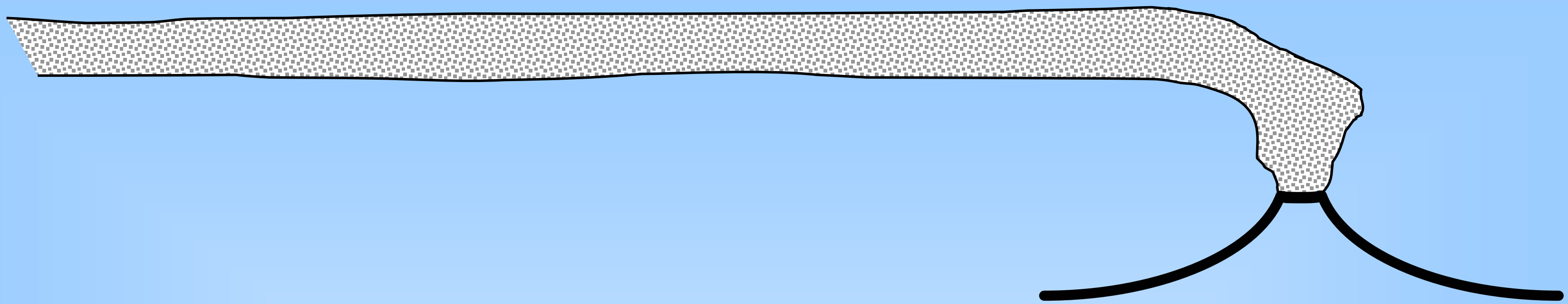

Mechanisms of Forced Arctic Oscillation Response to Volcanic Eruptions

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Collaborators

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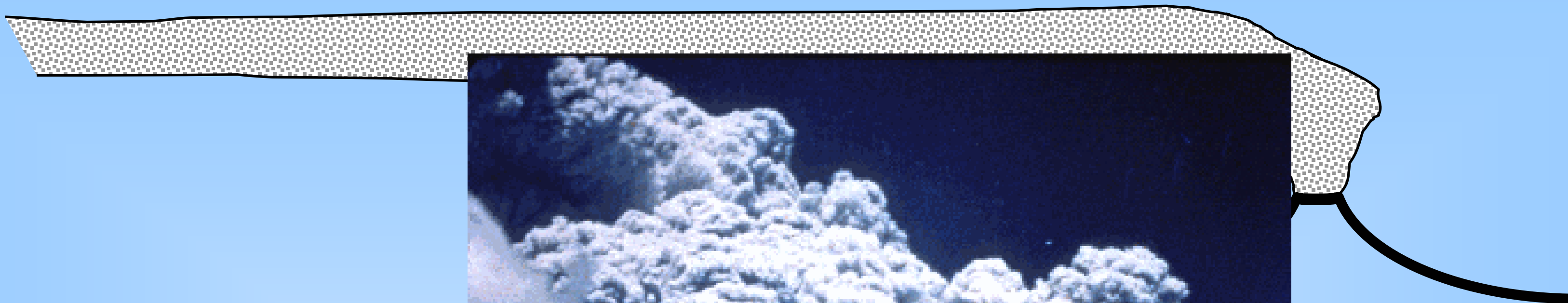
Max Plank Institute for Meteorology, Hamburg, Germany

S. Ramachandran

Physical Research Laboratory, Ahmedabad, India

Jianping Mao

Raytheon ITSS, Lanham, MD



Pinatubo
June 12, 1991

Three days before major eruption of June 15, 1991

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After Pinatubo, Cubi Point Naval Air Station, 40 km from volcano

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U.S. Navy photograph by R. L. Rieger

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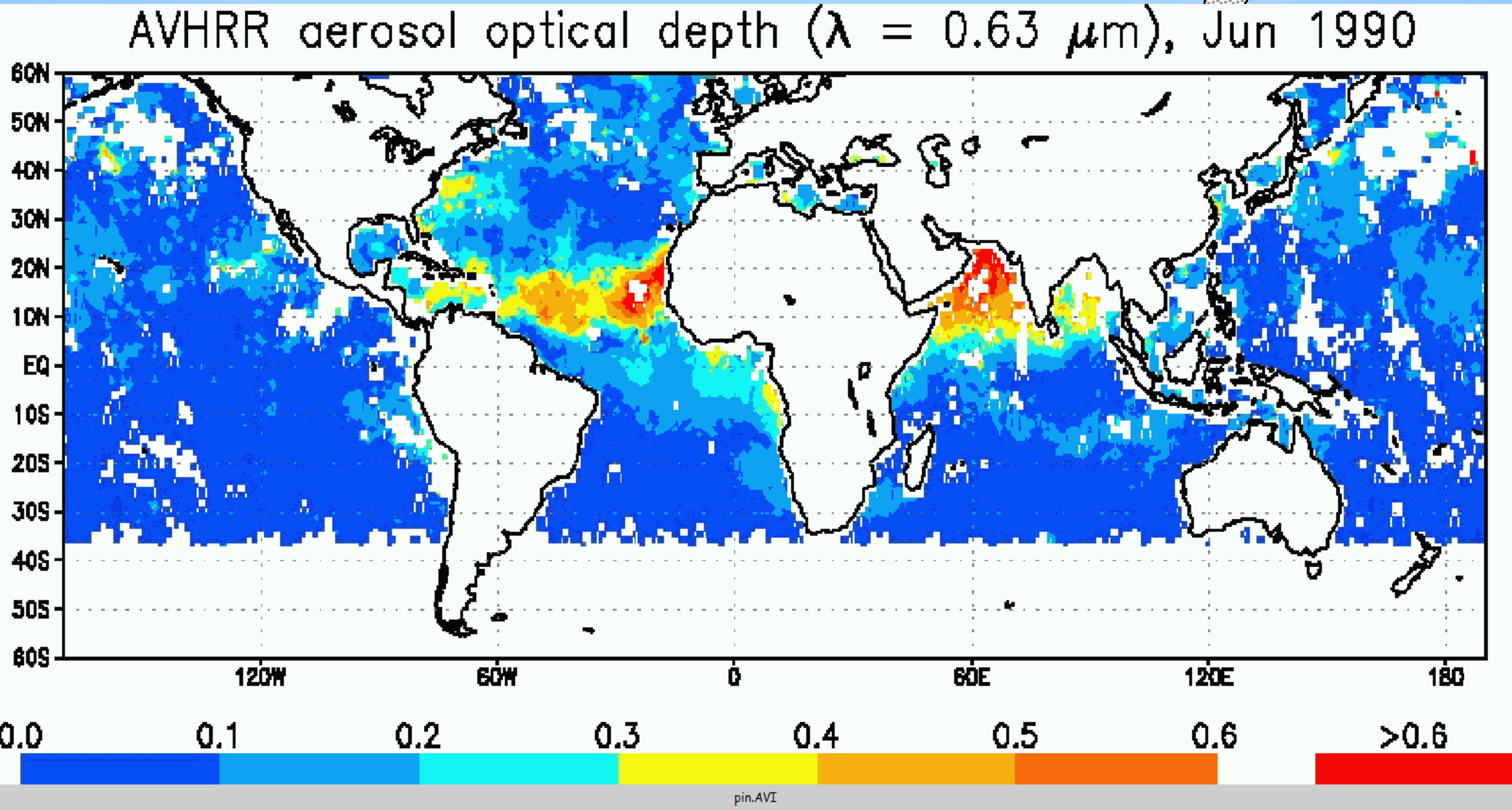

Stowe *et al.* (1997)

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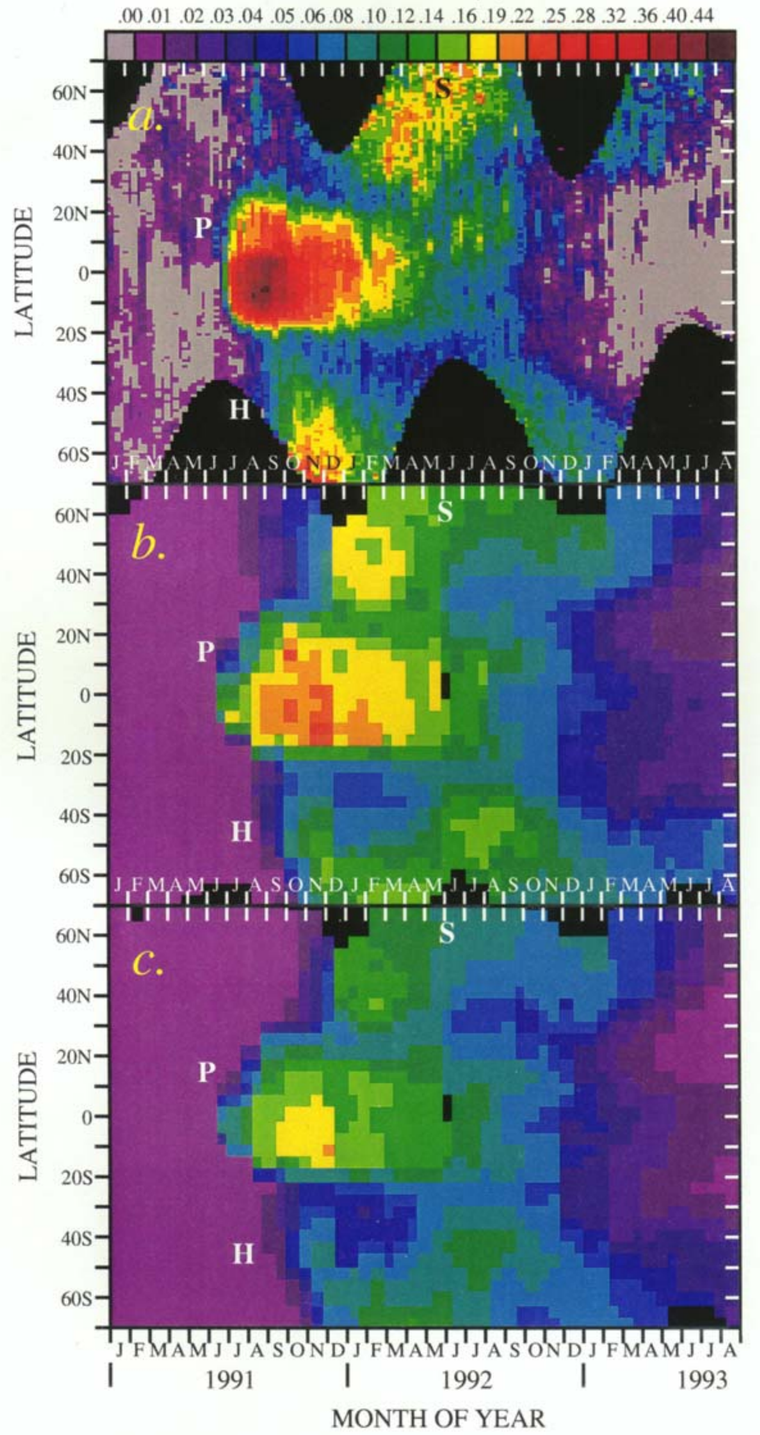
Zonal average stratospheric optical depth (Russell et al., 1996)

a. AVHRR, $\lambda = 0.5\ \mu m$
(Long and Stowe, 1994)

b. SAGE II, $\lambda = 0.525\ \mu m$
(Thomason, 1995)

c. SAGE II, $\lambda = 1.02\ \mu m$
(Thomason, 1995)



P, **H**, and **S** indicate time and locations of Pinatubo, Hudson and Spurr eruptions.

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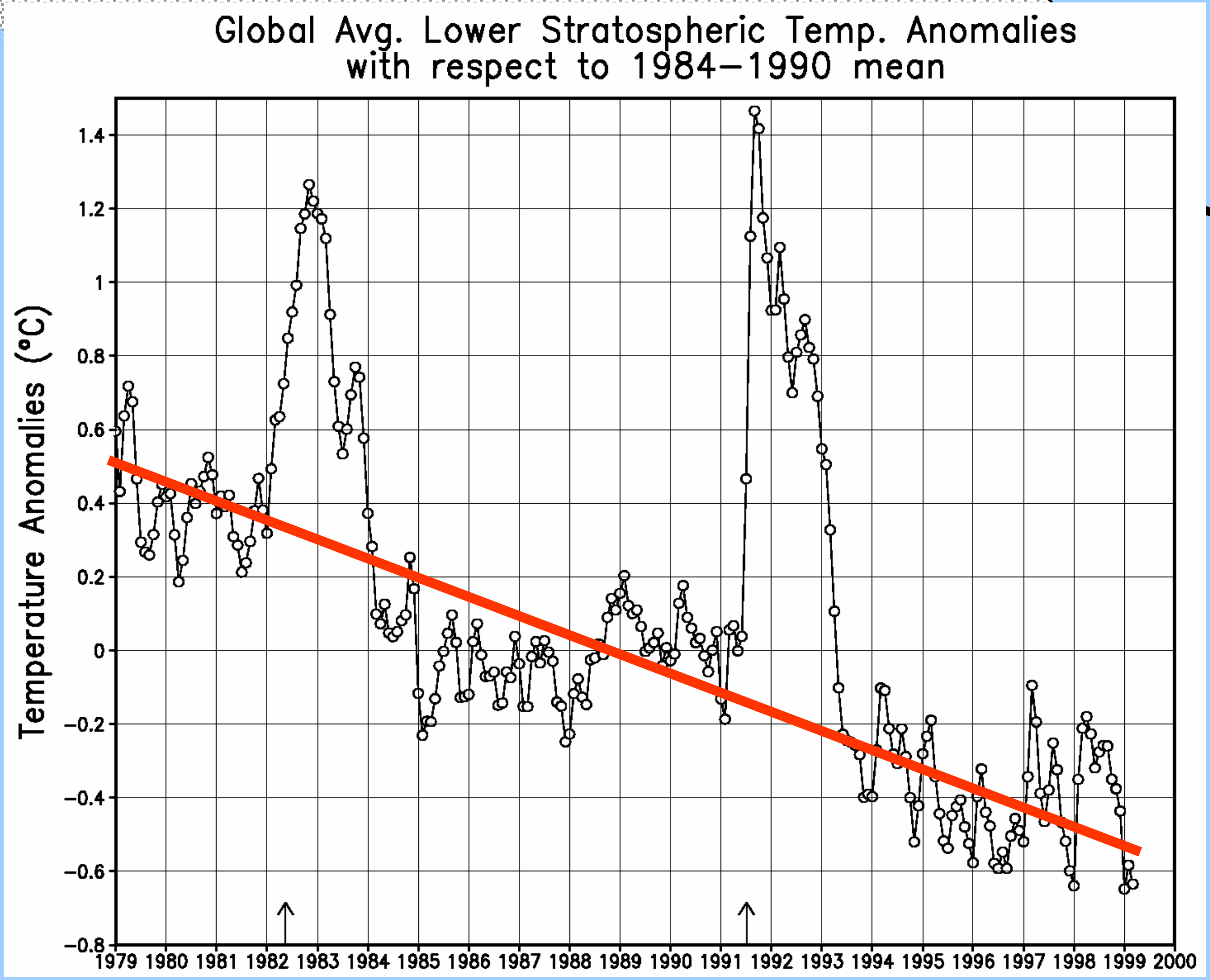

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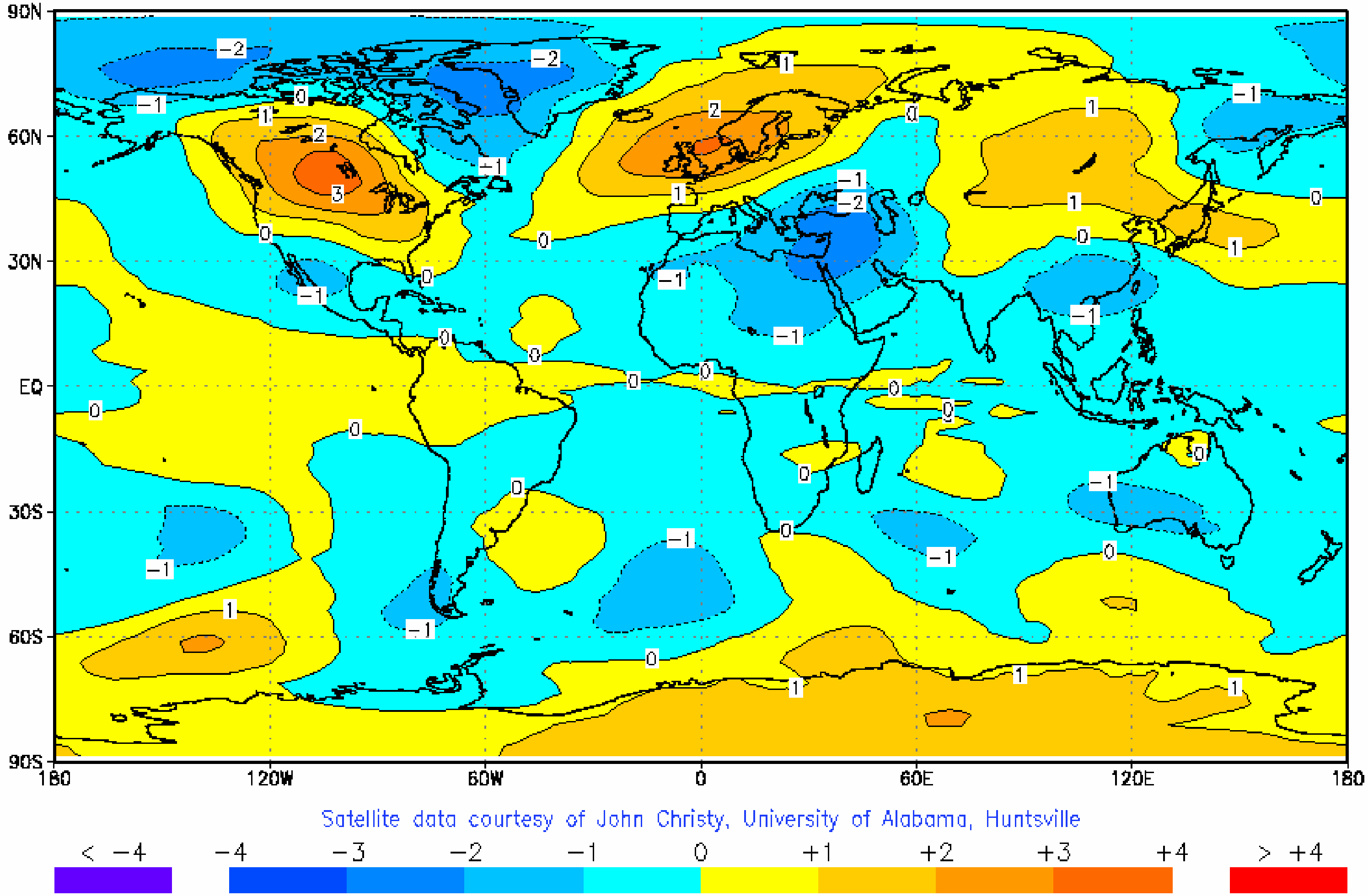
Winter (DJF) 1991–92
Average Lower Troposphere Temperature Anomalies (°C)



