Volcanoes and Climate Sensitivity

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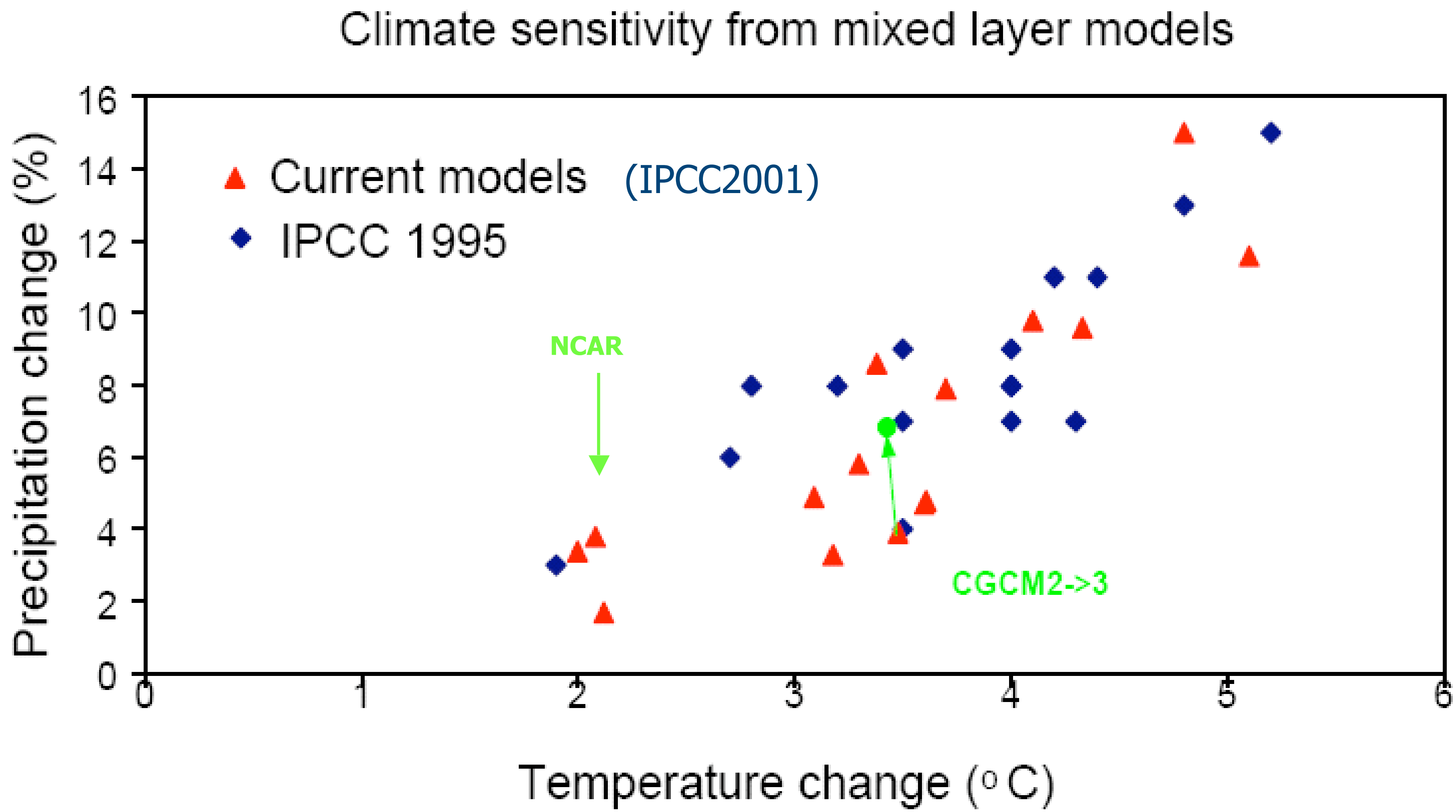
Topics

- Global climate sensitivity and response
- Climate sensitivity in climate models
- Aspects of feedback/sensitivity
  - energy budget
  - local and global contributions and processes
  - diagnostic feedback/sensitivity
- Volcanoes and climate
- Determining climate sensitivity from volcanic events
- Summary



2xCO2 equilibrium change

(Boer and Senior, IPCC2001, Chapter 9)

AOGCM	Equilibrium climate sensitivity (°C)	Transient climate response (°C)
1: BCC-CM1	n.a.	n.a.
2: BCCR-BCM2.0	n.a.	n.a.
3: CCSM3	2.7	1.5
4: CGCM3.1(T47)	3.4	*1.9*
5: CGCM3.1(T63)	*3.4*	n.a.
6: CNRM-CM3	n.a.	1.6
7: CSIRO-MK3.0	3.1	1.4
8: ECHAM5/MPI-OM	3.4	2.2
9: ECHO-G	3.2	1.7
10: FGOALS-g1.0	*2.3*	*1.2*
11: GFDL-CM2.0	2.9	1.6
12: GFDL-CM2.1	3.4	1.5
13: GISS-AOM	n.a.	n.a.
14: GISS-EH	2.7	1.6
15: GISS-ER	2.7	1.5
16: INM-CM3.0	2.1	1.6
17: IPSL-CM4	4.4	2.1
18: MIROC3.2(hires)	4.3	2.6
19: MIROC3.2(medres)	4.0	2.1
20: MRI-CGCM2.3.2	3.2	2.2
21: PCM	2.1	1.3
22: UKMO-HadCM3	3.3	2.0
23: UKMO-HadGEM1	4.4	1.9

The current generation of GCMs[5] covers a range of equilibrium climate sensitivity from 2.1°C to 4.4°C (with a mean value of 3.2°C; see Table 8.2 and Box 10.2), which is quite similar to the TAR. Yet most climate models have undergone substantial developments since the TAR (probably

- AR4 sensitivities
  - don't differ much from TAR and 1995
  - max 4.4, min 2.1
  - average 3.2

Climate Sensitivity

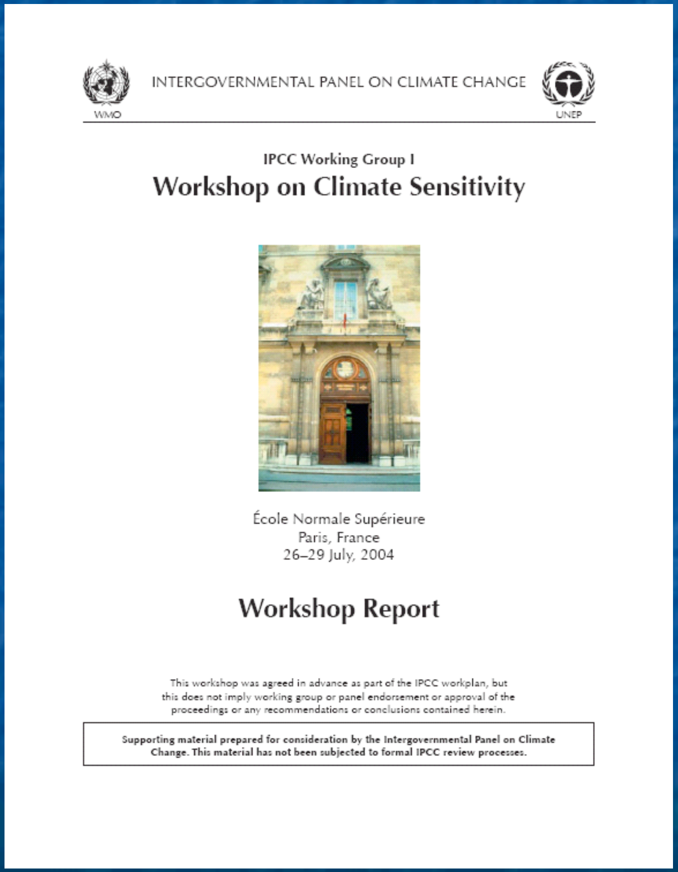
- Measures the link between *radiative forcing* $f(\lambda,\varphi,t)$ and surface temperature *response* $T'(\lambda,\varphi,t)$
- Standard measure is the temperature change for a doubling of CO_2
  - $<T'_{2x}>$ is global mean change
  - $< f_{2x} >$ is the global mean "radiative forcing"
- the equilibrium global "sensitivity parameter" *s* links the two as

$$<T'_{2x}> = s < f_{2x} >$$

  - *s* is reasonably independent of nature and pattern of the forcing
  - holds for other kinds/magnitudes of forcing

Climate Sensitivity

- Clearly not well determined by current global models
- IPCC very aware of the “problem” of climate sensitivity
  - model results differ by a factor of 2
  - results not converging (despite higher resolution etc.)
- Convened special Workshop and report
- Recommendations include:
  - improving understanding of the determinants of climate sensitivity
  - investigating the climate sensitivity of the real system from volcano effects



INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

IPCC Working Group I

Workshop on Climate Sensitivity

École Normale Supérieure
Paris, France
26–29 July, 2004

Workshop Report

This workshop was agreed in advance as part of the IPCC workplan, but this does not imply working group or panel endorsement or approval of the proceedings or any recommendations or conclusions contained herein.

Supporting material prepared for consideration by the Intergovernmental Panel on Climate Change. This material has not been subjected to formal IPCC review processes.

The question

- Can we infer *equilibrium* climate sensitivity from volcanic effects?
- Uncertainty in *model feedbacks* replaced by uncertainty in observations of forcing f and response T' for real system
- We first ask the question in the model world for 2 models with different equilibrium sensitivities
  - - CCCma CGCM3
  - - NCAR CCSM2
- Apply known forcing and attempt to infer equilibrium sensitivity from "observations"

Famous Volcanic Eruptions

Santorini, 1628 BC

Etna, 44 BC

Lakagígar, 1783

Tambora, 1815

Toba, 71,000 BP

Krakatau, 1883

Pinatubo, 1991

El Chichón, 1982

St. Helens, 1980

Agung, 1963

Material from A. Robock website

Krakatau, 1883
Watercolor by William Ascroft

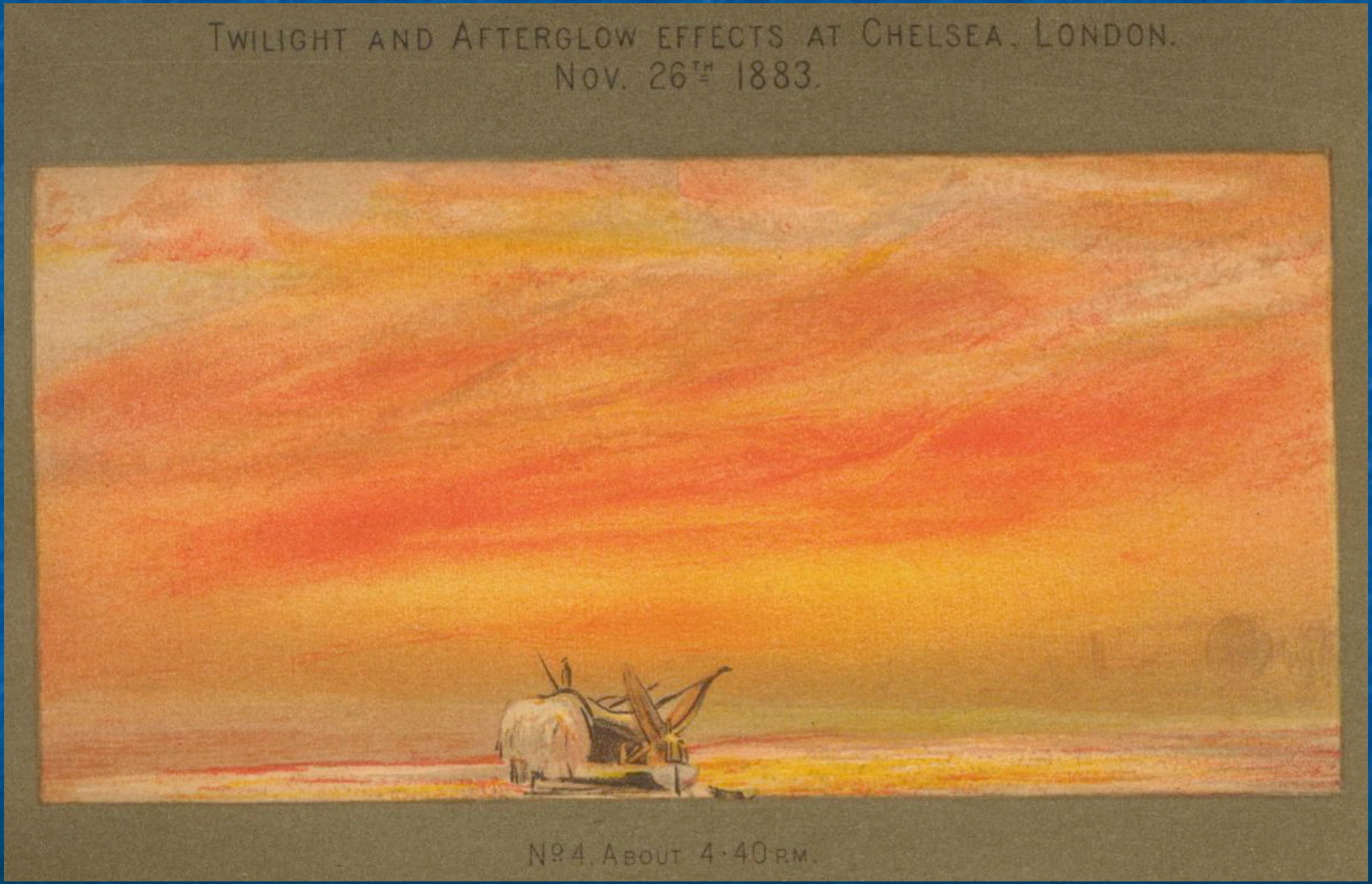
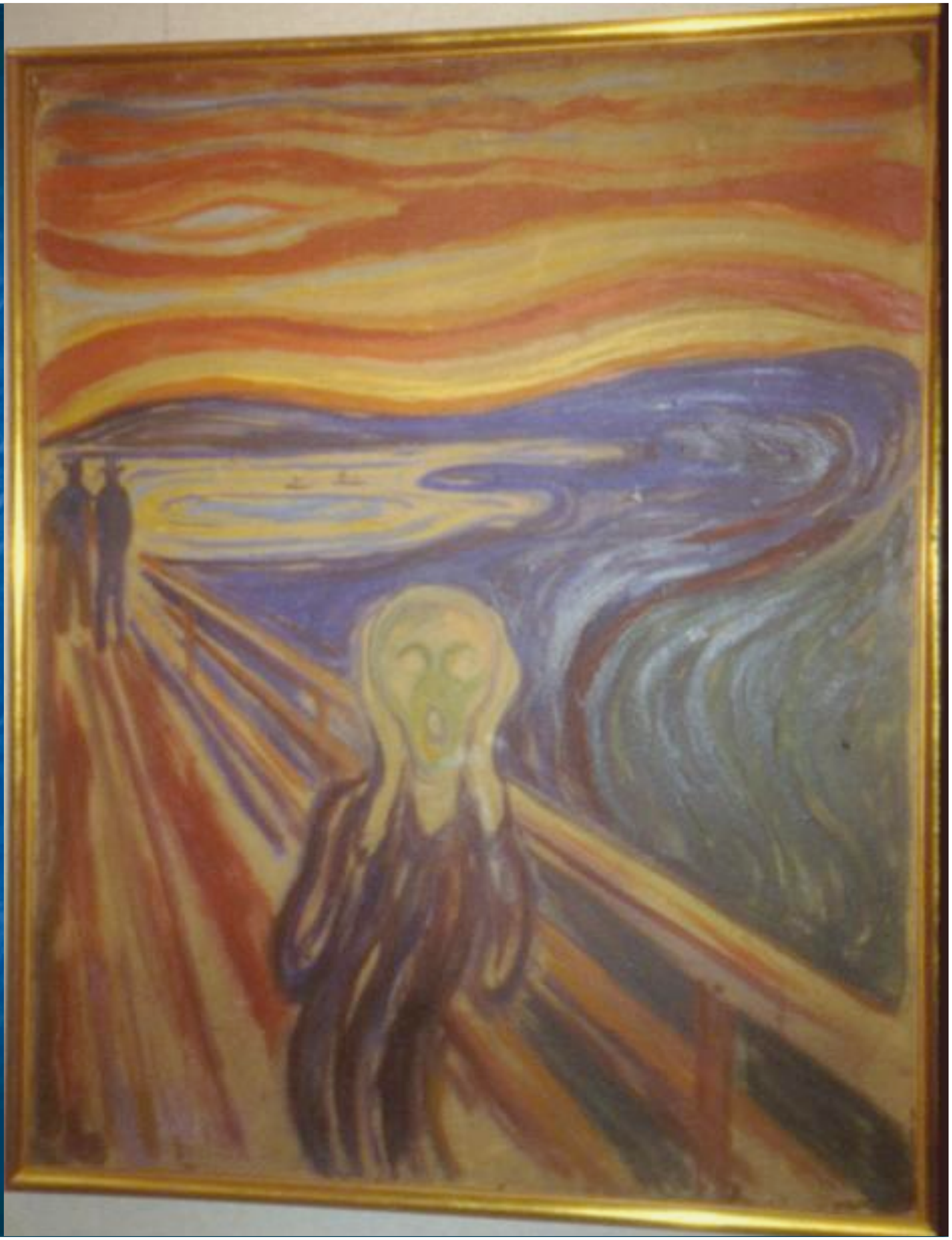


