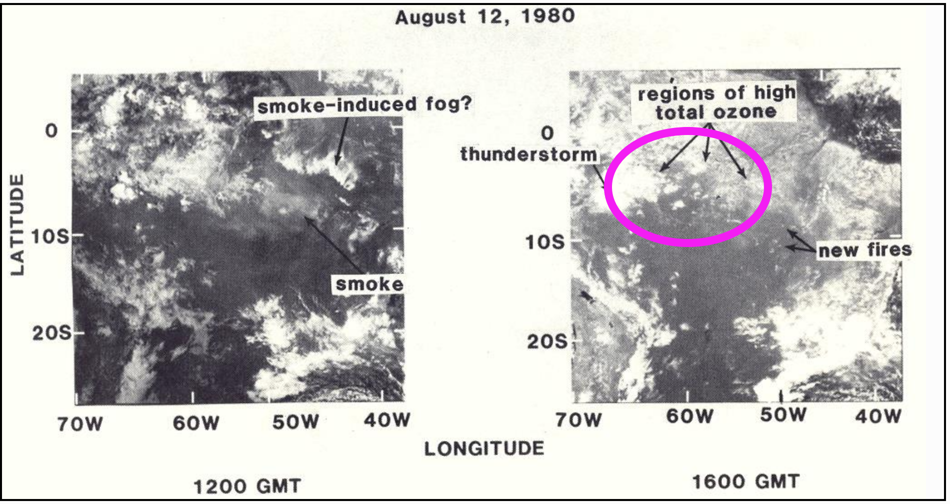
(from Fishman, Minnis & Reichle, *JGR*, 91, 1986)

- **Can the 10-20 Dobson Unit Enhancement Be Identified from TOMS Total Ozone Measurements?**

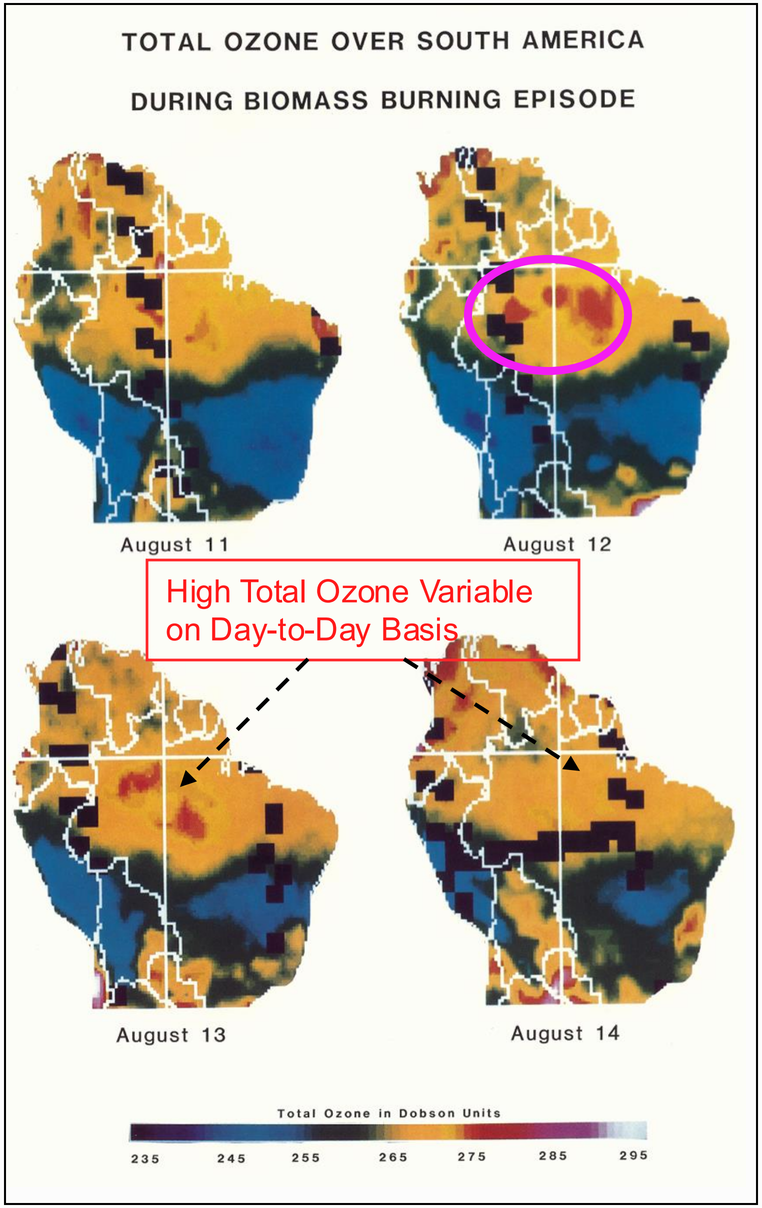
- Such Enhancements are Better Observed at Low Latitudes Due to Less Stratospheric Variability

- TOMS Precision is 1% (~ 3 DU)

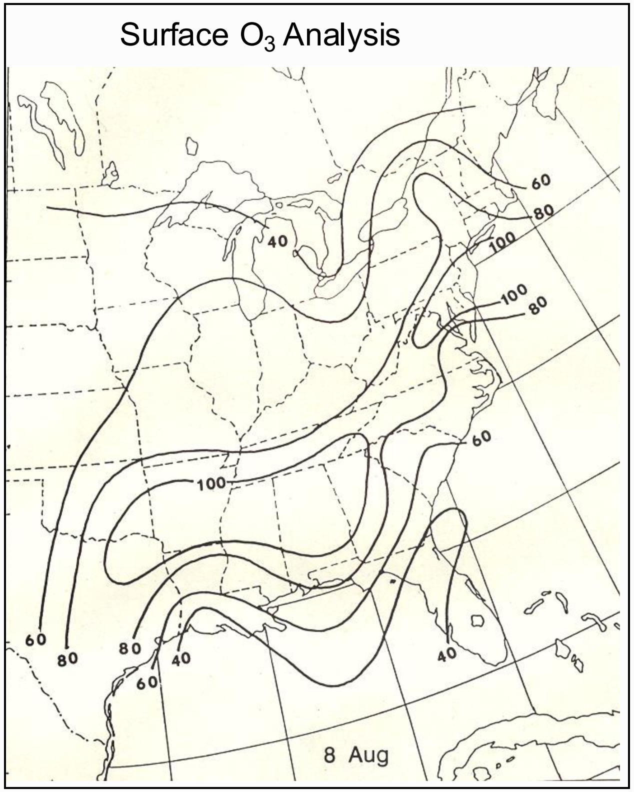
# Enhanced Total Ozone Observed in Conjunction with Biomass Burning in 1980 Episode