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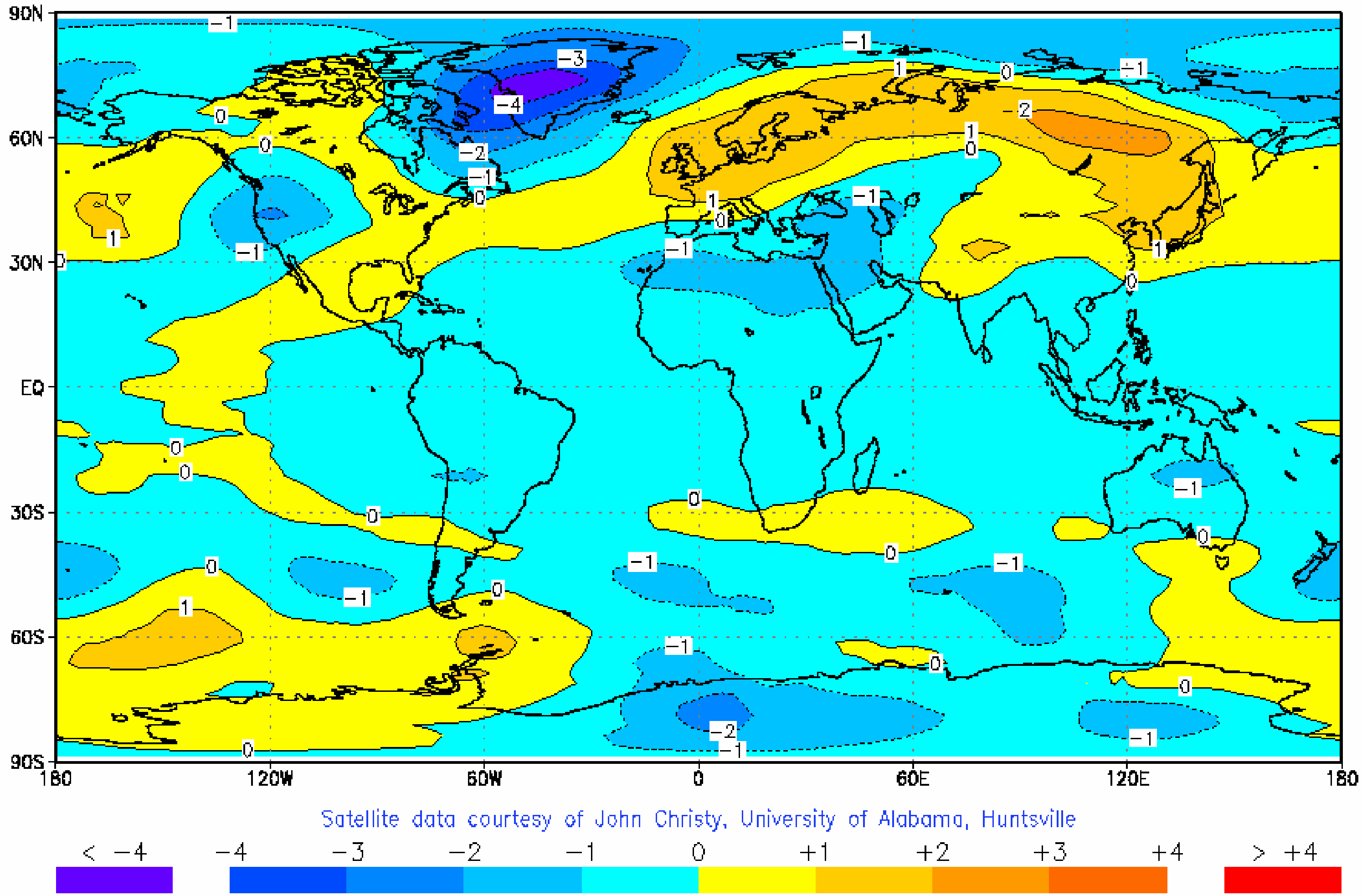
Winter (DJF) 1992–93
Average Lower Troposphere Temperature Anomalies (°C)



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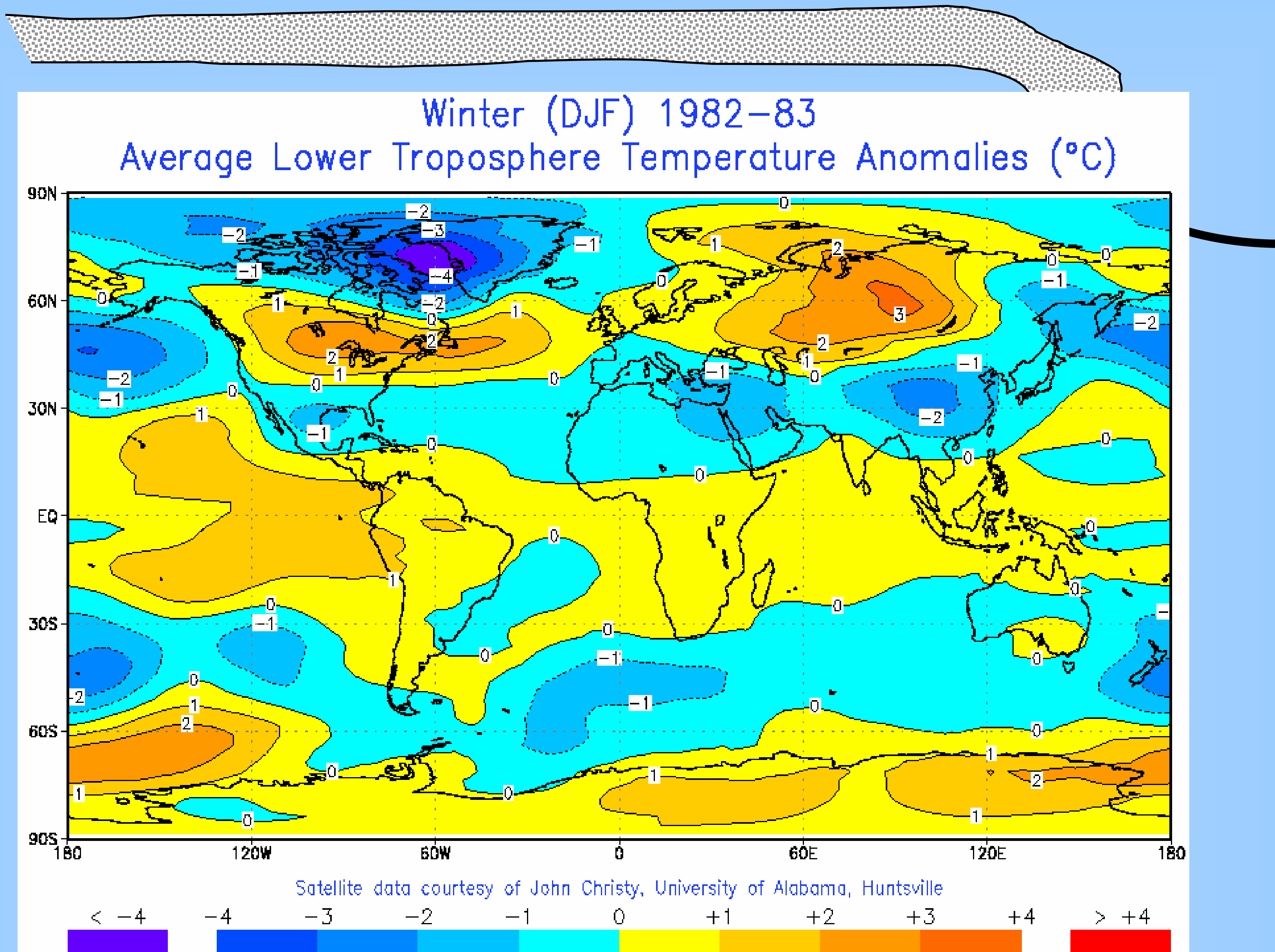

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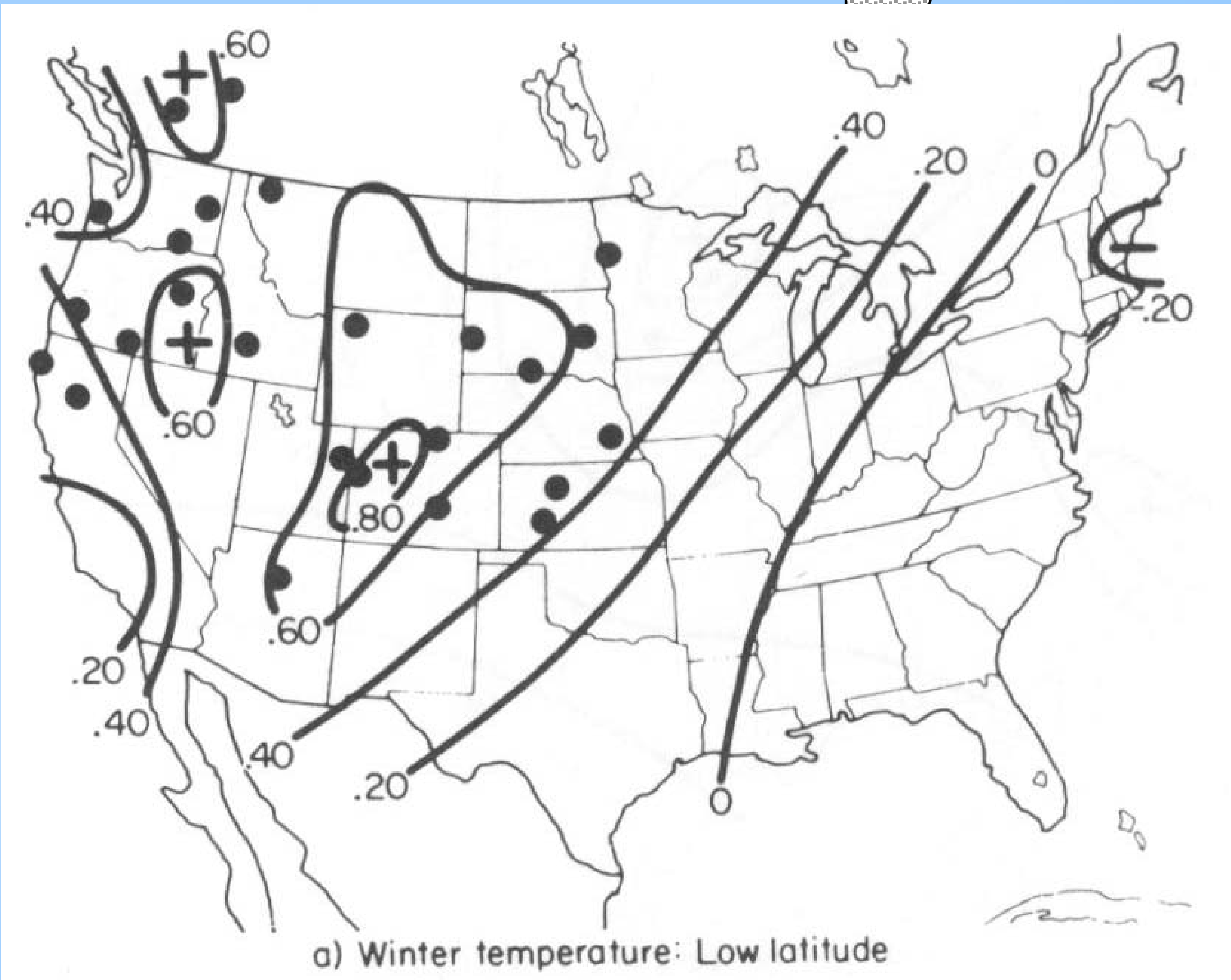
Tree ring analysis shows winter warming over most of U.S. after large low latitude eruptions



Average temperature anomaly (K)

Dots are stations with 95% significance

Lough and Fritts (1987)

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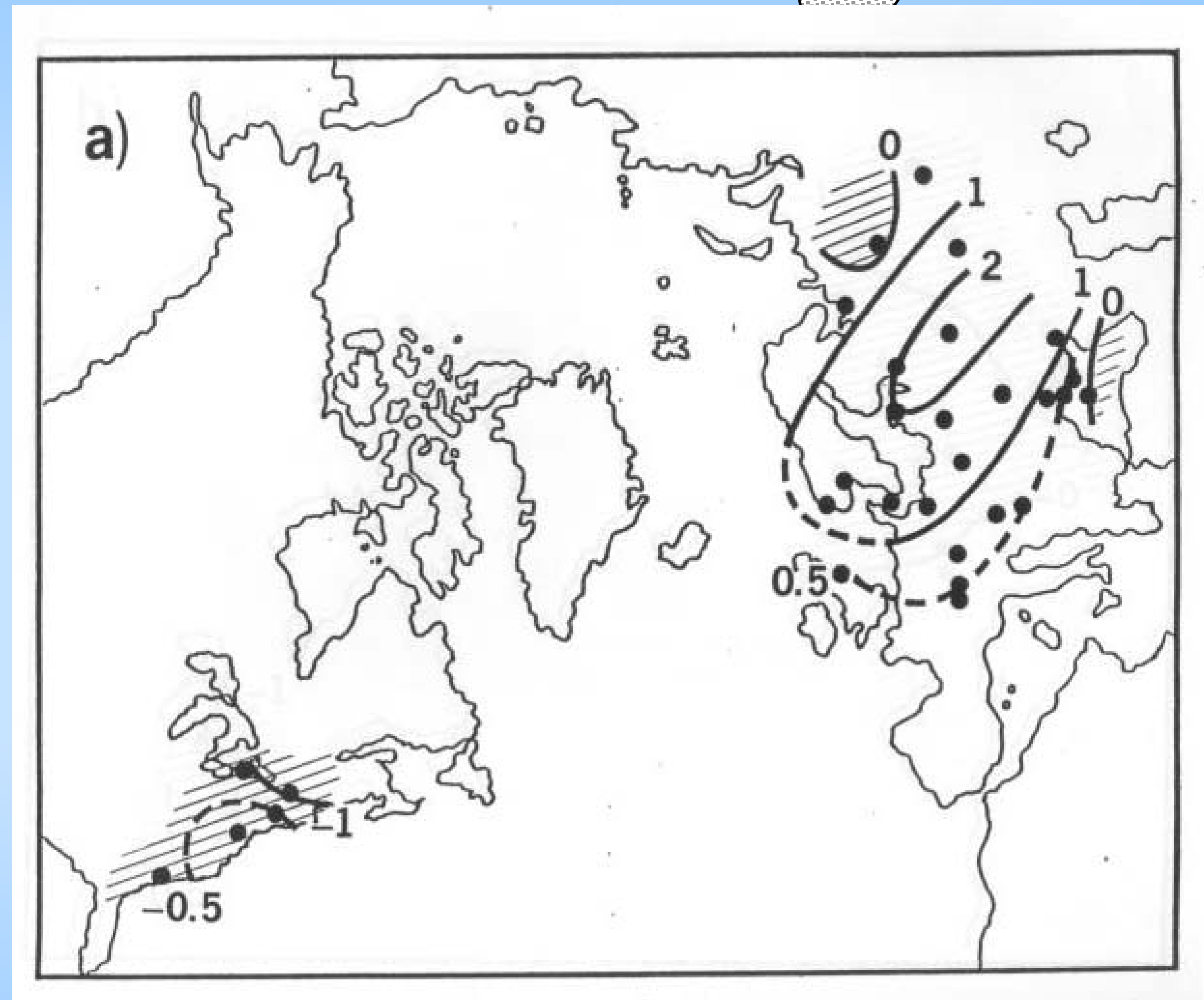
Groisman (1992), repeating previous Russian studies, found winter warming when averaging over 2-3 years following largest eruptions of the past two centuries.

Dots are stations.



Winter temperature anomaly (K)

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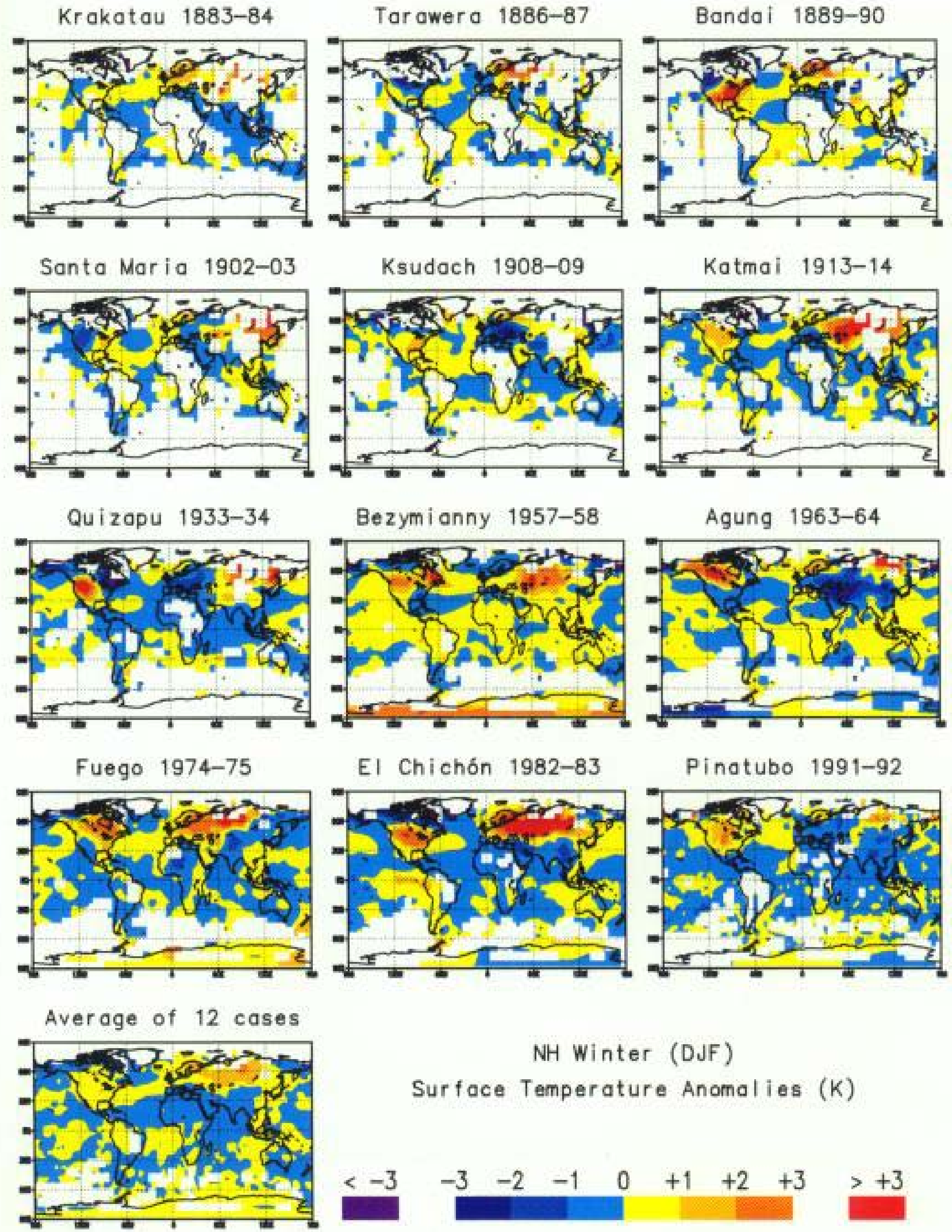
Winter Warming for largest eruptions of the past 120 years

Observed surface air temperature anomalies

Robock and Mao (1992)



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The Arctic Oscillation

Thompson and Wallace (1998)

Stronger polar vortex

Winter warming

Positive mode is the same as the response to volcanic aerosols.

