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From Contrails and Smoke Trails to Exhaust Particle Processes:

A brief history of aircraft particulate emissions

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14. ABSTRACT
In the beginning of the jet age, the visibility of the exhaust from airplanes drew attention to the particles being emitted. Whether at altitude in a contrail or near the ground due to visible smoke, the particles in the exhaust made the aircraft engines' emissions visible for all to see. This visibility motivated studies to understand and control the particles being emitted by aircraft, and resulted in some of the first regulations on particle emissions represented by the on-going certification requirement of a smoke number measurement. Scientific understanding of both the measurement of particles and their impact on climate and human health have advanced considerably since then, and there is much active research to continue to better understand Particulate Matter (PM) emissions and their resulting impacts. Important landmarks will be presented that represent steps along the way from earlier interest in contrails and smoke trails to present day understanding of PM emissions and particle microphysics.

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FROM CONTRAILS AND SMOKE TRAILS TO EXHAUST PARTICLE PROCESSES: A BRIEF HISTORY OF AIRCRAFT PARTICULATE EMISSIONS

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Contrails: white stripes in the sky

Smoke Trails: black lines on takeoff

Timeline: Dawn of the Jet Age to now …

- 1953 Appleman paper on contrails: Thermodynamics
- 1970 SAE E-31 Aerospace Recommended Practice for Smoke Number ARP1179 Measure smoke
- 1972-5 US DoT Research: CIAP Ozone in Stratosphere
- 1990s NASA and EC Research: IPCC 1999 Report
  - AEAP (AESA, SASS) Upper Atmospheric Pollution Impacts
  - POLLINAT, SULFUR1-7 Upper Atmospheric Pollution Impacts
- 2000s NASA, FAA, DoD, EPA, and EC:
  - NASA/QinetiQ, PartEmis Particle emissions issues focus
  - EXCAVATE Focus on Volatile Aerosol (Exhaust Organics & Oil!)
  - APEX1-3 Aviation Particle Emissions eXperiment (soot and vol)
- 2010s and on-going:
  - AAFEX1-2 Alternative Fuels
  - SERDP projects Soot, Volatile PM, and Alternative Fuel Projects
  - E-31 AIRs, ARP on particle measurements and SAMPLE1-3, FAA methods work Moving toward PM certification methods

Contrails and Smoke Trails

Contrails then:

- Visibility Issue
- Understanding of Thermodynamics

(military activities)

Contrails now:

- Global Climate Issues
- Cloud physics and the science of kinetics
  - Not just water,
  - ***Not just black carbon***

Smoke Trails then:

- Visible contribution to pollution
- US EPA then ICAO control visible smoke

"Smoke Trails" now:

- Global Climate Issues
  - Connections to contrails
  - Absorption of sunlight
- Local and regional air quality
  - ***Not just black carbon***

AIAA Paper 91-3158, 1991, AIAA JOURNAL OF AIRCRAFT (30) 467-479, 1993.

stratified atmosphere, it will
ıe to the higher pressures en-
›yancy. The effect of this buoy-
ı oscillatory vertical motion at