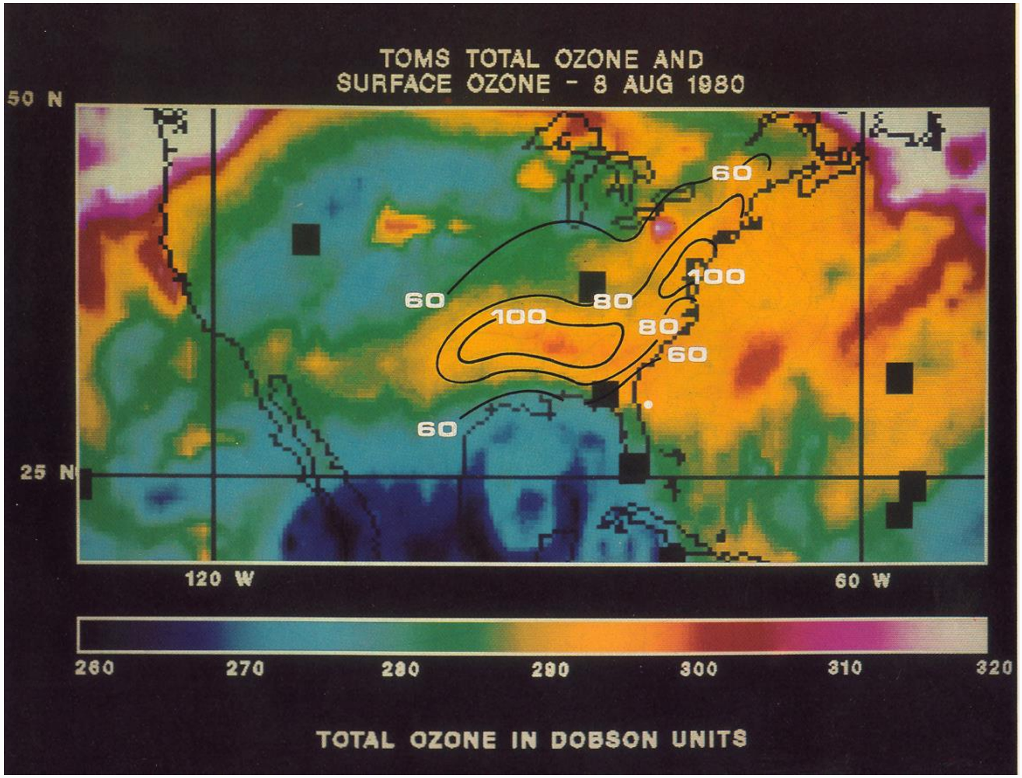



(from Fishman, Minnis & Reichle, *JGR* , 91, 1986)



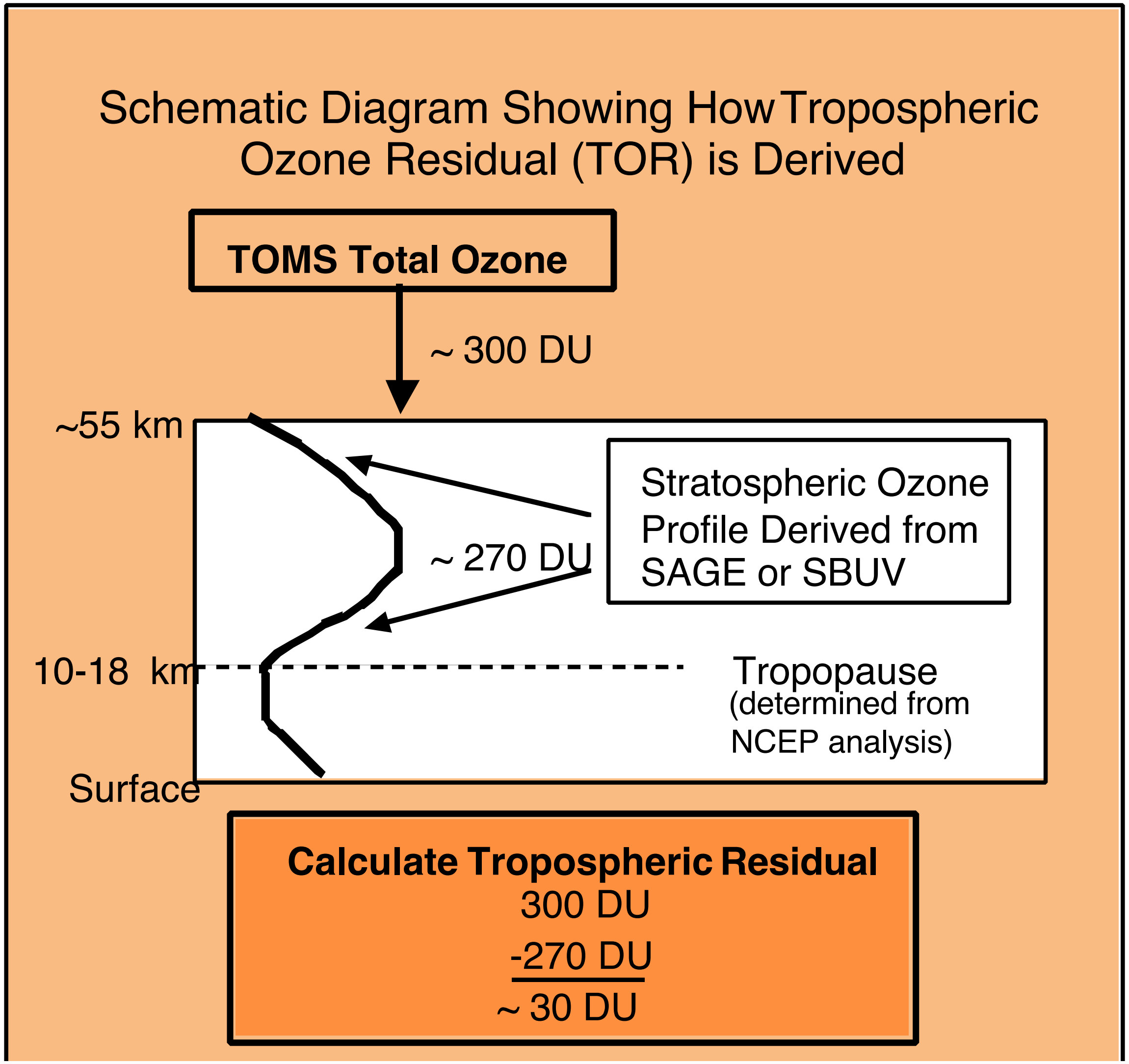
# High Surface Ozone Concentrations During Pollution Episode Also Observed in TOMS Total Ozone



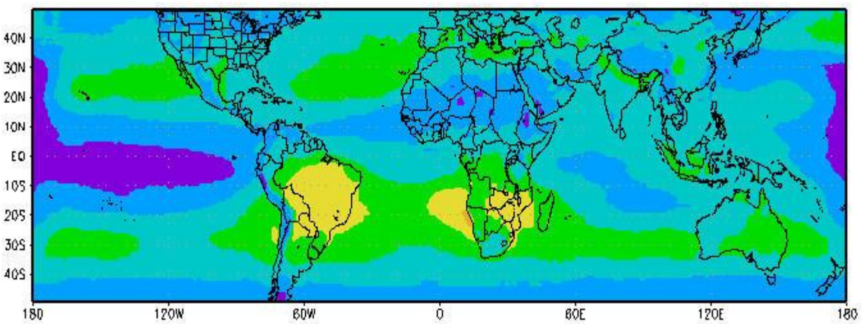

(from Fishman et al., *J. Clim. Appl. Met.*, 26, 1987)