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The Arctic Oscillation signature in the wintertime geopotential height and temperature fields (Fig. 1 maps)

David W. J. Thompson and John. M. Wallace

Geophysical Research Letters, May 1, 1998

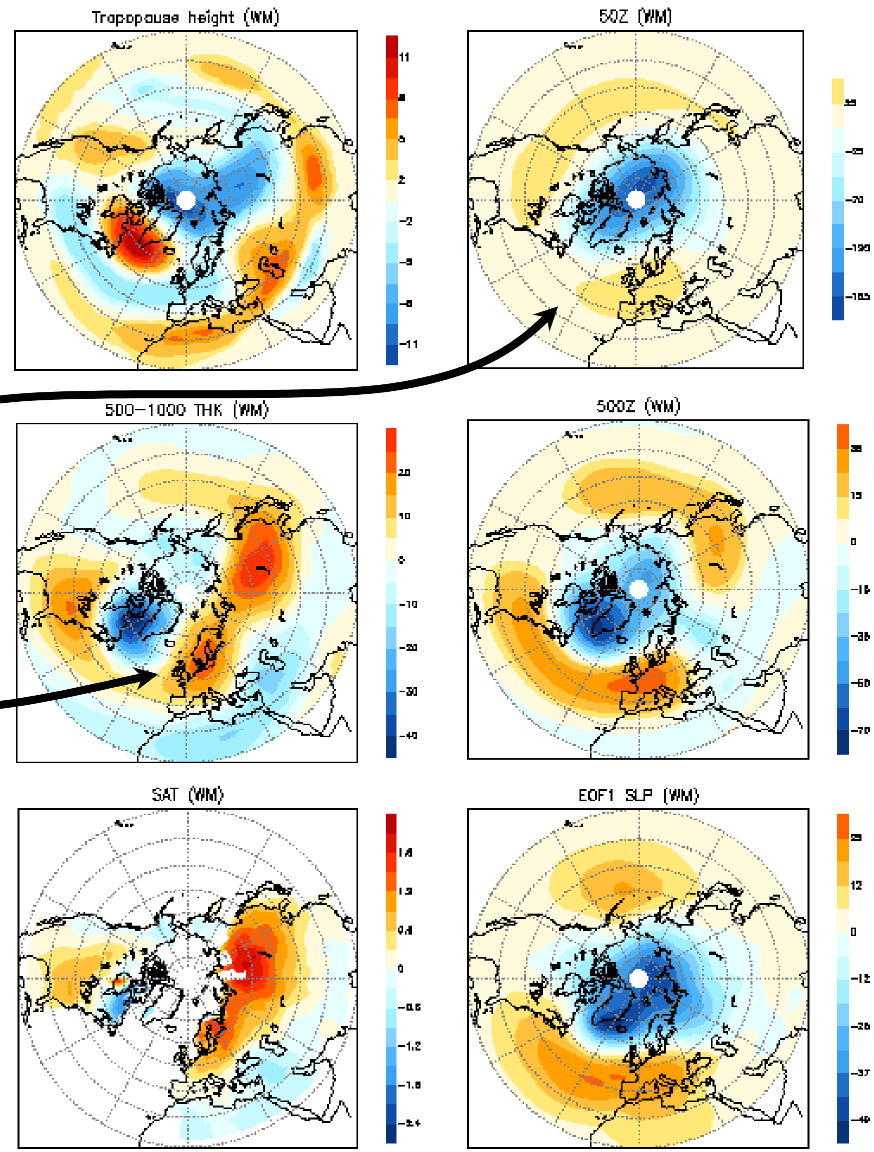
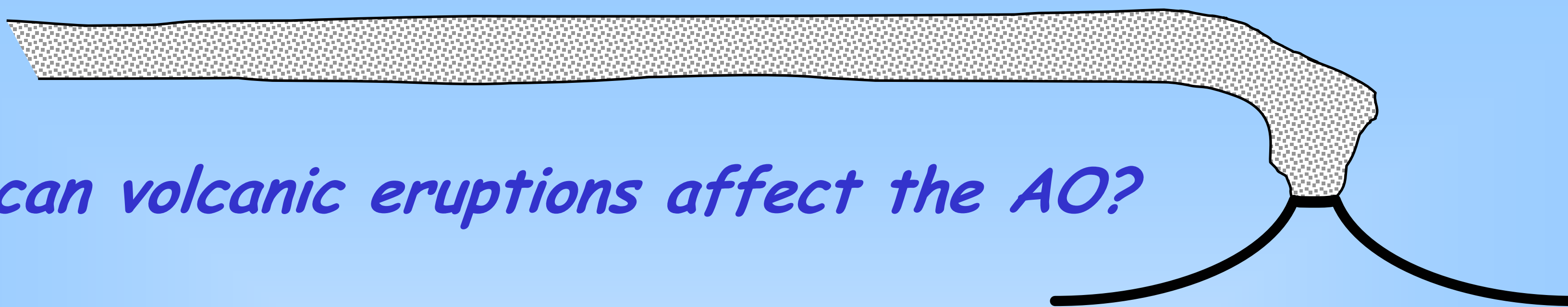


Figure 1. Regression maps for geopotential height (*meters*), tropopause pressure (*Pa*), 1000-500-hPa thickness (*m*), SLP (expressed as Z_{1000}: *m*) and surface air temperature (SAT-*K*) anomalies as indicated, based upon the AO index for 1947-1997. See text for details.



How can volcanic eruptions affect the AO?

- **Changes in the stratosphere:**

  Aerosol tropical warming

  Ozone polar cooling

  Both the above produce a stronger polar vortex

  QBO produces strong modulation of response

- **Changes in the troposphere:**

  Land cooling in subtropics and warming at higher latitudes

  Weaker planetary waves

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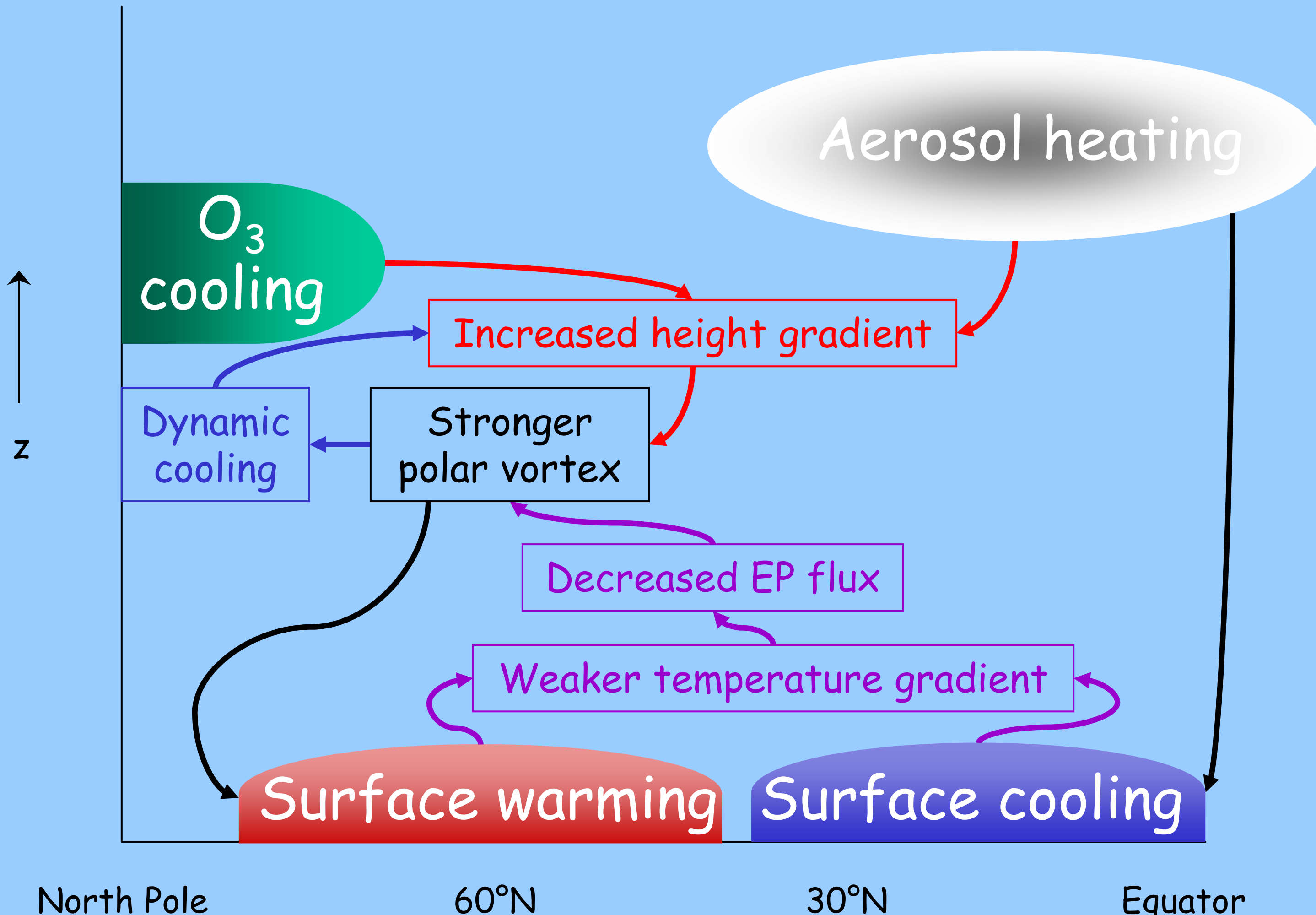
"stratospheric gradient" mechanism

"tropospheric gradient" mechanism

"wave feedback" mechanism

Ways Volcanic Eruptions Force Positive AO Mode



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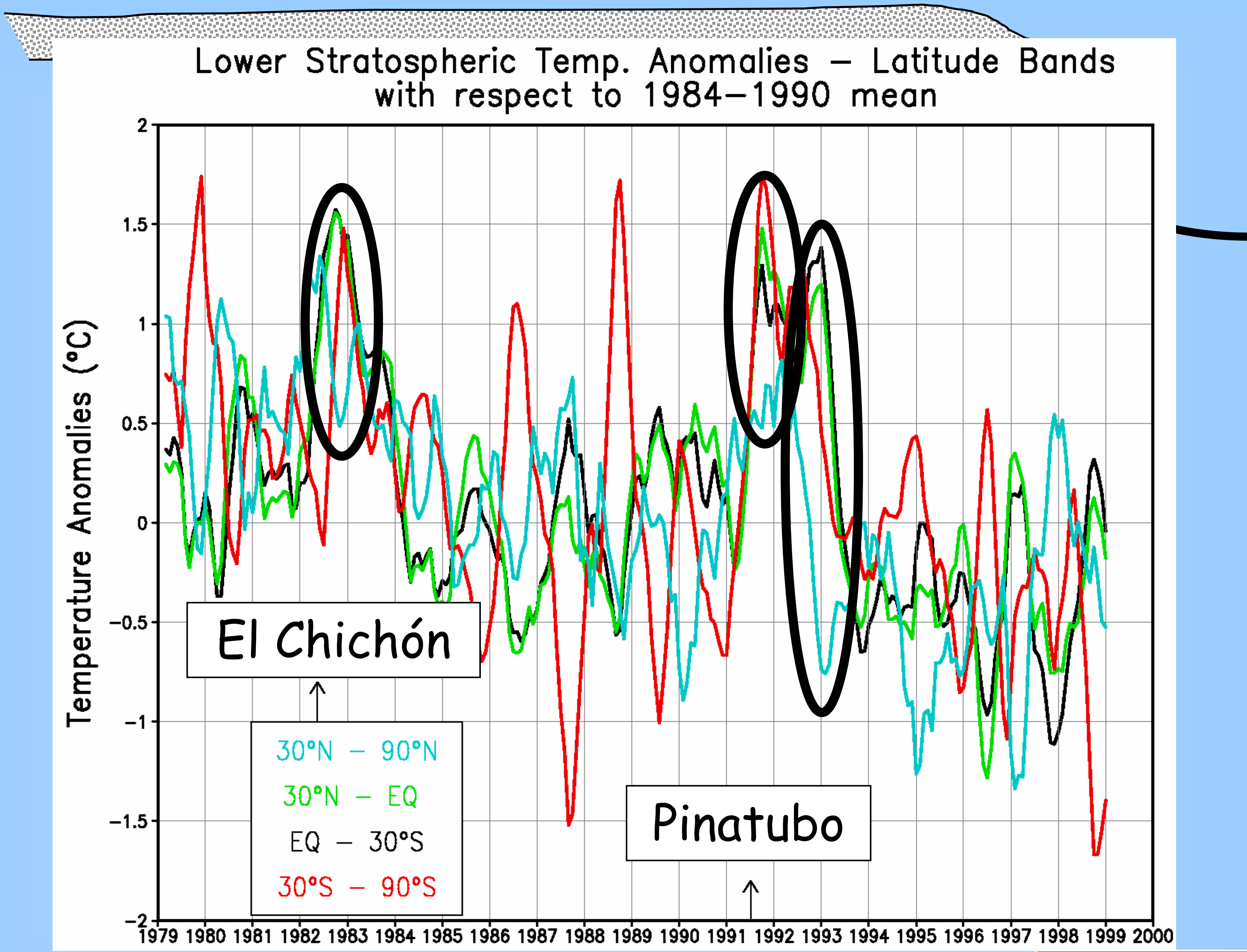

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General Circulation Model (GCM) experiments

GCMs Used

1. **MPI ECHAM-2**, T21L19, perpetual January
   off-line radiation (from El Chichón)
   Average of 58 Januaries for control and forced

2. **MPI ECHAM-4**, T42L19
   Ensembles of five 2-year runs for control and forced

3. **GFDL SKYHI**, 3°×3.6° (lat-lon) L40
   Ensembles of four, six, eight, or 24 2-year runs for forced and long control runs

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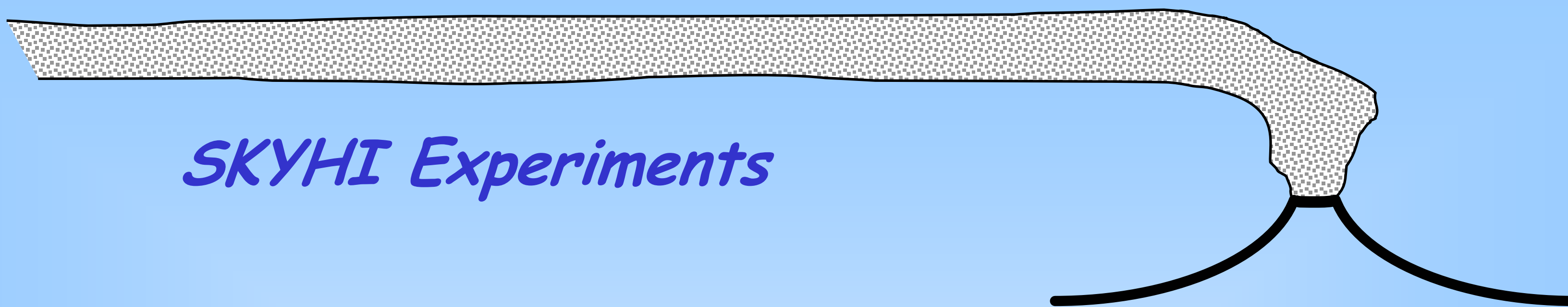

SKYHI Experiments

Ensembles of 2-year runs with specified climatological SST:

- **Aerosols with stratospheric and surface forcing (A)**
  - *8 ensemble members*

- **Aerosols with only surface Cooling (no stratospheric heating) (C)**
  - *4 ensemble members*

- **Observed Ozone anomalies only (O)**
  - *6 ensemble members*

- **Aerosols + QBO with stratospheric and surface forcing (AQ)**
  - *24 ensemble members*

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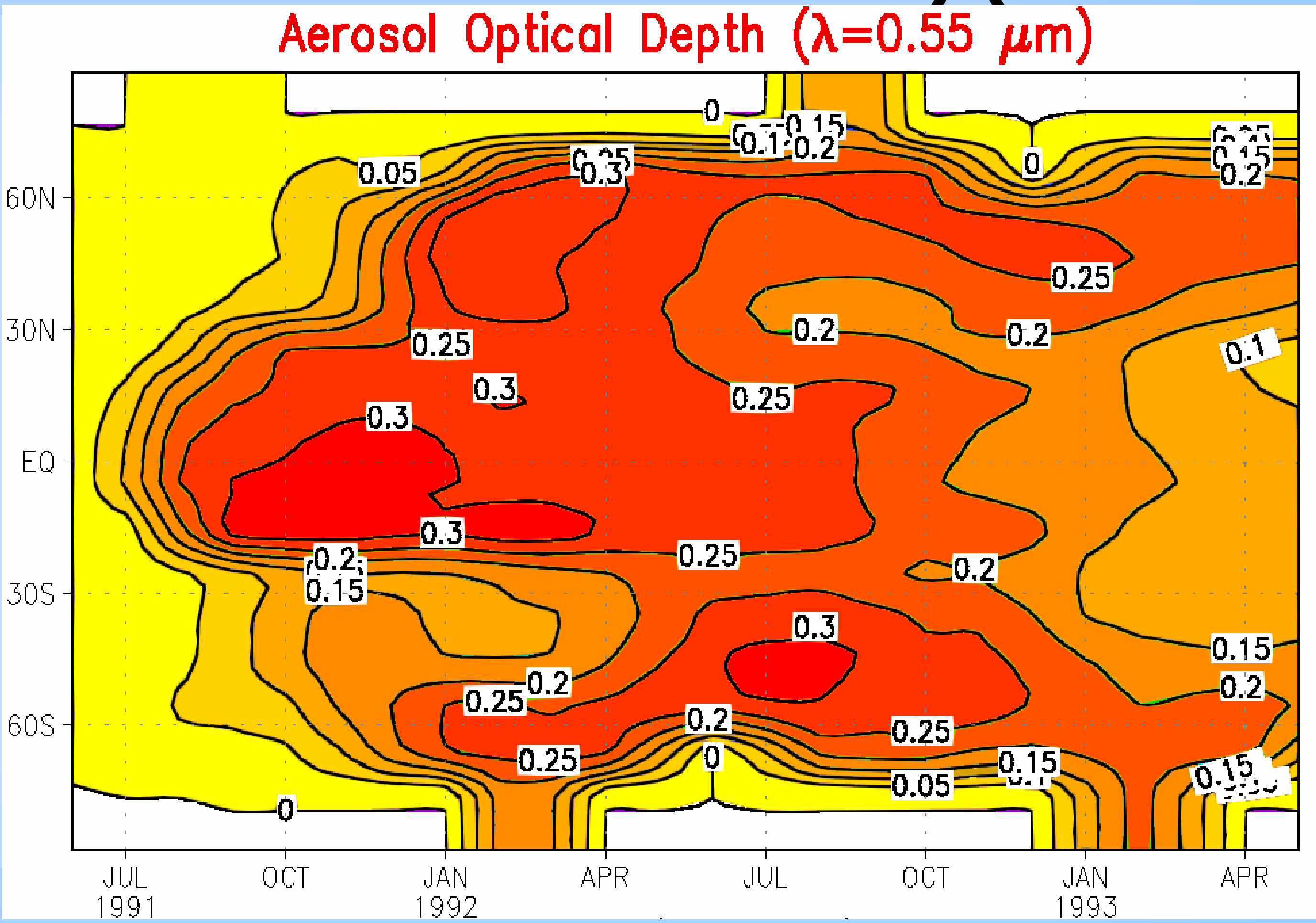
Stratospheric Aerosol Distribution