Figure from Symons (1888)

“The Scream”

Edvard Munch

Painted in 1893 based on Munch’s memory of the brilliant sunsets following the 1883 Krakatau eruption.

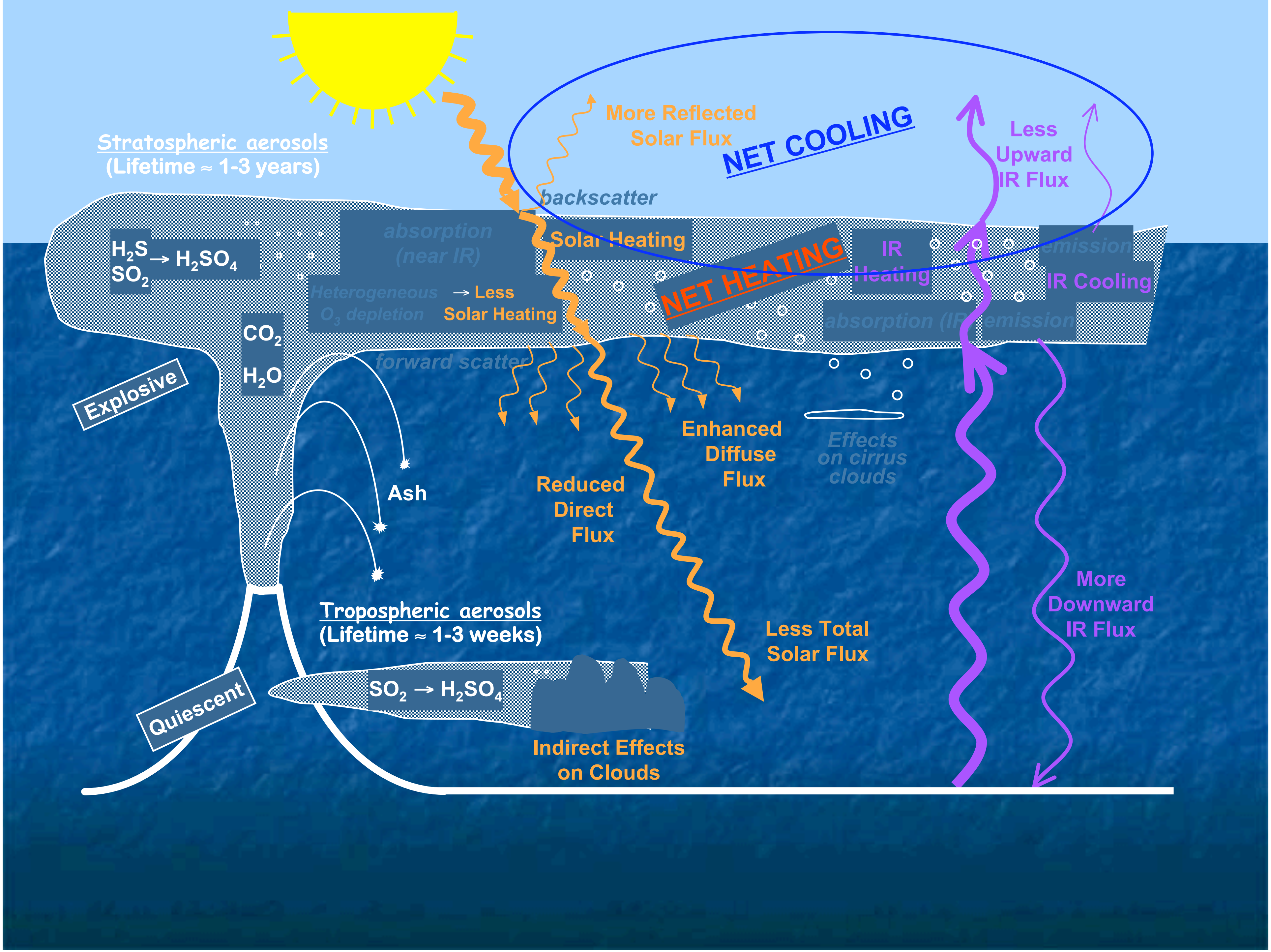


Pinatubo
June 12, 1991

Three days before major eruption of June 15, 1991

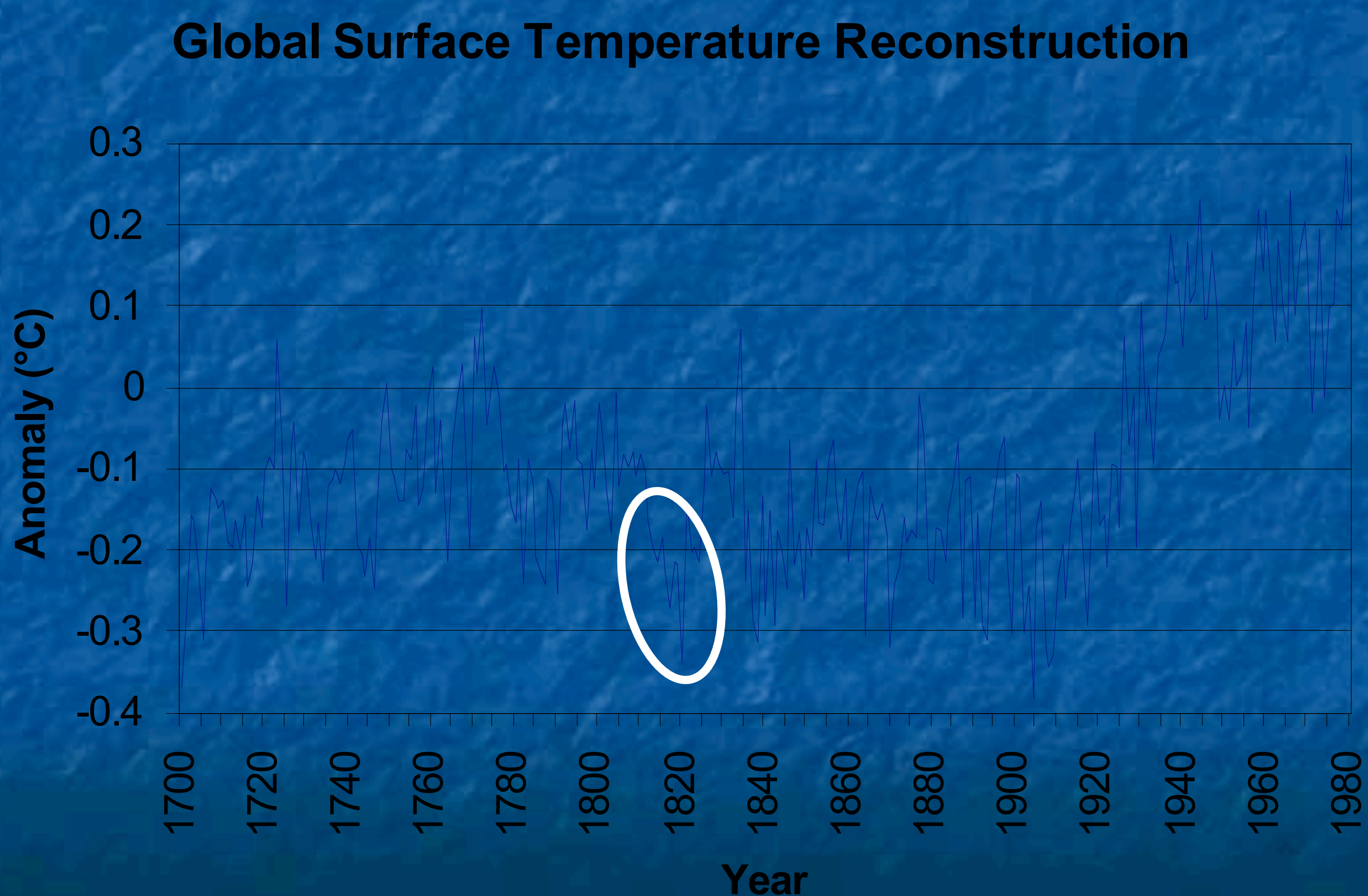
Major volcanic eruptions of the past 250 years

Volcano	Year	VEI	d.v.i/E_{max}	IVI
Lakagígar [Laki craters], Iceland	1783	4	2300	0.19
Unknown (El Chichón?)	1809			0.20
Tambora, Sumbawa, Indonesia	1815	7	3000	0.50
Cosiguina, Nicaragua	1835	5	4000	0.11
Askja, Iceland	1875	5	1000	0.01*
Krakatau, Indone sia	1883	6	1000	0.12
Okataina [Tarawera], North Island, NZ	1886	5	800	0.04
Santa Maria, Guatemala	1902	6	600	0.05
Ksudach, Kamchatka, Russia	1907	5	500	0.02
Novarupta [Katmai], Alaska, US	1912	6	500	0.15
Agung, Bali, Indonesia	1963	4	800	0.06
Mt. St. Helens, Washington, US	1980	5	500	0.00
El Chichón, Chiapas, Mexico	1982	5	800	0.06
Mt. Pinatubo, Luzon, Philippines	1991	6	1000	—



Stratospheric aerosols
(Lifetime ≈ 1-3 years)
More Reflected Solar Flux
NET COOLING
backscatter
Less Upward IR Flux
absorption (near IR)
Solar Heating
IR Heating
emission
IR Cooling
NET HEATING
H_2S SO_2 → H_2SO_4
Heterogeneous O_3 depletion → Less Solar Heating
absorption (IR) emission
CO_2
H_2O
forward scatter
Explosive
Ash
Enhanced Diffuse Flux
Effects on cirrus clouds
Reduced Direct Flux
Less Total Solar Flux
More Downward IR Flux
Tropospheric aerosols
(Lifetime ≈ 1-3 weeks)
SO_2 → H_2SO_4
Quiescent
Indirect Effects on Clouds

