Two Decades of Polar Ozone Research via Airborne Science Investigations

Addressing a NASA Mandate in Atmospheric Composition

Symposium for the 30th Anniversary of the Montreal Protocol

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A Bit of NASA History – 1970's

Birth of the Upper Atmosphere Research Program (UARP)

- ***Concern over the catalytic destruction of the ozone layer generated international interest in stratospheric photochemistry and kinetics.***
  - *The Climatic Impact Assessment Program (CIAP) of 1972-1974 provided a strong research foundation*
- ***In 1975 the US Congress directed NASA via its FY1976 authorization bill***

  "To conduct a comprehensive program of research, technology, and monitoring of the phenomena of the upper atmosphere."
  - *This mandate to perform research on ozone layer depletion gave rise to the UARP*

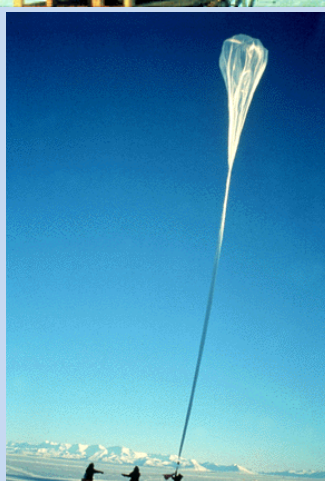
NASA Airborne Science

- ***Actually predates UARP, going back to 1971 when two (high-altitude) U-2 aircraft were utilized for collecting Earth Resource data***
  - ***ER-2's replaced the two U-2's in 1981 & 1989***
  - ***Both an ER-2 and U-2 were used together during the Stratospheric-Troposphere Exchange Project (STEP) from 1984-1987***
- ***Tropospheric airborne studies also began at this same time under NASA's Global Tropospheric Experiment (GTE)***
  - ***GTE was established as a contribution to the nation's Global Tropospheric Chemistry Program***

Antarctic Ozone Hole - 1985

- ***Provided a strong impetus for even more focused studies of the polar stratosphere***
- ***Various scientific hypotheses about dynamical vs. chemical causes drove research formulation and measurement foci***
  - *lofting of low ozone air*
  - *nitrogen chemistry*
  - *heterogeneous halogen chemistry*
- ***Ground-based and balloon measurements during the National Ozone Expeditions preceded the airborne studies and helped to prioritize the airborne measurements***

