Hindcasts of Chemistry and Aerosols

Peter Hess, Jennifer Logan, Michael Prather, Oliver Wild

Atmospheric Chemistry and Climate (AC&C):

Effort focused on representation of chemistry-climate interactions in earth system models

Activity #1: CHEMICAL HINDCASTS

Objective: Evaluate the performance of global chemistry-transport models (CTMs) in preparation for their use in future climate projections.

-Test the capability of current atmospheric chemistry models to integrate over the variations and trends in circulation and climate, in emissions, and in chemical feedbacks that control atmospheric composition.

-Quantify and derive objective measures of uncertainty when global chemistry models are used in climate system models to project conditions of the 21st century

Experimental Approach

-Use the past few decades for which we have observations of trends and variability in atmospheric composition.

-Focus on large space (1000+ km) and time scales (multi-year to decadal variability) that are essential in projecting 21st century change, and that effectively integrate over many atmospheric processes.

-Take an integrative approach and not focus on process validation, which will be examined in other activities.

Why a coordinated exercise?

- Coordinated framework to compare/evaluate model results.
- Ability to formulate more objective measures of the inherent uncertainty in modeling atmospheric chemistry and transport and thus in projecting future composition.
- The best estimate of model response, and arguably the most actionable in terms of policy implications, is one produced from a multi-model ensemble using different models and model formulations.
- Multi-model experiments run with common diagnostics and selected specified common forcings allow a better understanding of the differences in the model behavior.
- Biases in comparison with measurements across a wide range of models suggest systematic problems may exist in the model formulation
- A systematic comparison across different models is helpful in improving the individual models and their processes

Hindcast Experiments

We are not proposing a single hindcast experiment from 1980

But, a series of interrelated experiments

***Chemical Hindcasts Proposed*:**

- **1)** *Simple tracers (CFCs and N2O)*
- **2)** *Aerosols*
- ***3)*** *Ozone Variability (including simulations of OH)*
- *4) Methane Variability.*

***Each hindcast experiment defined by*:**

- -- a multi-year series (post-1980) of measurements of atmospheric trace species.
- -- a clear objective grading criteria for evaluating model success.
- -- a set of required diagnostics to facilitate model comparison and evaluation.
- -- multi-year external forcings (e.g., emissions) needed to drive the simulations.
- -- guidelines on the types of chemical models and meteorological fields that can usefully participate.

Simple Tracer Hindcast

(C. Nevison, M. Prather, N. Mahowald)

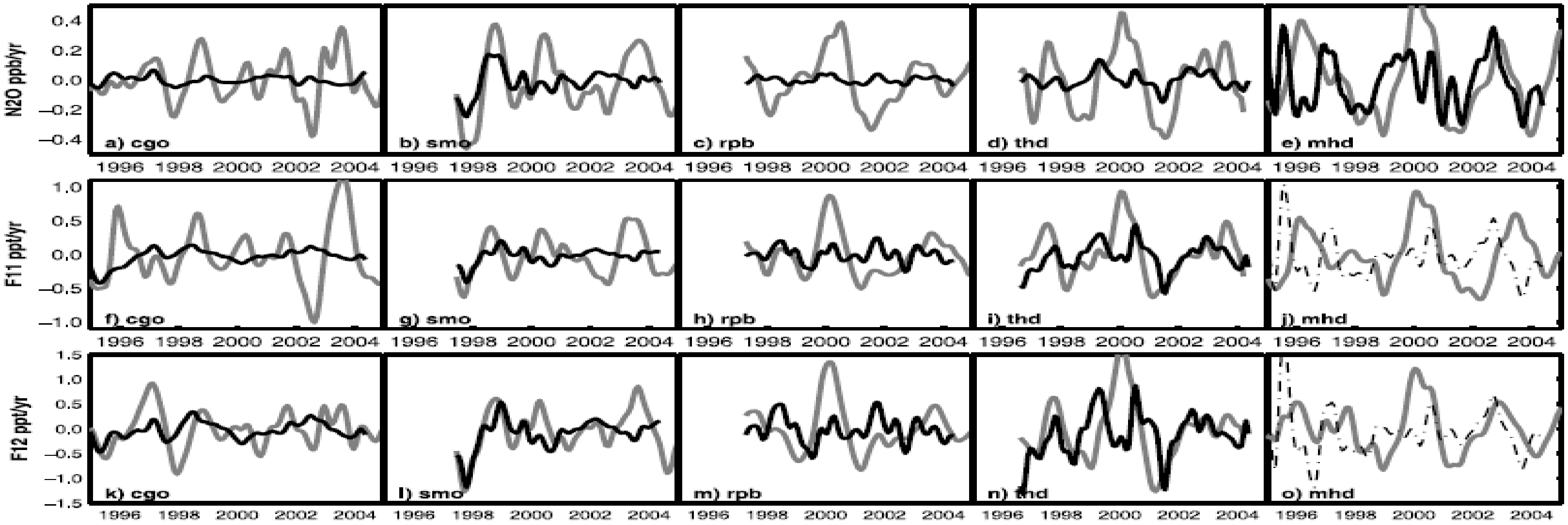
Goal: Match the trends and variability of the nearly-inert trace gases CFCs and N_2O as measured by stations of the ALE/GAGE network.

Quantify importance of:

-changing emissions

-tropospheric meteorology

-stratosphere-troposphere exchange variability.



From Nevison et al., Interannual Growth Rate Anomalies: Match and AGAGE

Aerosol Hindcast

(*Michael Schulz, Mian Chin)*

***Goals**:* Better understanding of:

-regional and global satellite observed trends in AOD

-regional differences in sulfate and black carbon deposition from the Arctic to the Alpes

-temporal trends in aerosol concentration, composition, optical properties and deposition

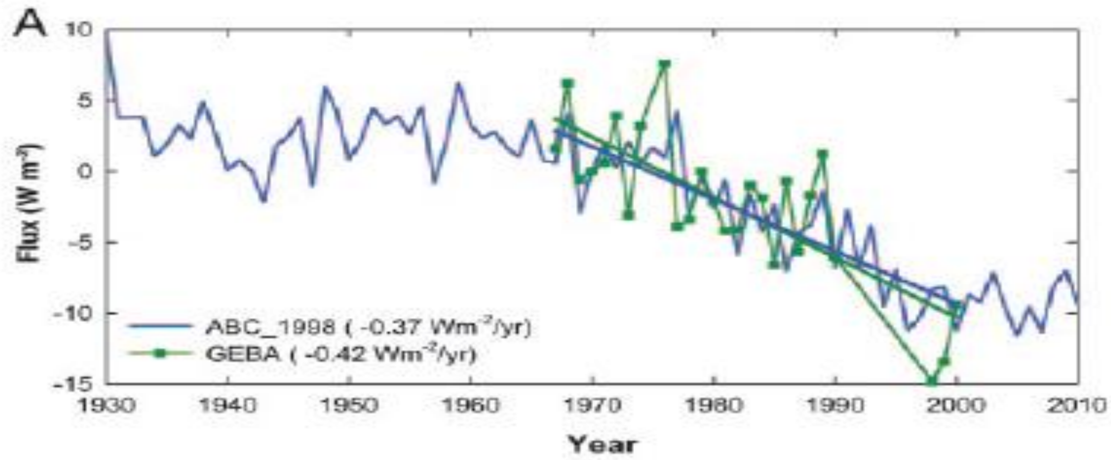
-emission trends of primary aerosols and aerosol precursor gazes