# Separate Stratosphere from Troposphere to Compute Tropospheric Ozone Residual (TOR)

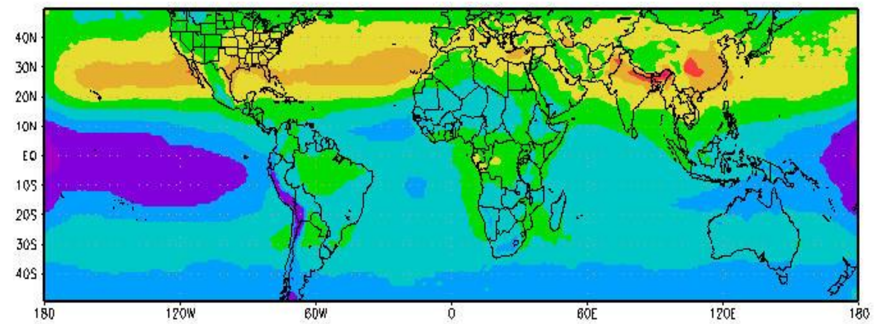


# Seasonal Depictions of Tropospheric Ozone

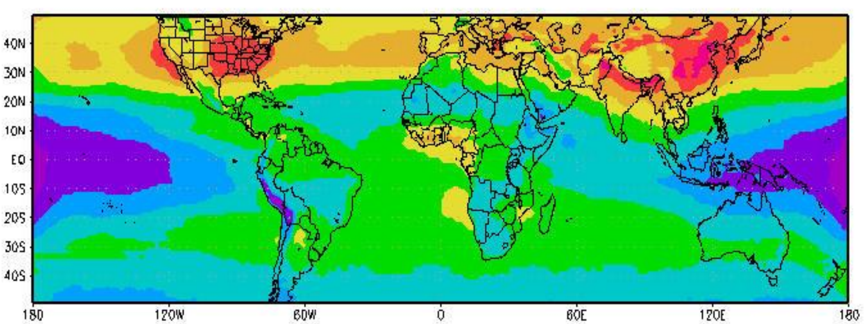
SBUV Tropospheric Ozone Residual (TOR) DJF 1979-2000



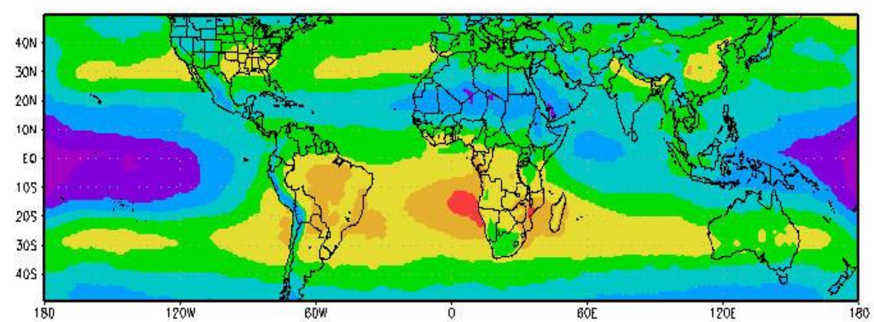

SBUV Tropospheric Ozone Residual (TOR) MAM 1979-2000




SBUV Tropospheric Ozone Residual (TOR) JJA 1979-2000

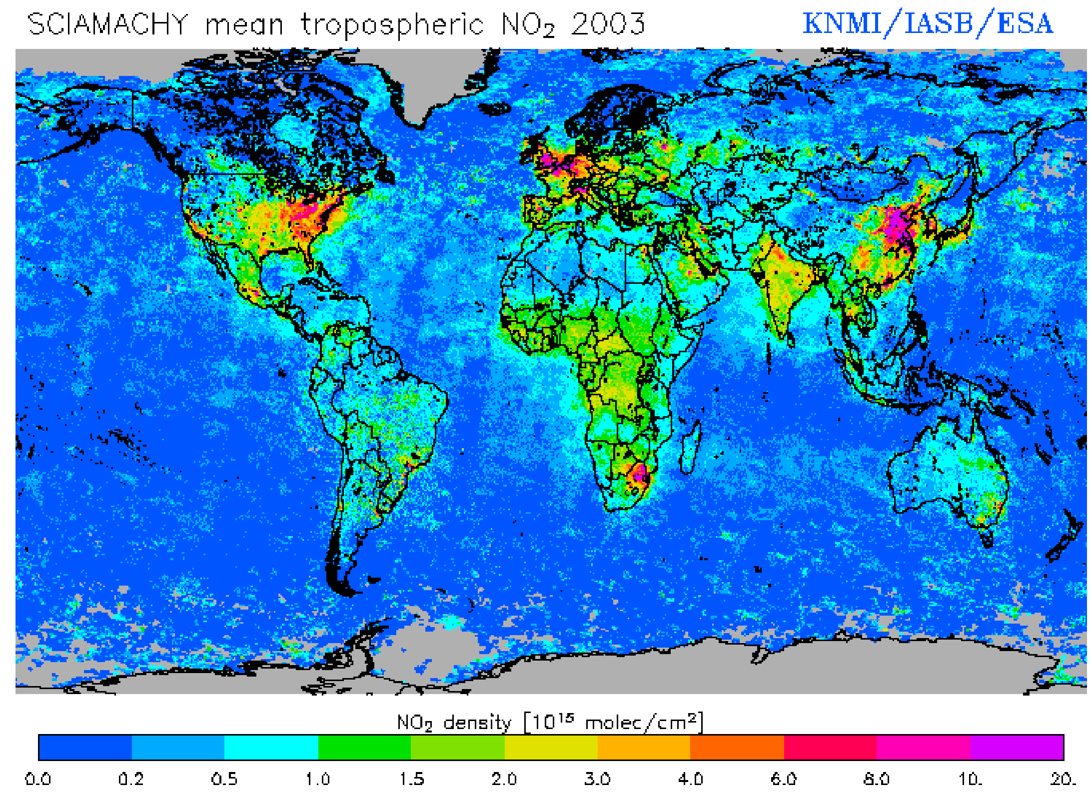



SBUV Tropospheric Ozone Residual (TOR) SON 1979-2000

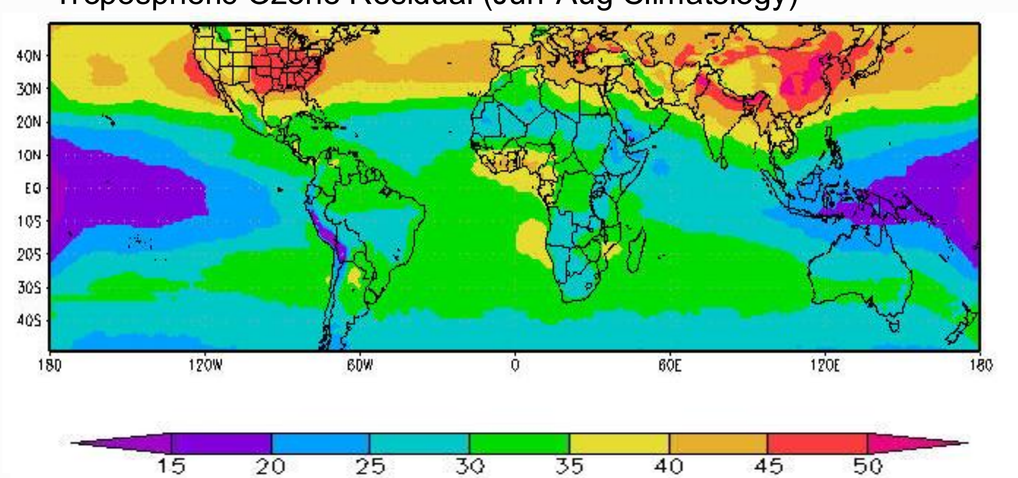




Integrated Tropospheric Ozone (Dobson Units)




