Simulations of Shuttle Main Engine Plume Effects on Lower Thermosphere Energetics and Chemistry

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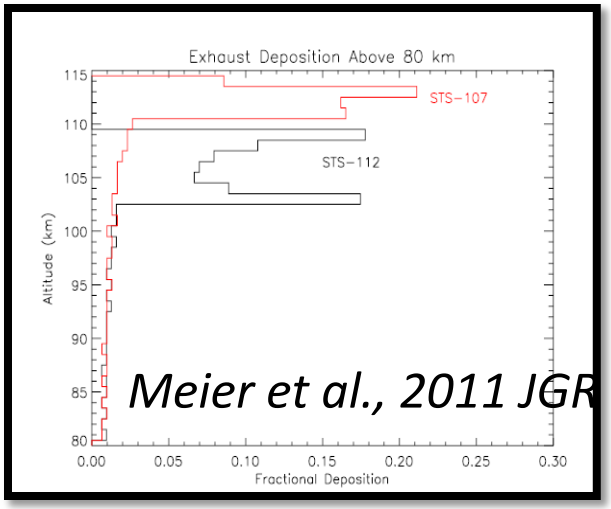
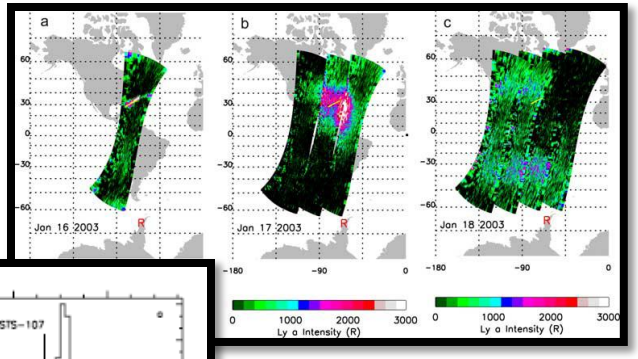
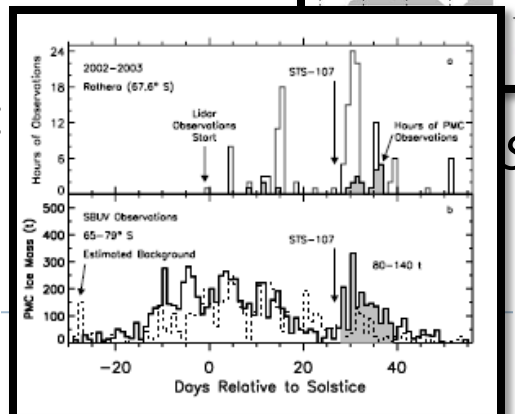
Introduction

- Space Shuttle's main engines deposit 300-400 t of water vapor exhaust (*Meier et al.*, 2011).
- Large evidence for unusually fast meridional transport of the plume (Stevens et al., 2002, 2003; Meier et al., 2011; Siskind et al., 2003; Niciejewski et al., 2011).
- This transport can create large bursts of polar mesospheric clouds (PMCs) that constitute 10-20% of the PMC mass for one summer season (Stevens et al., 2005a; Stevens et al., 2005b).





Stevens et al., 2005 GRL



Stevens et al., 2005 GRL

Objectives

- *Stevens et al*. [2002] reported ice in the presence of OH solar resonance fluorescence in their daytime STS-66 plume observation (November, 1994) for altitudes at and above 87 km.
- They interpreted the OH signal in November at these high altitudes to arise from photodissociation of the water vapor within the plume, but did not identify why ice was simultaneously present.
- This study focuses on the effects of the plume on atmospheric energetics and the chemistry of the lower thermosphere.
  - Shuttle plume water deposition leads to questions regarding the transport and other effects on the atmosphere
  - Here we focus on the effects on atmospheric energetics and chemistry of the lower thermosphere
  - We use a fully coupled chemical-dynamical model to address the effects of the shuttle plume on atmospheric energetics and chemistry.