SKYHI
4-ensemble
mean

Calculated from
Stenchikov
et al. (1998)
data set

Ramachandran et al. (2000)

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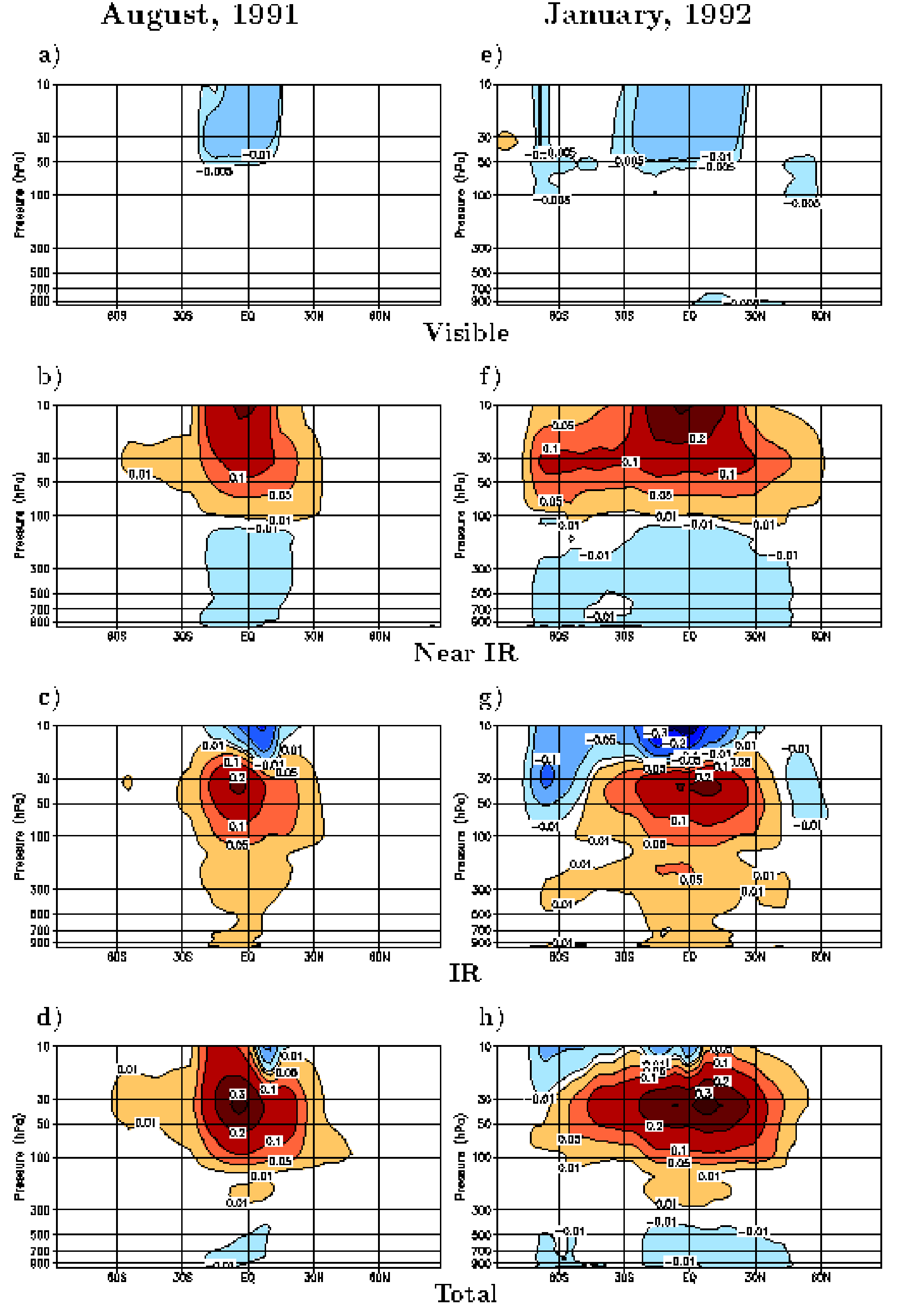
ECHAM4

5-ensemble mean

Heating rates (K/day) for different wavelengths and total

(Stenchikov et al., 1998)



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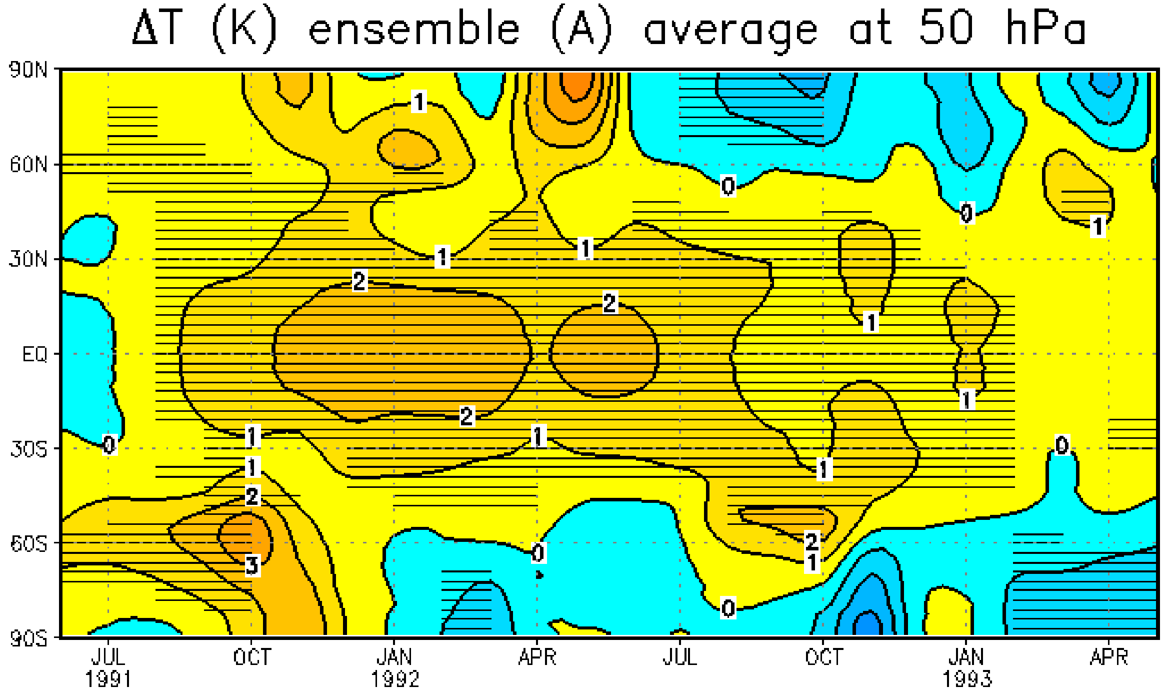
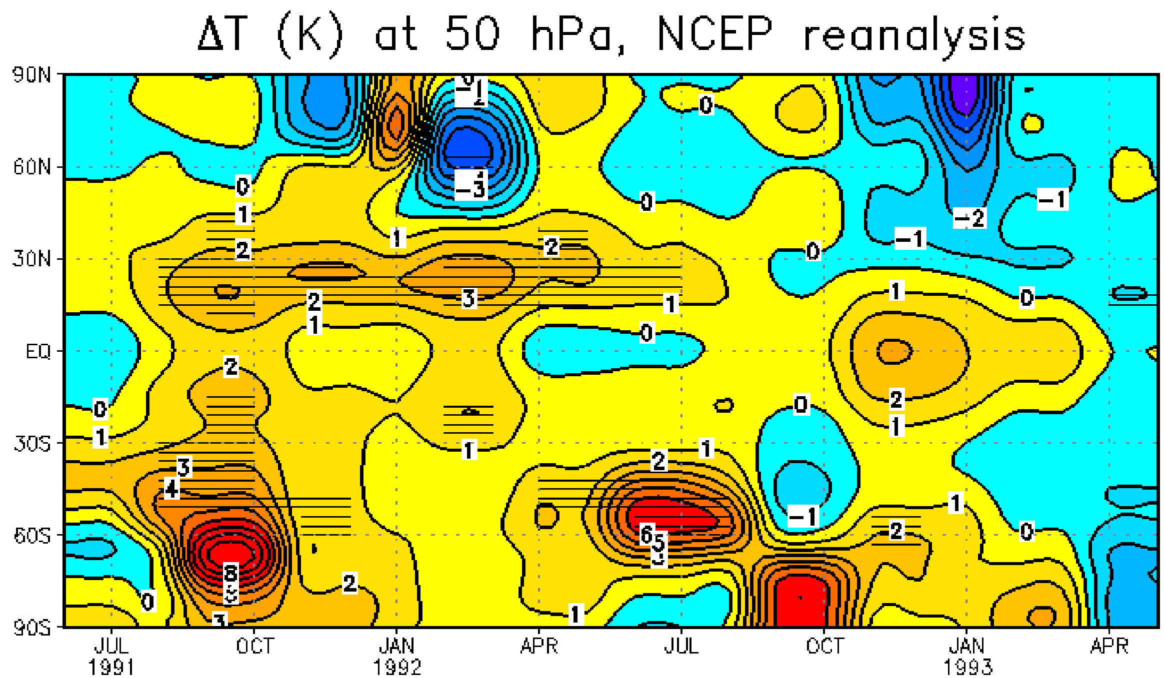
SKYHI simulations

Zonal mean temperature anomaly (K) at 50 mb caused by aerosols only (*A*)

Hatching shows 90% significance

NCEP observations





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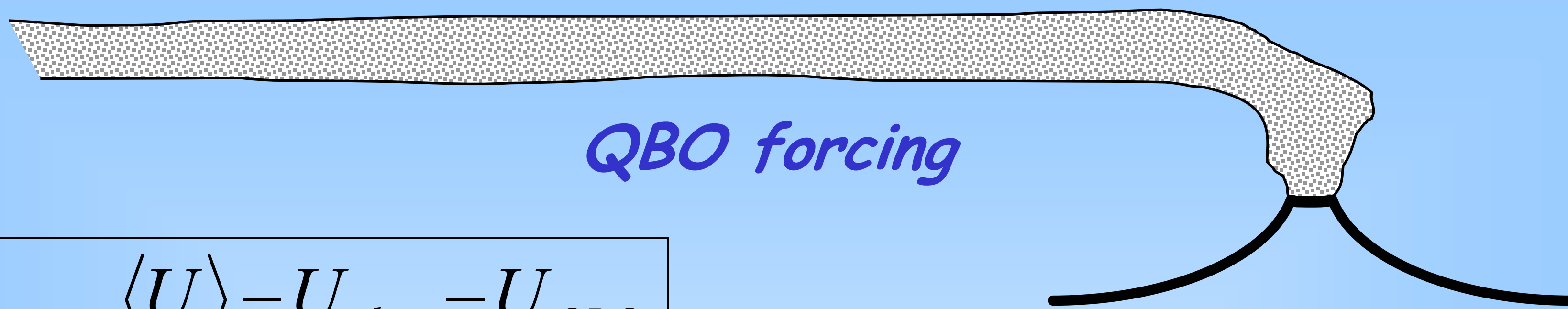

QBO forcing

$$\frac{dU}{dt} = -\frac{\langle U \rangle - U_{clim} - U_{QBO}}{\tau(p,\phi)}$$

$$U_{QBO}(p,\phi,t) = U_{Sing} \times e^{-\left(\frac{\phi}{13^\circ}\right)^2}$$

U_{Sing} - *smoothed deseasonalized monthly-mean Singapore zonal wind*

ϕ - *latitude,* p - *pressure,* $\tau(p,\phi)$ - *characteristic time*

$\tau(p,\phi) >$ *5 day for 0.01 mb* $< p <$ *100 mb*

$\langle U \rangle$ - *zonal mean zonal wind*

U_{clim} - *climatological mean of zonal mean zonal wind*

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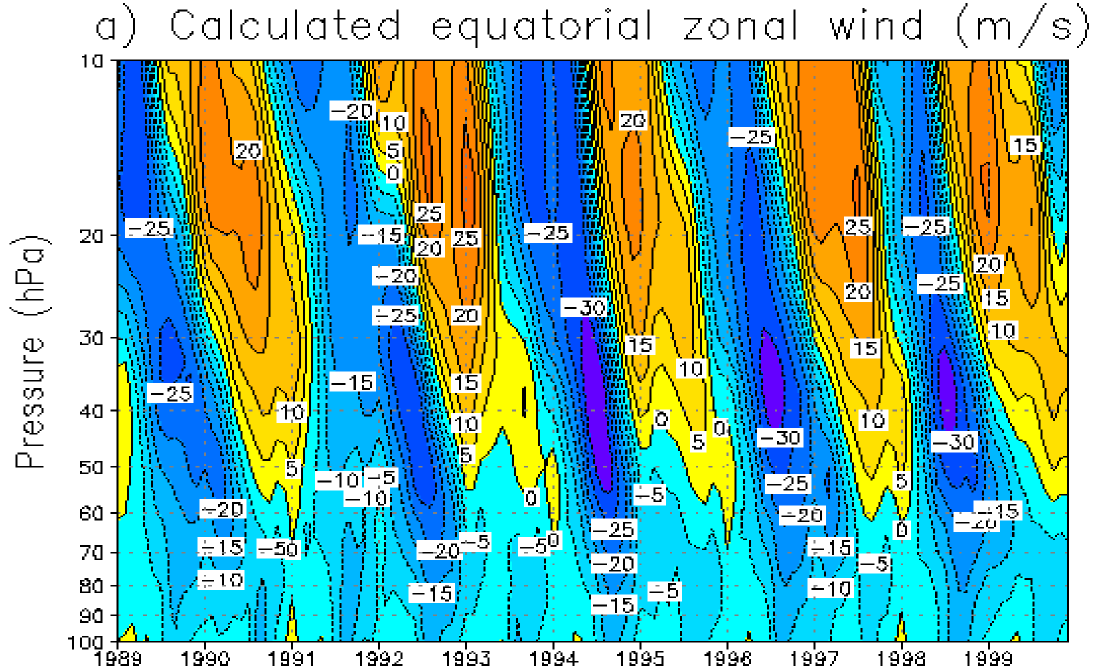
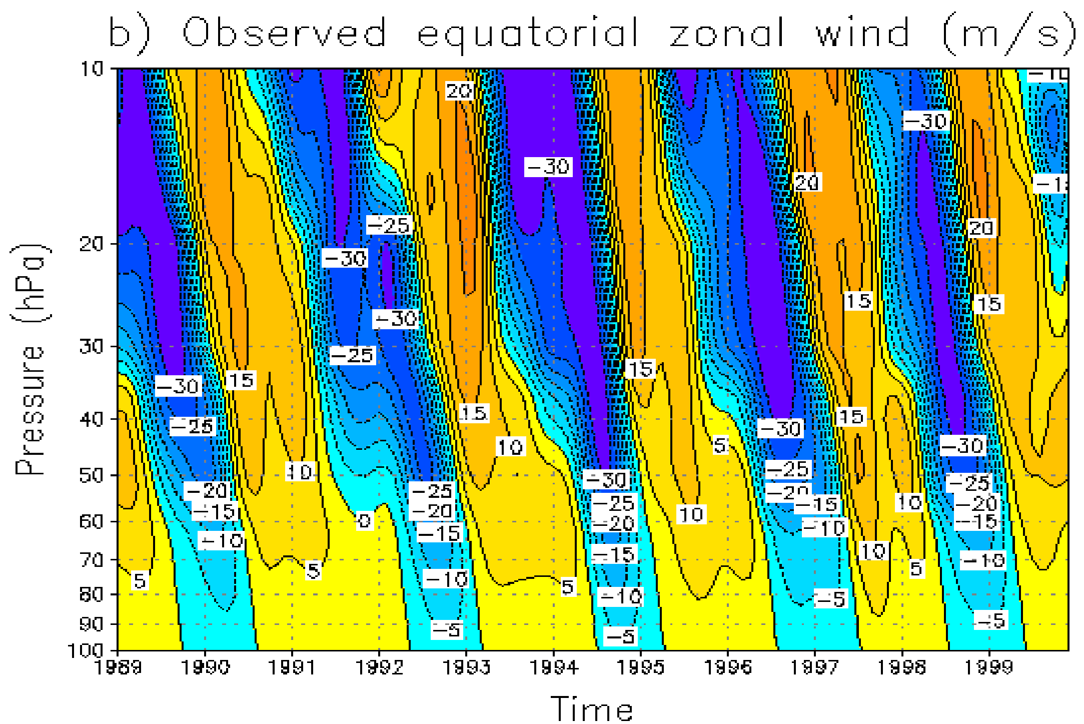
SKYHI simulation