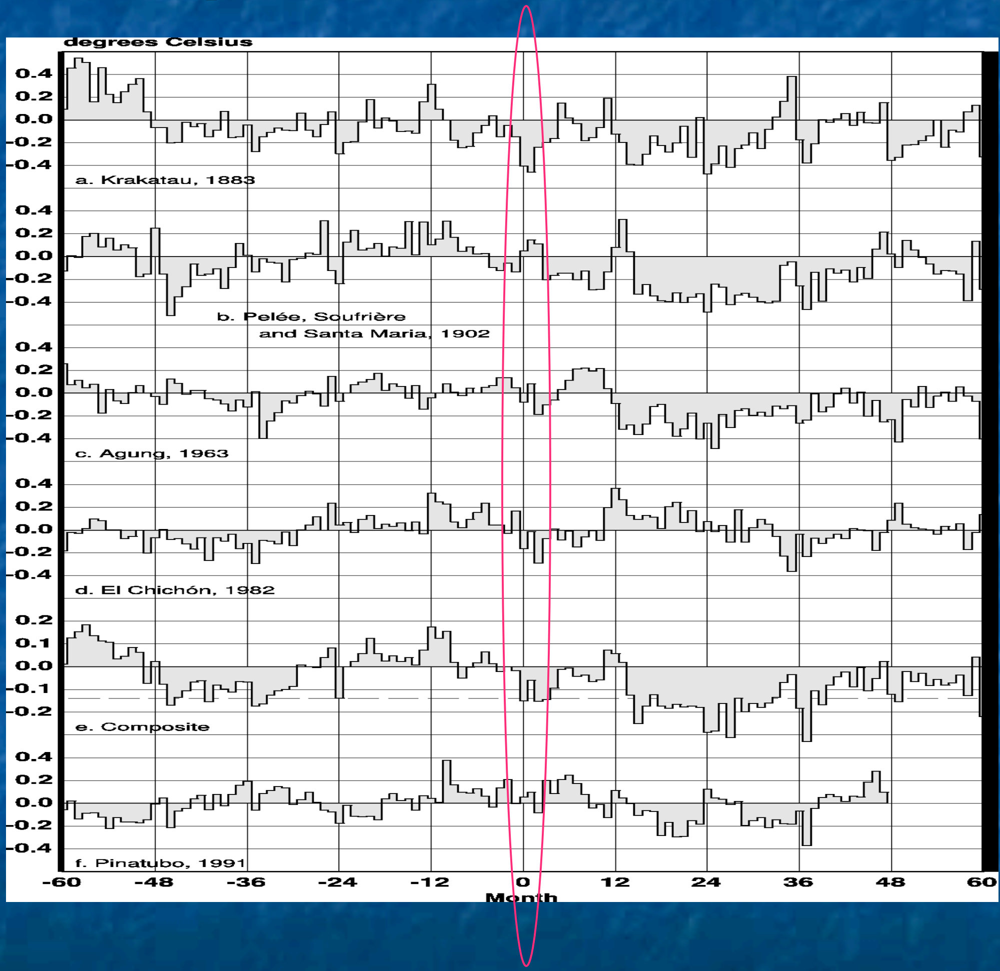
Tambora in 1815, together with an eruption from an unknown volcano in 1809, produced the "Year Without a Summer" (1816)



Mann et al. (2000)

Global temperature

- From Kelly et al., 1996
- Large volcano T perturbations



Hansen et al. (1978)

RCM

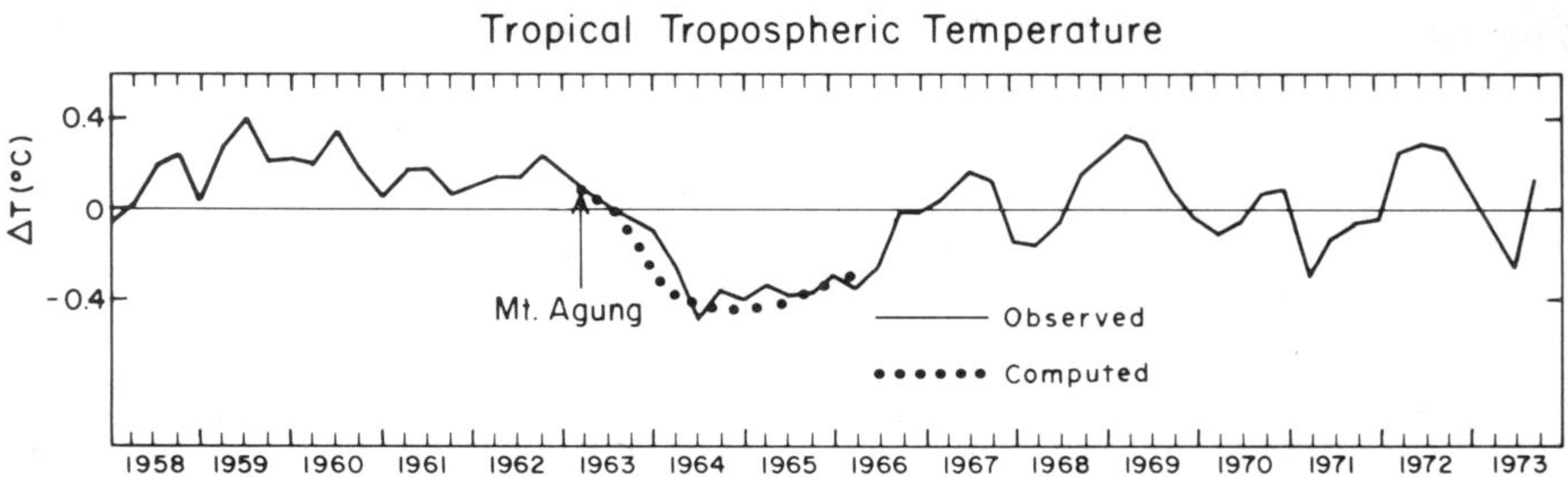
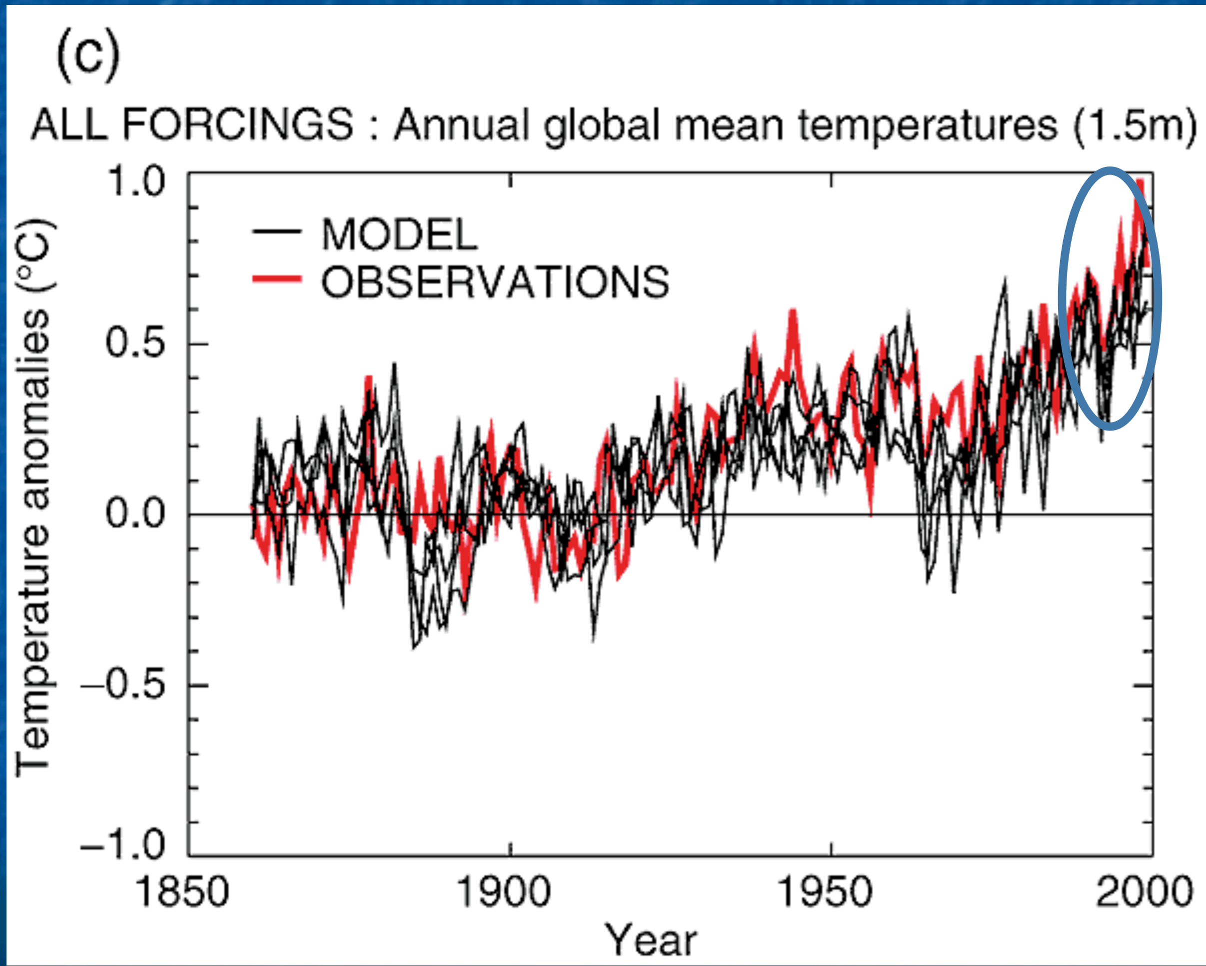


Fig. 2. Observed tropospheric temperatures between 30°N and 30°S (*19*) and computed temperatures after the eruption of Mount Agung, assuming that the added stratospheric aerosols are sulfuric acid and the average depth of the mixed layer of the ocean is 70 m.