Model Description

- **Model used: NCAR TIMEGCM**
- **Grid size: 5°×5° (latitude-longitude)**
- **Model Runs:**
  - Jan. 16, 2003

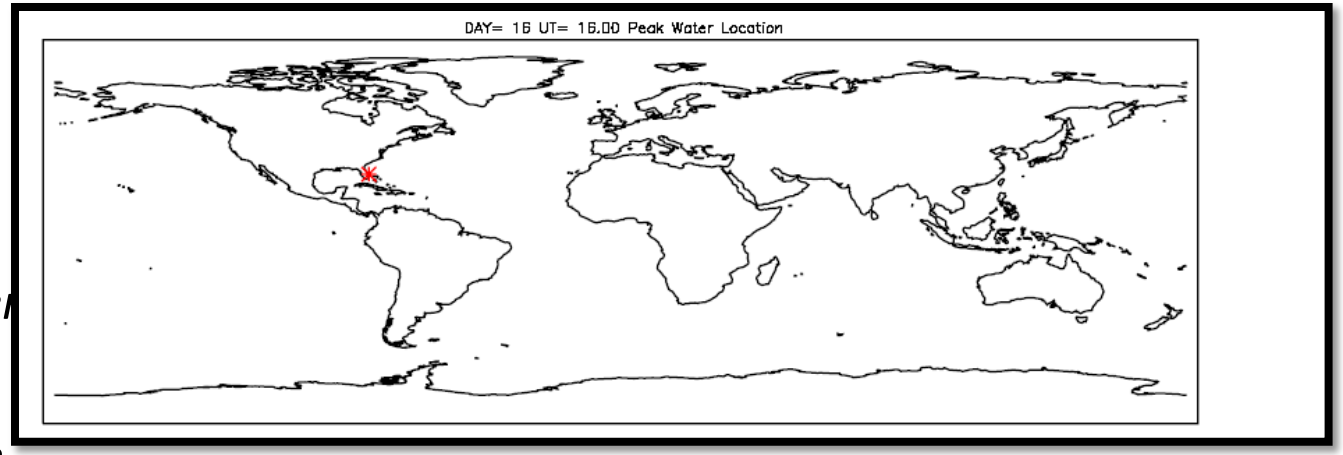
    i) Plume Case:

    350 tons of H_2O over Cape Canaveral, FL

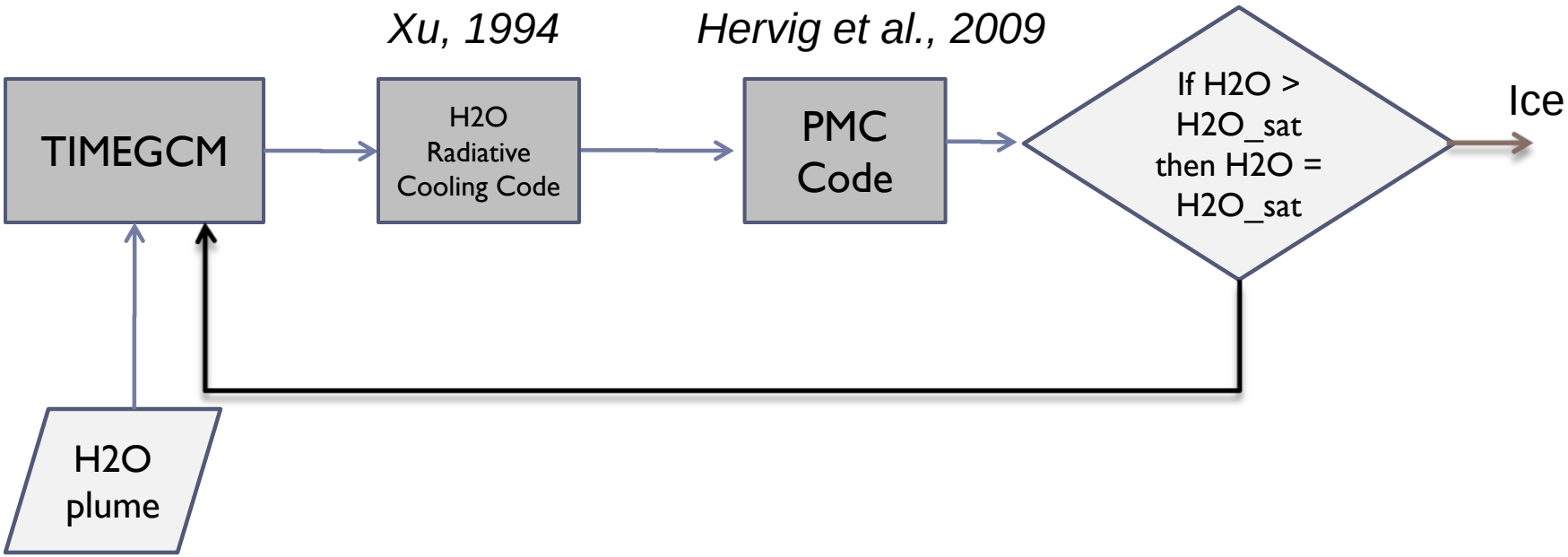
    STS-112 distribution

    ii) Control Case:

    Model run without the plume



Model Description

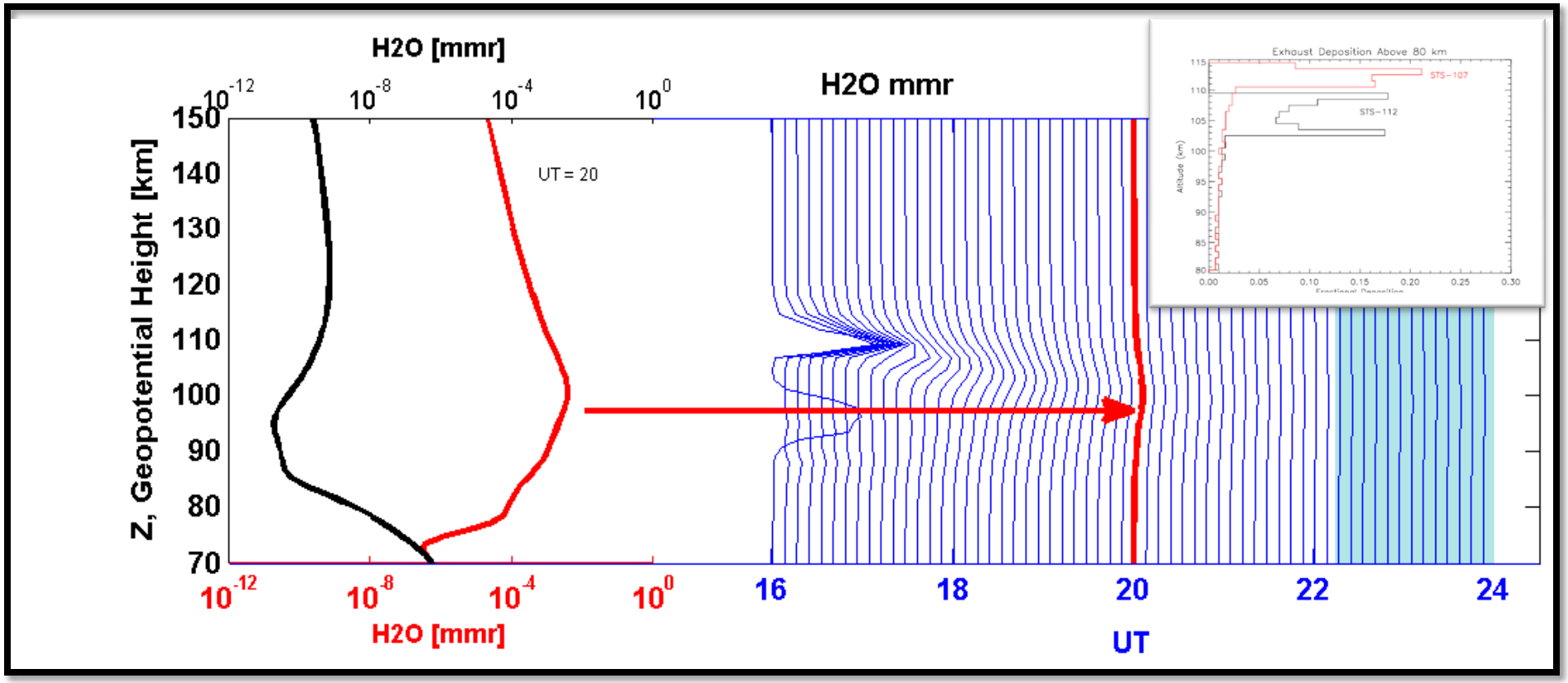


Model Description

- **TIMEGCM neutral chemistry includes:**
  - **Odd Hydrogen (HOx)**
  - **Odd Nitrogen (NOx)**
  - **Odd Oxygen (Ox)**
  - **Metastable Oxygen (O1D)**
  - **Carbon (CH4)**
  - **Chlorine (Clx)**
- **We compare effects of the plume on the heating rates of each chemical family**
- **Reactions in each family contribute to atmospheric energetics**
- **Each reaction has different sensitivity to the plume**