Zonal mean zonal wind (m/s) from 11-year QBO control run



Observed zonal mean zonal wind (m/s) at Singapore



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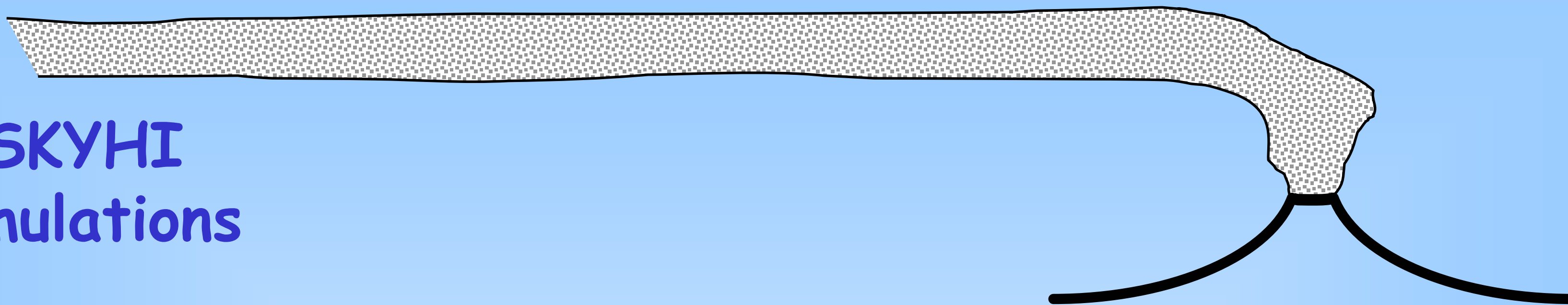
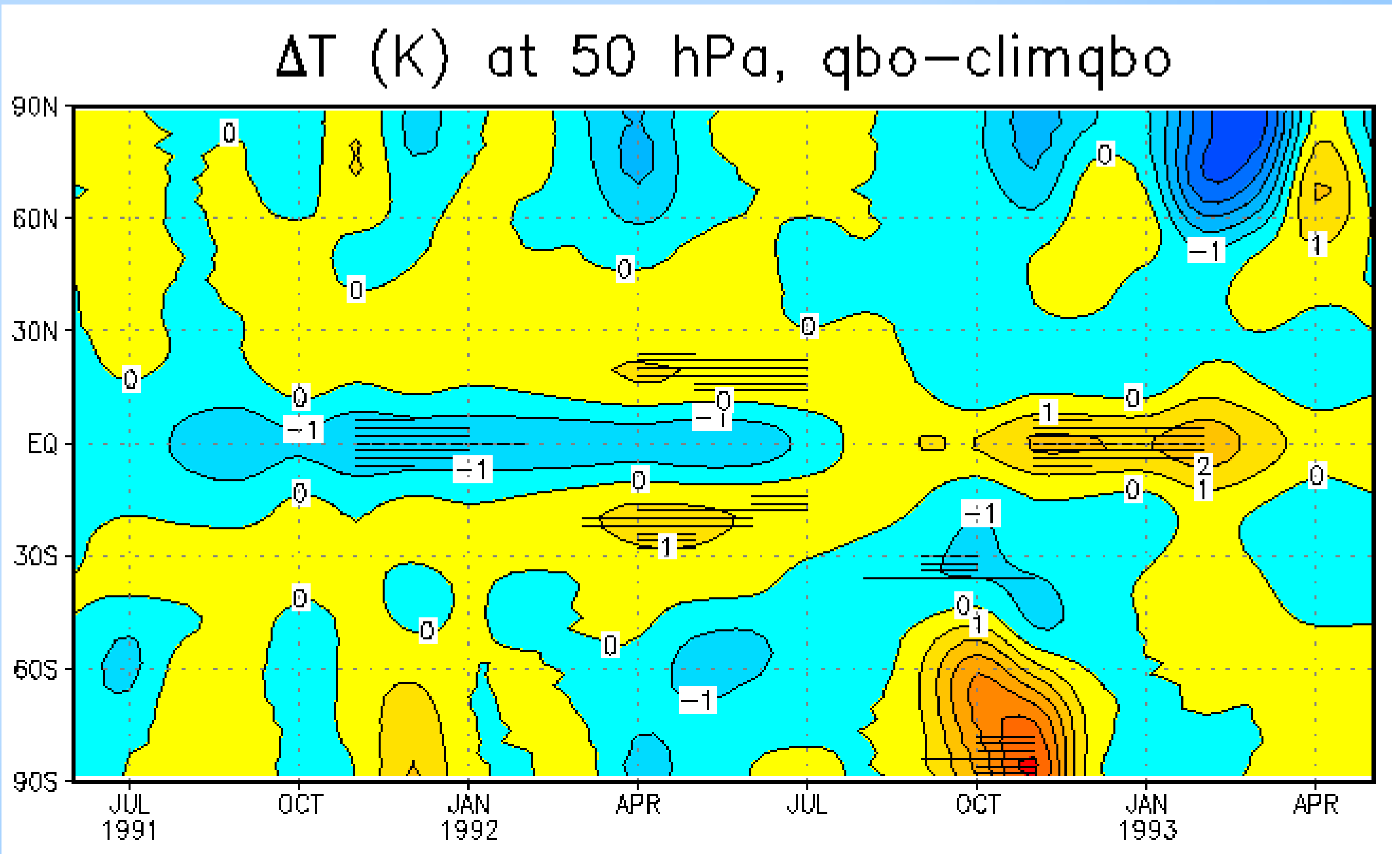


SKYHI simulations



Zonal mean temperature anomaly (K) at 50 mb caused by QBO only (from QBO control run)

Hatching shows 90% significance

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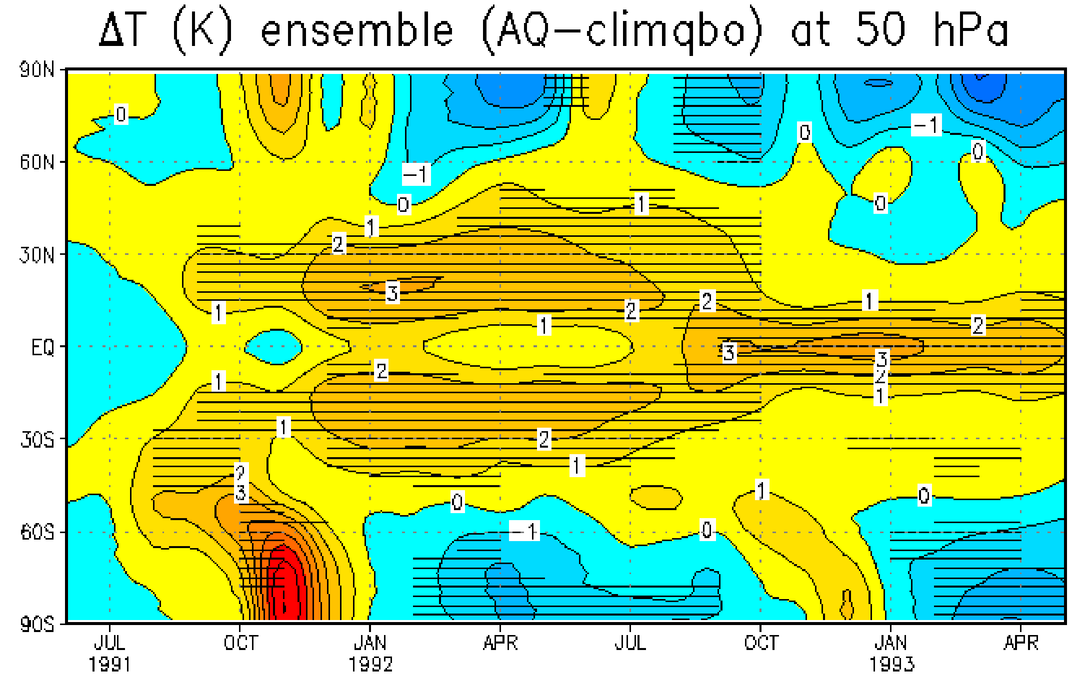
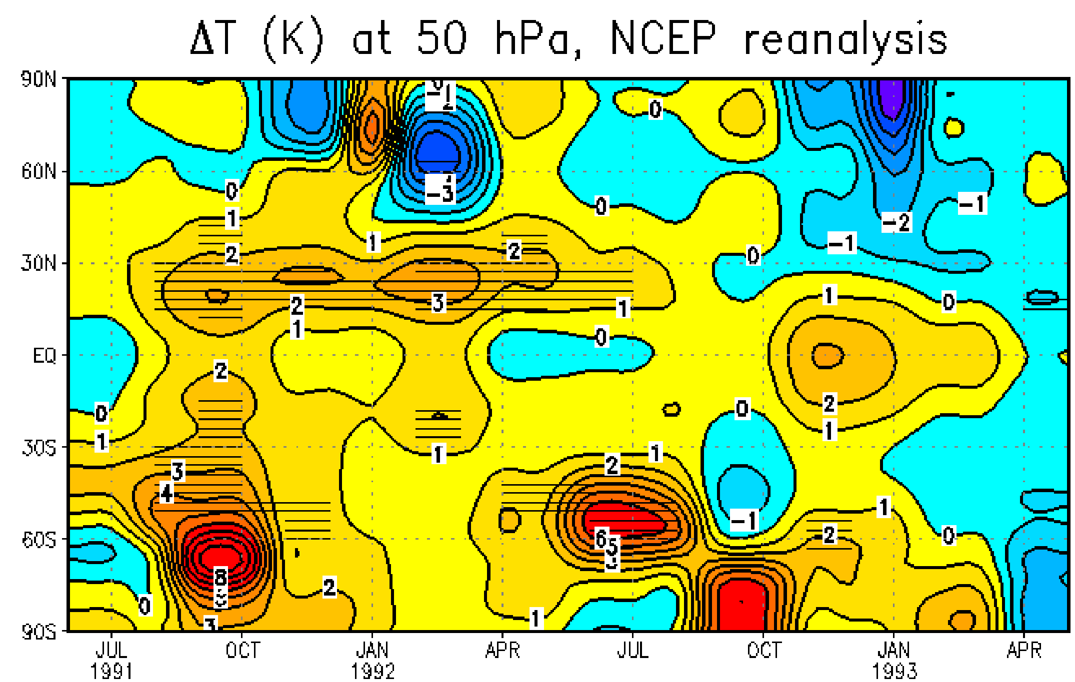
SKYHI simulations



Zonal mean temperature anomaly (K) at 50 mb caused by aerosols and QBO (AQ)

Hatching shows 90% significance

NCEP observations



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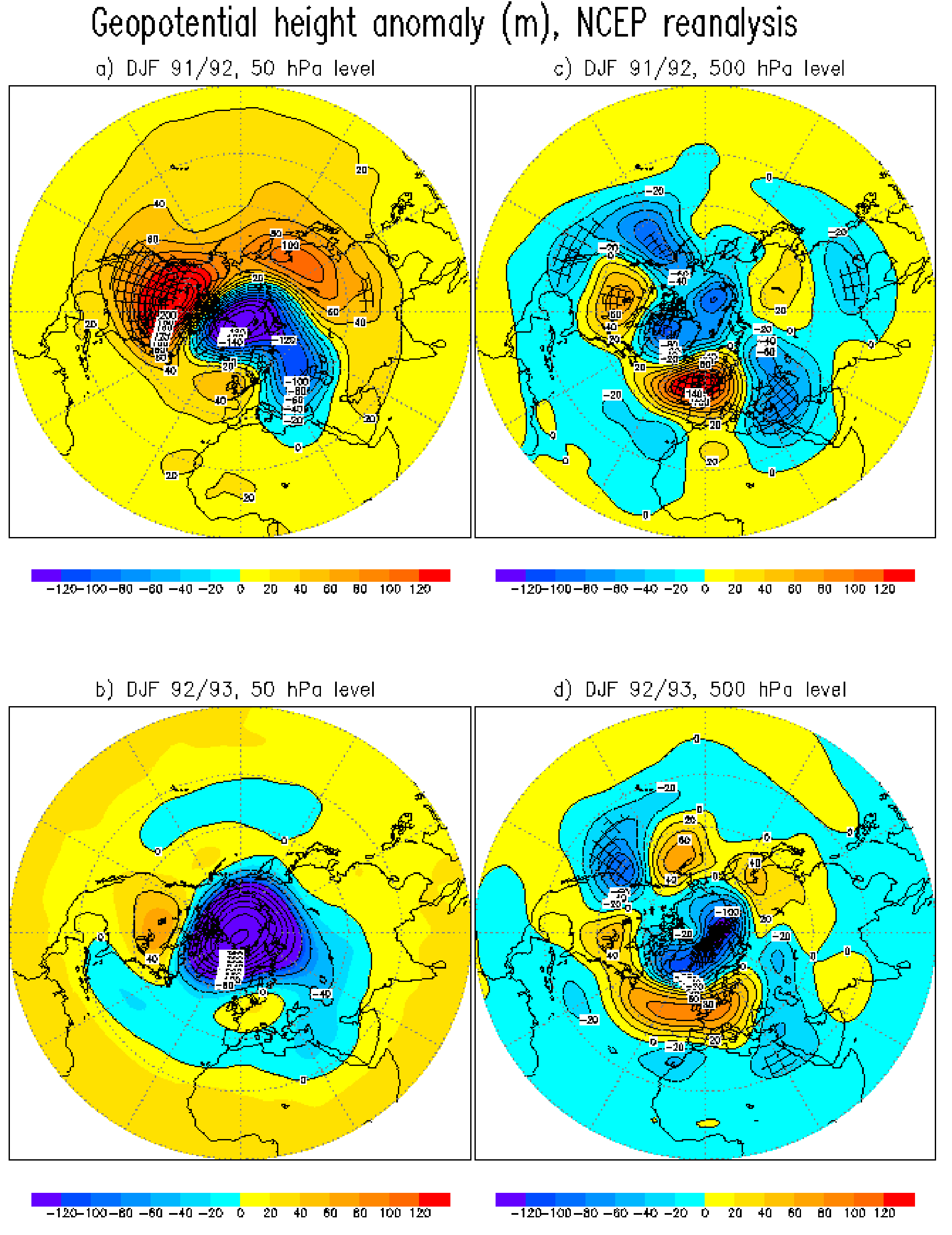
Winter 91/92

NCEP Observations

Geopotential height anomaly (m) with respect to 1985-1990 mean at 50 mb and 500 mb



Winter 92/93

Hatching shows 90% significance

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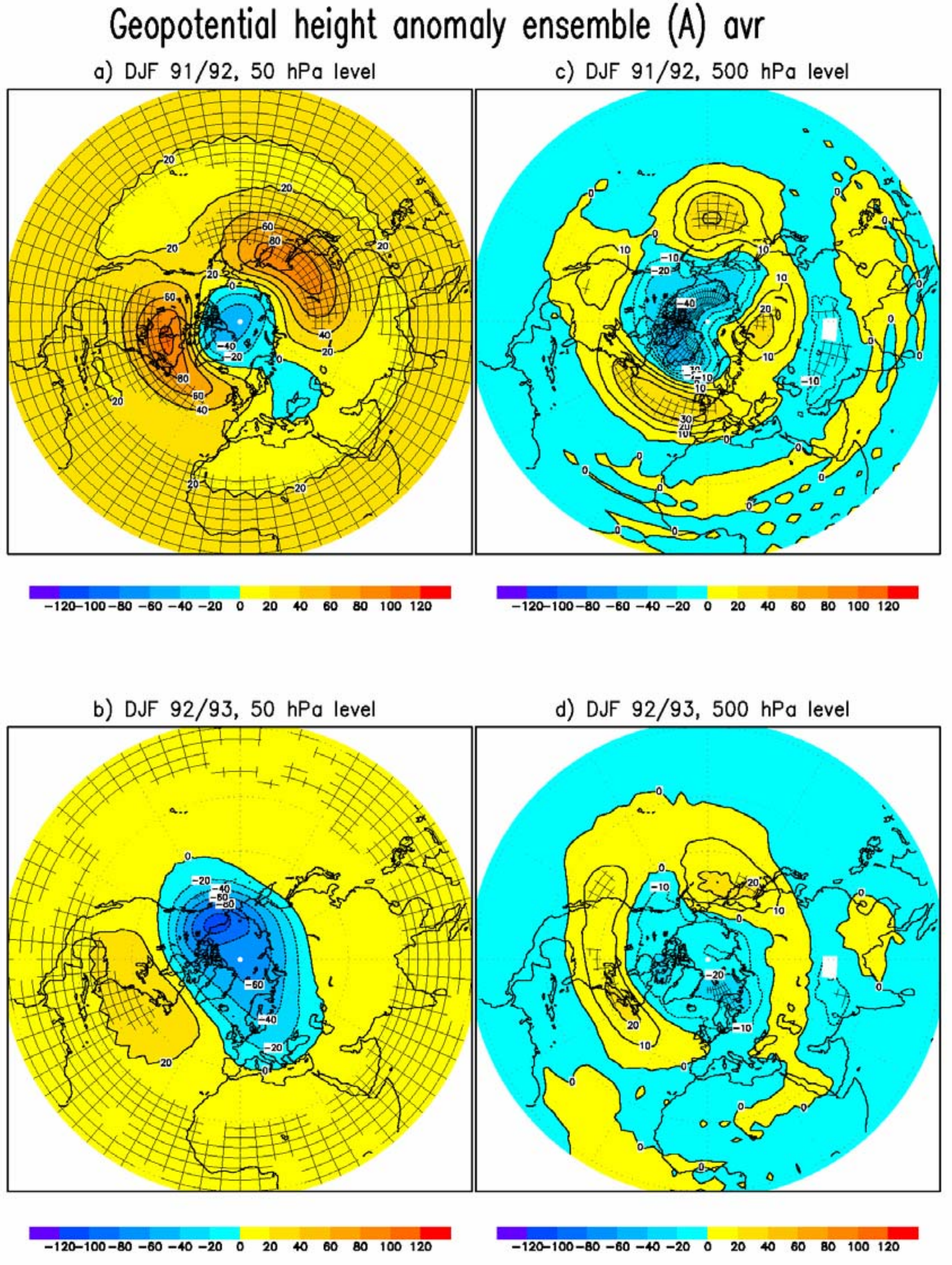
SKYHI simulations of geopotential height anomaly (m) at 50 hpa and 500 hPa caused by aerosols only (*A*)