$$\left(\frac{dT_a}{dz} - \frac{dT}{dz}\right) \qquad (15)$$

Better engine efficiency reduces ΔT (a little): more contrails, Schumann 1996

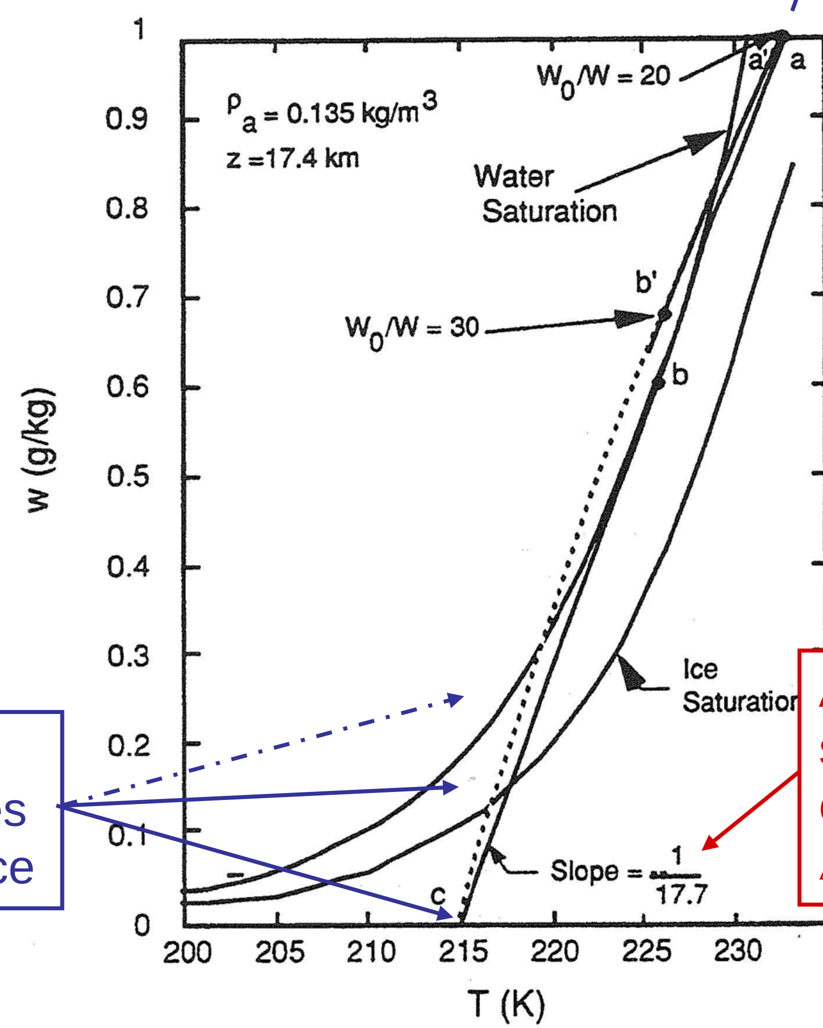
pheric laps

$$\frac{\gamma - 1}{\gamma}\frac{T}{H_p} \qquad (16)$$

cending air (H_p is the pressure). However, a second effect of is of interest to us. This is the te in sense to that of the wing ear from the two-dimensional

$$= -\frac{1}{\rho}\nabla\left(\frac{1}{\rho}\right) \times \nabla p \qquad (17)$$

End point determines persistence



Affect slope by changing ΔT or w_0

Fig. 5 Temperature—water vapor content (*T-w*) plane with water and ice saturation curves overlaying exhaust dilution trajectories.