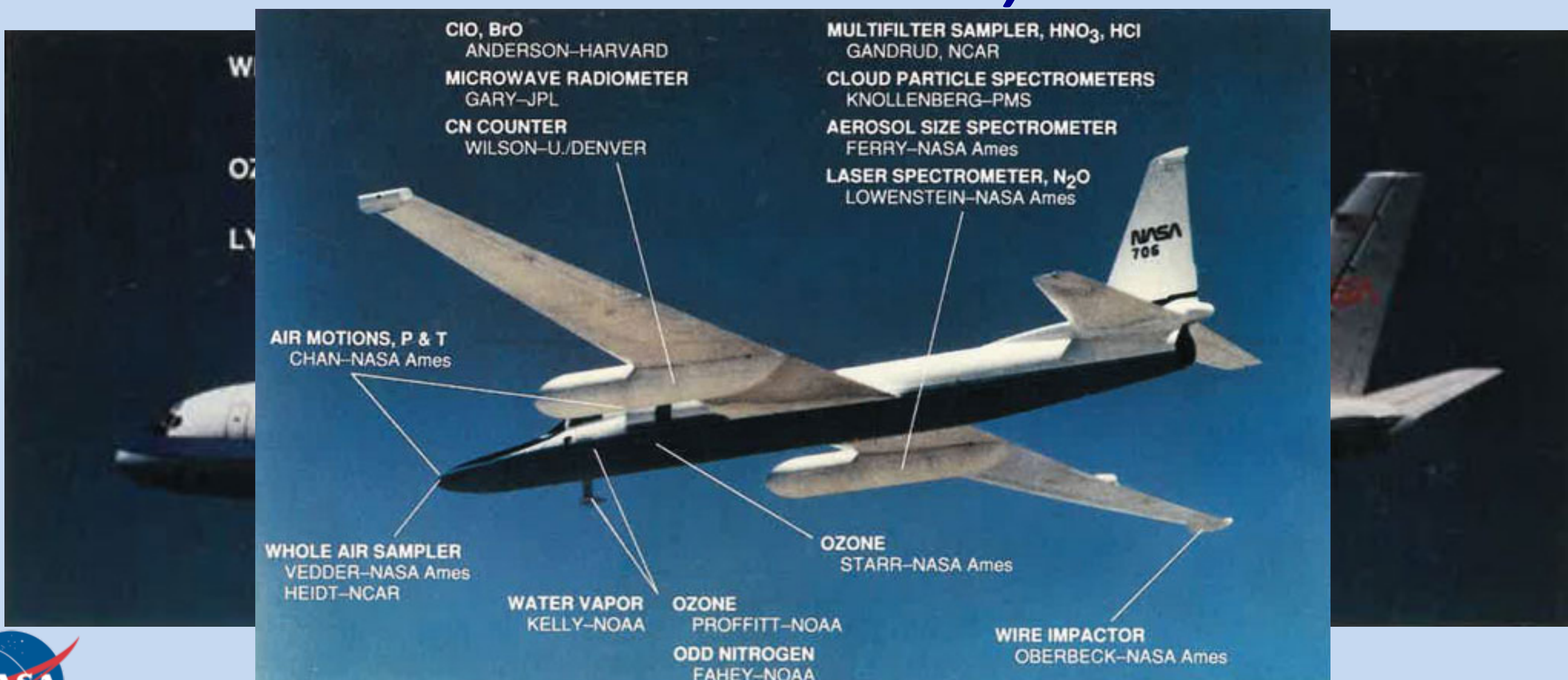
National Ozone Expeditions (NOZE I & II, 1986 & 1987) – McMurdo Station, Antarctica



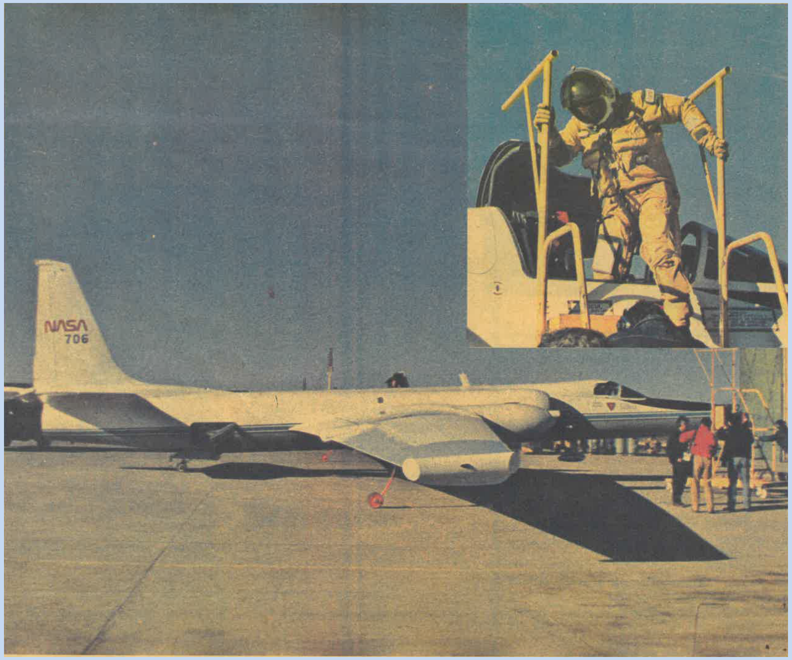
- ***Sponsored by NSF, NASA, NOAA, CMA, U.S. Navy, and ITT Antarctic Services***
- ***Measurements conducted using ozone & aerosol sondes and ground-based microwave emission, solar IR, and visible absorption instruments***
  - ***provided the initial evidence for the role of chlorine chemistry involving heterogeneous reactions on the surfaces of ice crystals***