Numerical Simulations

❖Science
❖ Technology
❖ Applications
Bringing It All Together

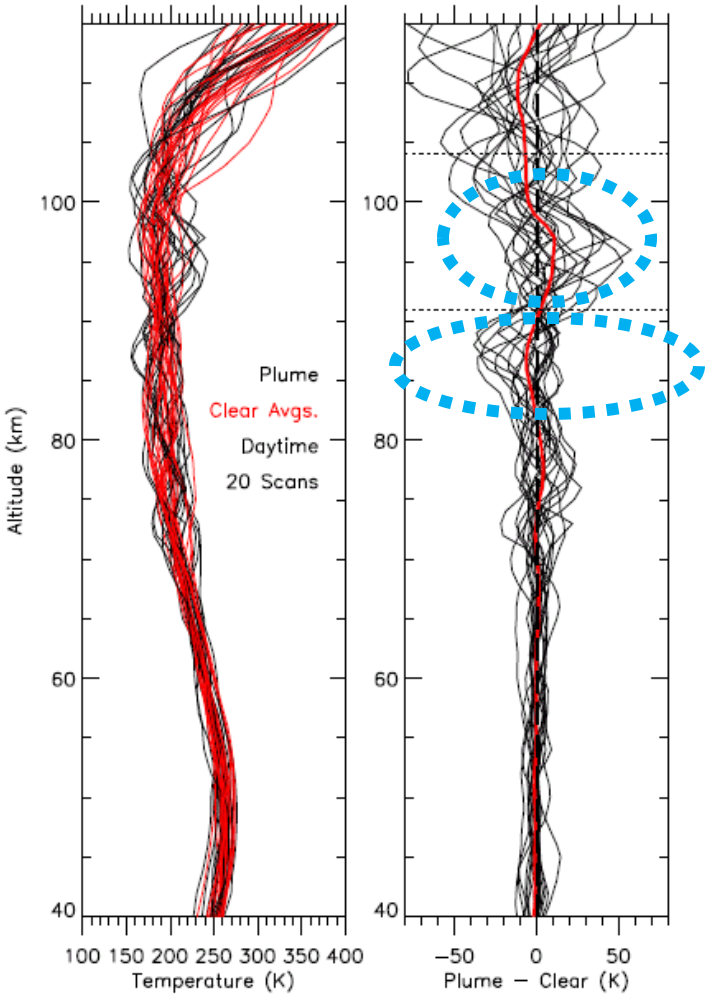


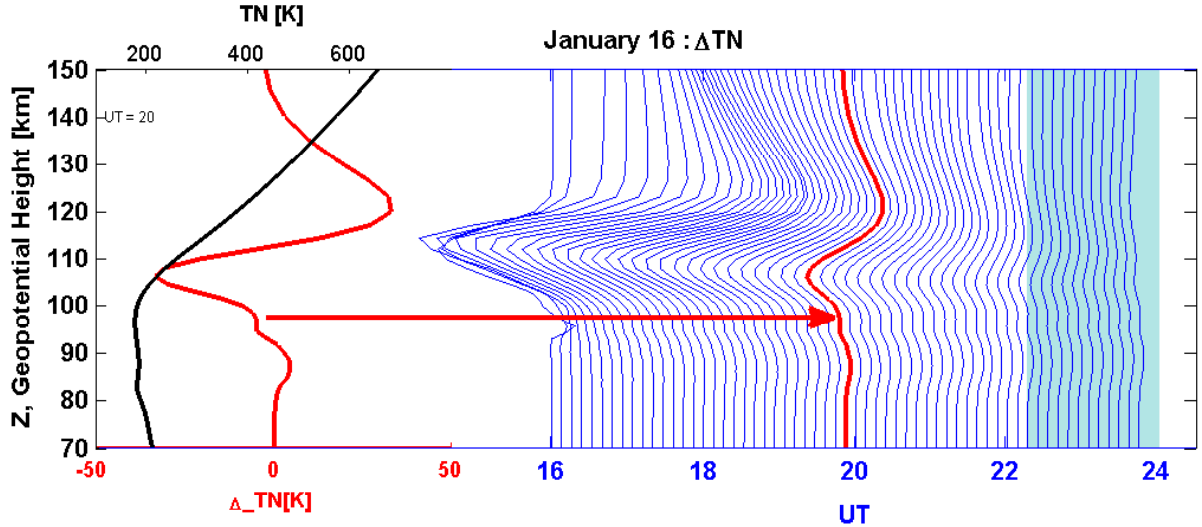
- TIMEGCM simulation of the shuttle plume showing the evolution of the additional water within the plume.
- The background water volume mixing ratio at 20 UT from the control run is shown in black in the left inset.