-the impact of changing meteorology vs changing emissions on aerosol trends

-dimming and brightening trends observed by surface radiation networks

-the evolution of the anthropogenic aerosols perturbation of the Earth radiative balance

To be run as part of AEROCOM



From
Ramanathan et al., 2005

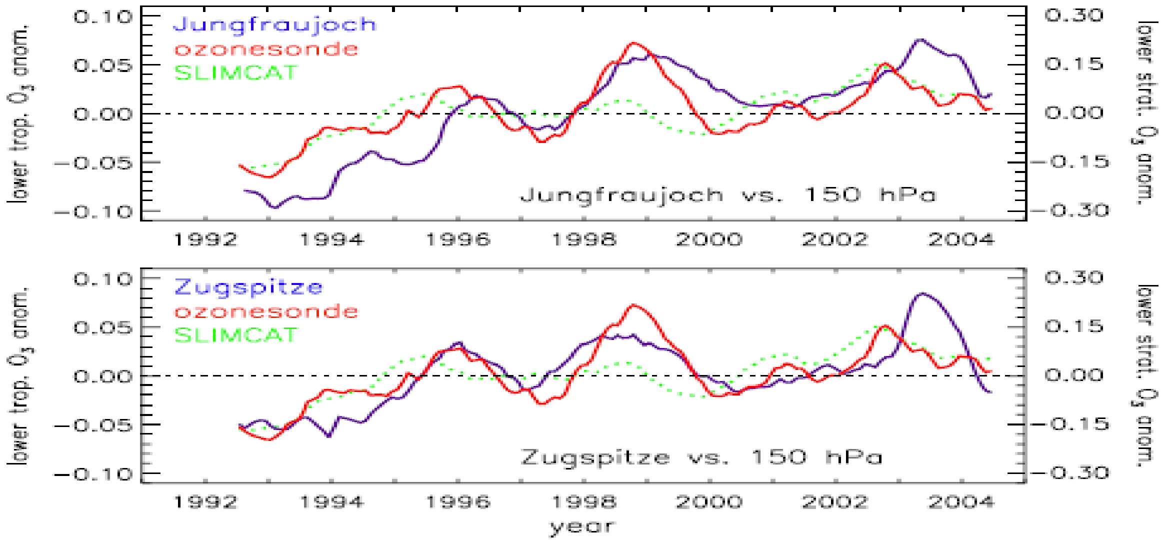
Observed and simulated
Surface Radiation
Fluxes over India

Ozone Hindcast

(Jennifer Logan, Peter Hess)

Goals: quantify impact on tropospheric ozone of:

-changes in emissions of ozone precursors (NO_x, CO, hydrocarbons)
-changes in methane
-changes in ozone in the lower stratosphere
-dynamical variability including STE, ENSO, NAO/AO



From Ordonez et al.

Interannual Ozone Variations and trends.

Methane Hindcast

(I. Bey, F. Dentener, A. Fiore, P. Hess, P. Bergamaschi)

***Goal**:* Match the observed methane trends and variability.

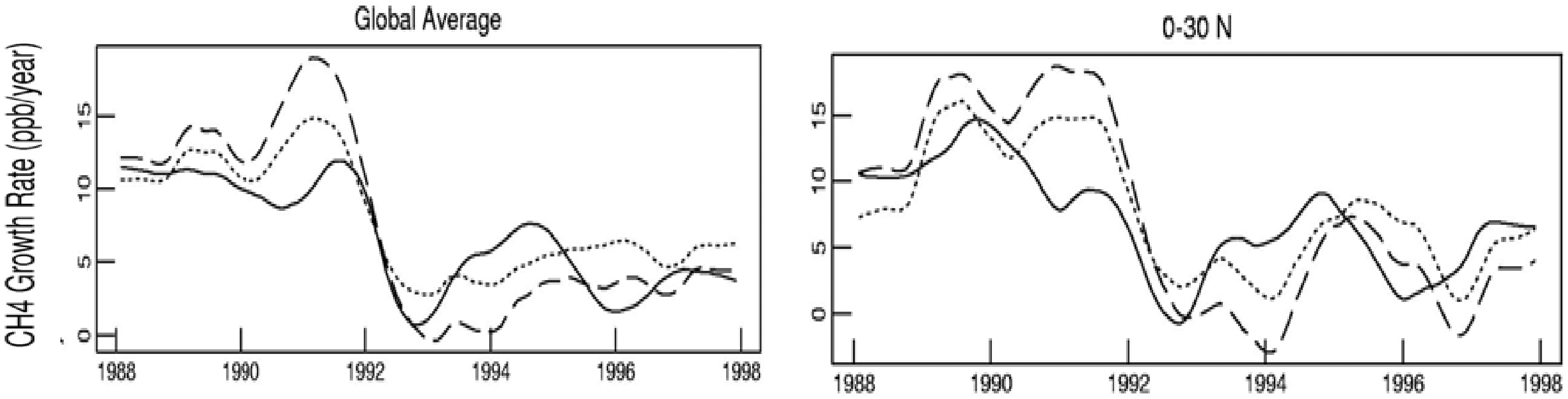
Quantify:

-the importance of changing anthropogenic and natural emissions

-the importance of OH variations.

Procedure:

use OH fields from the ozone hindcast in an inverse modeling calculation for methane emissions – reconcile top-down and bottom-up emission estimates.



From Wang et al, Modeled and Observed changes in CH4 growth rate.

Aerosol Hindcast

(*Michael Schulz, Mian Chin*)

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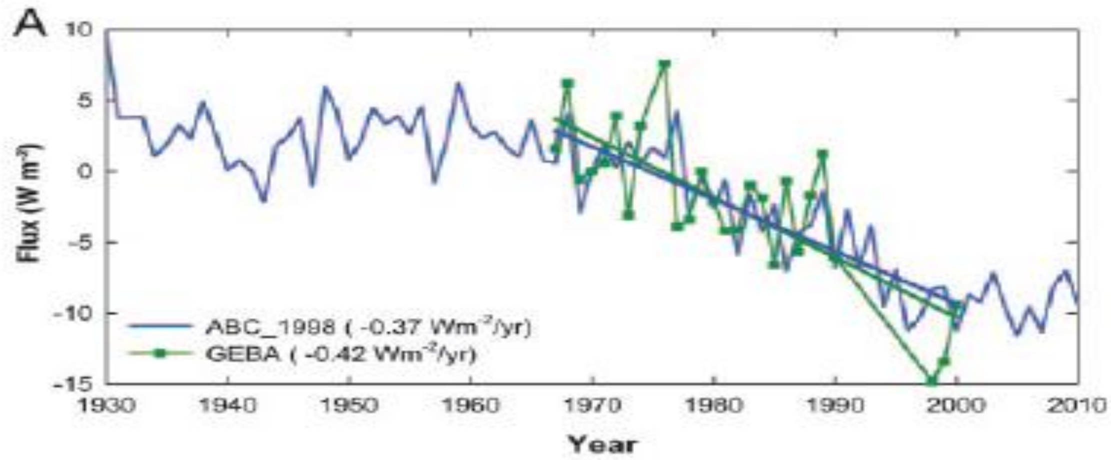


From
Ramanathan et al., 2005

Observed and simulated Surface Radiation Fluxes over India

Where do we go from here?