Schmidt-Appleman Plot

EPA push in late 60s for aviation SN

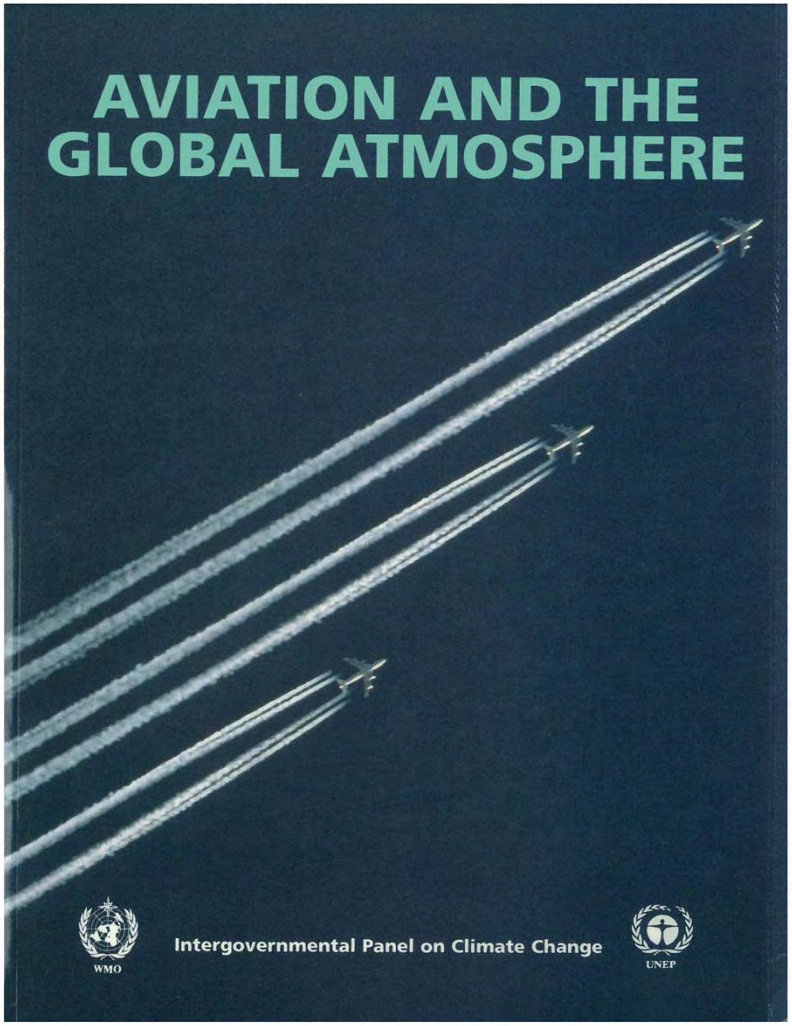
- Resulted in ARP 1179
- Diesel truck regulations in 2000s
  - Operation closer to population centers
  - Many more operations, more fuel consumed
- ARP 1179D no longer sufficient, need mass (and number) to better quantify PM emissions
- Airplanes use combustion control, not aftertreatment

Changes in soot emissions since 1970s

- SN certification requirement has reduced visibility of Smoke Trails
- Combustor improvements for NO_x and Smoke
- On-going combustor development continues (later talks)

Aviation and the Global Atmosphere

- Started to “rehash” the 1970s CIAP problem of Ozone at altitude in 1990s
- Recognized hetero-genous chemistry, and particle emissions studied
- Sulfur in fuel can help nucleate new particles. Particles can affect contrails.