Airborne Antarctic Ozone Experiment (AAOE, 1987) – Punta Arenas, Chile

- ***Initial formulation in 1986 (following NOZE I) using STEP instruments plus others specifically built for the ER-2***
- ***ER-2 (in situ measurements); DC-8 (in situ & remote measurements)***



AAOE (continued)

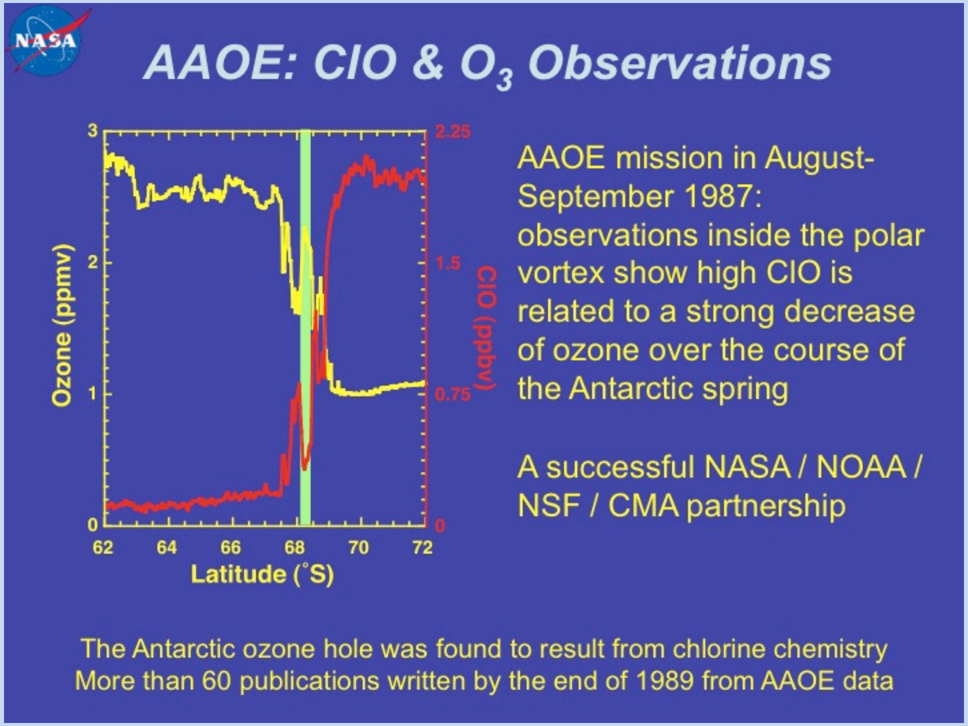


AAOE (continued)

AAOE (continued)

- ***Observations provided conclusive evidence of the role of active chlorine following its release from reservoir compounds via heterogeneous reactions***

Cold T → PSCs + high Cly → het reactions → catalytic O3 loss



- ***Raised concern about the implications for the NH***

Airborne Arctic Ozone Expeditions

(AASE I, 1989) – Stavanger, Norway

(AASE II, 1991/1992) –Fairbanks, AK & Bangor, ME

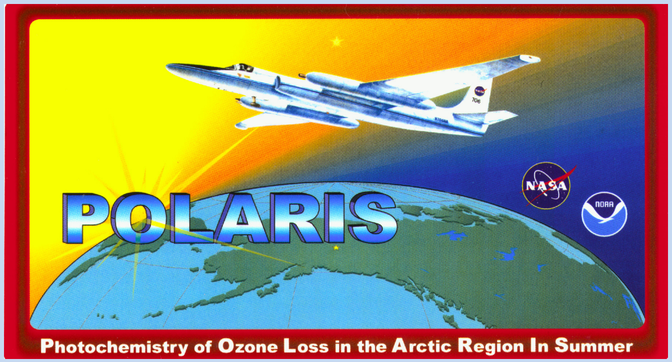
- *Enhancements of chemically active chlorine occur in the Arctic stratosphere as well*
- *Such PSC-induced buildup of reactive chlorine had not been included in assessment models initially used for the Montreal Protocol*