Tropospheric Ozone Residual (Jun-Aug Climatology)




Integrated Tropospheric Ozone (Dobson Units)

Measurement of Ozone Precursors such as Nitrogen Dioxide ($NO_2$) on Aura will Provide Important Information that Should Lead to a New Understanding of the Origin and Distribution of Global Ozone (Smog) Pollution

Fishman et al. [2003, *ACP*, 3, 1453]

# Summary:

**< 1975**

- The scientific disciplines that led to the launch of TEMPO have two origins:
  - Aeronomy
  - Atmospheric (Air) Chemistry

- Being awarded the Nobel Prize in Chemistry greatly enhanced the legitimacy of both disciplines
  - Nobel citation recognized both **formation** and destruction of ozone

- Crutzen searched for missing source of CO to balance global budget
  - Interest in biomass burning resulted in NCAR expedition to quantify source
  - Theoretical calculations suggested tropospheric $O_3$ source linked to CO

**>1975**

- Global-scale tropospheric chemistry NASA becomes core program (GTE)

- Results from 1979 NCAR field study presented at initial GTE planning meeting
  - Elevated tropospheric $O_3$ profiles shown for first time
  - Is there a strong enough $O_3$ signal to be seen in TOMS total ozone satellite data?

- Results published in 1990 showing that existing satellites can see large-scale distribution of tropospheric $O_3$

# The Scientific Evolution of TEMPO:

## Which Scientific Discipline Hatched Us?

### Aeronomy?

AER*ON*O*MY \A(E)R-'AN-O-ME\N [FR. GK AERO-] A BRANCH OF SCIENCE THAT DEALS WITH THE ATMOSPHERE OF THE EARTH AND THE OTHER PLANETS WITH REFERENCE TO THEIR CHEMICAL COMPOSITION, PHYSICAL PROPERTIES, RELATIVE MOTION, AND RESPONSES TO RADIATION FROM SPACE.

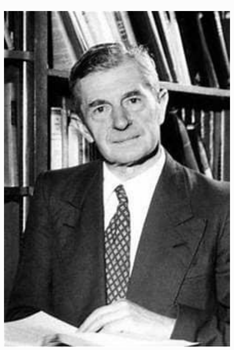

### Atmospheric Chemistry?

**Junge's Students:**
**Dieter Ehhalt ($CH_4$)**
**Wolfgang Seiler (CO)**
**Peter Fabian ($O_3$)**
**Ulrich Schmidt ($H_2$)**

IUGG

IAGA International Association of Geomagnetism and Aeronomy

$IO_3C$ International Ozone Commission



**Sydney Chapman**

Described the chemical mechanism that explains the existence of the stratospheric ozone layer

1888-1970

iCACGP

IGAC

**Chris Junge**

Recognized as the "Father of Atmospheric Chemistry": Studied Chemical Cycles of CO, $O_3$, $CH_4$, $H_2$, others

1912-1996

## *Atmospheric Chemistry Achieved Unparalleled Respect in 1997:*

The Nobel Prize in Chemistry Was Not Awarded Solely for the Chemistry Related to Stratospheric Ozone Depletion

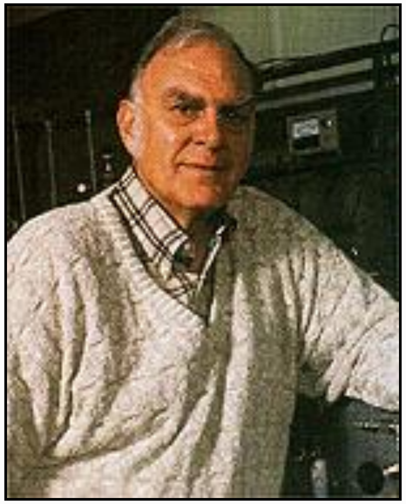
".. the Royal Swedish Academy of Sciences awarded the 1995 Nobel Prize in Chemistry to **Paul Crutzen, Mario Molina** and **F. Sherwood Rowland** for their work in atmospheric chemistry, particularly concerning **the formation** and decomposition **of ozone**."

1933-2021

Modeler/Meteorologist

1943-2020

Kineticist (Experimenter)



1927-2012

Observationalist

# Where does ozone in the troposphere come from?

- Aeronomers Didn’t Venture into the Land of *Tropos*
- Atmospheric Chemistry Community Focused on Urban Air Pollution (Kinetics & Urban-scale Meteorology)
- Meteorologists Focused on Regional-Scale Transport
  - Mesoscale Meteorologists Concentrate on Severe Storm Environment
- No “Home” for Global-scale Atmospheric Chemists

<u>Classical</u> Studies Assumed Only Source of Tropospheric $O_3$ was from stratosphere (<1977)

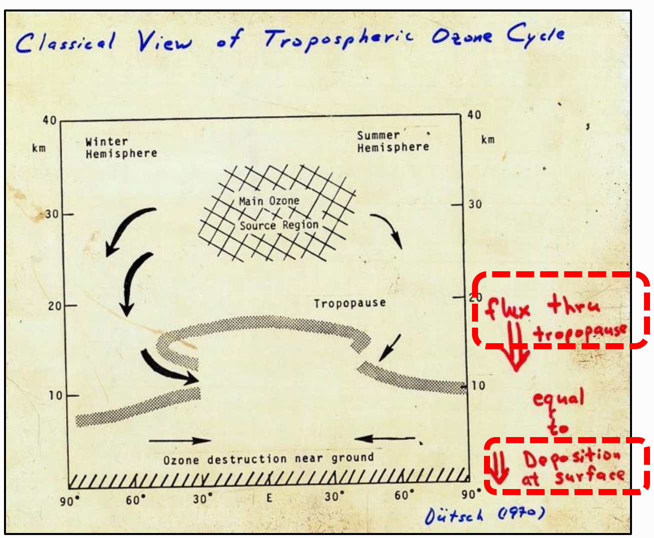



TABLE 1. Results of Studies of the Tropospheric Ozone Budget

| Estimated Ozone Flux, molecules $cm^{-2} s^{-1}$ | Domain of Interest | Reference |
|---|---|---|
| $4 \times 10^{10}$ | global average | *Paetzold* [1955] |
| $7.5 \times 10^{10}$ | global average | *Junge* [1962] |
| $6 \times 10^{10}$ | one local calculation | *Kroening and Ney* [1962] |
| $4.4–7.6 \times 10^{10}$ | northern hemisphere | *Fabian and Junge* [1970] |
| $3.7–8.2 \times 10^{10}$ | 30°–50°N | *Fabian* [1973] |
| $7.4 \times 10^{10}$ | northern hemisphere | *Fabian and Pruchneiwicz* [1976] |
| $7.95 \times 10^{10}$ | 30°–40°N | *Fabian and Pruchniewicz* [1976] |
| $4.3 \times 10^{10}$ | southern hemisphere | *Fabian and Pruchniewicz* [1976] |
| $7 \times 10^{10}$ | northern hemisphere | *Danielsen and Mohnen* [1977] |