- Strawman proposals have been formulated.

We need your:

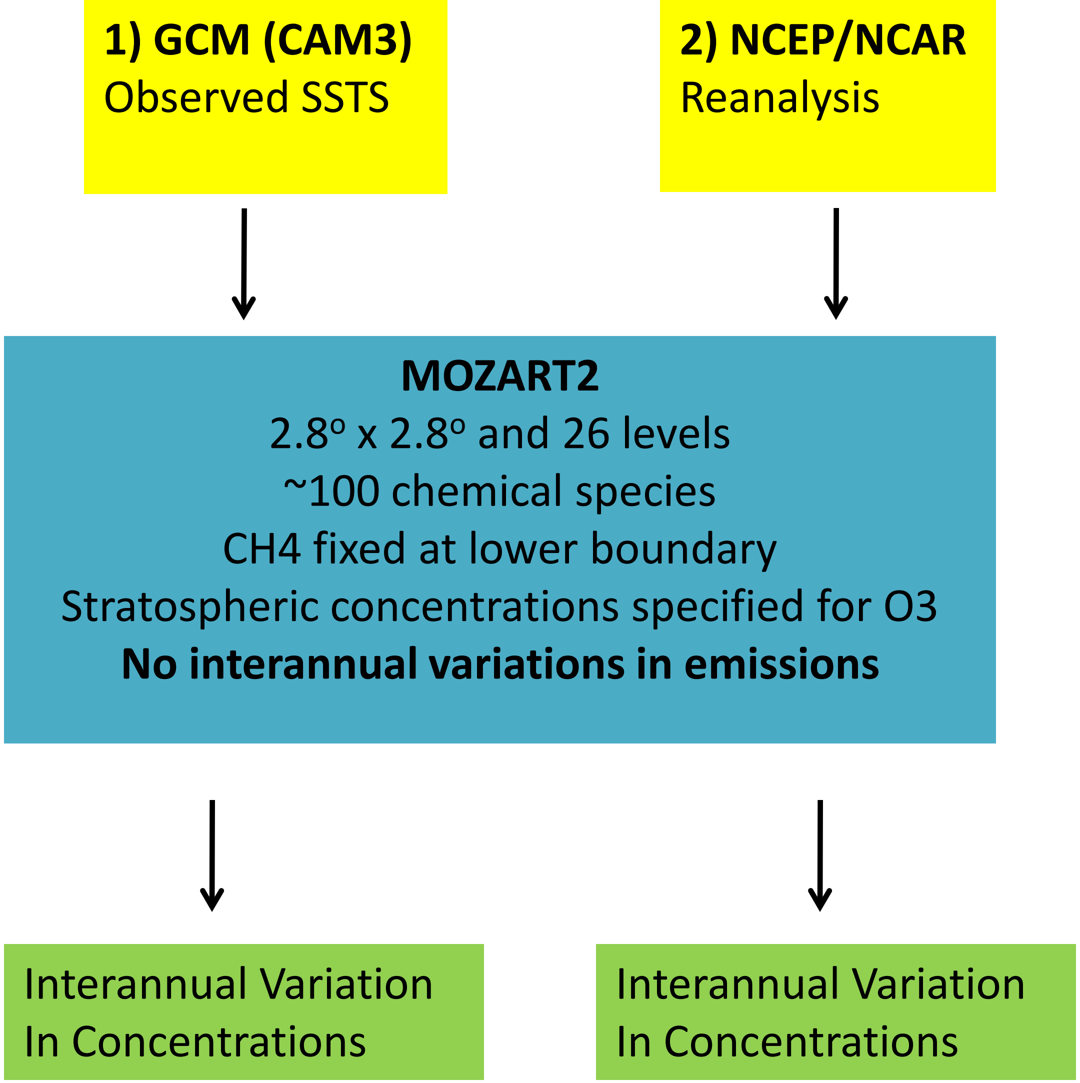
-input

-enthusiasm

-leadership

Results of Two Experiments
Examining Chemical Interannual
Variability (1960-2000)
with Constant Emissions

Experiment: 1 and 2*



Meteorology:
(1960-2000)

1) GCM (CAM3)
Observed SSTS

2) NCEP/NCAR
Reanalysis

Chemistry Model

MOZART2
2.8° x 2.8° and 26 levels
~100 chemical species
CH4 fixed at lower boundary
Stratospheric concentrations specified for O3
No interannual variations in emissions