Third Assessment Report of the IPCC (2001):
General circulation model results

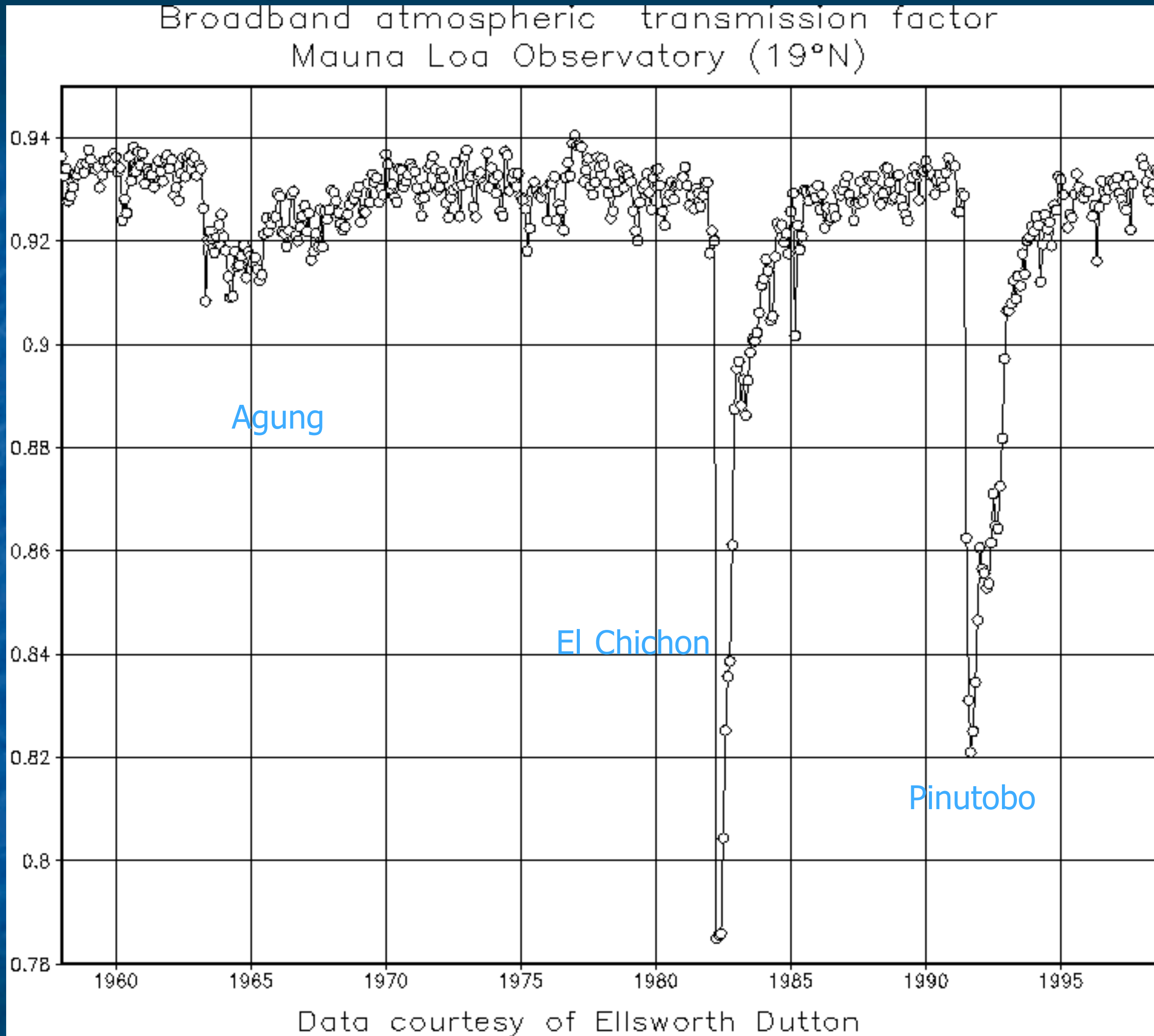


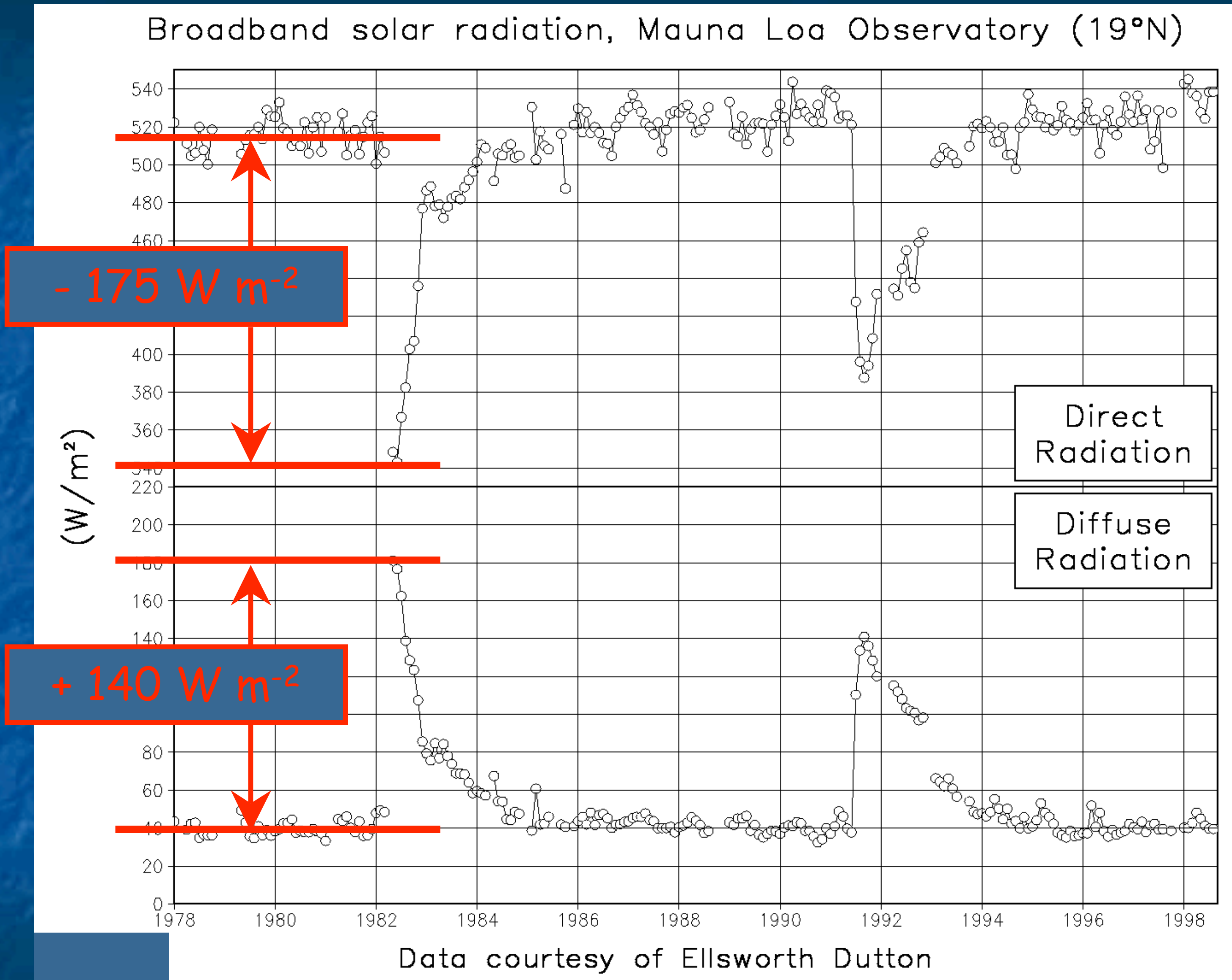
Pinatubo

Fig. 12-7

Volcano radiative effects

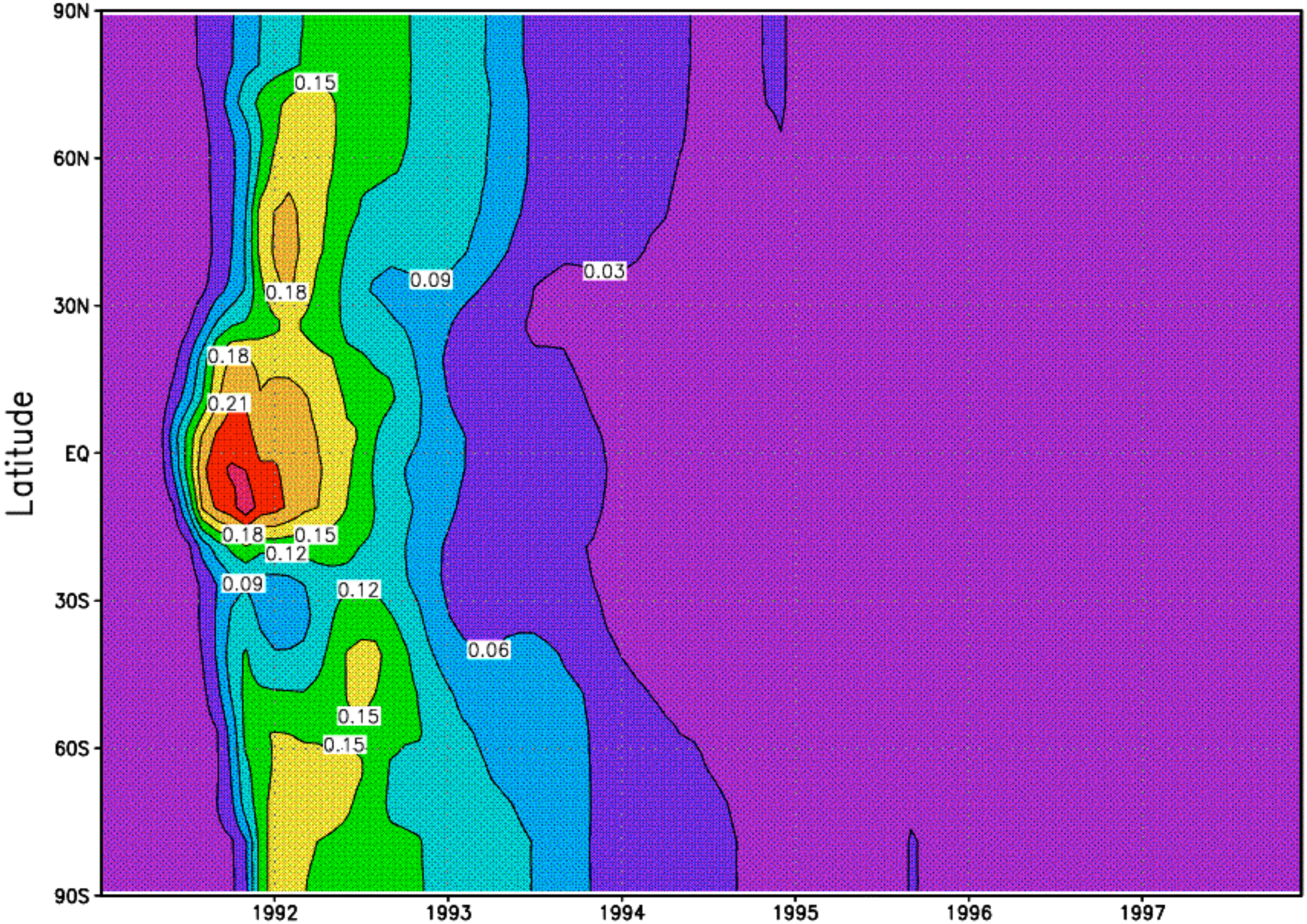
- Some observations of radiative effects although not always global
- Often "inferred" based on dust veil index or other indirect evidence – at least in the past
- potentially observable by satellite for future volcanoes


Broadband atmospheric transmission factor
Mauna Loa Observatory (19°N)
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
1960
1965
1970
1975
1980
1985
1990
1995
Agung
El Chichon
Pinutobo
Data courtesy of Ellsworth Dutton

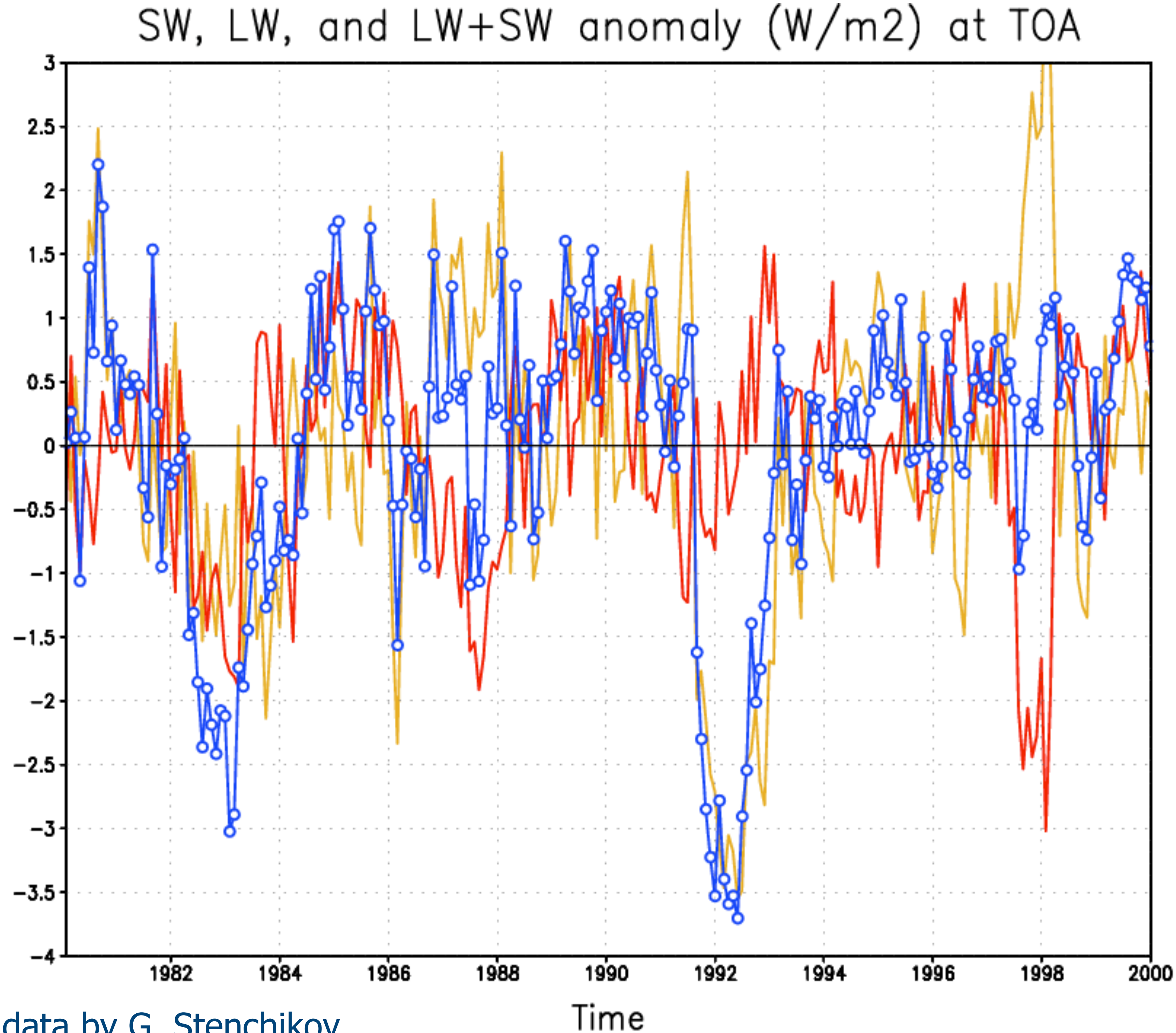


Robock (2000), Dutton and Bodhaine (2001)

Aerosol extinction optical depth for 0.55 micron



Reconstructed from satellite data by G. Stenchikov



SW

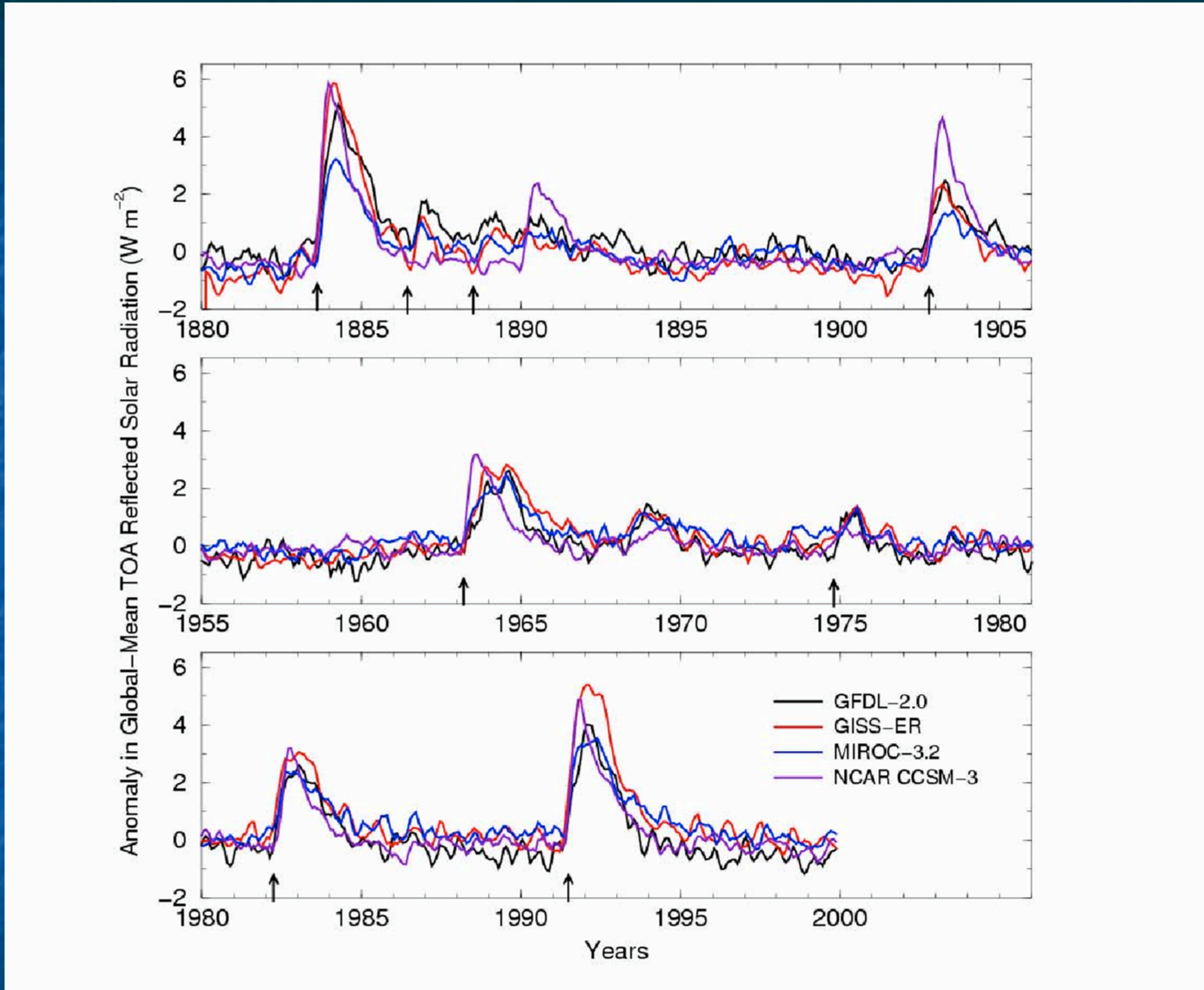
LW

SW+LW

Averaged Over

60S-60N

From ERBE data by G. Stenchikov



Modelled TOA reflected solar from volcanoes (Stenchikov et al., 2006)

Pinatubo analysis (Douglass and Knox, 2005)

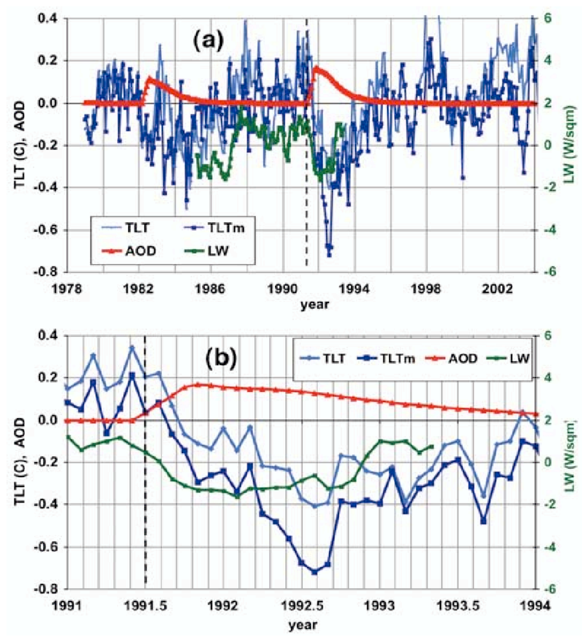


Figure 1. Data sets for temperature (TLT), modified temperature (TLTm), aerosol optical density (AOD), and outgoing long wave radiation (LW). The modified data set has the El Niño and solar signals removed (see text). (a) Complete sets and (b) expanded view showing the subsets used in the Pinatubo analysis.