Numerical Simulations

- Double peak distribution of the shuttle plume at the start of the model
- Rapid modifications due to chemical losses, ice formation and diffusion effects.
- The plume peak in the upper mesosphere dissipates much more rapidly than the peak in the lower thermosphere.
- At 20 UT water concentration is still about 7 orders of magnitude more than the background level.
- The model simulation also shows that the plume peak at 109 km gradually descends in altitude.

Plume Effects on Temperature





- SABER temperature limb scans from daytime H_2O plume observations are shown in black.
- Red scans indicate "clear air" averages from the same region and 2 days prior;
- Right panel - Differences between the plume scans and clear air scans. The average difference is shown in red.

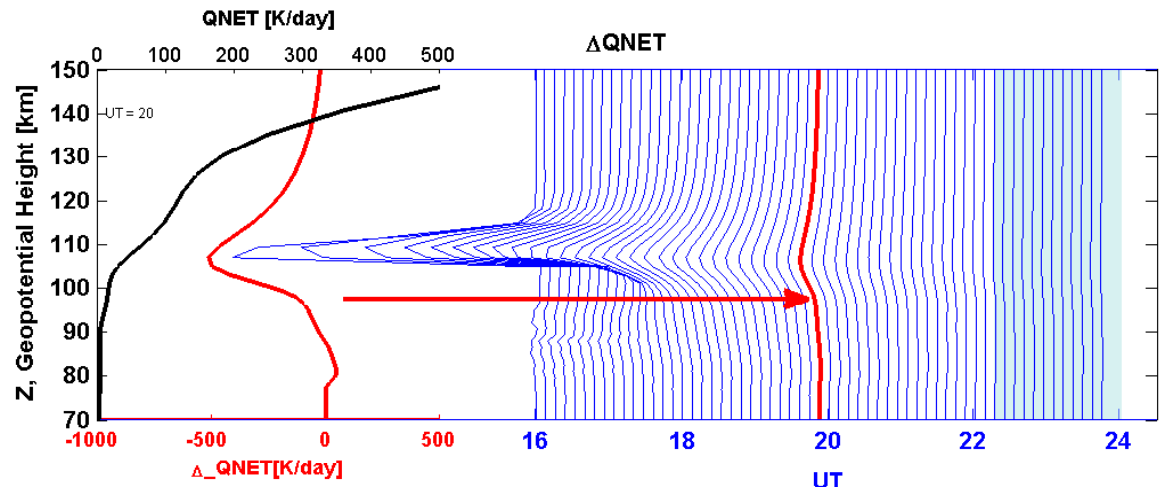
- net heating rate= heating +cooling rates
- -8000 K/day cooling rate at 16 UT
- Max. heating rate of 180 K/day at 20:30 UT