# Special Recognition for the Advancement of Global Scale Atmospheric Chemistry Should be Given to

# Ralph Cicerone

**President National Academy of Science**
**2005-2016**

1943-2016

**Cicerone welcomed this new breed of atmospheric chemists into the American Geophysical Union**

## Despite Their Scientific Credibility and Claim to Fame, Each of these Remarkable Individuals Remained Approachable and Involved in the Advancement of Science

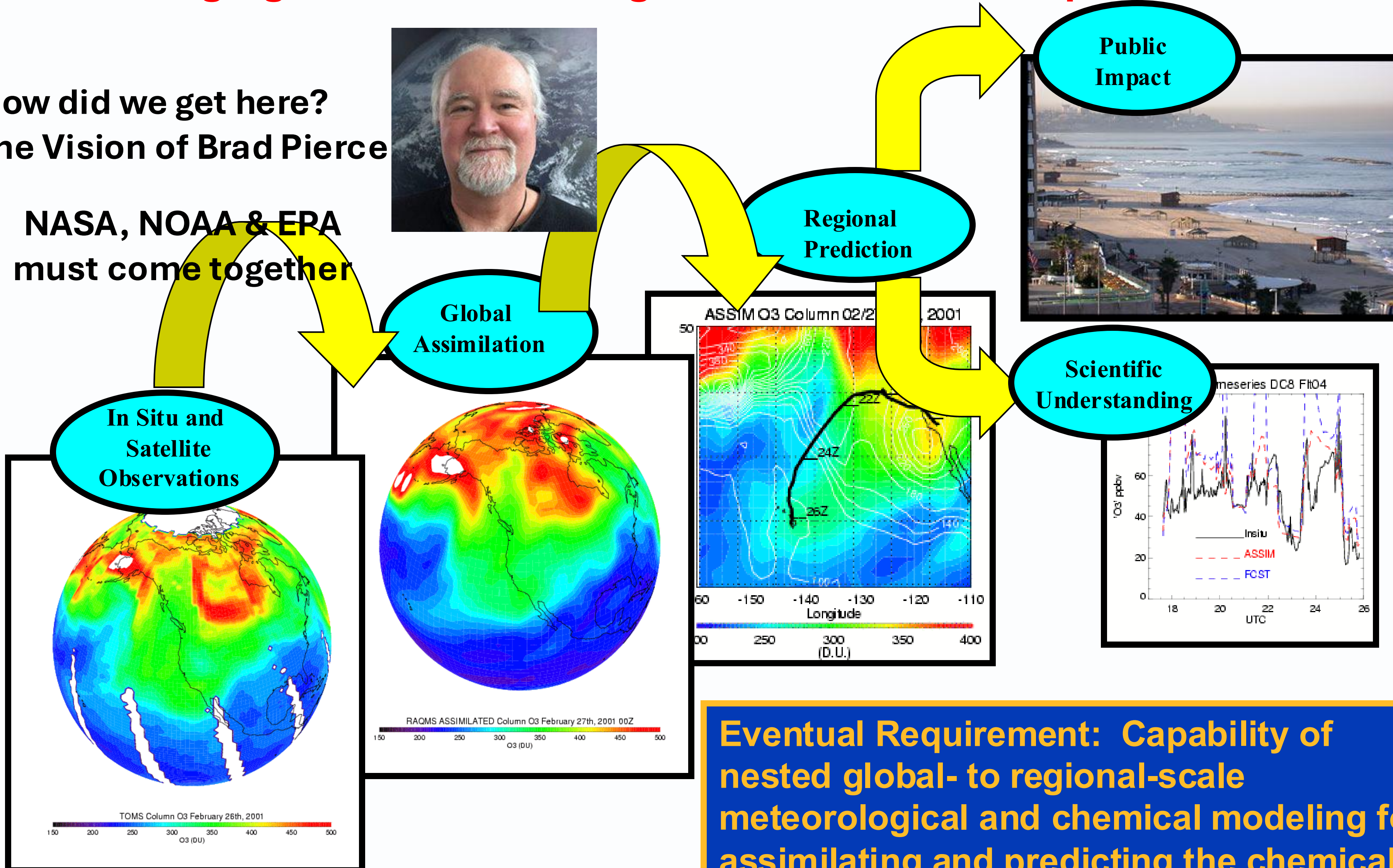
**From a Personal Perspective:**
**I have been blessed to have known these incredible people for the past half century**

***Last, but not least:***

# Air Quality Forecasts Will Require Infusion of Satellite Observations and Merging of Global and Regional Chemical Transport Models

**How did we get here?**
**The Vision of Brad Pierce**

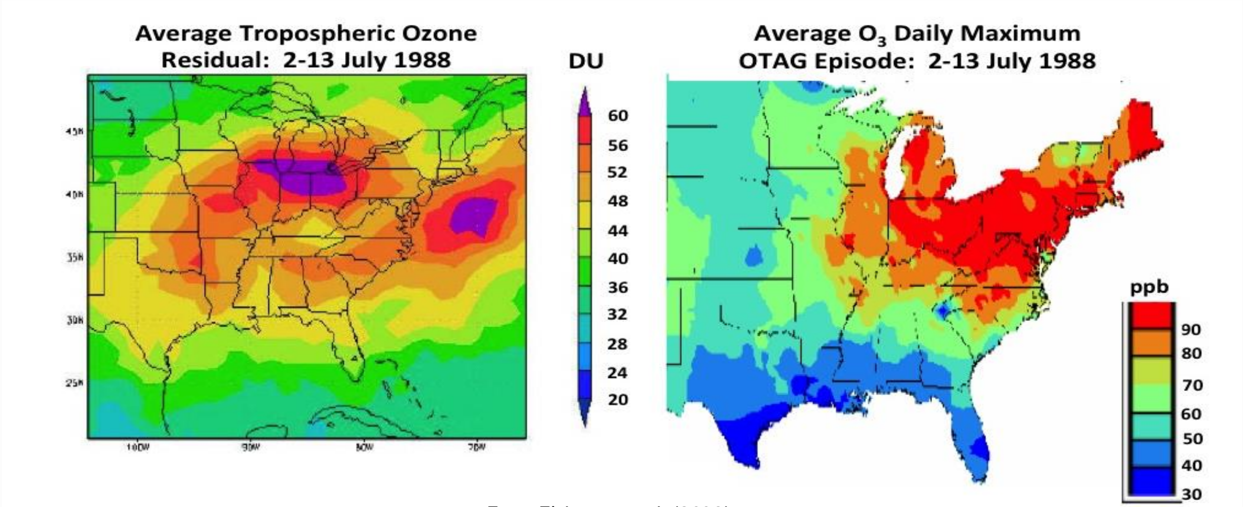
**NASA, NOAA & EPA must come together**




**Eventual Requirement: Capability of nested global- to regional-scale meteorological and chemical modeling for assimilating and predicting the chemical state of the atmosphere (air quality)**