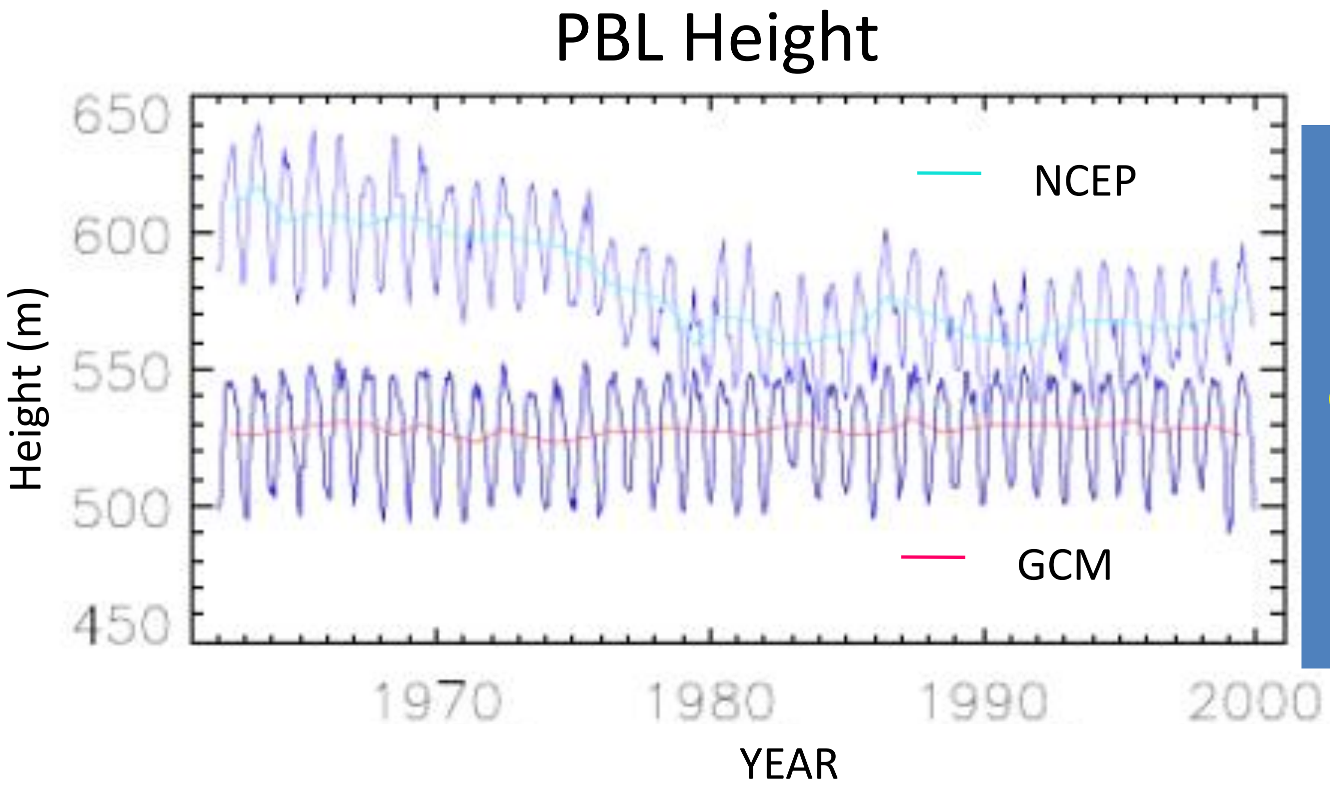
Analysis

Interannual Variation
In Concentrations

Interannual Variation
In Concentrations

*Hess et al, In preparation

Analyzed Large Scale Interannual Variability 1979 -2000



Large changes in reanalysis in the 1970s. These are due to changes in the observing system with the advent of satellite observations (e.g., Bengtsson et al., 2004)

1) NCEP does not capture observed trends in many global

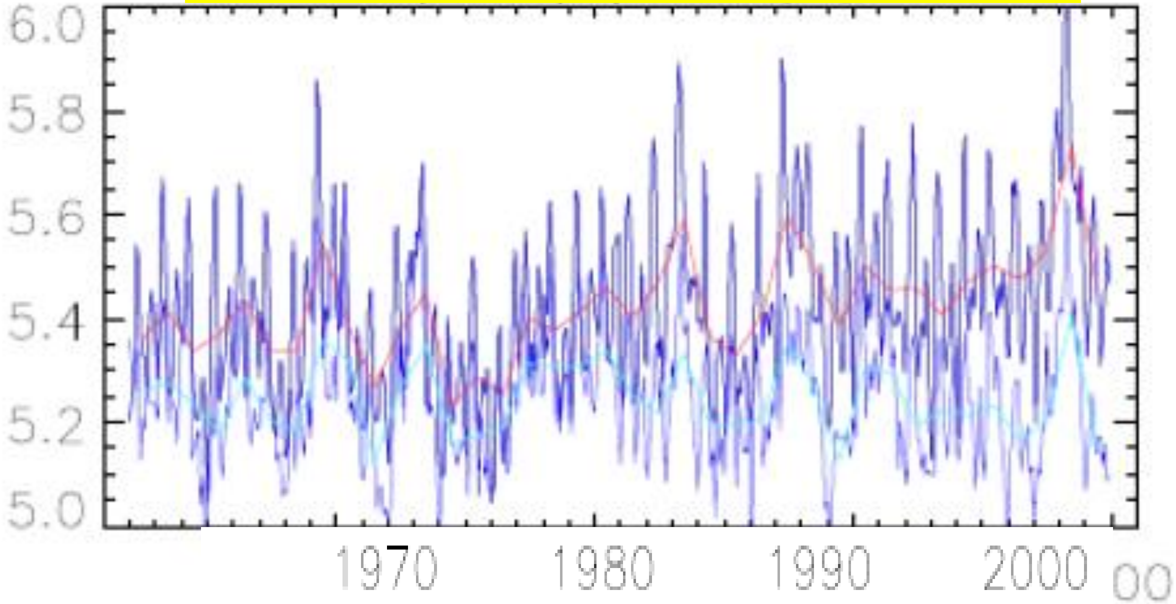
Trends after 1980 in Globally Averaged Tropospheric Fields

(circled trends have an observational basis)

	GCM	NCEP	Notes
O3 surface	−	+	
O3 troposphere		+	
T surface	⊕		
Precip. surface	+	+	Long-term 20th trends
Q	⊕		Trenberth et al., 2005
J_{NO2} surface	⊖		Dai et al., 2006; Norris, 1999

2) Importance of the hydrological cycle in forcing tropospheric interannual variability

Q **Tropical Troposphere**



Key: — NCEP — CAM

Principal Component Analysis of Tropospheric Timeseries
Correlation of 1st PCA with Global Timeseries

	GCM	NCEP
	1st PC (57%)	1st PC(42%)
T surface	**0.89**	**0.51**
Q	**0.97**	**0.68**
OH	**0.94**	**0.94**
CO	**-0.80**	**-0.87**
Precipitation	**0.97**	**0.17**
Lightning NOx	**0.74**	**0.79**
J_{NO2} surface	**-0.85**	**-.043**
sfcO3	**-.58**	**+0.64**
PBLH	**0.33**	**0.55**
O3	**-0.23**	**0.74**
HNO3	**0.54**	**0.41**
El Nino	**+0.08**	**-0.13**
Year Correlation	**+0.58**	**+0.33**

Correlation coefficient of the time series from the PCA analysis including all variables with the globally and annually averaged time series of each variable.

3)Global response of chemical variables to interannual variability and climate change

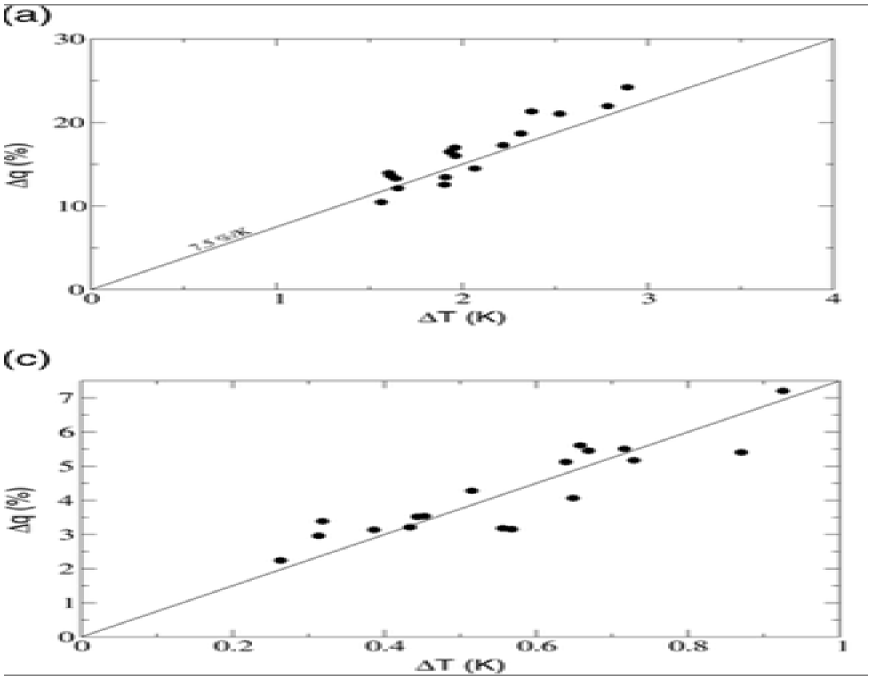
- How to measure this response?