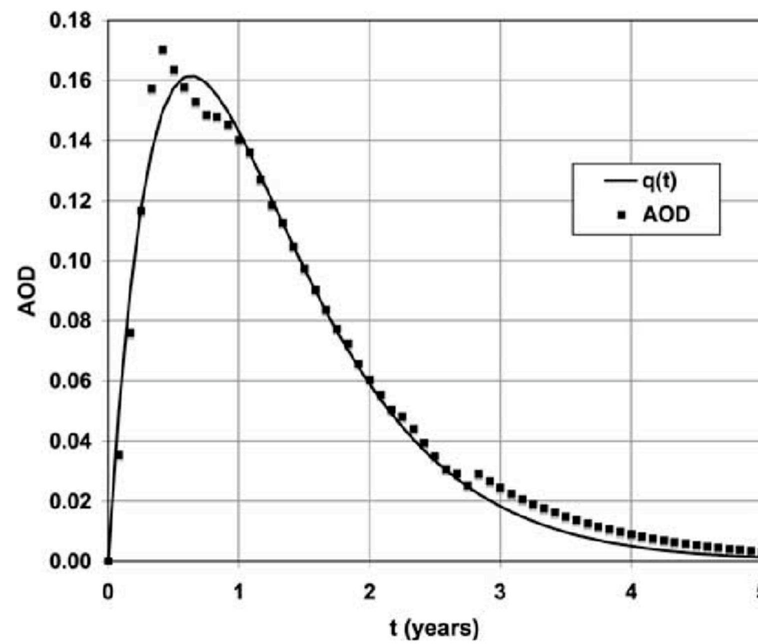


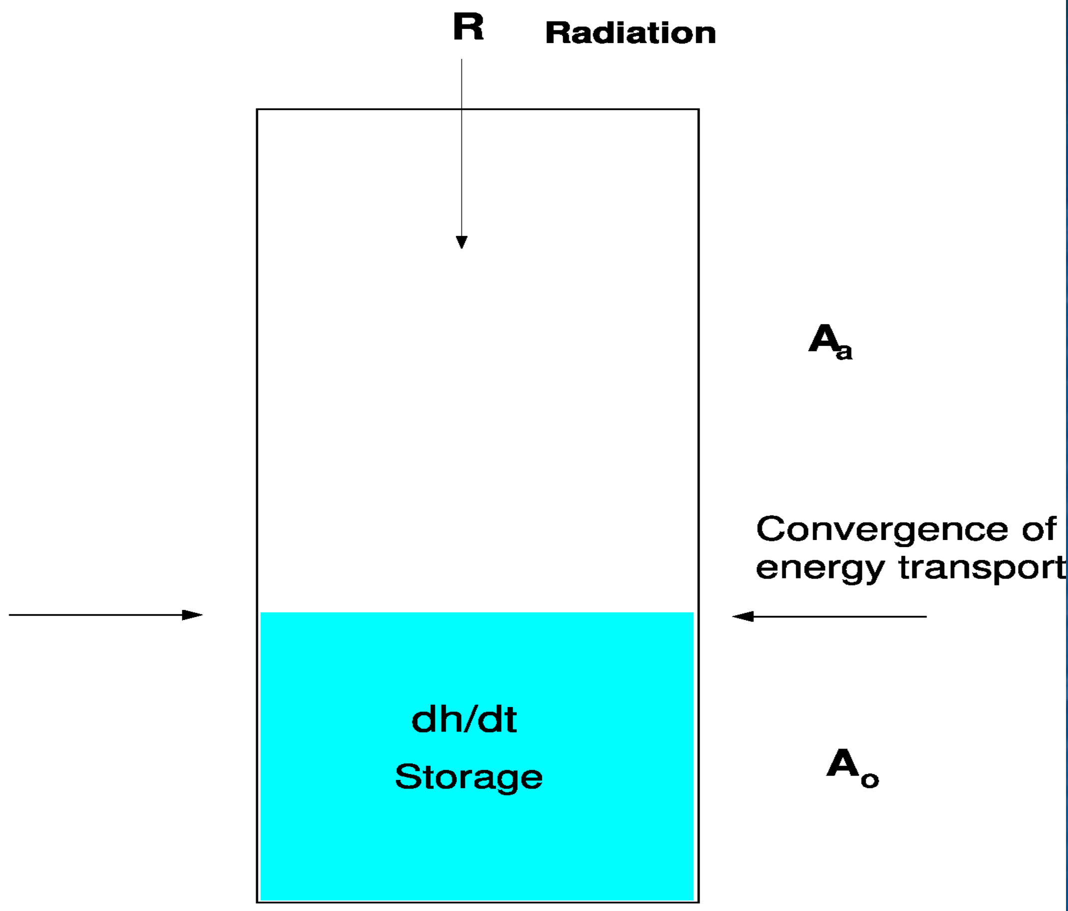
Figure 2. Volcano AOD function (detail from Figure 1) and the analytic fit $q(t)$ (text, equation (5)).

Aerosol Optical Depth (AOD)
transformed into forcing

Climate sensitivity and volcanoes

- Volcano provides "observable" :
  - temperature response to forcing
  - radiative perturbation
- Offers the possibility of inferring "climate sensitivity" *directly* via energy budget

Vertically integrated energy balance



$$dh/dt = A + R$$

Climate sensitivity via the energy budget

- Consider vertically integrated energy budget
  - $dh/dt = A + R$
  - dh/dt is storage of energy (in ocean)
  - A is convergence of horizontal energy transport
  - R is the radiative flux into the conlum
- For climate change with $X' = X - X_o$ becomes

$$dh'/dt = A' + R'$$

Forcing and feedback/sensitivity

- $dh'/dt = A' + R'$ where terms are functions of (λ,φ,t)

- Write radiative flux change for $R_* = R(X_o,C_o+C')$ as $R' = R-R_o = (R-R_*) + (R_*-R_o) = g + f = \Lambda T' + f$

- $f(\lambda,\varphi,t) = R_*-R_o$ is the *radiative forcing*
- $g(\lambda,\varphi,t) = R- R_* = \Lambda T'$ is the *radiative response* expressed in terms of
  - surface temperature change $T'(\lambda,\varphi,t)$
  - the signed feedback parameter $\Lambda(\lambda,\varphi,t)$

$$dh'/dt = A' + \Lambda T' + f$$

Global feedback/sensitivity

- For global average $\langle A' \rangle = 0$

$$\langle dh'/dt \rangle = \underline{\Lambda} \langle T' \rangle + \langle f \rangle$$

- global feedback parameter $\underline{\Lambda} = \langle \Lambda T' \rangle / \langle T' \rangle$ is *temperature weighted* average of *local* feedback parameter
- need negative feedback, $\underline{\Lambda} < 0$ to balance forcing

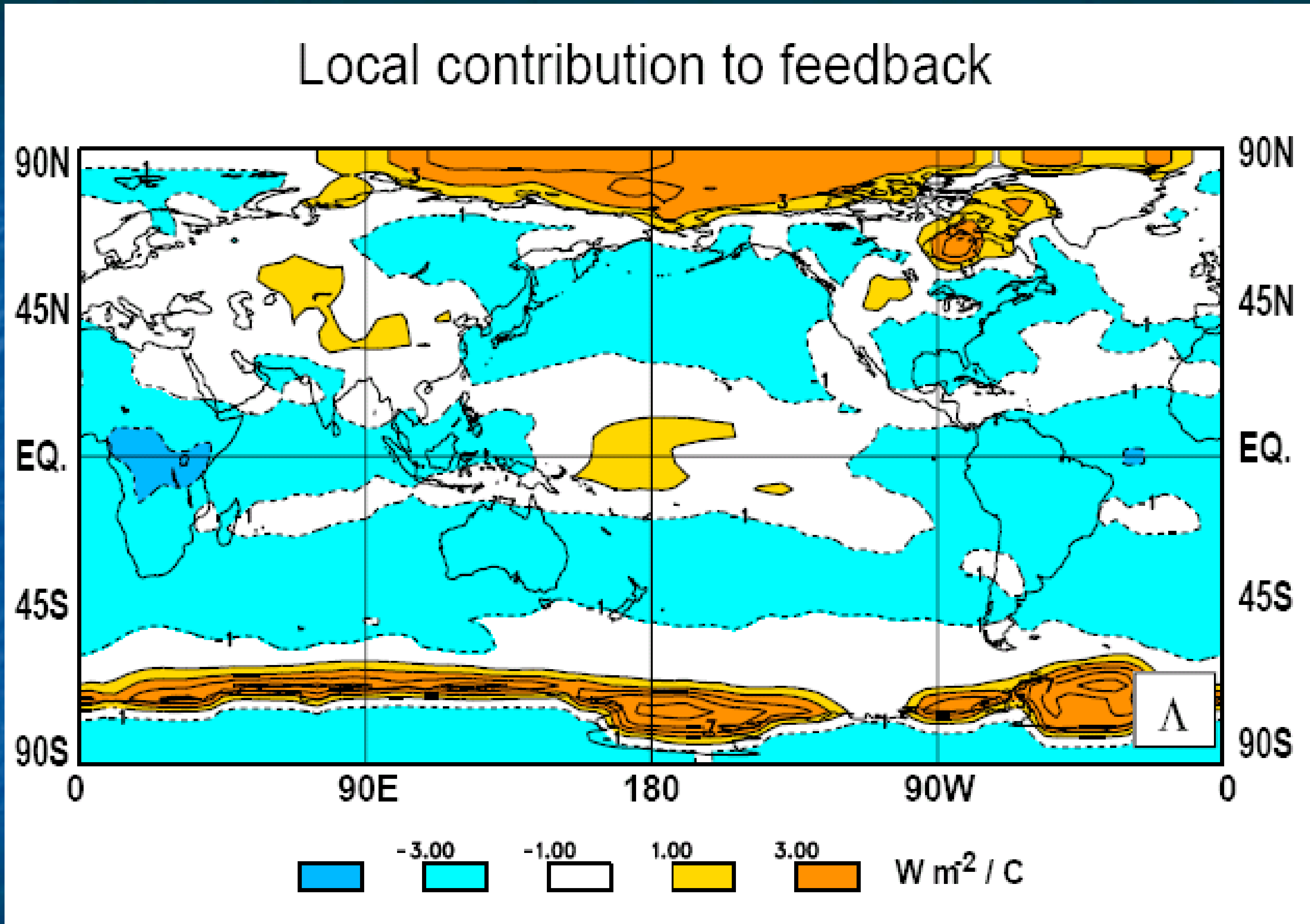
- For new equilibrium $\langle dh'/dt \rangle \Rightarrow 0$

$$\langle T' \rangle = -\langle f \rangle / \underline{\Lambda} = s \langle f \rangle$$

- inverse connection between feedback and sensitivity

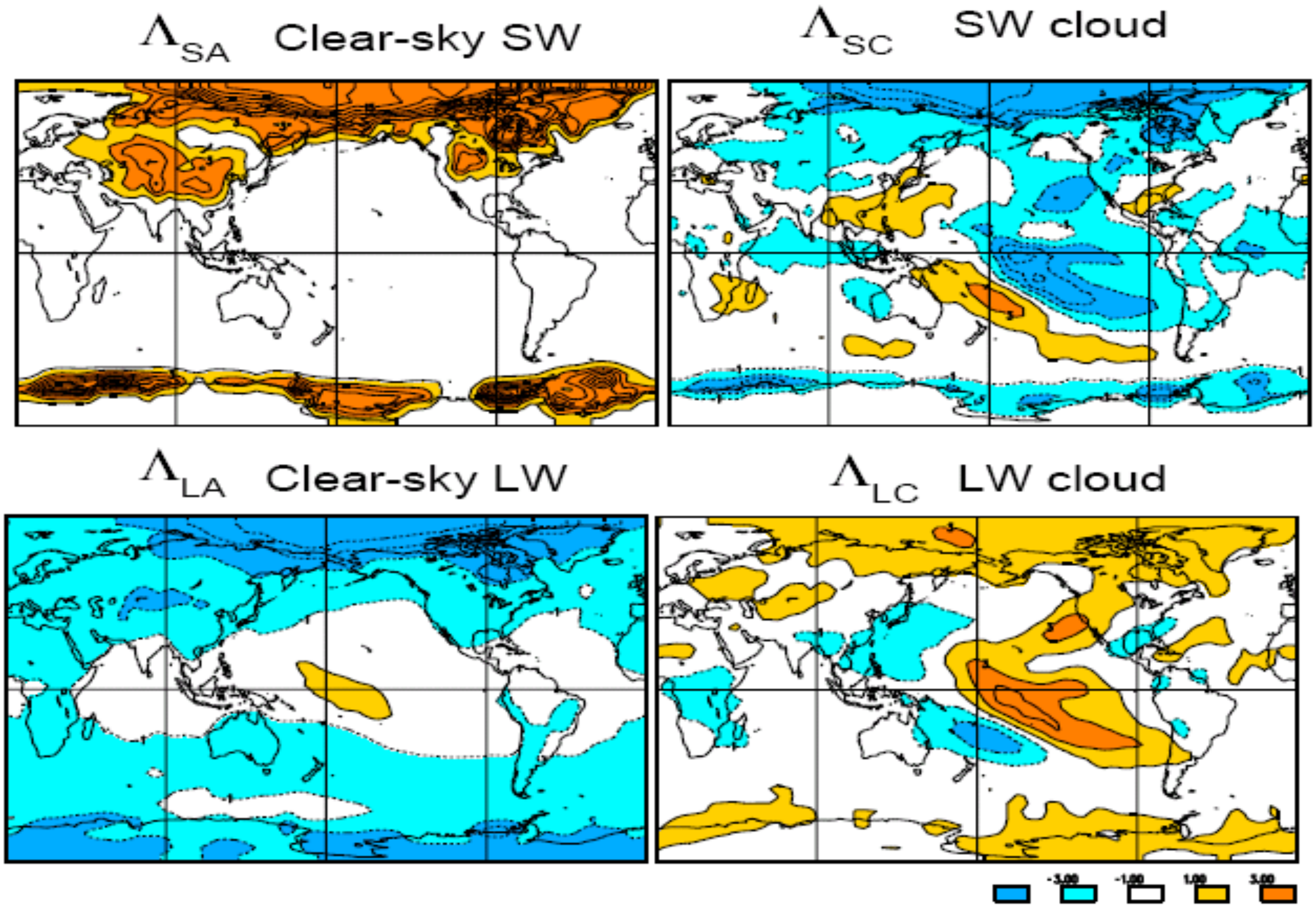
$$s = -1/\underline{\Lambda} \quad \Rightarrow (\lambda_o/(1\text{-fback+}))$$