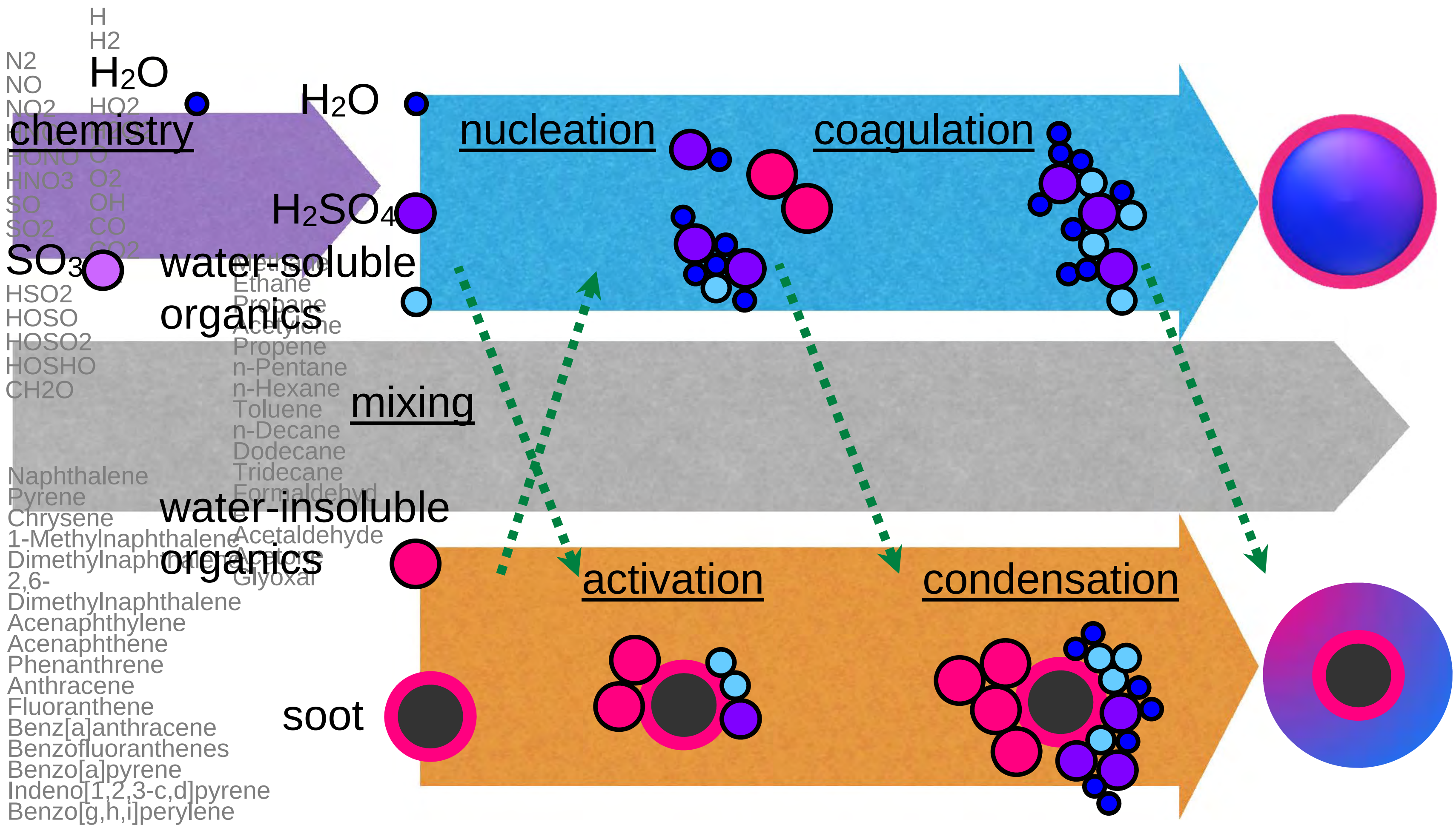


Since IPCC report

- Many measurement programs to better understand particle emissions and how they form and evolve (basic science questions)
- Lab and fields studies better quantify soot, sulfate, organics, oil, and how they all interact
- Many advances in measurement tools and sampling techniques
- Significant steps in developing theoretical understanding of what is important for ***climate*** and for ***local air quality***

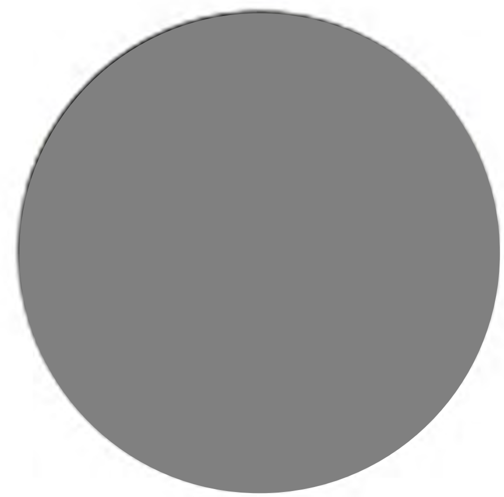
…. (later talks)

Volatile PM processes



Current focus: Particle Processes

- Particle “microphysics” complex and involves soot and volatile contributions
- Species condense whether or not a contrail forms, and they contribute to PM mass
- Contrails and Smoke Trails interrelated and share many key PM scientific elements



Smoke trails are mostly gone

But particles present, still evolve