# Extra Slides

# Massive Air Pollution Episode from 1988




From Fishman et al. (2003)

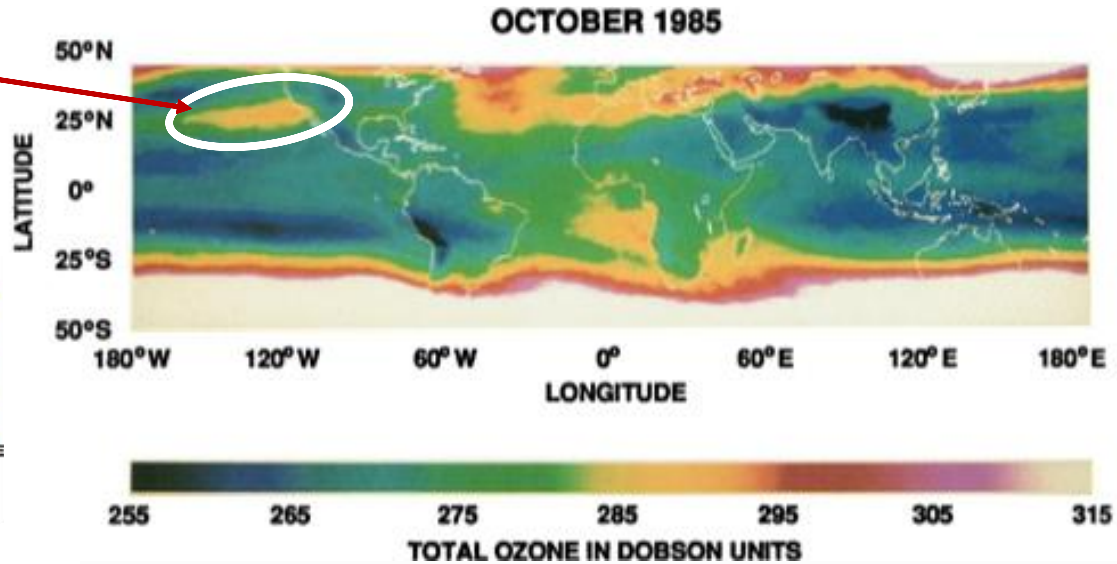
# Observation of Pollution Plumes in Total Ozone TOMS Measurements Suggested in Initial TOR Study (1990)

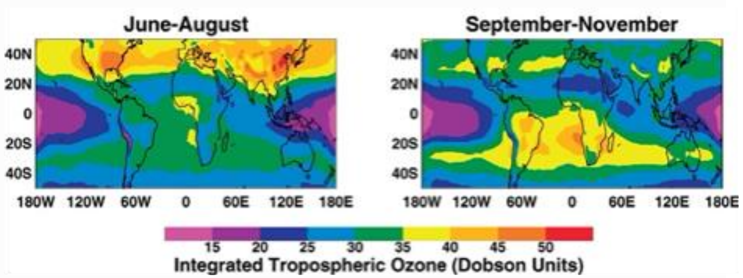
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. D4, PAGES 3599-3617, MARCH 20, 1990

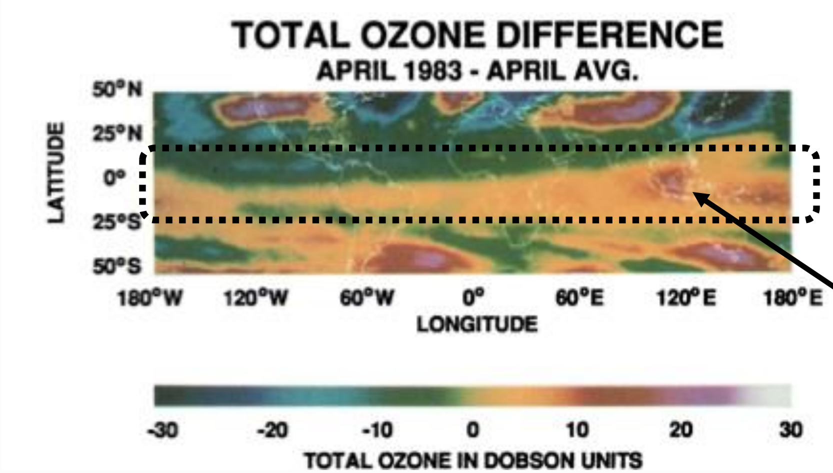
## Distribution of Tropospheric Ozone Determined From Satellite Data

JACK FISHMAN,[1] CATHERINE E. WATSON,[2] JACK C. LARSEN,[3] AND JENNIFER A. LOGAN[4]

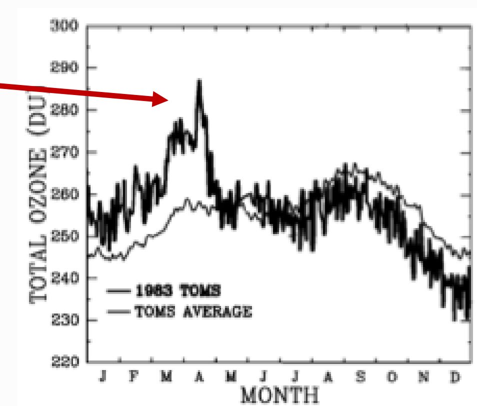
Unusually Elevated $HNO_3$ Concentrations Measured in Hawaii in October 1985 (Huebert)



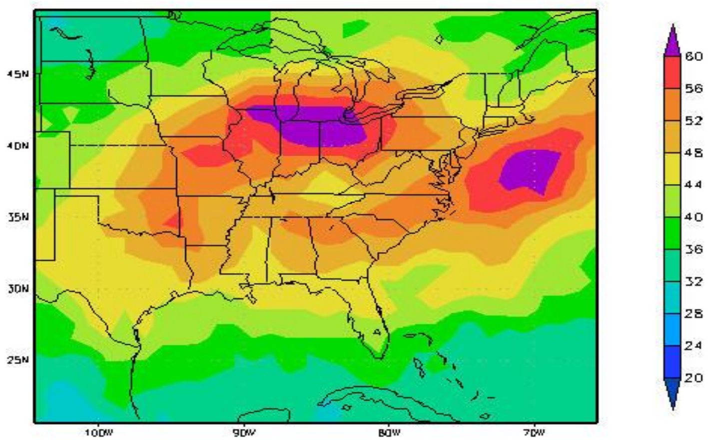



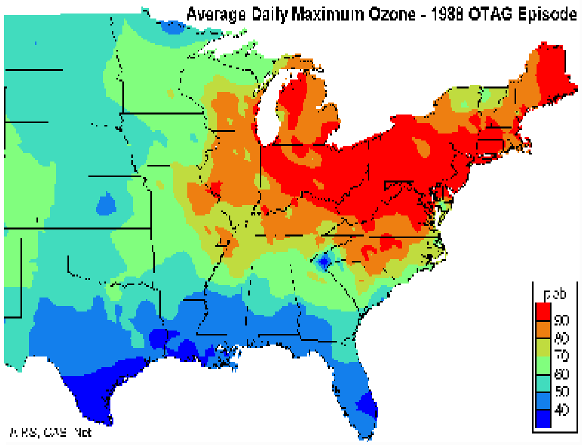




Strong El Niño in 1983 Leads to Unusually High Total Ozone throughout Tropics from Burning over Indonesia