- strong (negative) feedback ⇔ low climate sensitivity
- weak feedback ⇔ high climate sensitivity



(Boer and Yu, 2003)

Feedback Components



$$\Lambda = \Lambda_S + \Lambda_L = \Lambda_A + \Lambda_C = \Lambda_{SA} + \Lambda_{SC} + \Lambda_{LA} + \Lambda_{LC}$$

Direct "observational" approach

- Basic global energy budget (for *global averages*)

  $dh'/dt = \Lambda T' + f$
- Method 1

  - express dh'/dt in terms of T'

  - solve equation for $T'(t)$ and fit to obs of temperature
- Method 2

  - solve directly from observations

  $\Lambda = (dh'/dt - f)/T' = (R' - f)/T' = -1/s$

  - need to know *"forcing-storage" term* and T'

The solar forcing approach

- Specify forcing simply through change in solar constant

  - solar flux at TOA for control simulation/current climate

  $$S_o = (1-\alpha_o)\Sigma$$

  α is planetary albedo

  Σ incoming solar

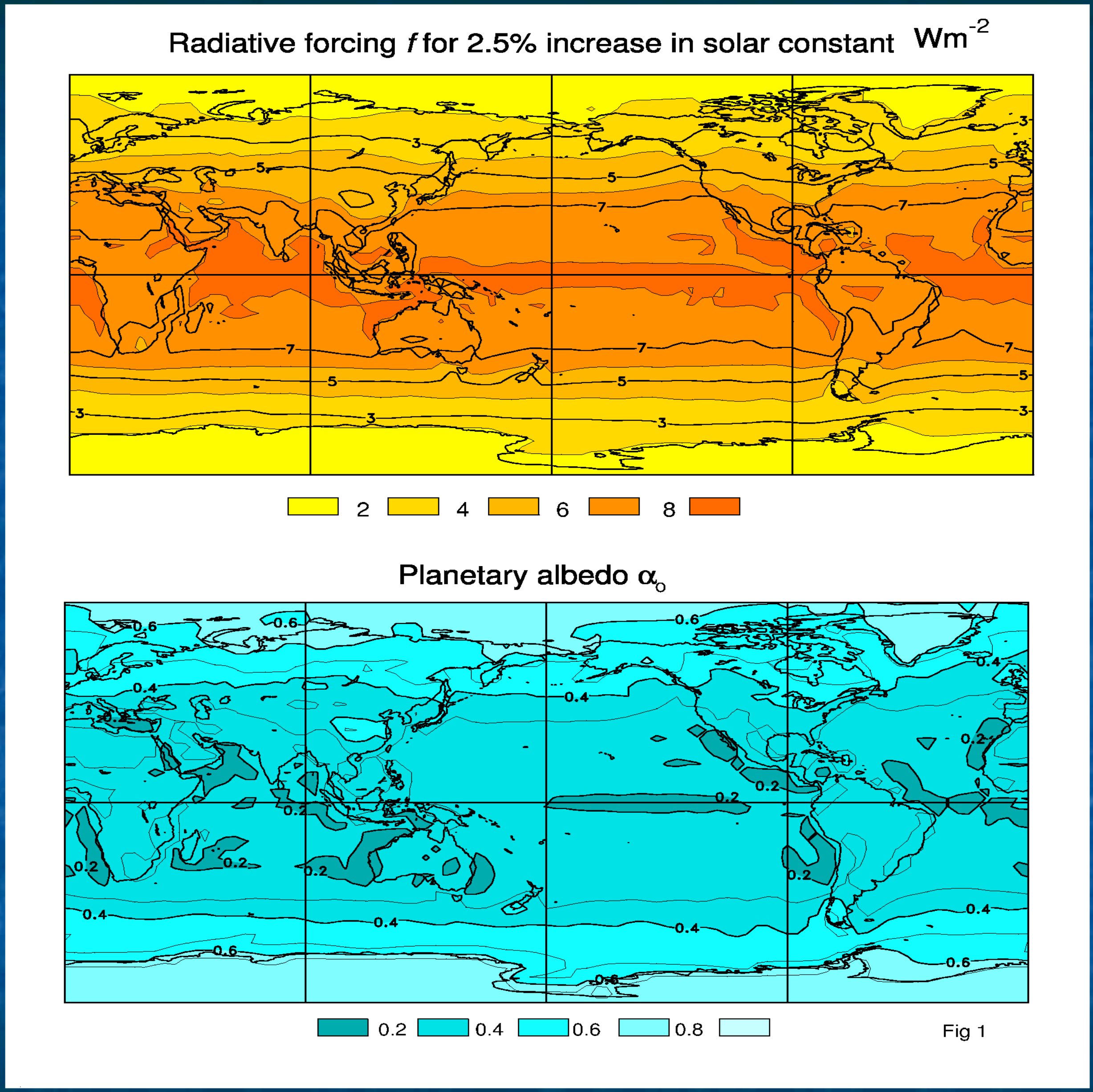
- We can get accurate forcing as

  $$f = a(t)S_o$$

  where *a(t)* is fractional change in solar constant

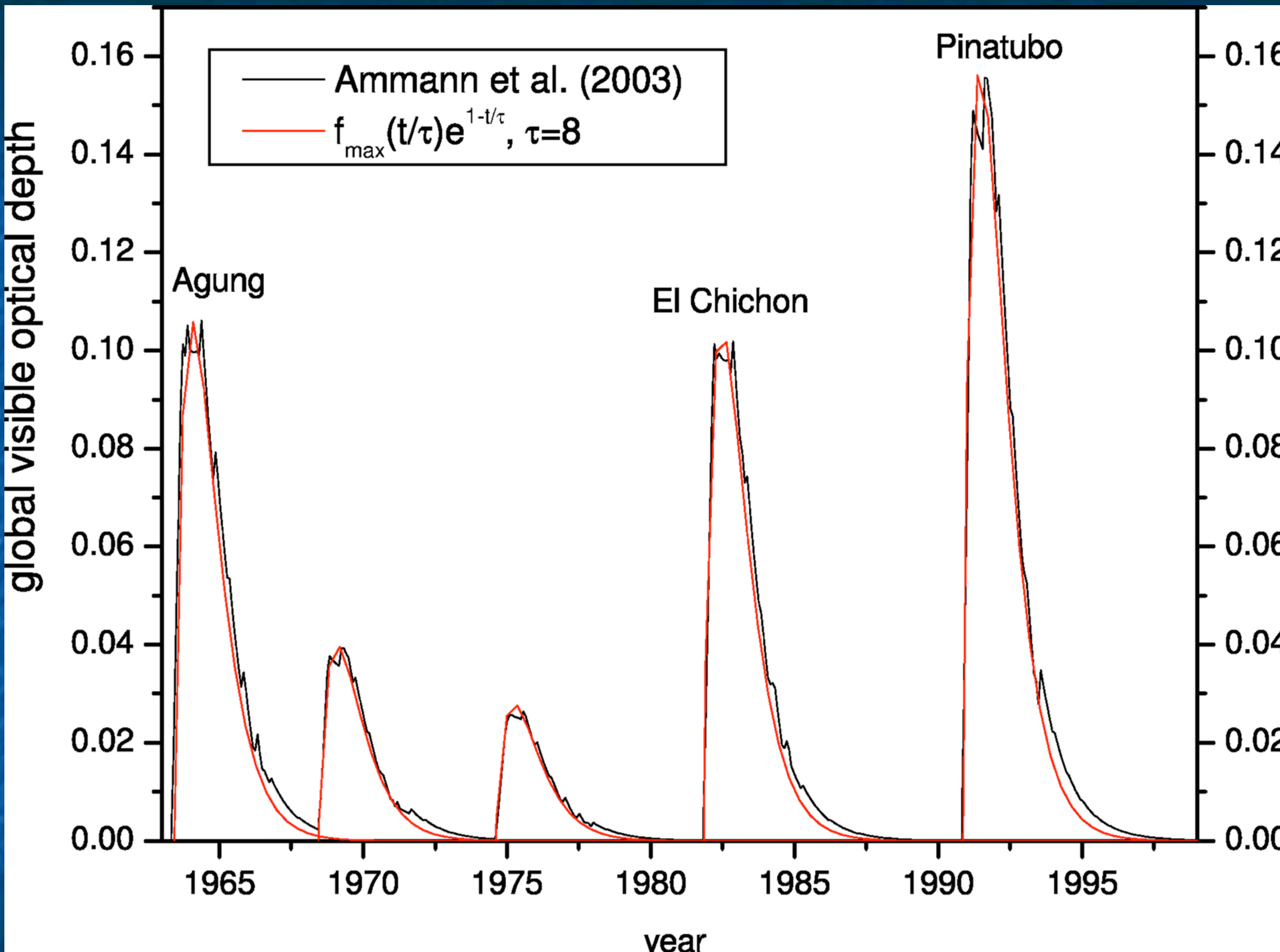
$f = 1.025 S_o$

$S_o = (1 - \alpha_o)\Sigma$



Imposed volcano-like forcing

- Choose form of forcing as
  $$f(t) = f_{max}(t/\tau)\exp(1-t/\tau)$$
- Gives reasonable fit to optical depth of past volcanoes for τ = 8 months
- We use "strong" f_{max} of 6 Wm^{-2}
  - somewhat larger than Pinatubo



Ammann et al. (2003)
$f_{max}(t/\tau)e^{1-t/\tau}$, τ=8
Pinatubo
Agung
El Chichon
global visible optical depth
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1965
1970
1975
1980
1985
1990
1995
year

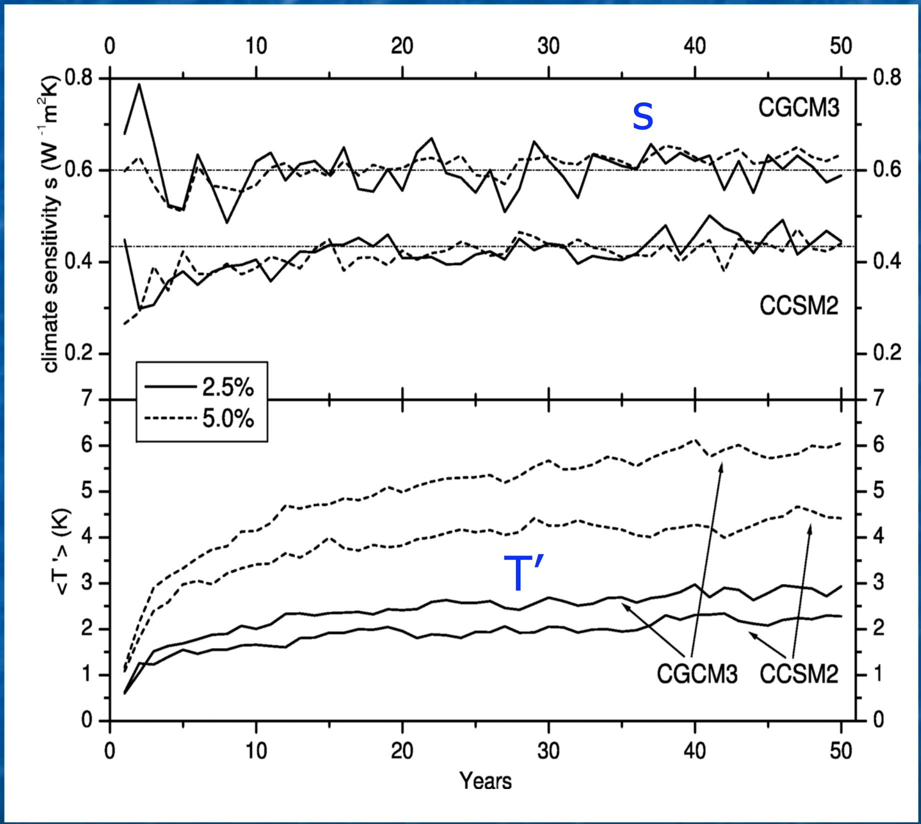
Volcanoes and sensitivity in the model world

- CCCma CGCM3 and NCAR CCSM2
- 3 volcano-like simulations with each *coupled* model with the same volcano-like forcing

  \- begin Jan 1 for 25-30 years
- 1 volcano-like experiment with CCCma model with “mixed layer” ocean
- 2.5% and 5% solar constant increase forcing experiments

Near-equilibrium sensitivity

- Constant forcing for increases of 2.5 and 5% in solar constant
- Get good estimate of equilibrium sensitivity by 30 years
- NCAR sensitivity low, CCCma sensitivity average for models in IPCC2001/07
- *T′* and *s* differences apparent