Change in Global Water Vapor versus Global SurfaceTemperature:

C-C relationship 7%/K

21st Century

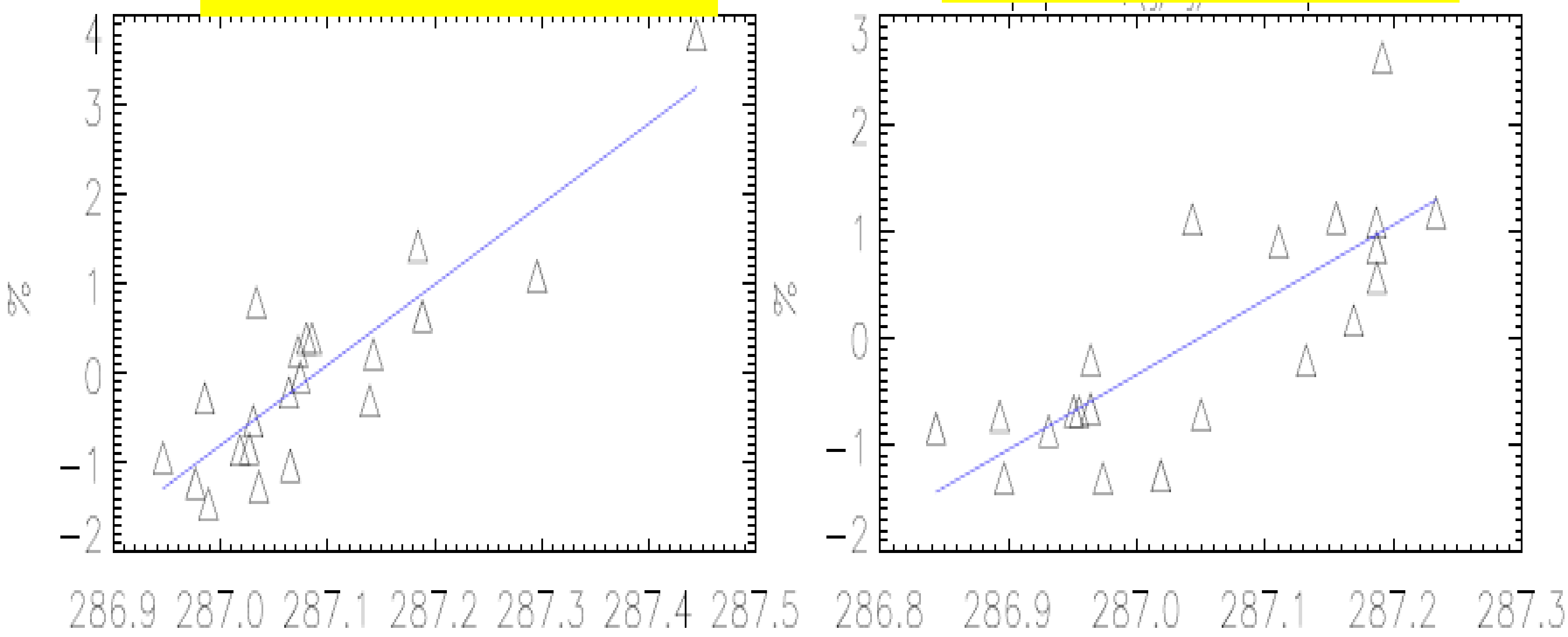
20th Century



Held and Soden, 2006

Does this robust response translate to short-term simulations?

% Change in Tropospheric Q vs Temperature



GCM

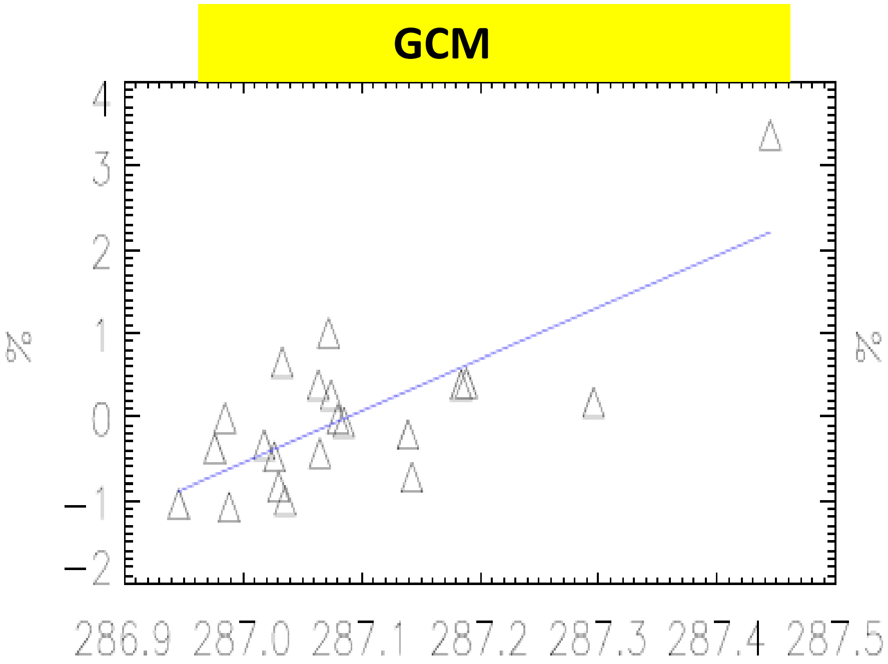
R=0.88
Slope 20 years 9.0%/K
Slope 21st Century 7.3%/K