# Comparison of U.S. Air Pollution Using Satellite Measurements



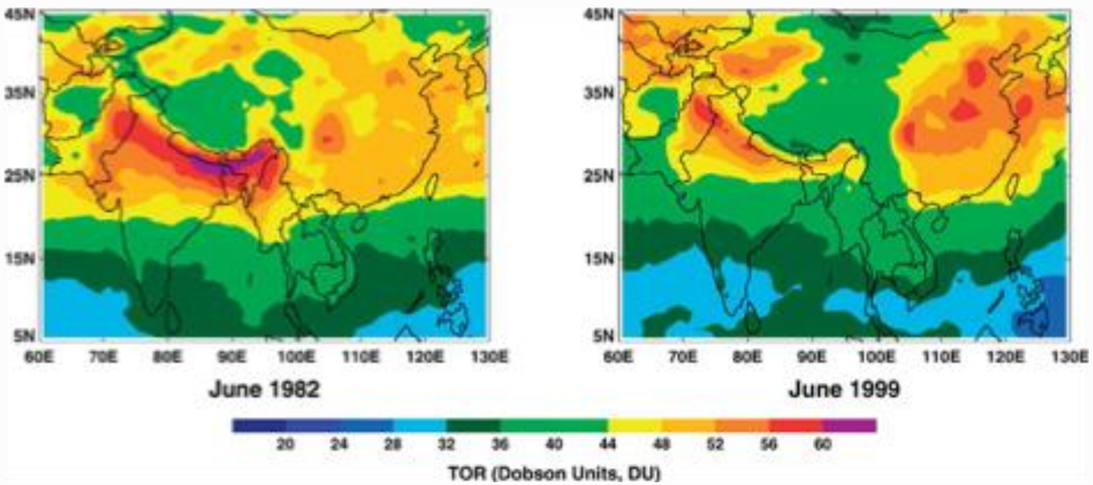




TOR and Surface $O_3$ Depiction During July 3-15 Pollution Episode

# Interannual variability of stratospheric and tropospheric ozone determined from satellite measurements

Jack Fishman, John K. Creilson,[1] and Amy E. Wozniak[1]
NASA Langley Research Center, Hampton, Virginia, USA

Paul J. Crutzen[2]
Max-Planck-Institute for Chemistry, Mainz, Germany



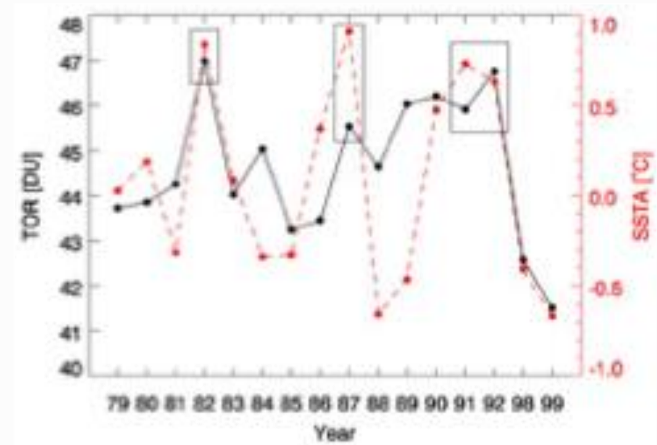




**Figure 9.** Relationship between summer TOR over India and ENSO Region 4 SSTAs. TOR values over northern India between 1979 and 1999 for the years that complete summertime data are available and the SSTA over the western Pacific (i.e., Region 4, see Figure 4). Blocked areas refer to strong El Niño episodes.

# Satellite remote sensing of atmospheric pollution: The far-reaching impact of burning in southern Africa

Jack Fishman*[a], Jassim A. Al-Saadi[a], Doreen O. Neil[a], John K Creilson[a], Kurt Severance[a], Larry W. Thomason[a] and David R. Edwards[b]
[a]NASA Langley Research Center, Hampton, VA 23681
[b]National Center for Atmospheric Research, Boulder, CO 80307

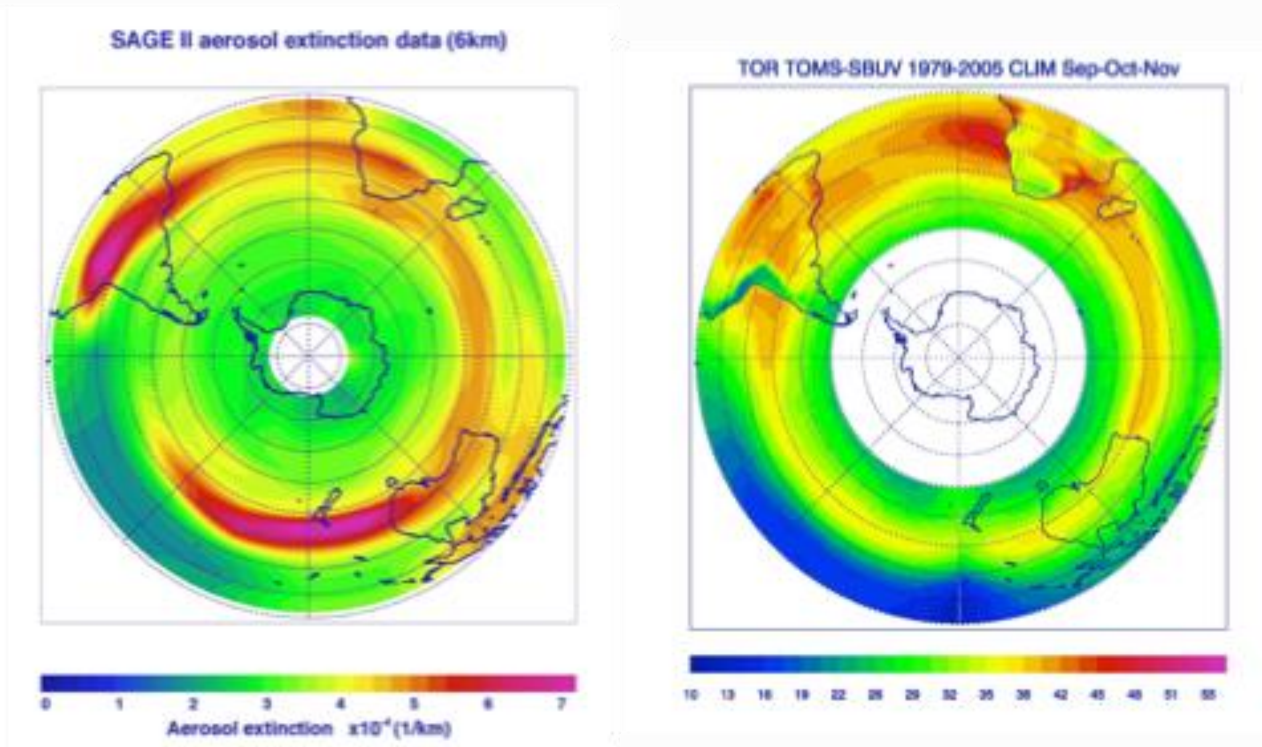



Figure 8. The September-November aerosol distribution from SAGE at an altitude of 6 km is shown in the panel on the left; the right panel shows the climatological distribution of tropospheric ozone and is the same dataset depicted in Figure 2, but from a different perspective and with a color bar more consistent with the SAGE data shown in the left panel.