Winter 91/92

Hatching shows 90%significance

Winter 92/93



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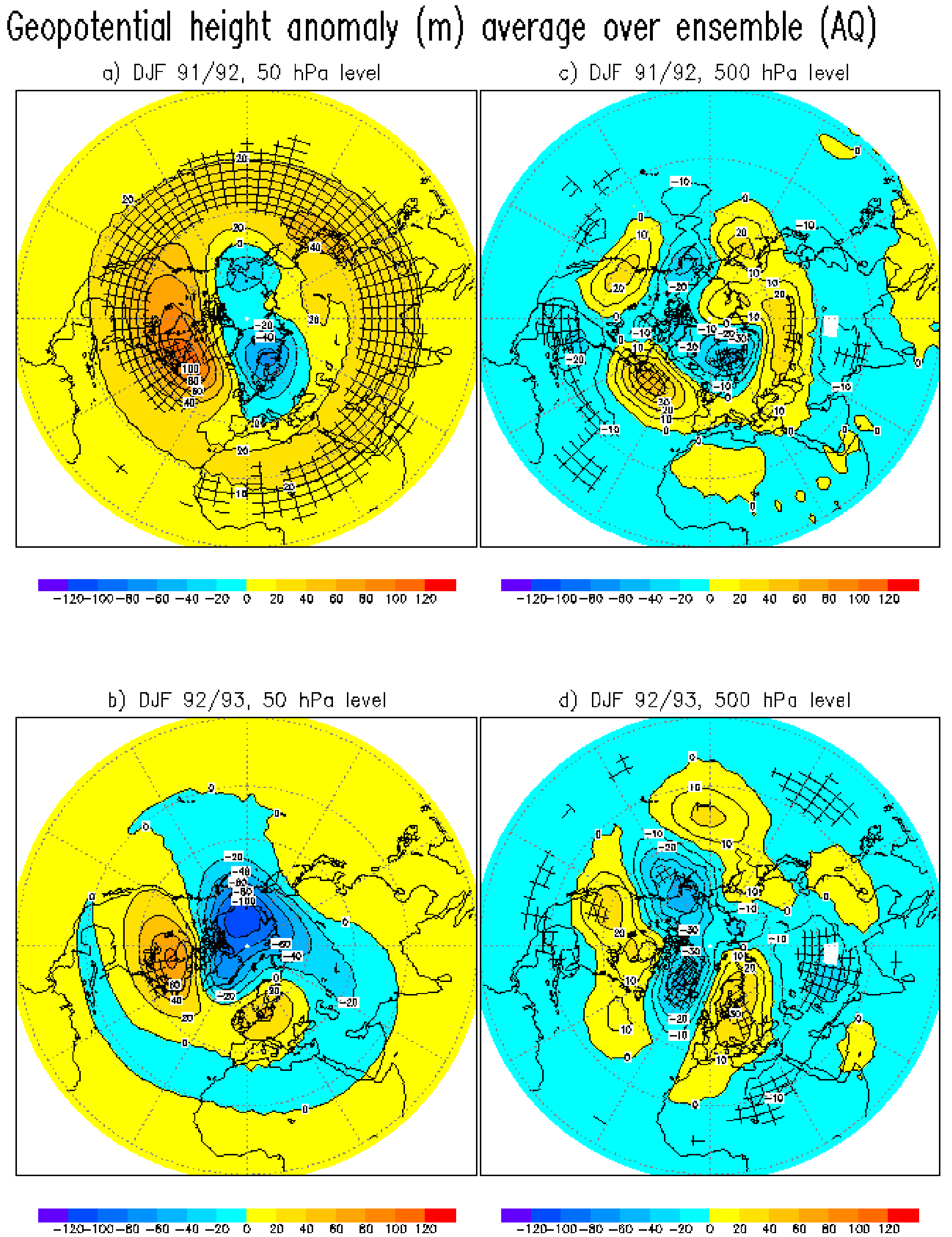
SKYHI simulations of geopotential height anomaly (m) at 50 hpa and 500 hPa caused by aerosols and QBO (AQ)

Winter of 91/92

Hatching shows 90% significance

Winter of 92/93



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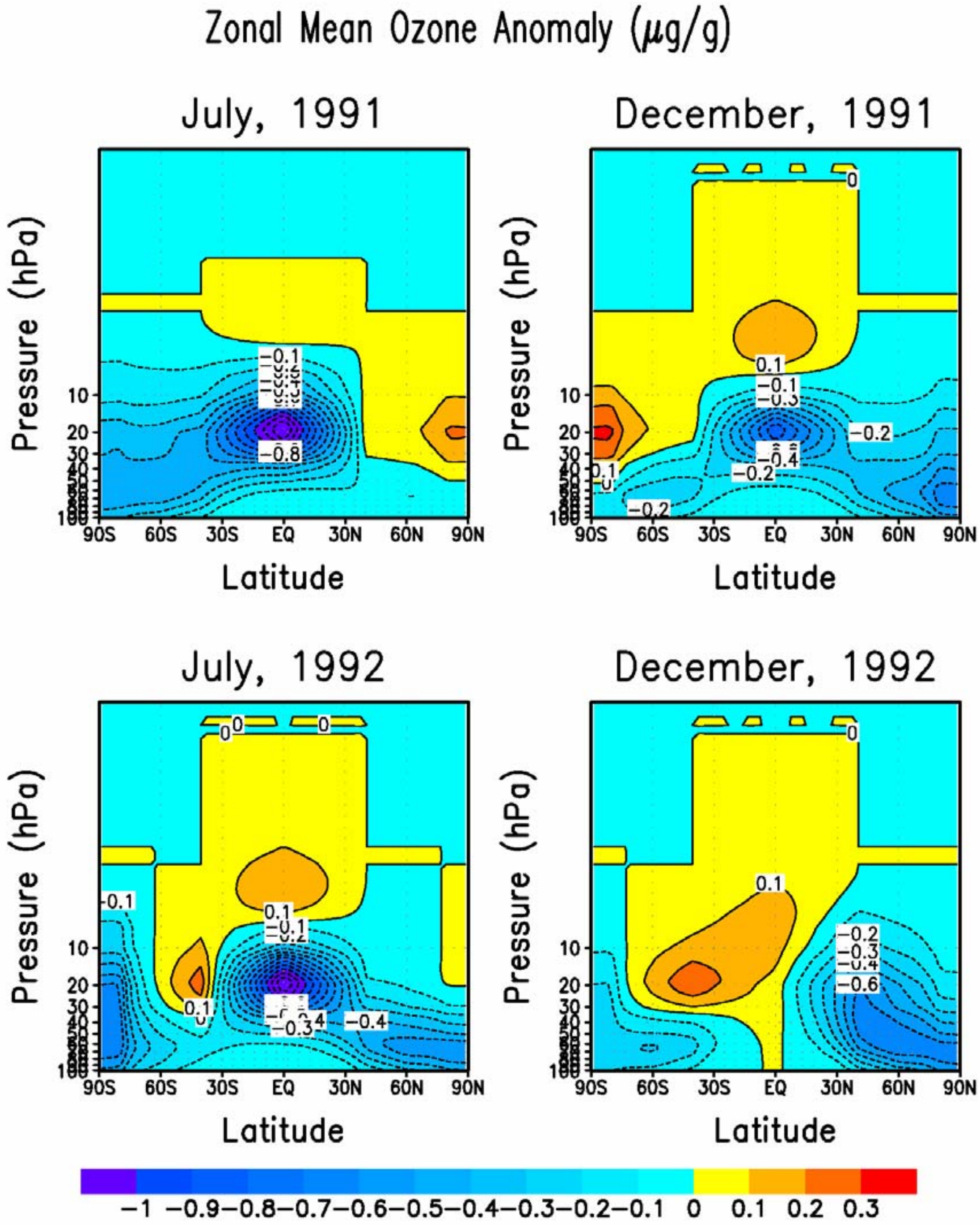
Zonal mean ozone anomalies (μg/g) as calculated using ozonesonde

Data provided by Jim Angell



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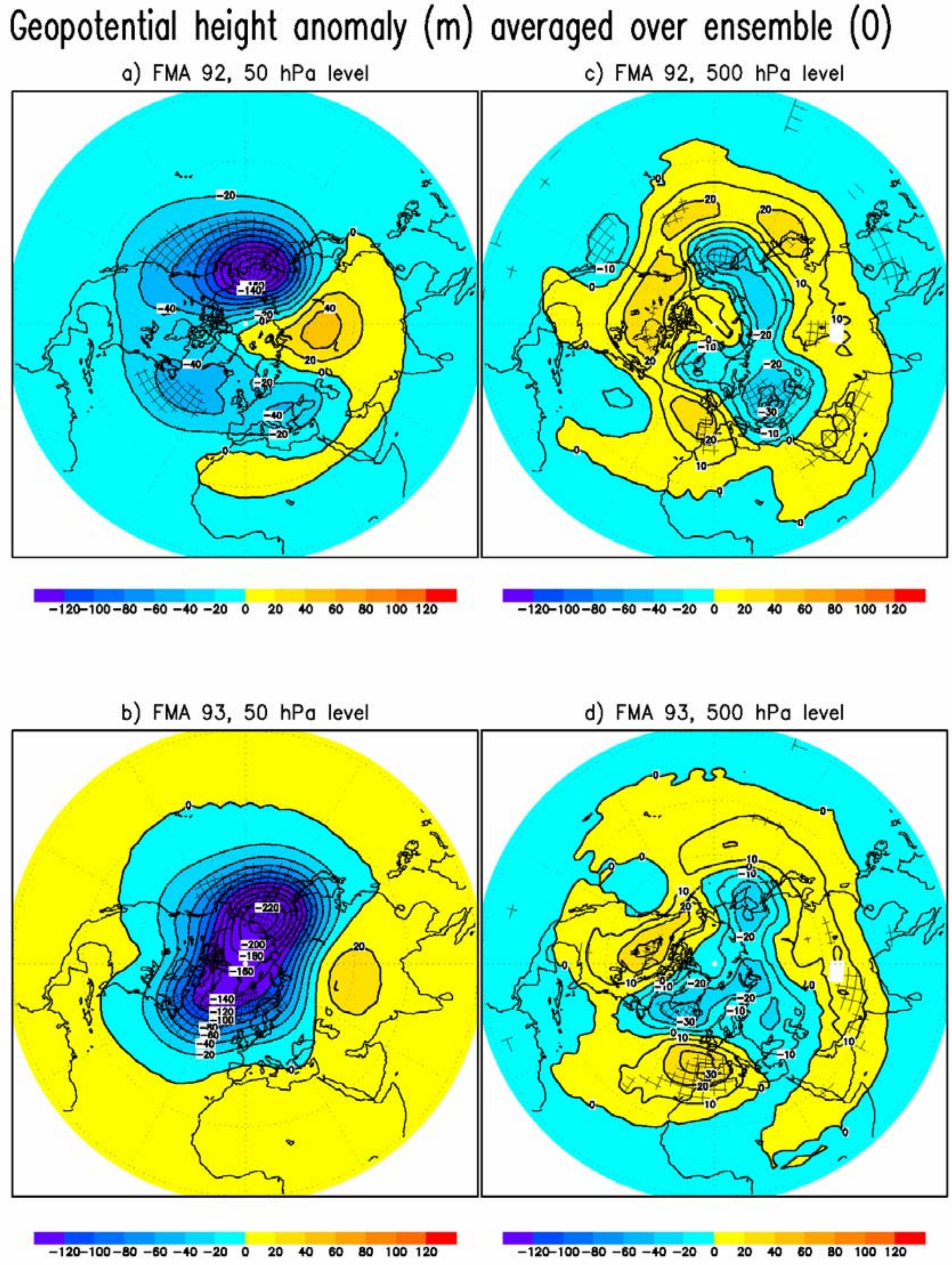
SKYHI simulations of geopotential height anomaly (m) at 50 hPa and 500 hPa caused by ozone only (O)

February-April 1992

Hatching shows 90% significance

February-April 1993



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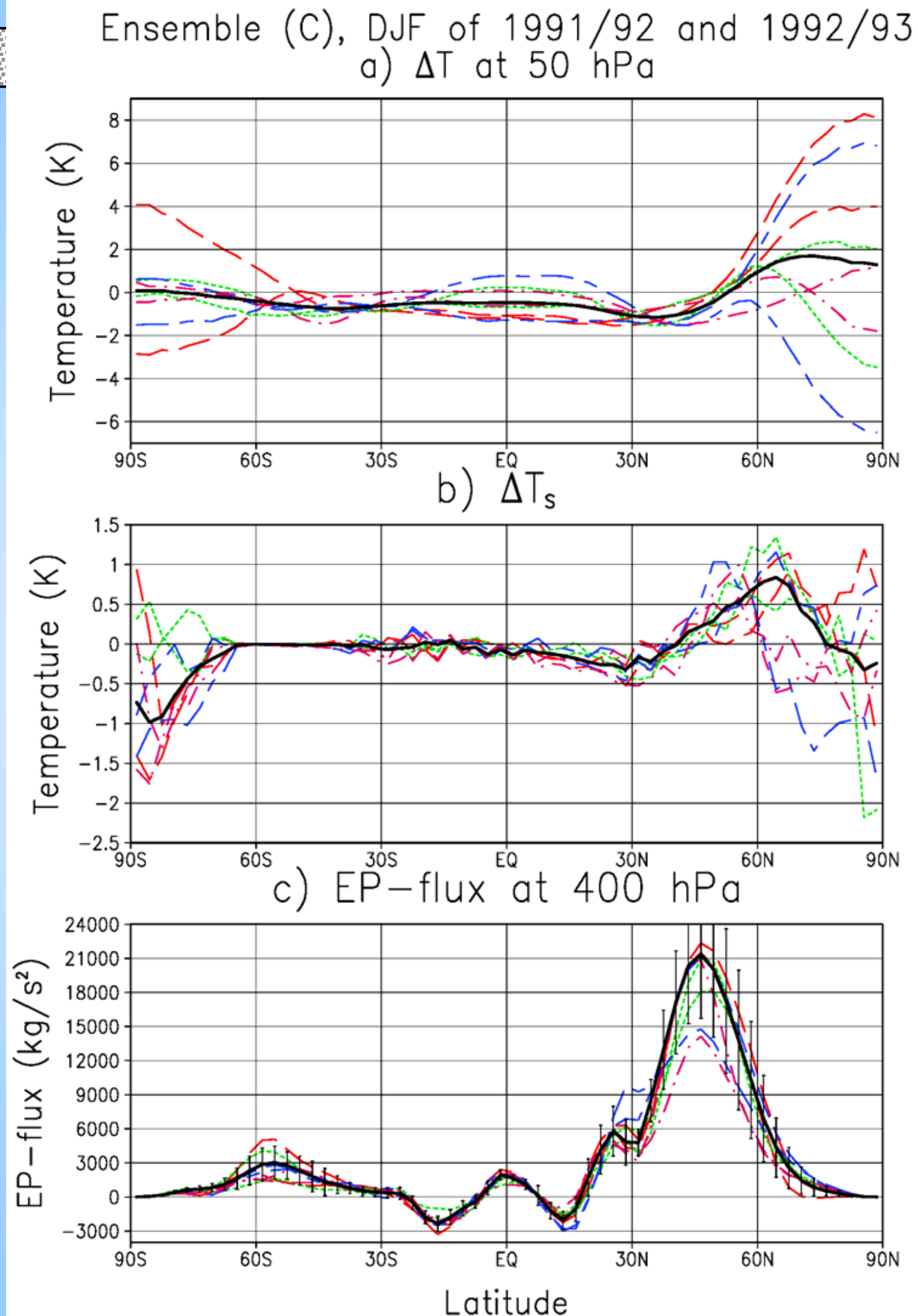
Zonal mean anomalies from ensemble (C) for the winters (DJF) of 1991/1992 and 1992/1993; each line is one member of the ensemble and the solid line is the mean; anomalies are calculated with respect to a 40-year mean from the control run for ensemble (A):

(a) temperature at 50 hPa;

(b) surface air temperature;

(c) vertical component of the EP flux (kg/s^2) at 400 hPa; bars show one standard deviation calculated from 40-year control (in black).



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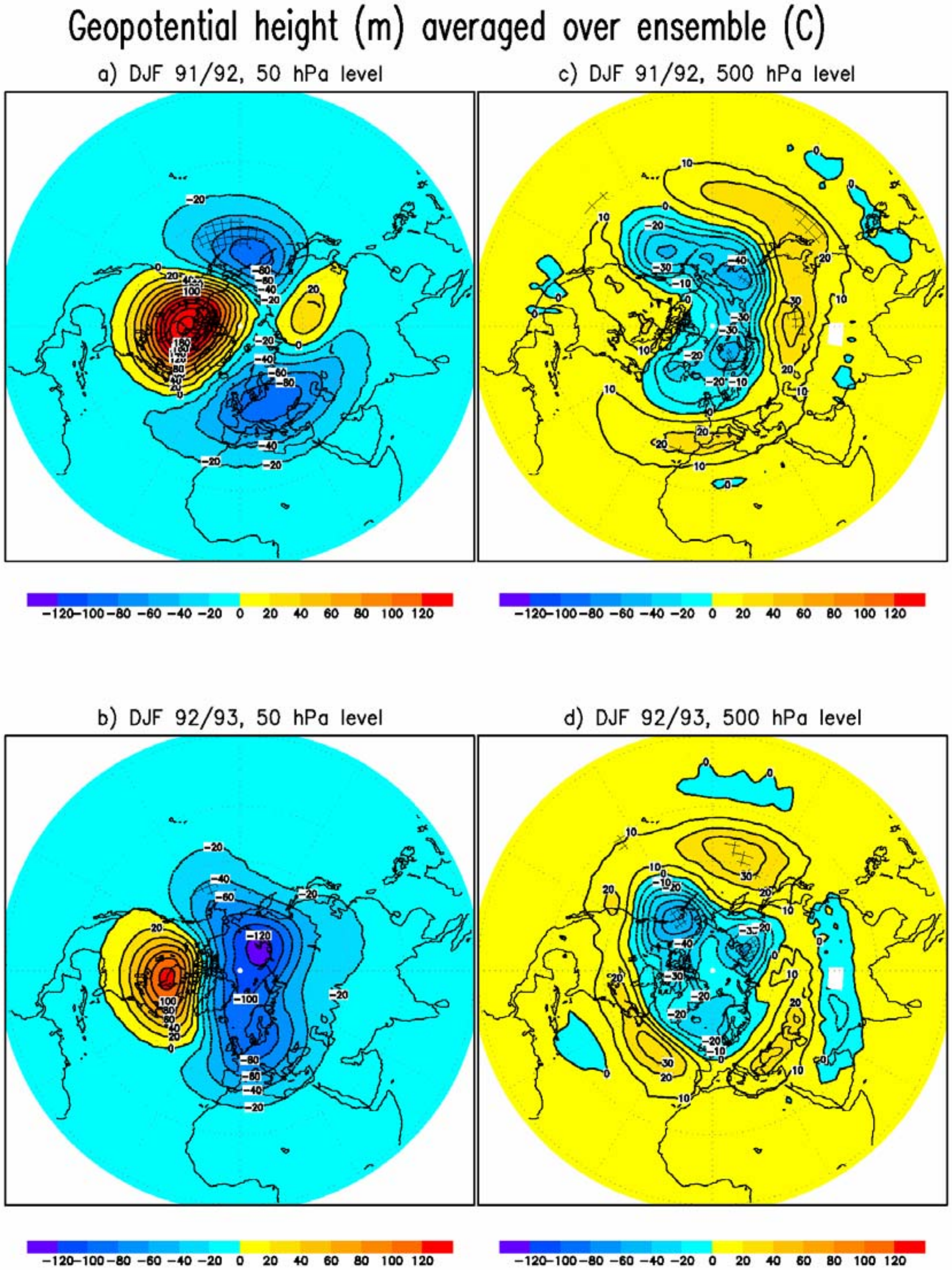
SKYHI simulations of geopotential height anomaly (m) at 50 hPa and 500 hPa caused by aerosol surface cooling only (C)