NCEP

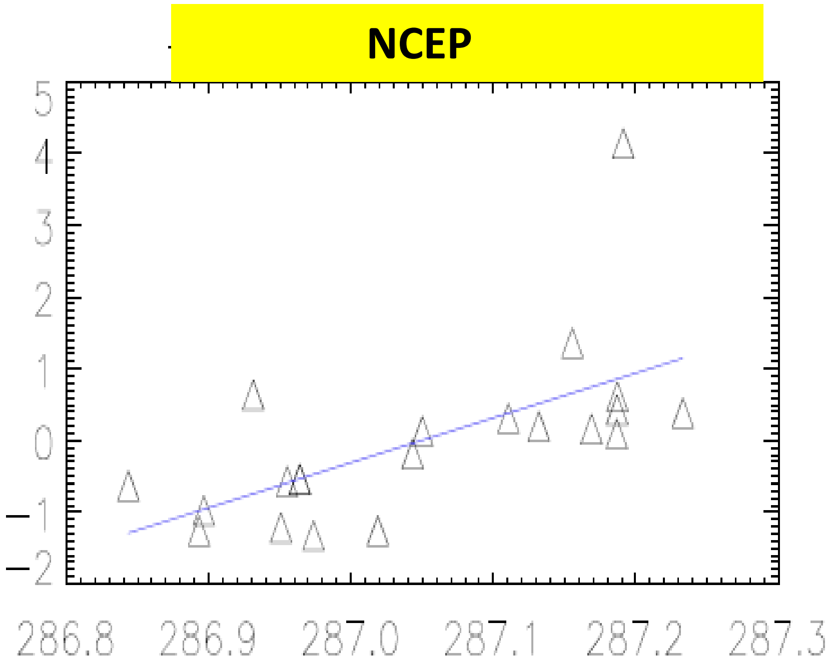
R=0.79
Slope 20 years 7%/K

Does this robust response translate to global averages of chemical variables versus temperature?

% Change in Tropospheric OH vs Temperature



R=0.75
Slope 20 years 6.2%/K
Slope 21st Century 3.9%/K

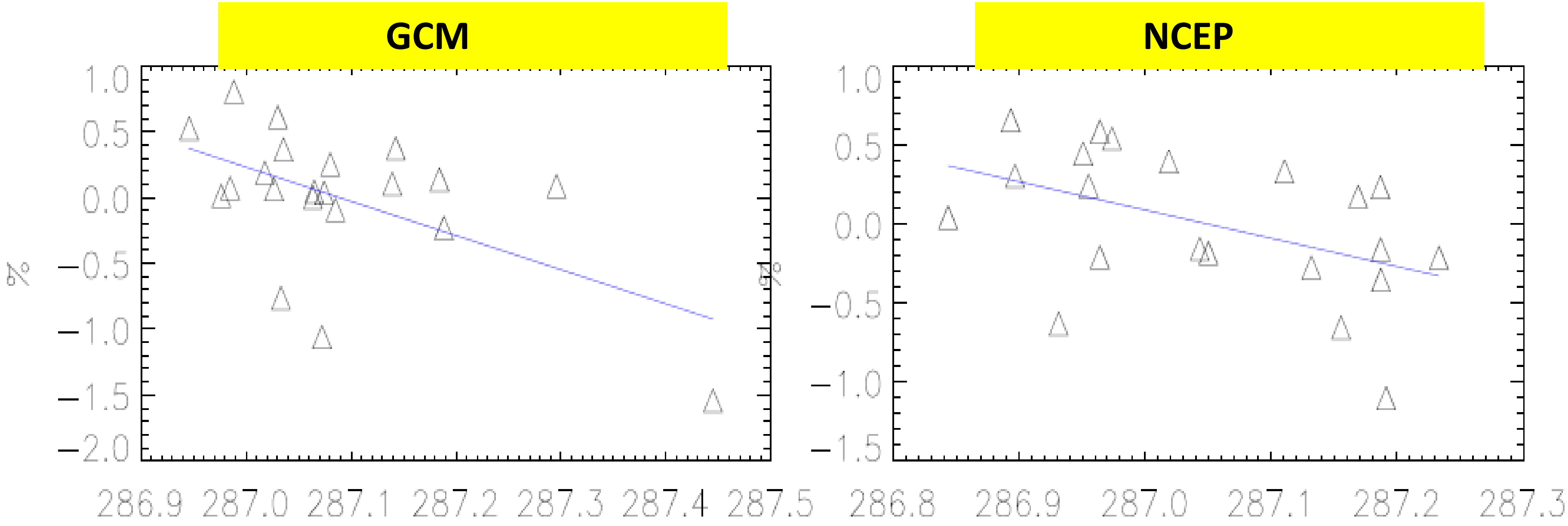


R=0.63
Slope 20 years 6.3%/K

$$[\mathrm{OH}] = \frac{2\, j_1 k_3}{k_2 [M][HC]} \quad [\mathrm{O3}][\mathrm{Q}]$$

$$\delta[OH] \big/ [OH] = \delta[Q] \big/ [Q] \cong 0.07\,\delta T$$

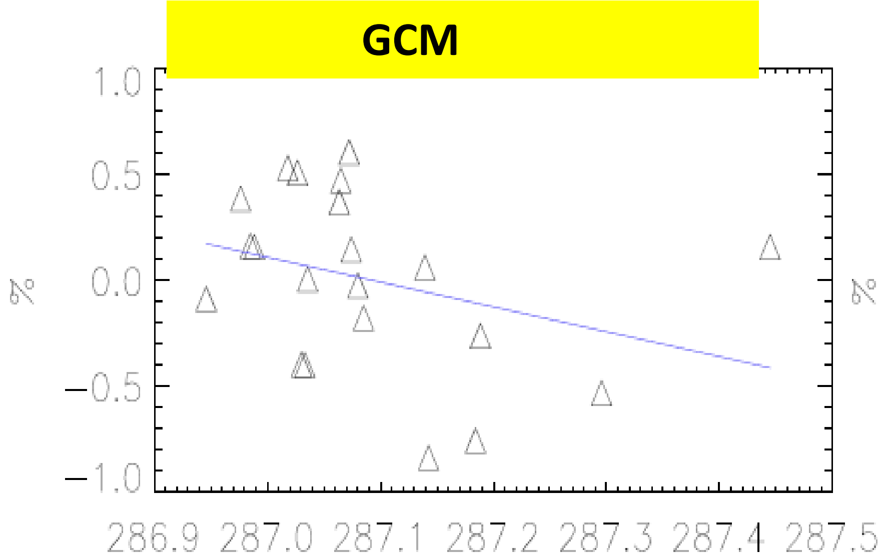
% Change in Tropospheric CO vs Temperature