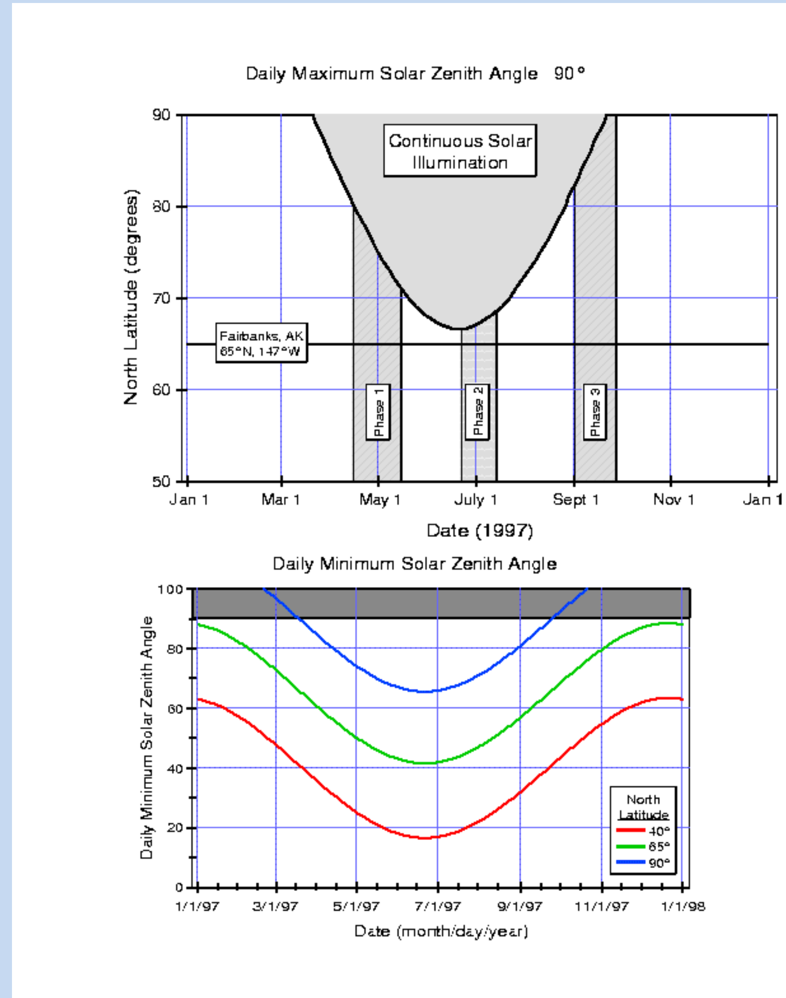
- *Increased vulnerability of the NH ozone shield to depletion by man-made halogen*
  - *US Congress voted 96-0 to accelerate CFC ban*
- *Amount of ozone destroyed is controlled by*
  - *total stratospheric chlorine & bromine abundances*
  - *timing and vertical extent of PSC threshold temperatures*

Intensive Scientific Campaign Period During the mid-1990's

- ***Addressed a broad spectrum of objectives***
  - ***ozone depletion***
  - ***atmospheric effects of aviation via a UARP/AEAP partnership***
  - ***global scale transport of atmospheric gases & particles***
- ***ASHOE/MAESA – 1994 (Christchurch, NZ)***
- ***STRAT – 1995/1996 (NAS Barbers Point, HI)***
- ***TOTE/VOTE – 1995/1995 (tropics to Arctic)***
- ***SUCCESS – 1996 (Salina, KA)***
- ***POLARIS – 1997 (Fairbanks, AK)***
- ***SONEX – 1997 (US, Ireland, Portugal)***

Photochemistry of Ozone Loss in the Arctic Region In Summer (POLARIS, 1997) – Fairbanks, AK





Provided an improved understanding of the seasonal behavior of polar stratospheric ozone as it changes from very high concentrations in spring to very low concentrations in autumn