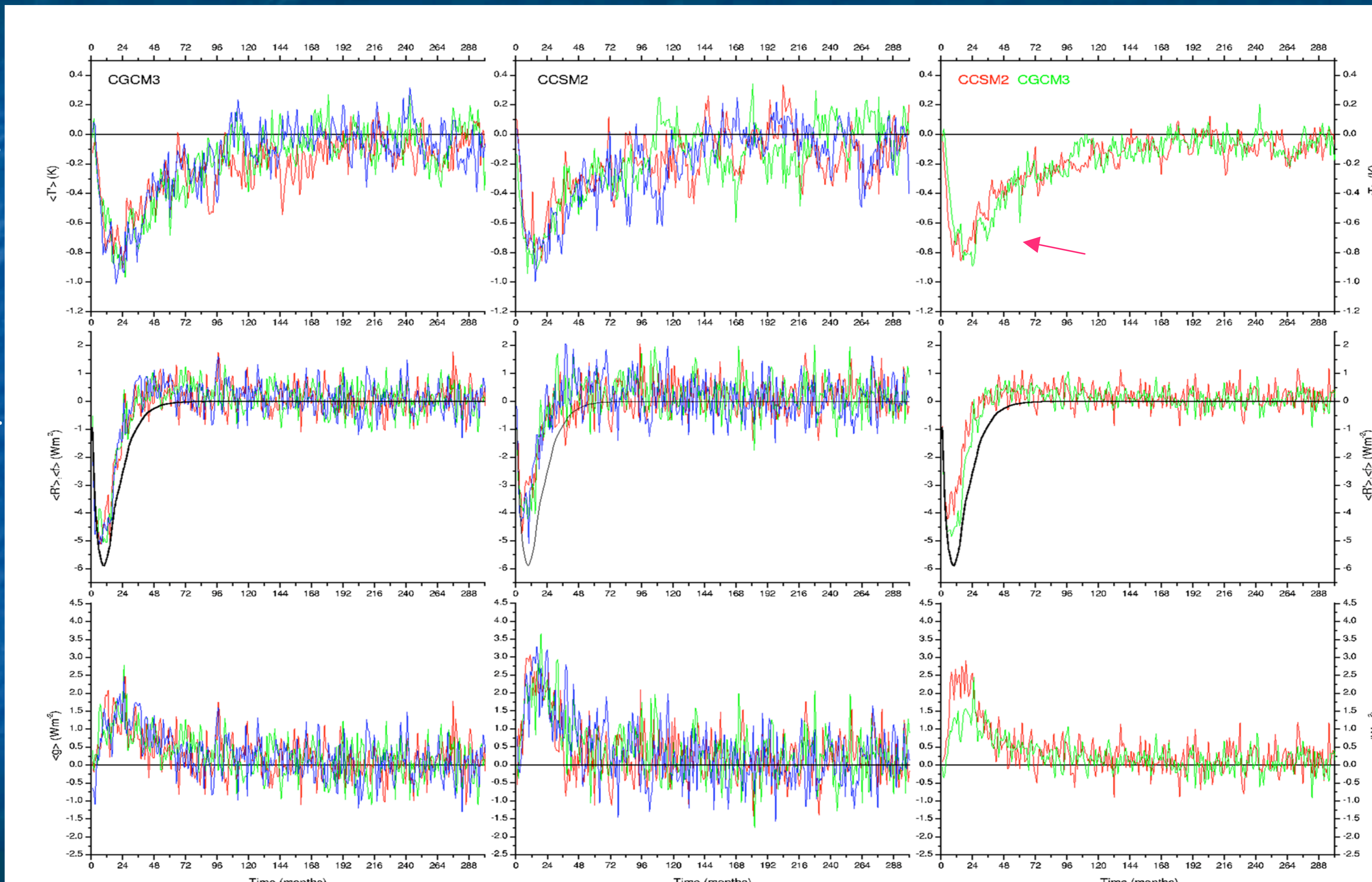
CGCM3 and CCSM2 individual and average responses to volcanic forcing

<T'>

<R'>

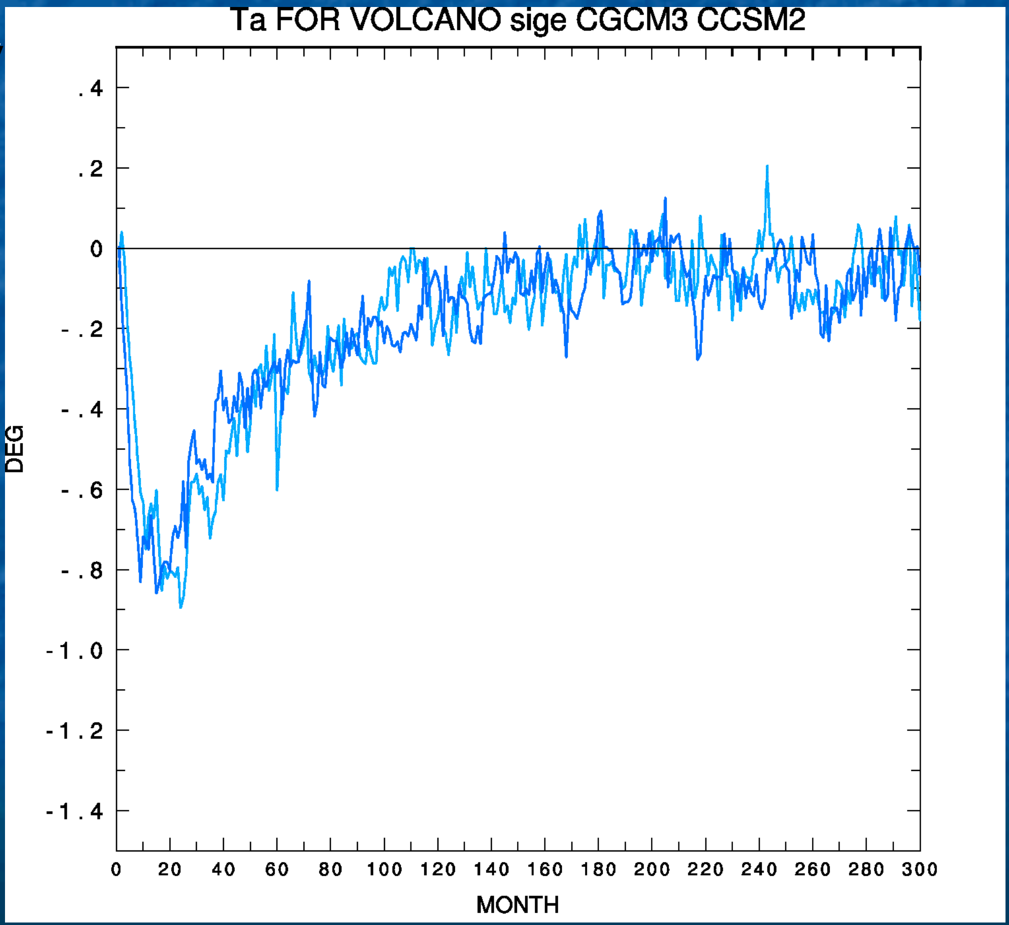
<f>

<g>



Temperature response

- Remarkable similarity in temperature responses despite different model sensitivities
- Argues against volcanic T response being useful to determine climate sensitivity



Method 1 – fit to temperature

- Doesn't look easy but can try with

$$dh'/dt = C^* dT'/dt = \Lambda T' + f$$

  - C* is an "effective" system heat capacity
- Solution for known *f(t)* is

$$T'(t) = f_{max}\{\tau e^{1-\beta t} - [\tau + (1-\beta\tau)t]e^{1-t/\tau}\}/C(1-\beta\tau)^2$$

$$\beta = -\Lambda/C^*$$

- Fit by non-linear least squares – returns values of C* and Λ

- Inferred values

Λ = (-3.35, -3.34) (Wm^{-2}/ ^oC)

s = (0.30, 0.30) (^oC/ Wm^{-2})

T_{2x}=>(1.2, 1.2) (^oC)

(CCCma, NCAR)

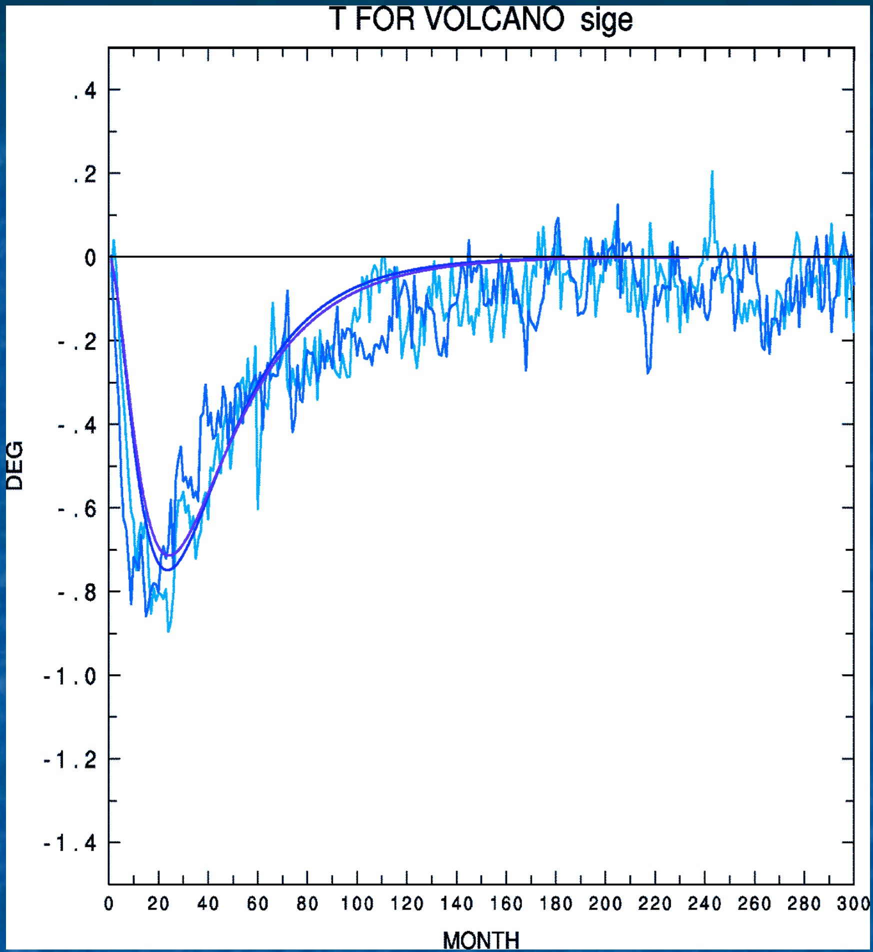
- But *actual* equilibrium values are

Λ = (-1.30, -2.30)

s = (0.78, 0.44)

T_{2x} =>(3.2, 1.8)

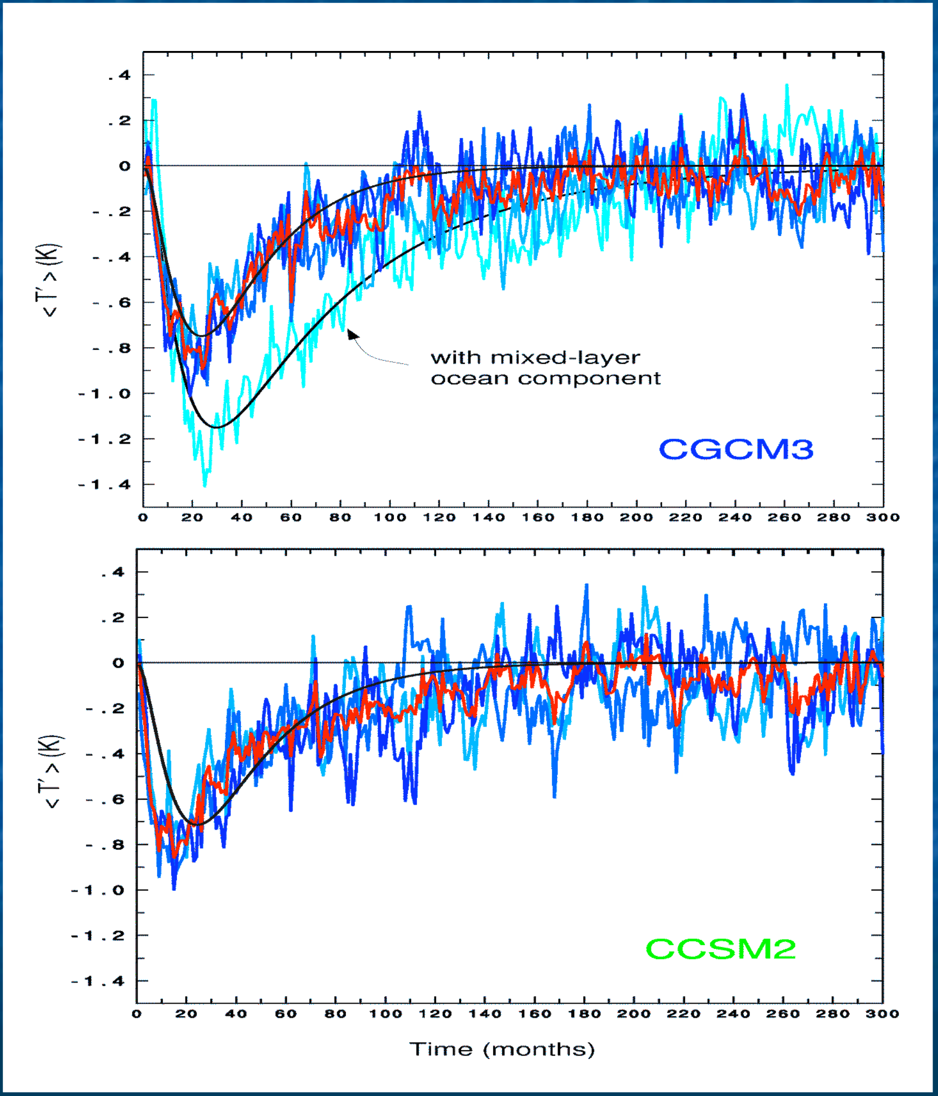
(CCCma, NCAR)



This type of fitting to T curve doesn't work

Method 1 –fit to T

- *Overestimates* strength of feedbacks hence *underestimates* sensitivity
- Heat exchange with the deep ocean neglected – interpreted as strong system feedback
- For mixed-layer (50m) ocean get stronger cooling and reasonable Λ, s
- Can't approximate storage as dh'/dt = C*dT/dt



Method 1

- Douglass and Knox (2005a) use Method 1 on Pinatubo get weak climate sensitivity
- Wigley et al. (2005), Robock (2005) point out neglect of exchange with deep ocean
- Douglass and Knox (2005b,c) respond that exchange is small in actual system so method is OK and sensitivity really is small
- This *doesn't* agree with CCCma, NCAR (other) coupled model results

L05710 DOUGLASS AND KNOX: CLIM

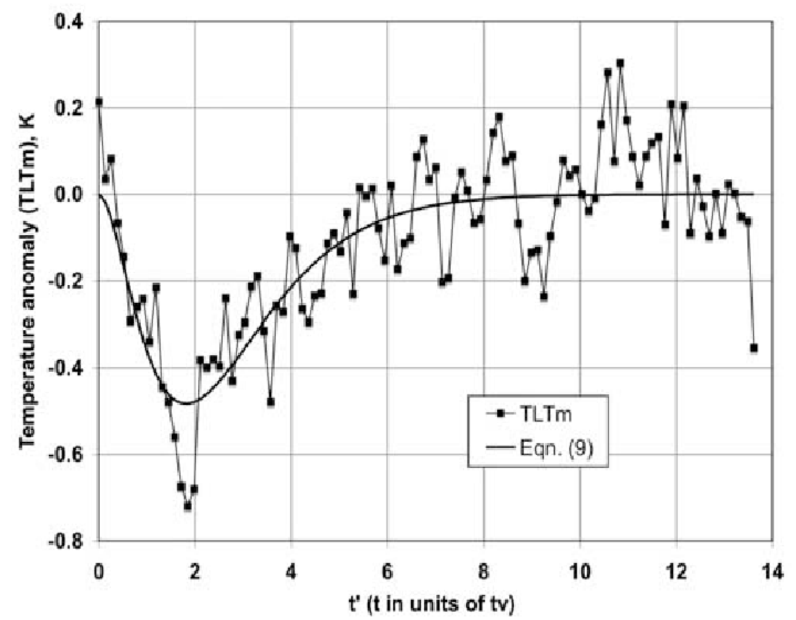


Figure 3. Fit of the analytic solution $\Delta T(t)$, equation (6), to the temperature data set TLTm.