R=-0.56
Slope 20 years -2.5%/K
Slope 21st Century -1.3%/K

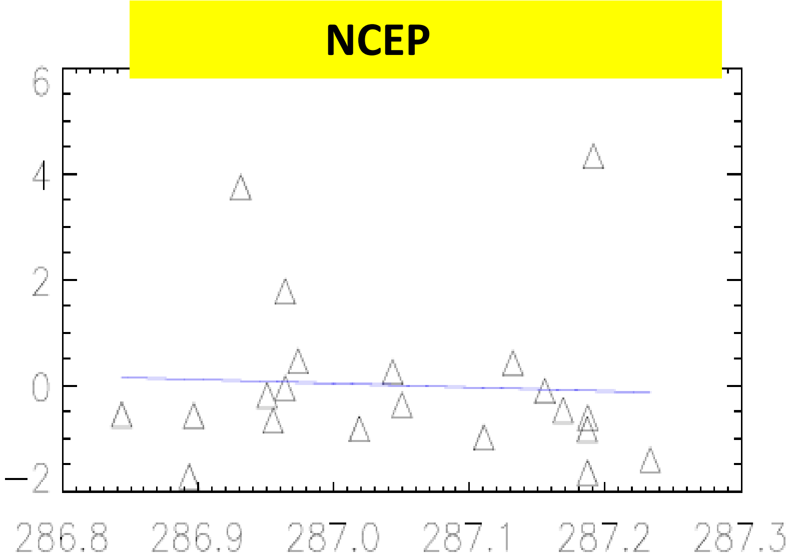
R=-.47
Slope 20 years -1.8%/K

% Change in Tropospheric O3 vs Temperature



GCM

R= -.32
Slope 20 years -1.2%/K
Slope 21st Century -1.1%/K



NCEP

R= -.06

Ozone shows a very weak response.

Conclusions

- **Strong coupling of interannual variability to the hydrological cycles for many variables.**
- **Changes in ozone** show little or weak relation with temperature
- **Percent change in field against surface temperature**. Global measure of change and interannual variability.
    - Very simple, one number to compare across models
    - Very robust for Q. Changes in Q drive interannual variability for many fields.
    - Simple analytic formulation for many chemical species
    - Many species show good correlation, although not always as predicted
    - Reporting this number across model simulations would be valuable in understanding the response of tropospheric chemistry to climate.

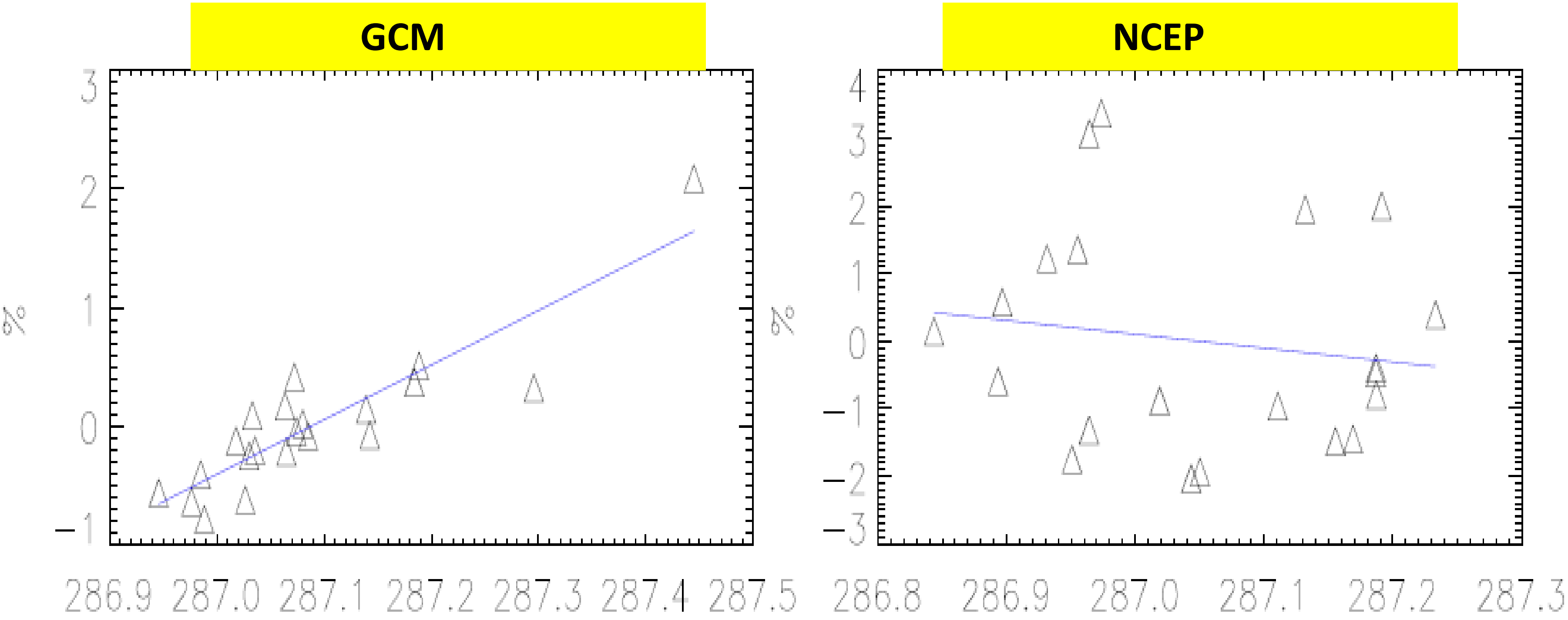
Conclusions

- **GCM fields versus NCEP Reanalysis fields**
  - **Reanalysis fields** best capture interannual meteorology on short timescales (e.g., the meteorology relevant for a particular field campaign)
  - **GCM fields** best capture many observed trends on longer timescales (These are simply not captured in the NCEP reanalysis).
  - **Reanalysis fields** rapidly change throughout the 1970s. Comparisons before and after 1980 must be made with caution.
  - **Reanalysis and GCM simulations** show similarities in a number of fields: Q, OH, Lightning NOx, and CO highly are highly correlated. Global variations in these fields are largely driven by the SSTs.

Conclusions

- **AC&C, Activity 1:** Quantify and derive objective measures of uncertainty when global chemistry models are used in climate system models to project conditions of the 21st century
- **Experimental Approach**: Use the past few decades for which we have observations of trends and variability in atmospheric composition to provide a test of the models used to project future atmospheric chemistry and climate.
- **Experiments**: Some examples given, but only examples. Experiments and design need to be carefully considered by participants.
- **Exciting Opportunity** to develop a program that provides scientific curiosity, excitement, and opportunity for researchers trying to understand the coupling of atmospheric chemistry and climate.
- **Success** will depend on community involvement.