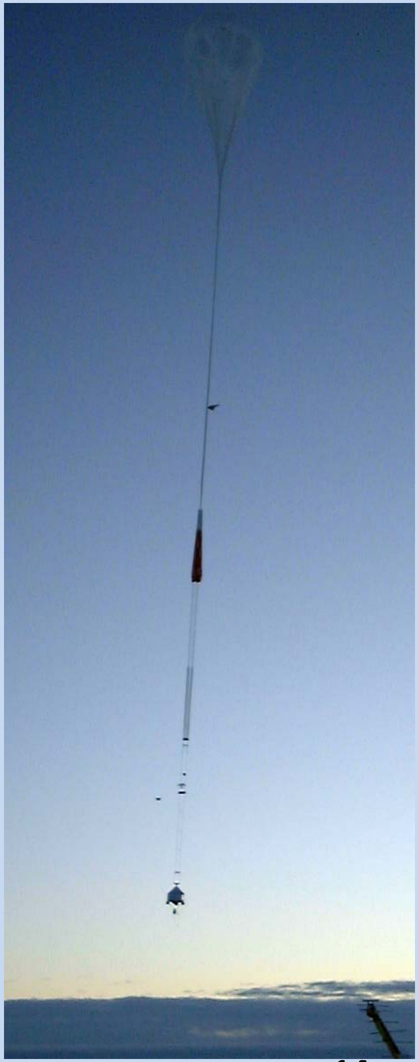
- ***due to an increased role of NO_x catalytic cycles during periods of prolonged solar illumination in the summer***

Return to the Arctic Vortex

SAGE III Ozone Loss and Validation Experiment & the THird European Stratospheric Experiment on Ozone (SOLVE & THESEO, 1999/2000) – Kiruna, Sweden

SOLVE / THESEO

Multi-aircraft measurements (DC-8, ER-2, Falcon, ARAT, and Learjet) from Arena Arctica augmented by a heavy-lift balloon campaign at Esrange



SOLVE / THESEO Results

An outstanding scientific success via international cooperation

- *O_3 loss by rate-limiting radical reactions were determined up to 90°N latitude*
- *Discovery of large "ice particles" → possible consequences for atmospheric microphysics and polar ozone changes*
- *Severe and extensive denitrification possible in the future Arctic stratosphere (climate change effects?)*
- *Significant ozone loss effects due to denitrification depends on seasonal conditions*

Continuation of International Cooperation in Arctic Ozone Research

Joint SOLVE II / VINTERSOL–EUPLEX Campaigns (2003)

Joint Mission Strategy

Developed from the SOLVE / THESEO Experience

Early Winter	Mid-Winter	Late Winter
Set up of the polar vortex	Coldest temperatures - most PSCs Chlorine activated	Maximum ozone loss rate Shut down of ozone loss system
	Platforms	
DC-8 Balloon Ground	ER-2 DC-8 Falcon Arat Balloons Ground	ER-2 DC-8 Balloon Learjet Mystere Ground