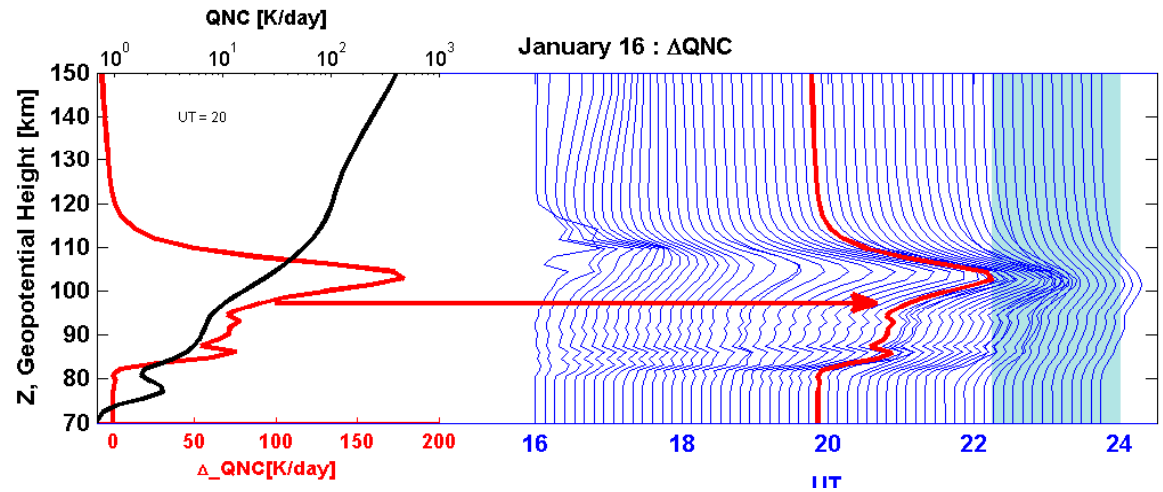
$$OH + O \rightarrow H + O_2$$

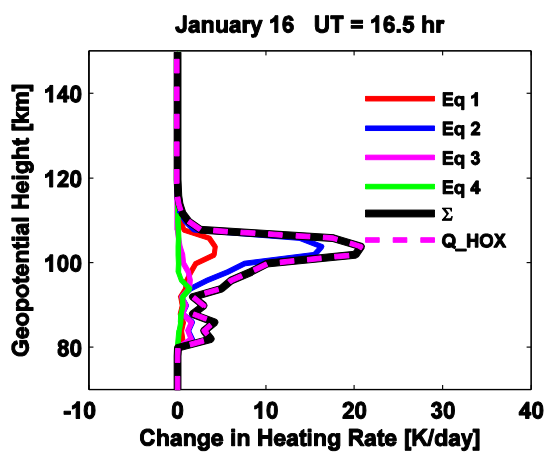
$$HO_2 + O \rightarrow O_2 + OH$$

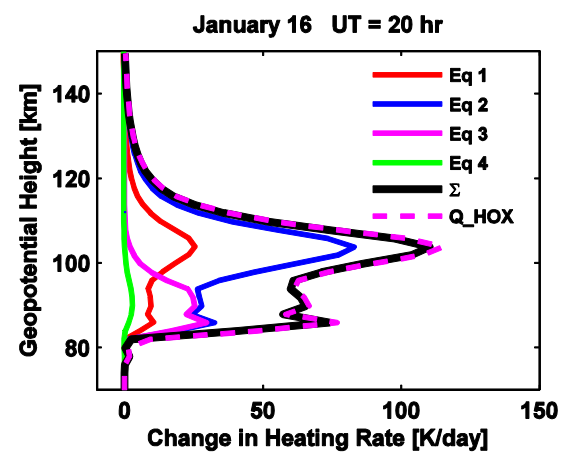
$$H + O_2 + M \rightarrow HO_2 + M$$

$$H + O_3 \rightarrow OH + O_2$$



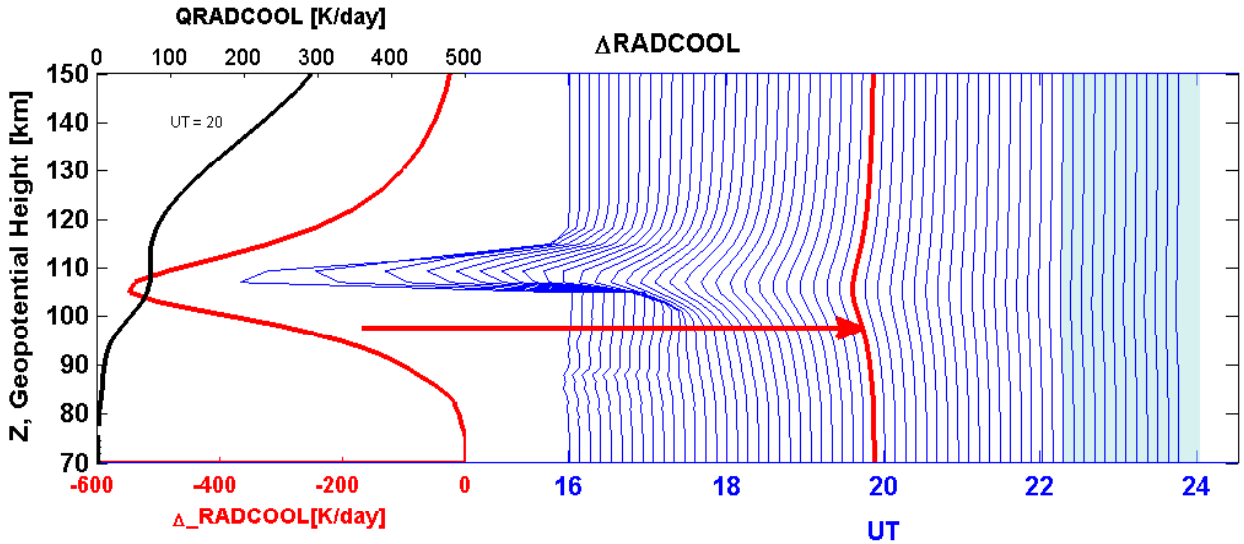


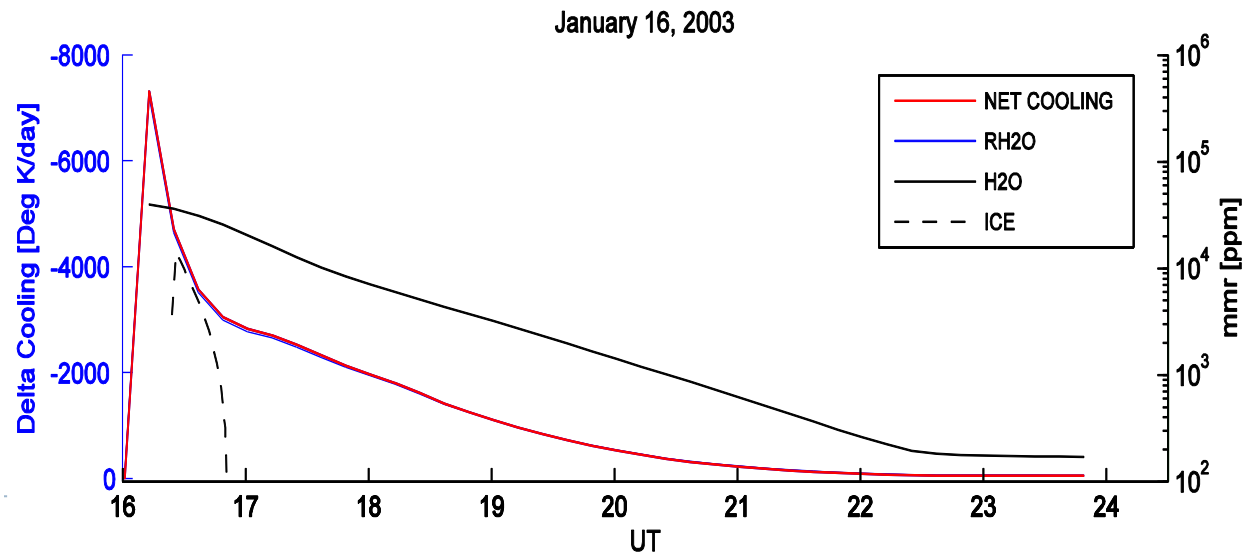