Winter of 91/92

Hatching shows 90% significance

Winter of 92/93



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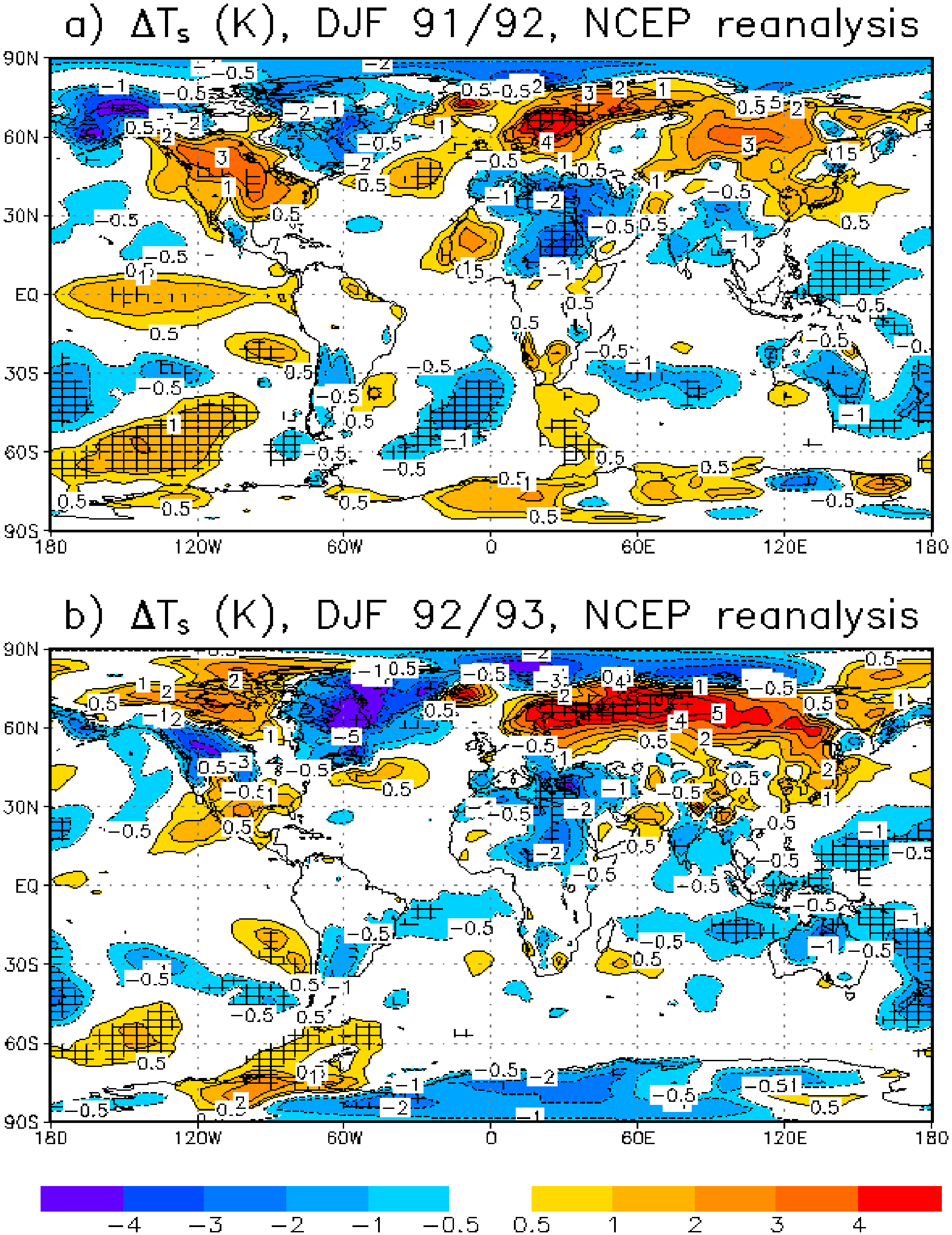
NCEP observations of surface air temperature anomalies (K) with respect to 1985-1990 mean

Winter 91/92

Hatching shows 90% significance

Winter 92/93



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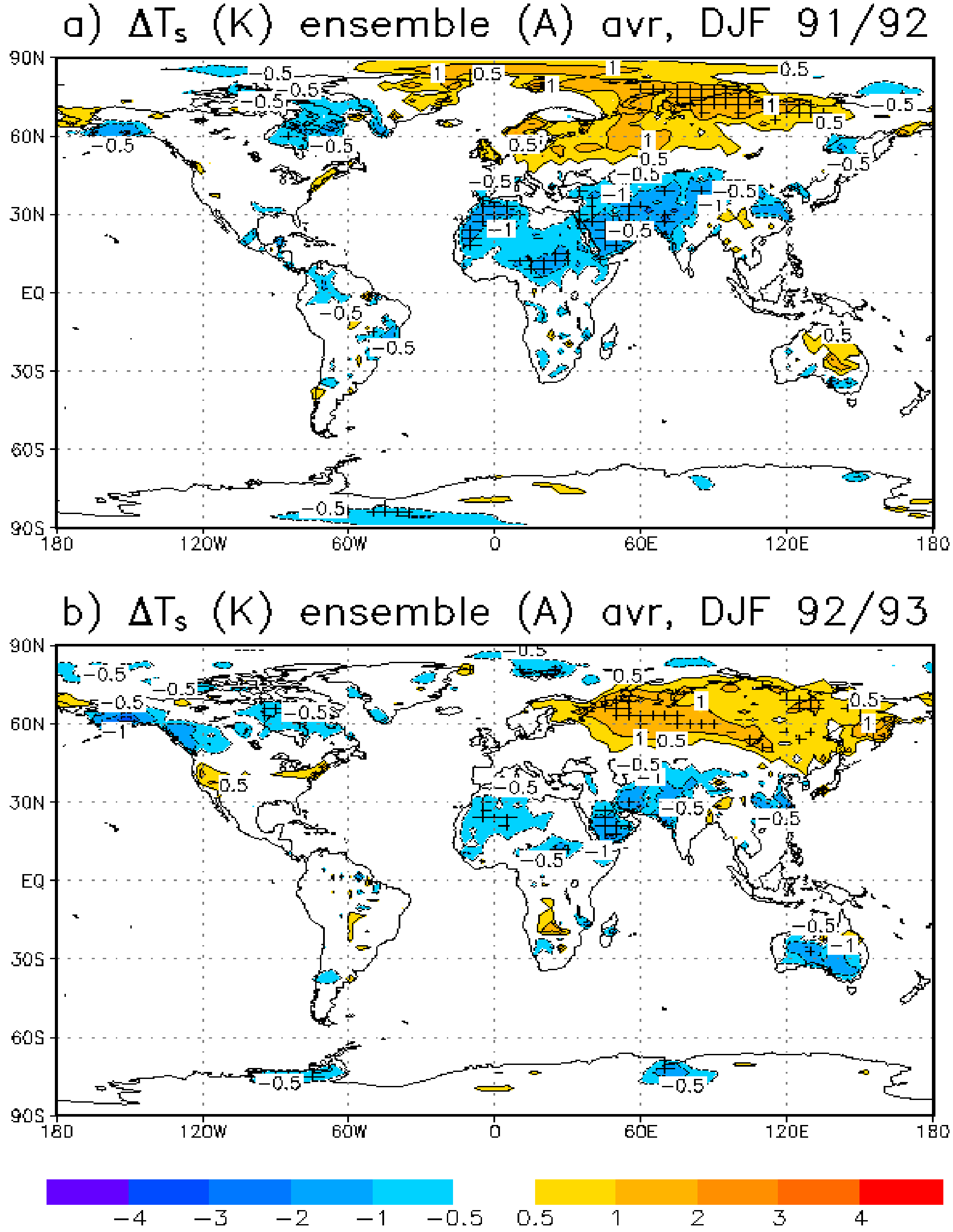
SKYHI simulations of surface temperature anomaly (K) caused by aerosols only (A)

Winter 91/92

Hatching shows 90% significance

Winter 92/93



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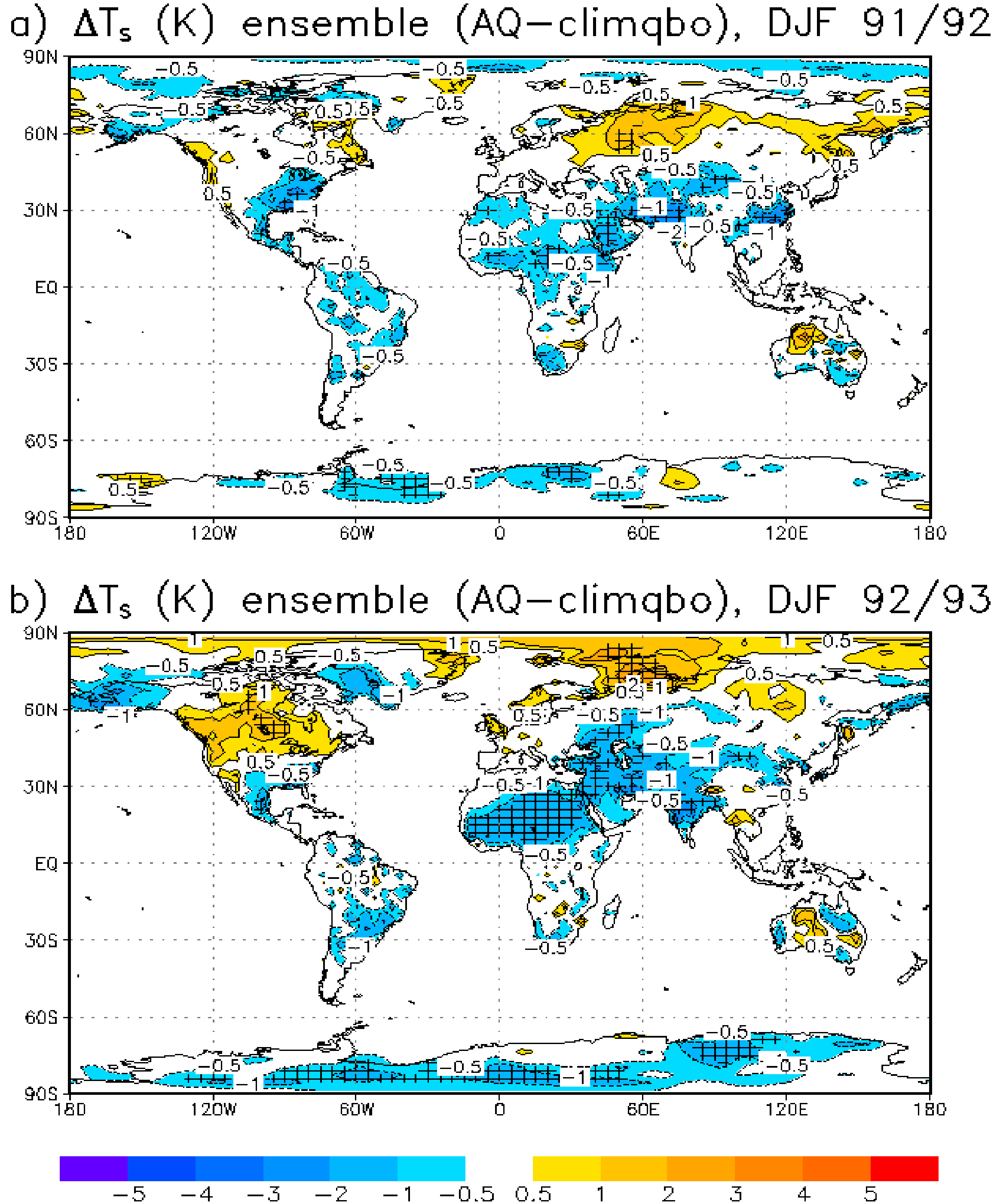
SKYHI simulations of surface temperature anomaly (K) caused by aerosols and QBO (AQ)

Winter of 91/92

Hatching shows 90% significance

Winter of 92/93



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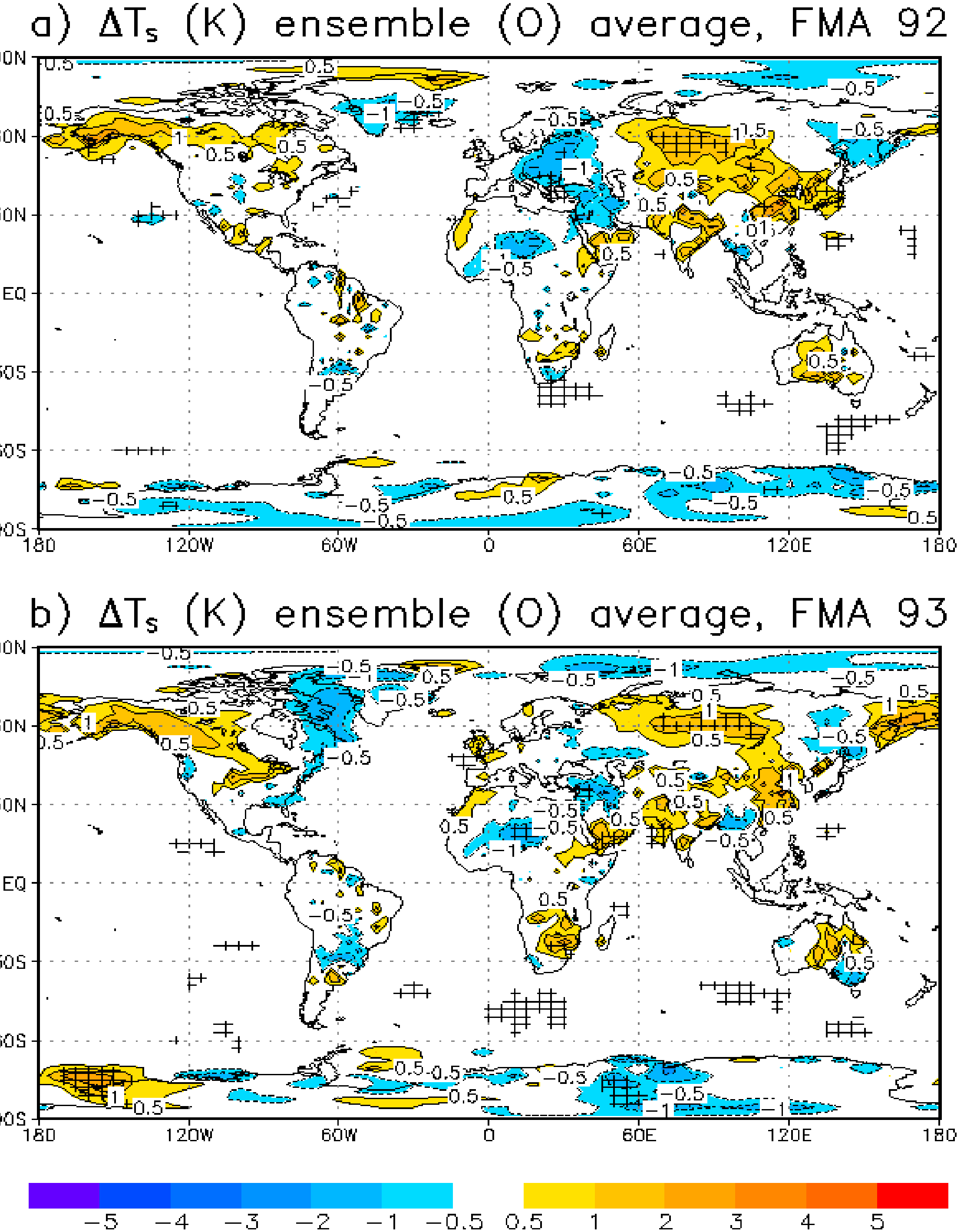
SKYHI simulations of surface temperature anomaly (K) caused by ozone changes only (O)

February-April 1992

Hatching shows 90% significance

February-April 1993



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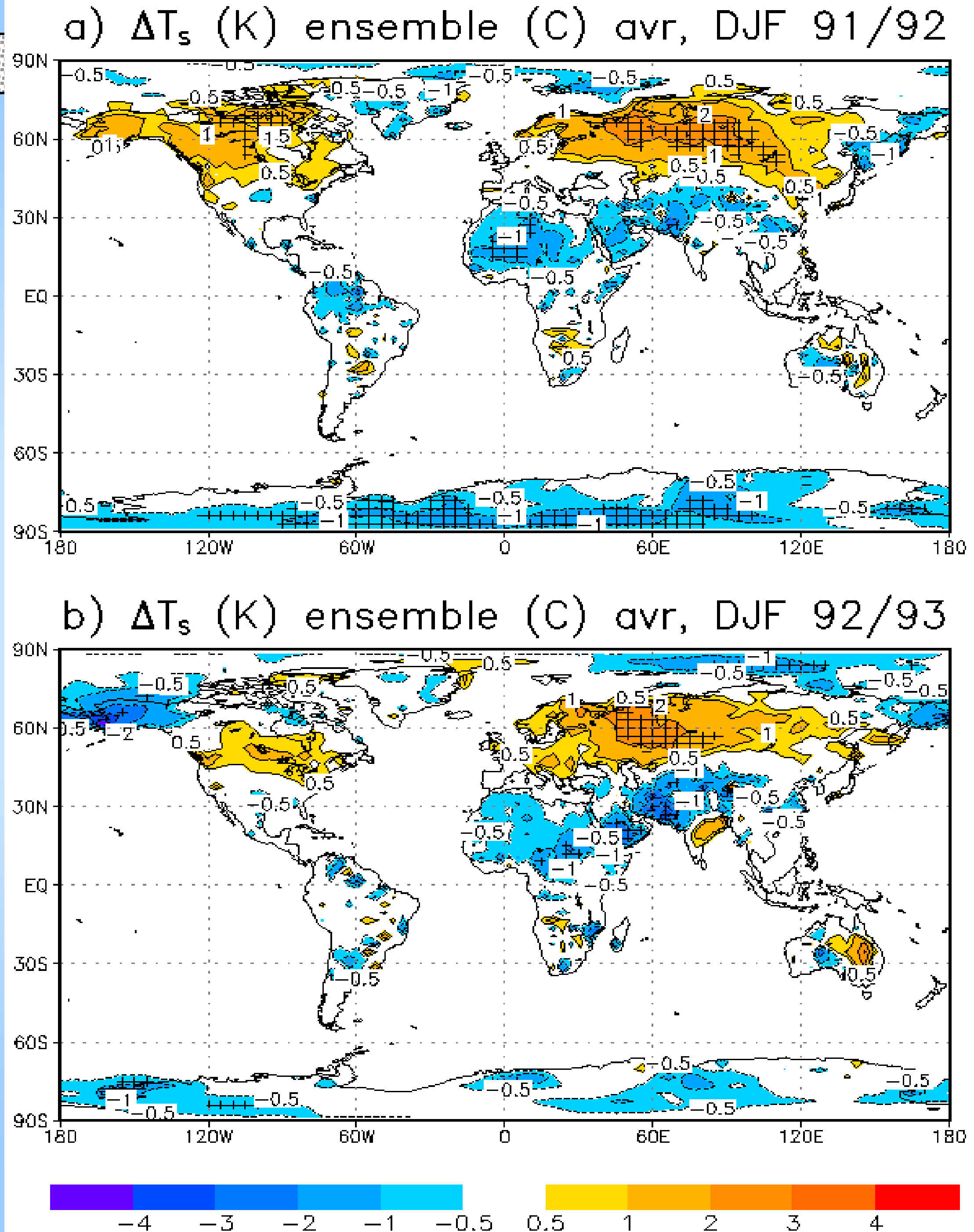
SKYHI simulations of surface temperature anomaly (K) caused by aerosol surface cooling only (C)

Winter of 91/92



Hatching shows 90% significance

Winter of 92/93

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Conclusions

Stratospheric aerosol heating, ozone depletion, and changes to the tropospheric temperature gradient all act to produce an Arctic Oscillation response following large tropical eruptions.