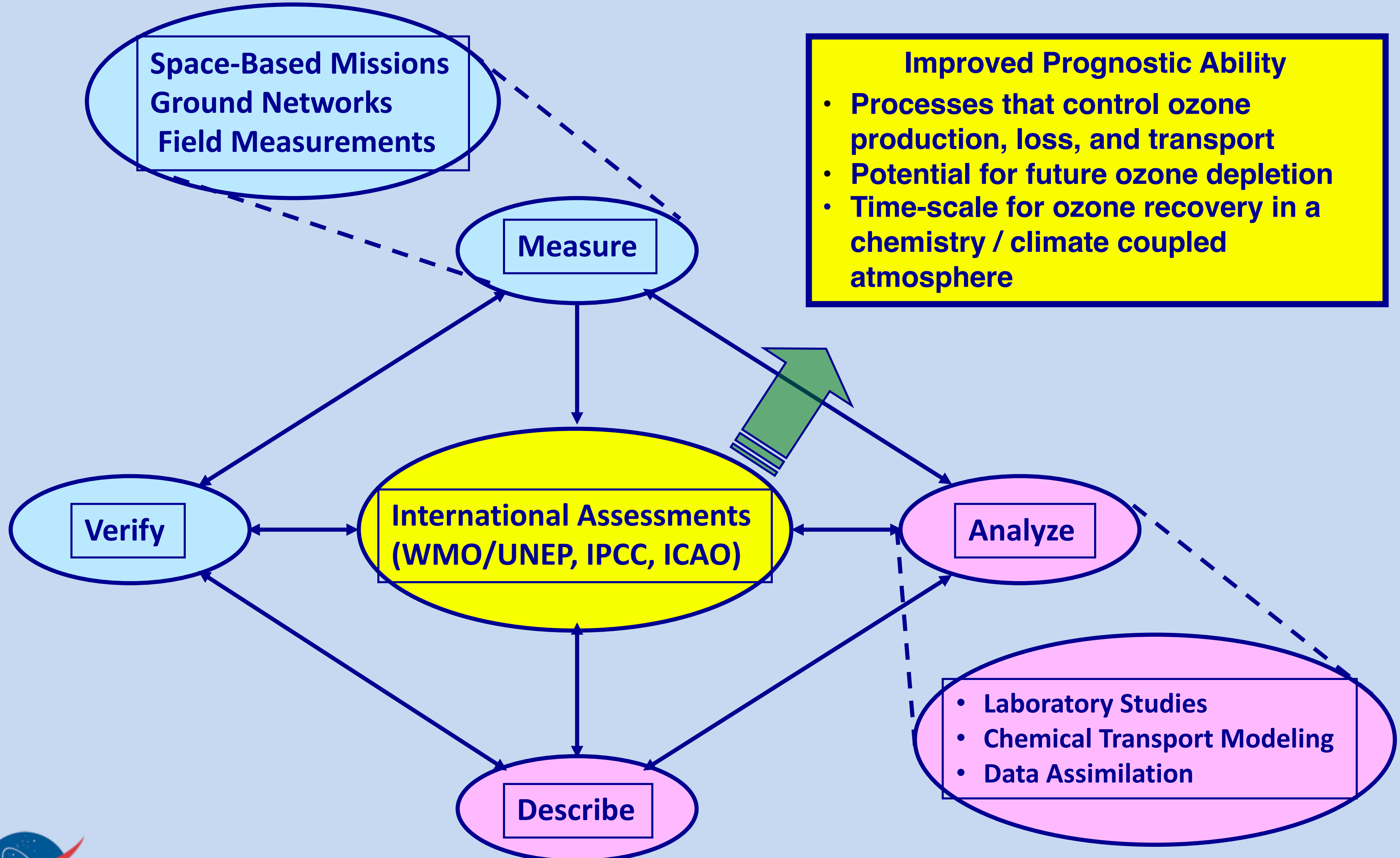
SOLVE II / VINTERSOL-EUPLEX
Highlights

- ***Early cold winter with extensive PSC observations***
- ***Regionally extensive denitrification (albeit moderate in comparison to 1999/2000) was well modeled***
- ***Significant Cl activation was observed***
- ***Relatively active dynamics during the campaigns with two wave-2 warmings***
- ***Observation of ozone loss via lidars, sondes, in-situ instruments, and satellites***
- ***Satellite validation (SAGE III) and correlative measurements (ADEOS II & ENVISAT)***

Successful Airborne Campaigns

A Partnership Between Science and Operations is Critical!

Today's Interactive Research Elements Addressing Ozone Depletion and Recovery



Concluding (Personal) Reflections

It has been almost 50 years since I began a journey that has taken me from laboratory research, to scientific program management and field studies, to the interface between science and international environmental policy.

As I look back, I cannot think of a finer group of traveling companions than those with whom I have shared this road. I believe that we have changed, and will continue to change, the course of history in understanding and protecting the Earth's environment by providing a sound scientific basis for such policy decisions.

Thanks to all of you for listening
and (more importantly) for being
mentors, scientific colleagues, and friends.