Plume Effects on Cooling Rates

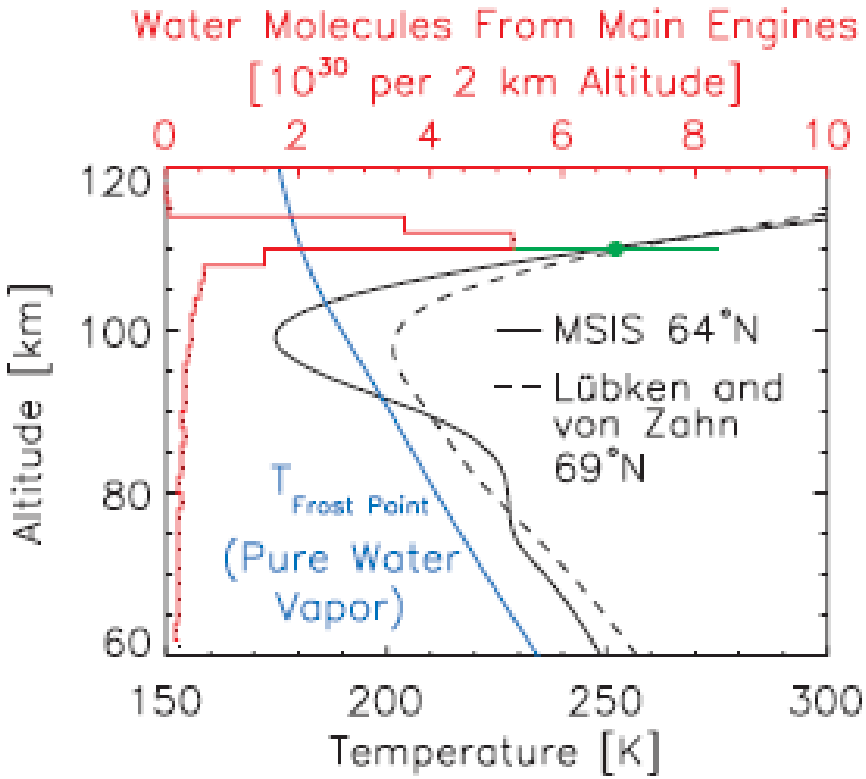
- molecular heat conduction;
- eddy heat conduction;
- radiative cooling from CO_2 (LTE and non-LTE 15 mm cooling), NO (non-LTE 5.3 mm cooling), O (63 mm cooling), O_3 (9.6 mm cooling),
- Cooling from H_2O rotational transitions in the infrared