% Change in Precip vs Temperature

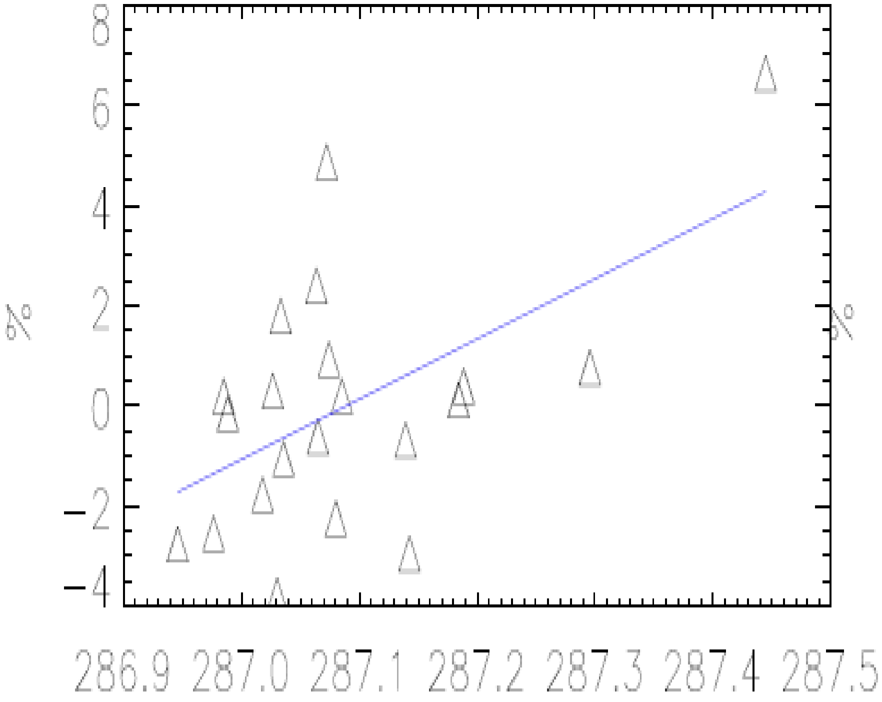


R=0.89
Slope 20 years   4.2%/K
Slope 21st Century 2.5%/K

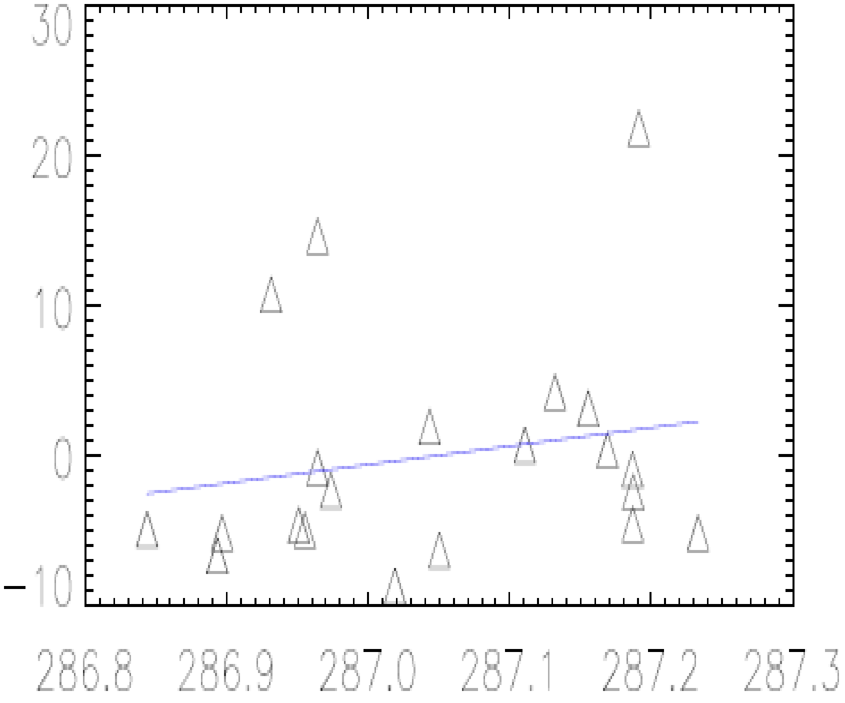
R=-.015

% Change in Lightning N0x vs Temperature

GCM



NCEP



R=0.55
Slope 20 years 12%/K
Slope 21st Century 9.6%/K

R=0.20

ΔSpecies ↔ΔSurface Temperature

We can make simple, if naïve, predictions. For example, if

$$[\mathrm{OH}] = \frac{2 j_1 k_3}{k_2 [M][HC]} [\mathrm{O3}][\mathrm{Q}]$$

and O3 remains constant

$$\rightarrow \quad \delta[OH] \big/ [OH] = \delta[\mathrm{Q}] \big/ [\mathrm{Q}] \cong 0.07\,\delta T$$

Similarly,

$$\delta[CO] \big/ [CO] = -\,\delta[OH] \big/ [OH] \cong -0.07\,\delta T$$

Conclusions

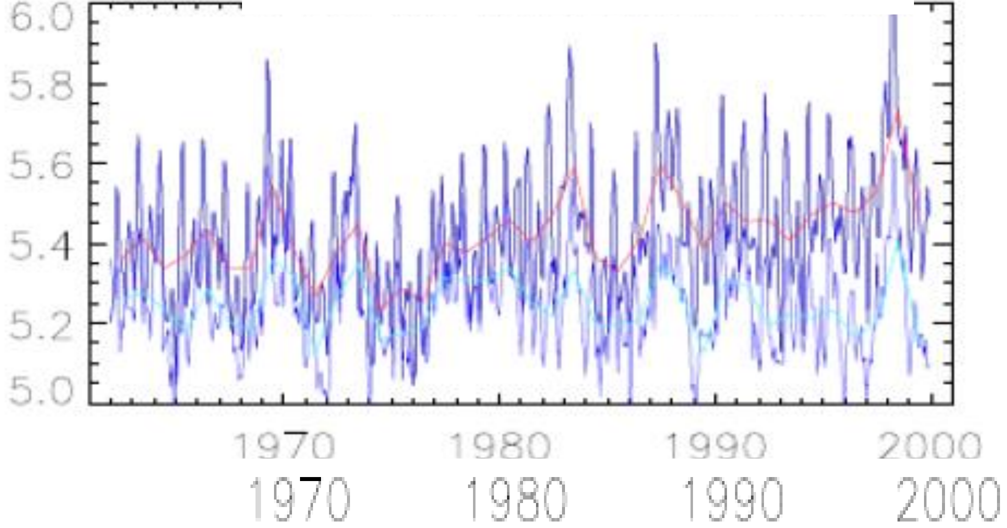
- **Global measure of change and interannual variability.** Percent change in field against surface temperature.
  - ***Negatives:***
    - Cannot be compared to observations
    - Only comparable for constant emission simulations
    - Short term change not always comparable to long-term change
  - ***Positives***
    - Very simple, one number to compare across models
    - Very robust for Q
    - Simple analytic formulation for many chemical species
    - Many species show good correlation although not as predicted
    - Reporting this number would be valuable.
    - Could a similar robust response be expected across a spectrum of models for chemical variables?
- **Changes in ozone** show little relation with temperature

Trends after 1980

(circled trends have an observational basis)

		GCM	NCEP	Notes
O3	**surface**	−	+	
O3	**troposphere**		+	
T	**surface**	+		
Precip.	**surface**	+	+	Long-term 20th trends
Q		+		Trenberth et al., 2005
J_{NO2}	**surface**	−		Dai et al., 2006; Norris, 1999

Q tropical troposphere R = 0.67



Key: = NCEP = CAM

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2) **Principal Component Analysis of Tropospheric Timeseries (11 variables)**

Importance of the hydrological cycle