Method 2 – feedback/storage term

- Use direct method with

  $\Lambda = (dh'/dt - f)/T' = (R'-f)/T' = g/T'$
- Need to know *f* + heat storage term either as dh'/dt in the ocean or TOA radiation R'
- Both g and T' composed of volcano forced "signal" plus natural variability "noise"
- We try to remove noise by averaging

Method 2 calculation

- Estimate from $$\Lambda(\tau) = \int_0^\tau g\,dt \Big/ \int_0^\tau T'\,dt = -1/s(\tau)$$
- $g = (R'-f) = g_s + g^*$
- $T = T_s + T^*$

  - integral of signal X_s will become constant

  - integral of noise X^* "wanders" as random walk

  - optimum averaging not obvious - should integrate over signal but avoid noise
- Something like 8 years seems reasonable

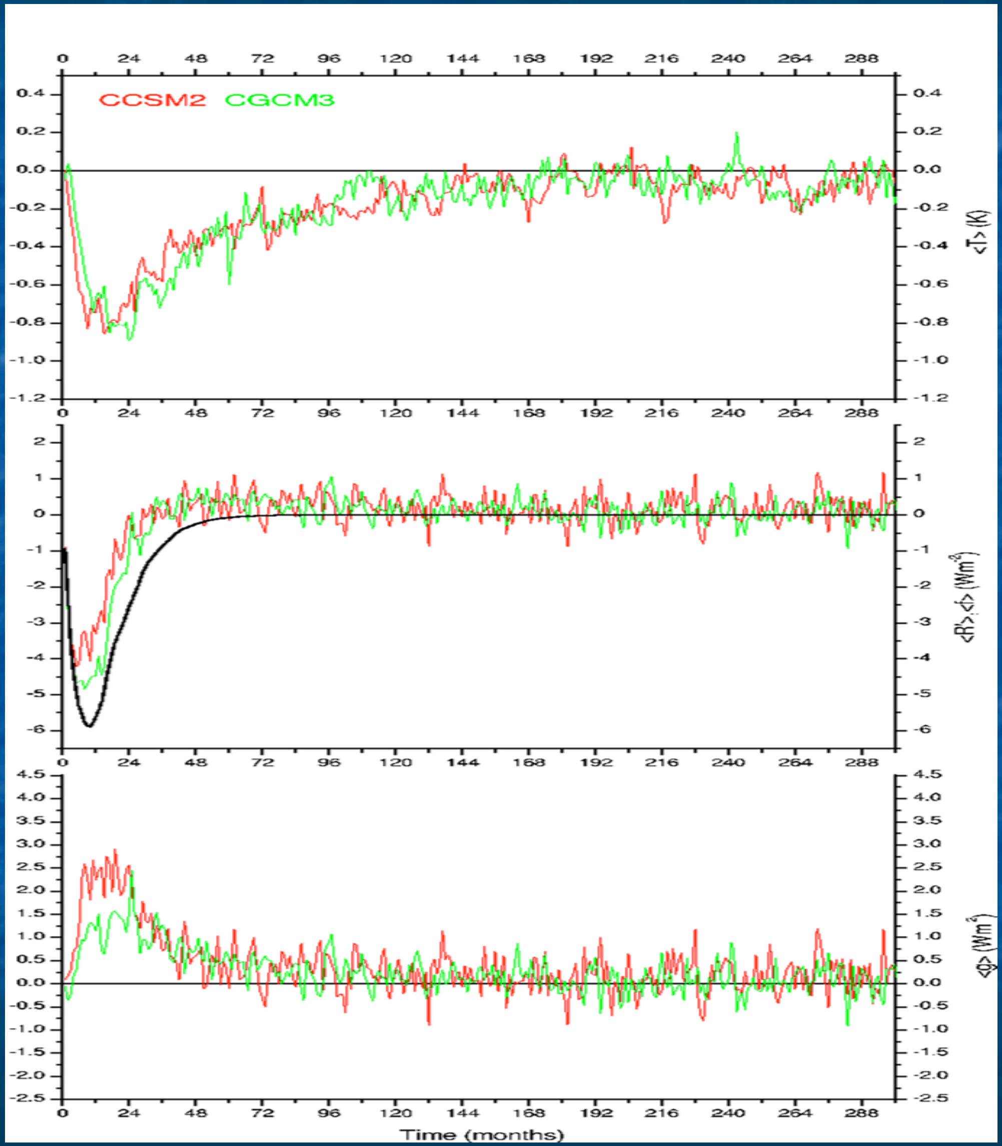
CGCM3 and CCSM2 average of 3 cases response to volcanic forcing

<T’>

<R’>

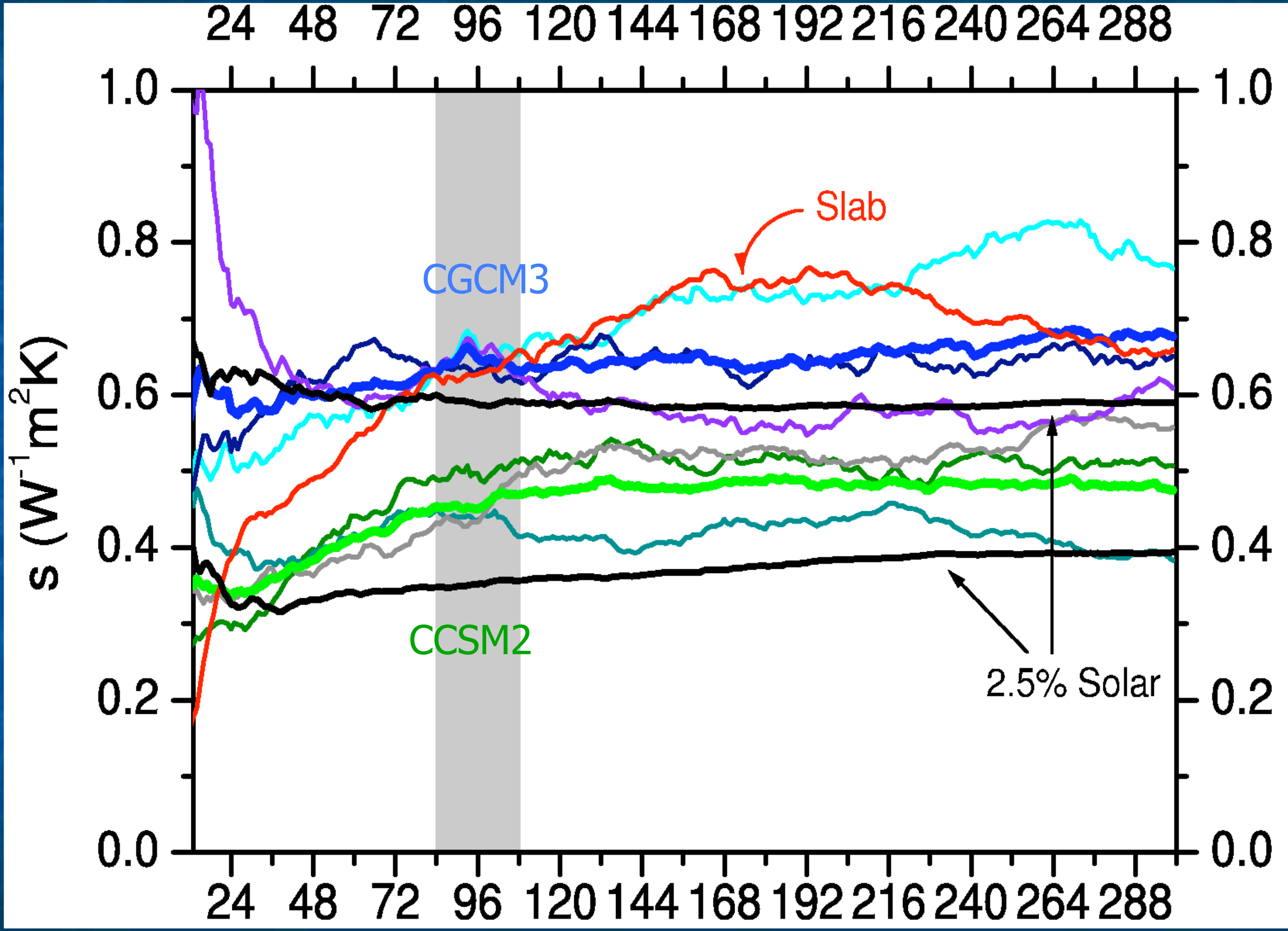
<f>

<g>



$$\Lambda(\tau) = \int_0^\tau g\,dt \Big/ \int_0^\tau T'\,dt = -1/s(\tau)$$

individual and mean (thick) values



time (months)

Method 2 – works if you know enough

- Effect of errors in g=(dh′/dt-f) or T′ for known forcing

$$\frac{\delta\Lambda}{\Lambda} = \frac{\delta\int g\,dt}{\int g\,dt} - \frac{\delta\int T'\,dt}{\int T'\,dt}$$

For value of Λ within 25% errors in terms need to be at least this accurate - which is very demanding

Accuracy of terms

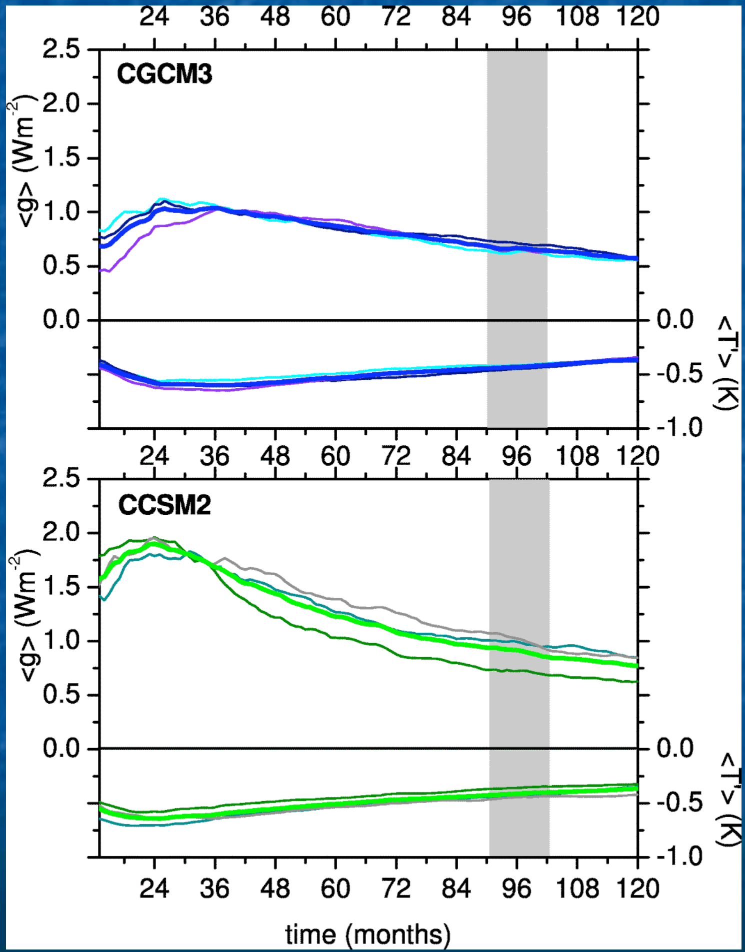
- If need to know terms to 25%
- For 96 month *average*

  - g term about 0.7 W/m2

  - T′ term about 0.4 C
- Rather stringent requirement at

  δg = 0.18 W/m2

  $\delta T'$ = 0.1 C
- more scatter for model with lower sensitivity



Method 2

- Volcanic perturbations can nominally give equilibrium sensitivity – at least in the model world
- However, need to know storage-forcing dh’/dt-f or R’-f and T’ to high accuracy
- Possibility of this accuracy is moot

Probability considerations

- s = T'/ (f-R') => (λ_o/(1-*feedback+*))
- uncertainty in *averaged* values of T' and (f-R') determine uncertainty in s
- Replaces uncertainty in model feedback term 1/(1-*feedback+*)

Volcanoes and sensitivity

- *Can't* get climate sensitivity from T′ alone
  - models with different sensitivities have "same" T′
  - storage dh′/dt=R′ important (exchange with ocean)
  - current CGCMs (system) have non-trivial exchange
- *Can* get reasonable climate sensitivity from volcano
  - transient Λ, s "close" to equilibrium values
  - need *both* forcing and storage: g = R′-f =dh′/dt –f
  - but accuracy requirements daunting
- *For volcano* uncertainty in *model feedbacks* replaced by uncertainty in averaged values of *observed* T′ and forcing/storage term f-R′

end of presentation