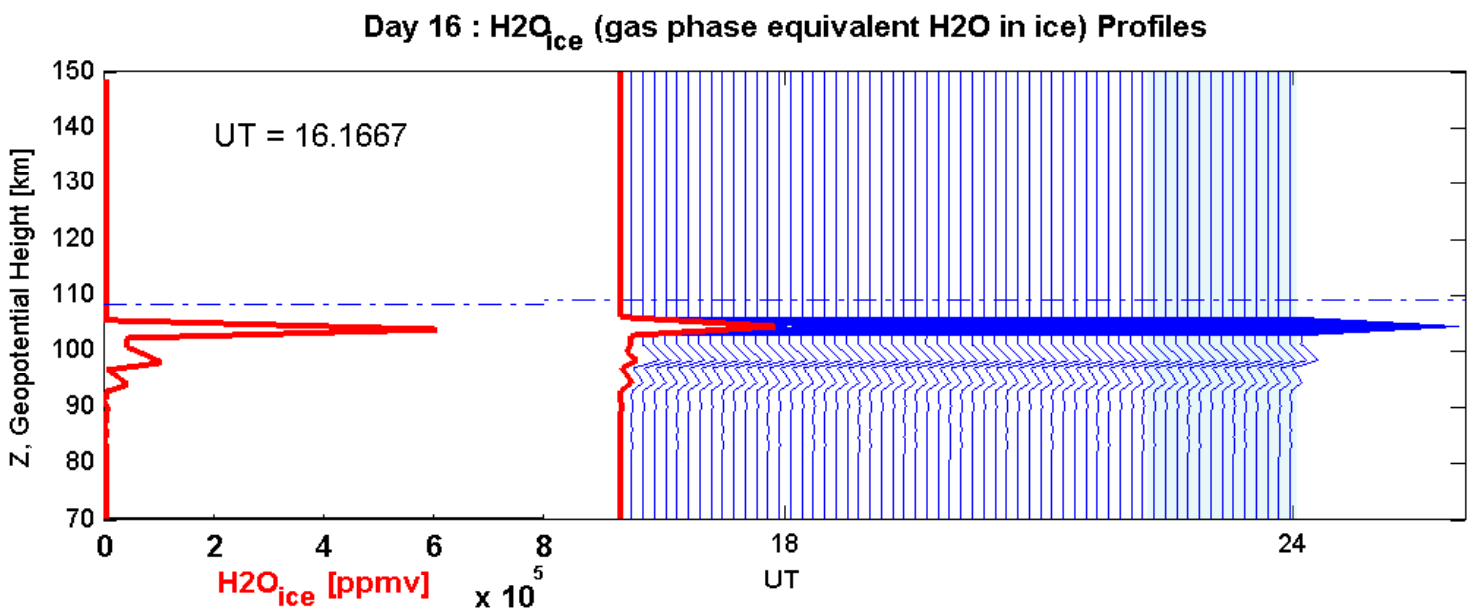
Ice Formation

- Ice formation from the shuttle exhaust can transport water to the middle atmosphere [Stevens et al., 2002]
- Ambient temperature profiles (black) and the frost point temperature (blue) for pure water vapor.
- The red histogram referenced to the top axis shows the amount of water vapor injected into 2 km layers of the atmosphere by the shuttle.
- The study raised questions regarding the process and location of ice formations.



Stevens et al., 2002 GRL

Ice Production in TIMEGCM



- Cumulative abundance of ice produced in the model
- Initial growth phase and then a steady state concentration is reached at which point no new ice is formed
- This result illustrates that the radiative cooling by water vapor is strong enough to reduce the temperature to the frost point, thereby forming ice.

Conclusions

- The cooling and low temperatures predicted by the model suggests that the shuttle plume can quickly impact the PMC microphysics.
  - This large reduction in temperature can bring the local temperature down to the frost point, thereby producing conditions where ice can form.
- Stevens et al. [2002] showed that higher H_2O concentrations such as those present in the shuttle plume drive the frost point up so that ice can form at temperatures as high as 180 K for pure water vapor.
- The results presented in this current study indicate that the water vapor is radiatively cooling the shuttle plume and driving the temperature down to the frost point, providing a plausible explanation of the presence of ice in the STS-66 plume observations in November reported by *Stevens et al*. [2002].