## Summary (Welsh and Fishman)

- CAMx Model Provides Good Simulation of July 2012 Pollution Event in St. Louis
  - Surface concentrations increased to ~90 ppb during episode
  - Plume transported by prevailing weak southwesterly winds
  - Model calculations correlate with observations: r=0.69 to 0.87

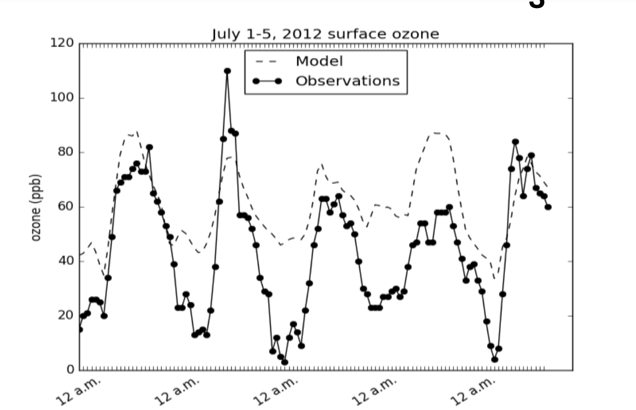
- $O_3$ Plume Emanating from St. Louis is ~16 DU
  - Calculation consistent with size of urban source (?)

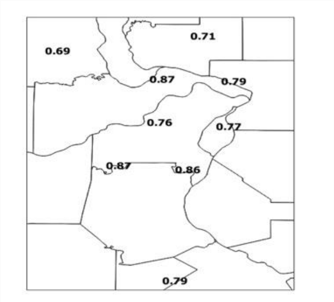
- Plumes from Large Air Pollution Events in 1980s as large as 40-60 DU

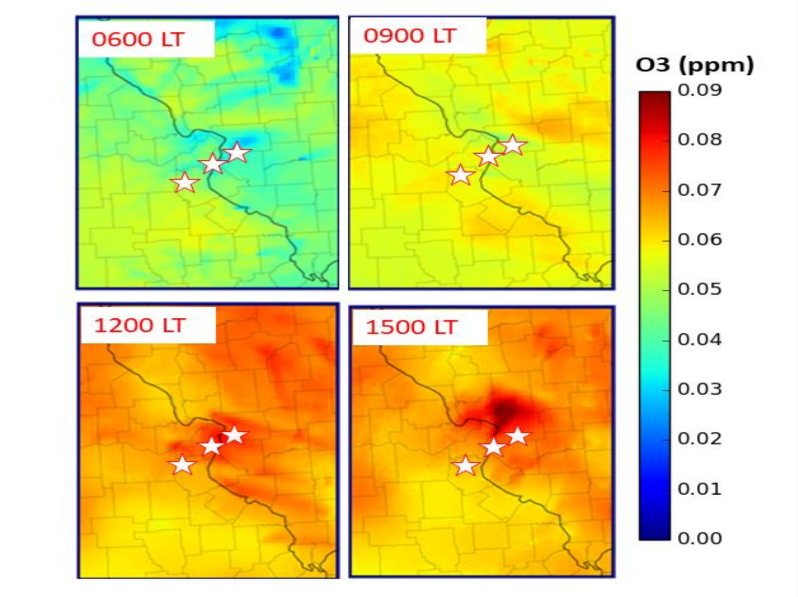
- Emission Controls Might Be Primary Reason for Smaller $O_3$ Episodes

- Seeing $O_3$ Pollution from TEMPO will Be More Challenging:
Synoptic-scale Episodes seen in the 1980s will likely not Exist in the 2020s

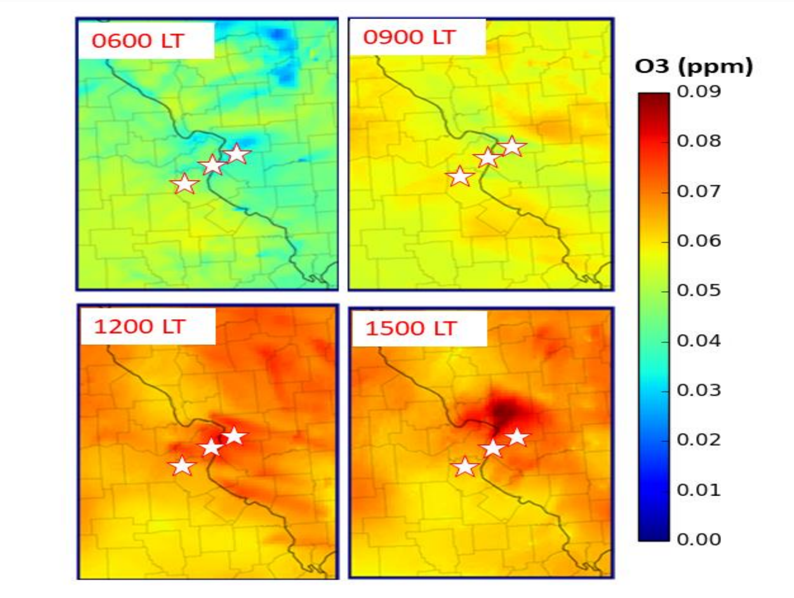
# Surface $O_3$ Model Calculations

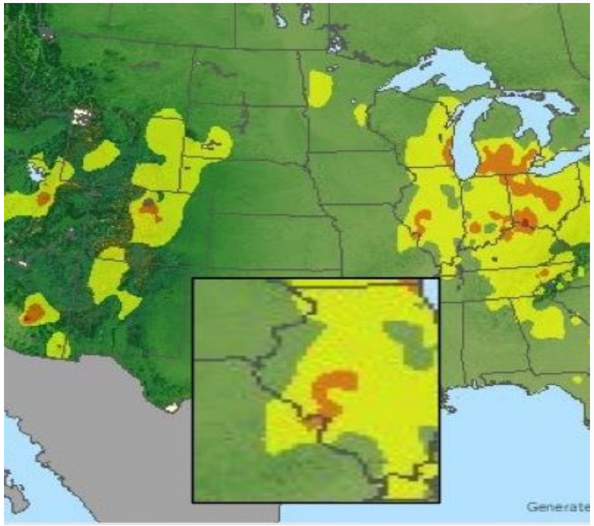


# Surface $O_3$ Model Calculations



# Integrated $O_3$ Model Calculations