The ozone and tropospheric mechanisms are probably also important for long-term climatic response to ozone depletion and global warming.

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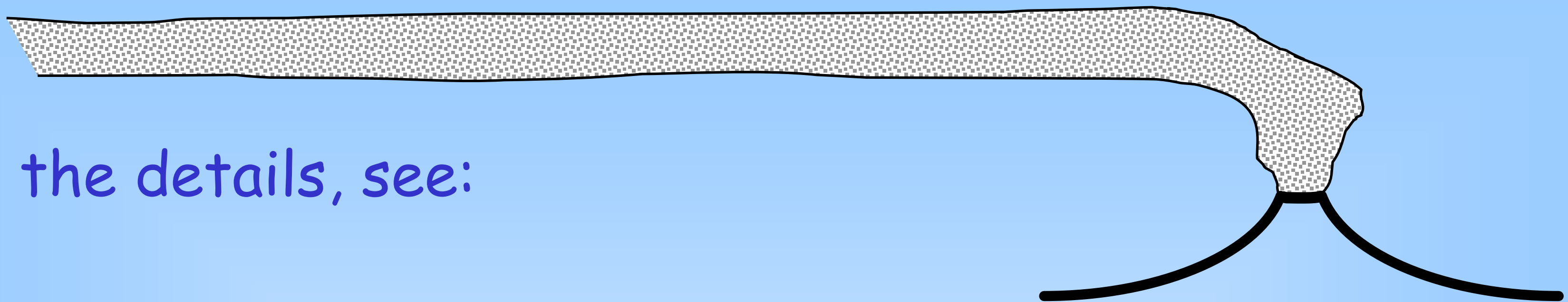
For the details, see:



Stenchikov, Georgiy, Alan Robock, V. Ramaswamy, M. Daniel Schwarzkopf, Kevin Hamilton, and S. Ramachandran, 2002: Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion. *J. Geophys. Res.*, **107 (D24)**, 4803, doi:10.1029/2002JD002090.

Stenchikov, Georgiy, Kevin Hamilton, Alan Robock, V. Ramaswamy, and M. Daniel Schwarzkopf, 2003: Arctic Oscillation response to the 1991 Pinatubo eruption in the SKYHI GCM with a realistic Quasi-Biennial Oscillation. Submitted to *J. Geophys. Res.*

Available at http://envsci.rutgers.edu/~robock

The Relationship Between Snow Cover, Soil Moisture, and the Indian Summer Monsoon: Observations and Model Simulations

Alan Robock, Rutgers University

Collaborators:

Mingquan Mu, Rutgers University

Konstantin Vinnikov, University of Maryland

David Robinson, Rutgers University

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Blanford found a negative correlation between snow cover and Indian summer monsoon rainfall:

Blanford, H. F., 1884: On the connexion of the Himalaya snowfall with dry winds and seasons of drought in India. *Proc. Roy. Soc. London*, 37, 3-22.

"the varying *extent* and *thickness* of the Himalayan snows exercise a great and prolonged influence on the climatic conditions and weather of the plains of North-Western India...."

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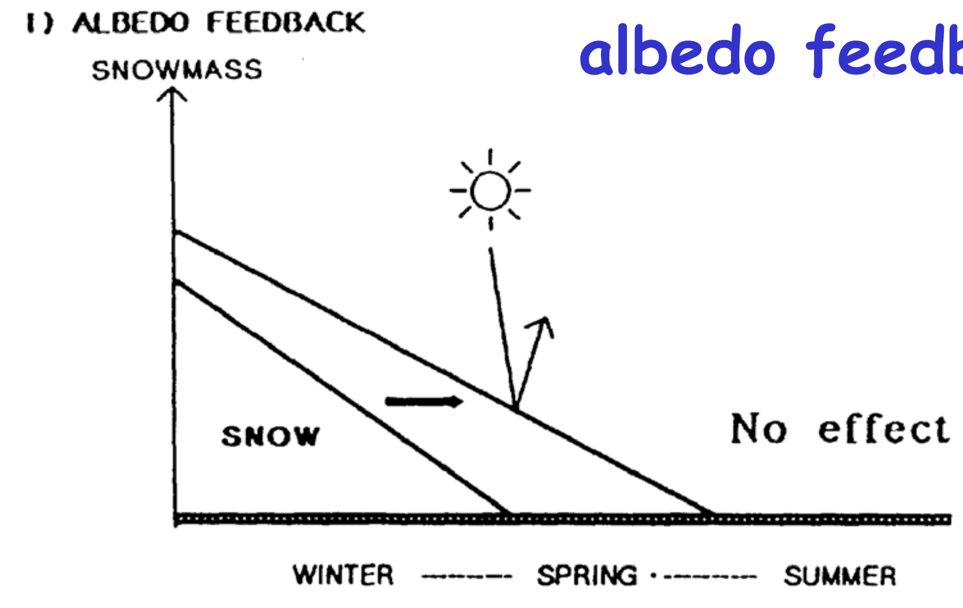
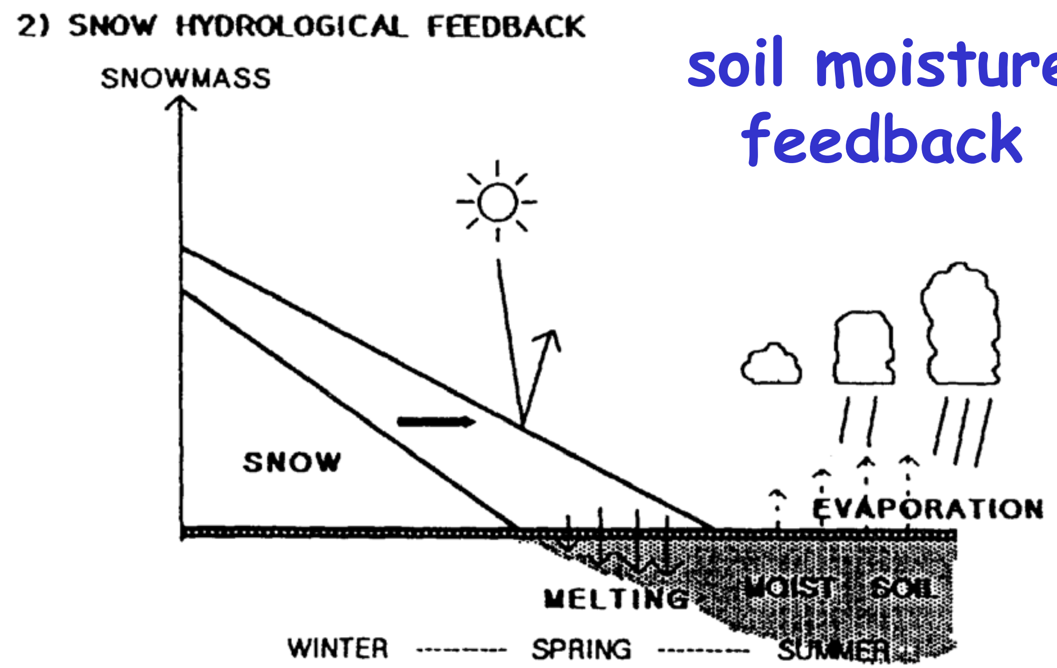
Yasunari et al. (1991)

Snow can affect the surface heat budget through albedo and soil moisture feedbacks.

Are these responsible for the observed relationship between snow and the monsoon?



albedo feedback



soil moisture feedback

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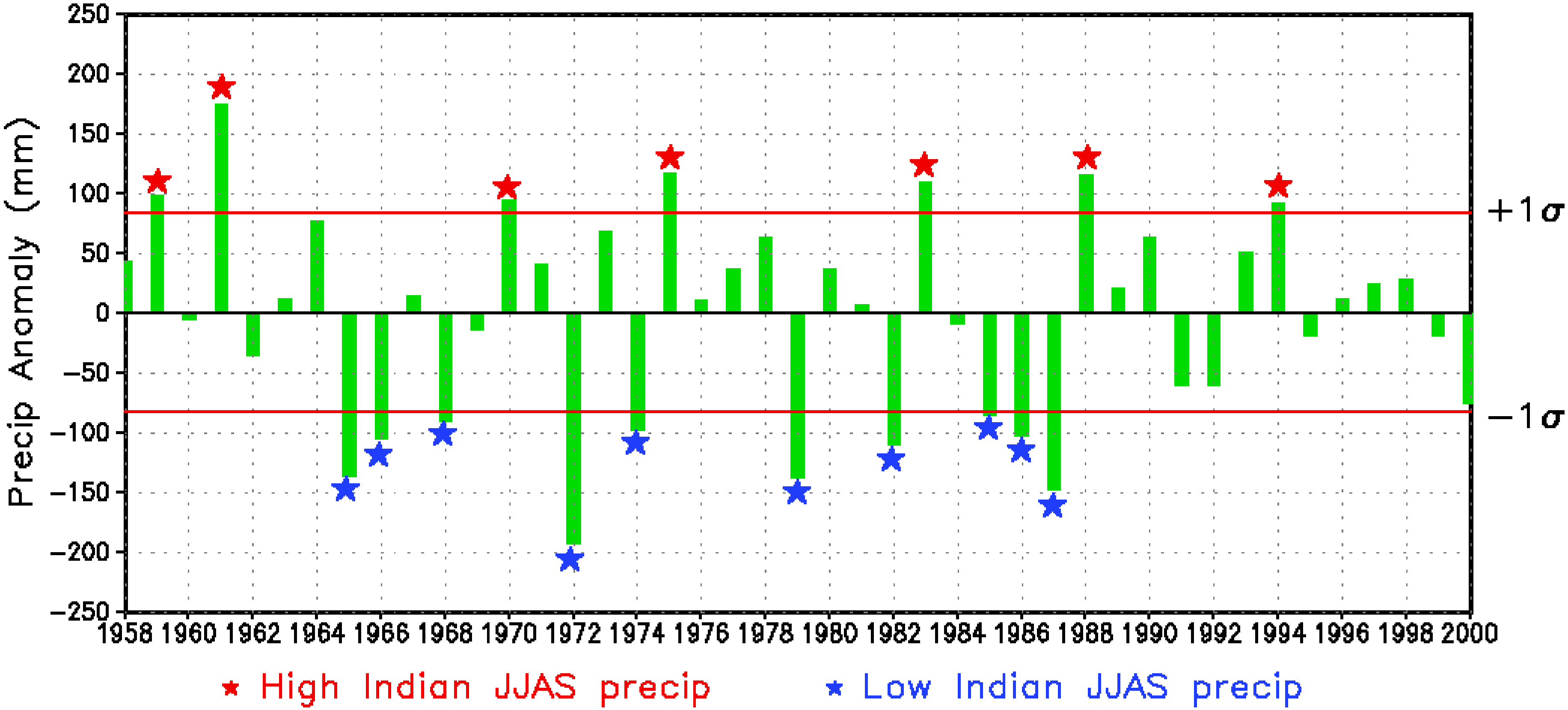

All−India JJAS precipitation anomaly with respect to 1958−1998 mean

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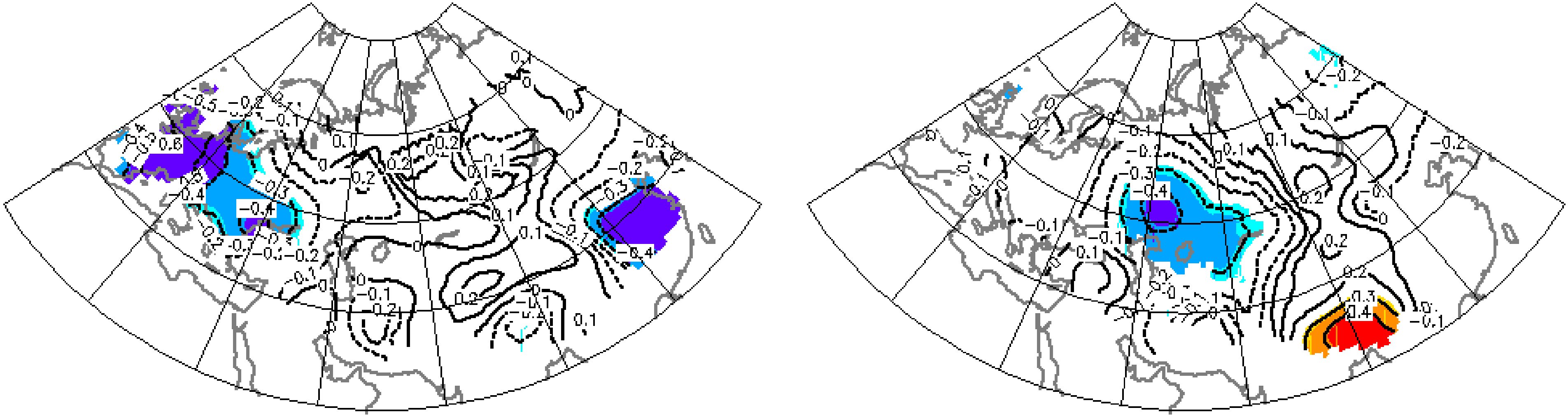
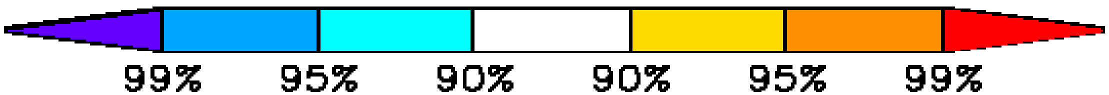
Department of Environmental Sciences



DJF MAM

1967-2000 detrended

Significance level



Correlation between All-India rainfall (1967–2000) and the previous winter and spring snow cover

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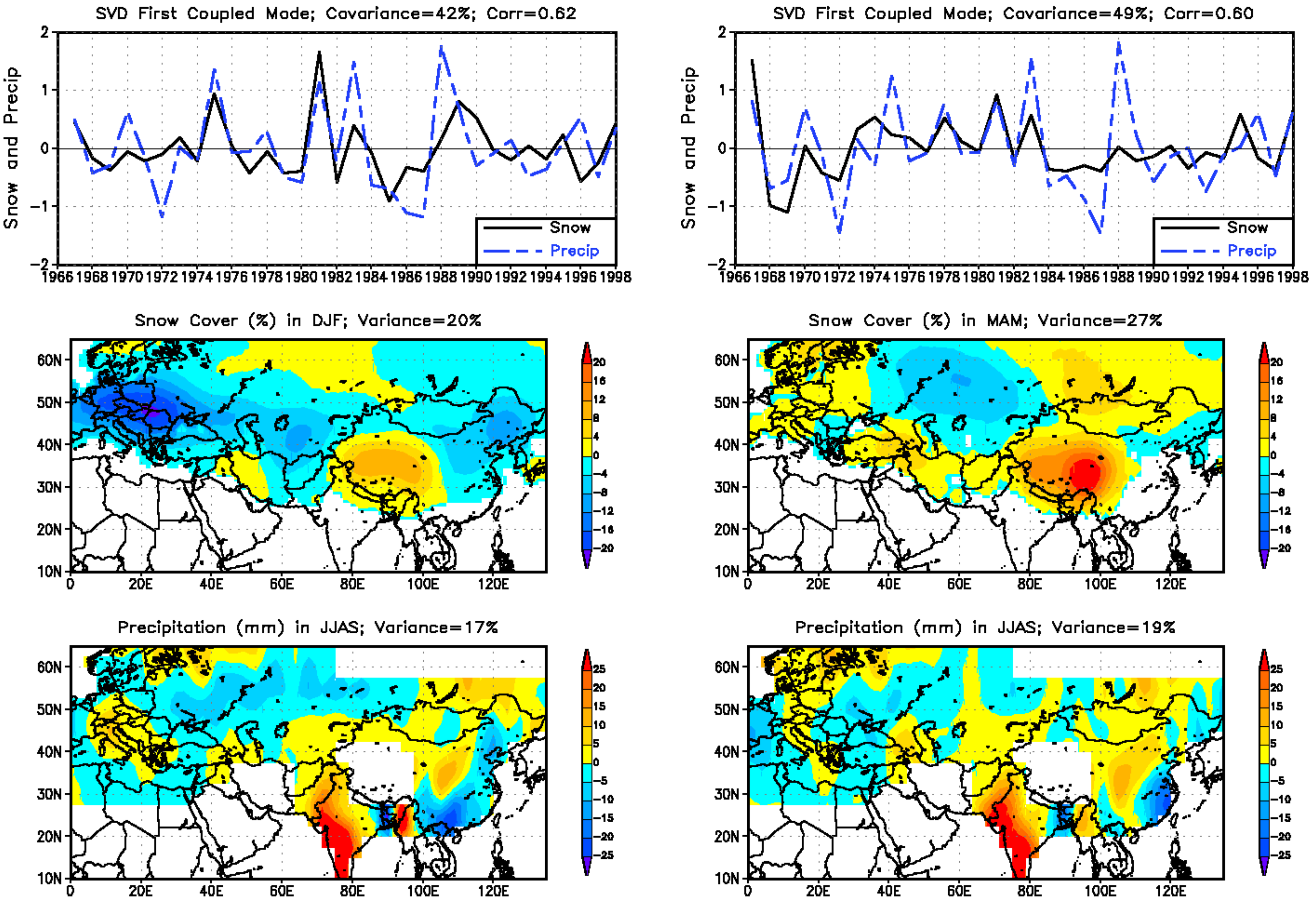
Detrended snow and precipitation - first SVD coupled mode, 1967-1998

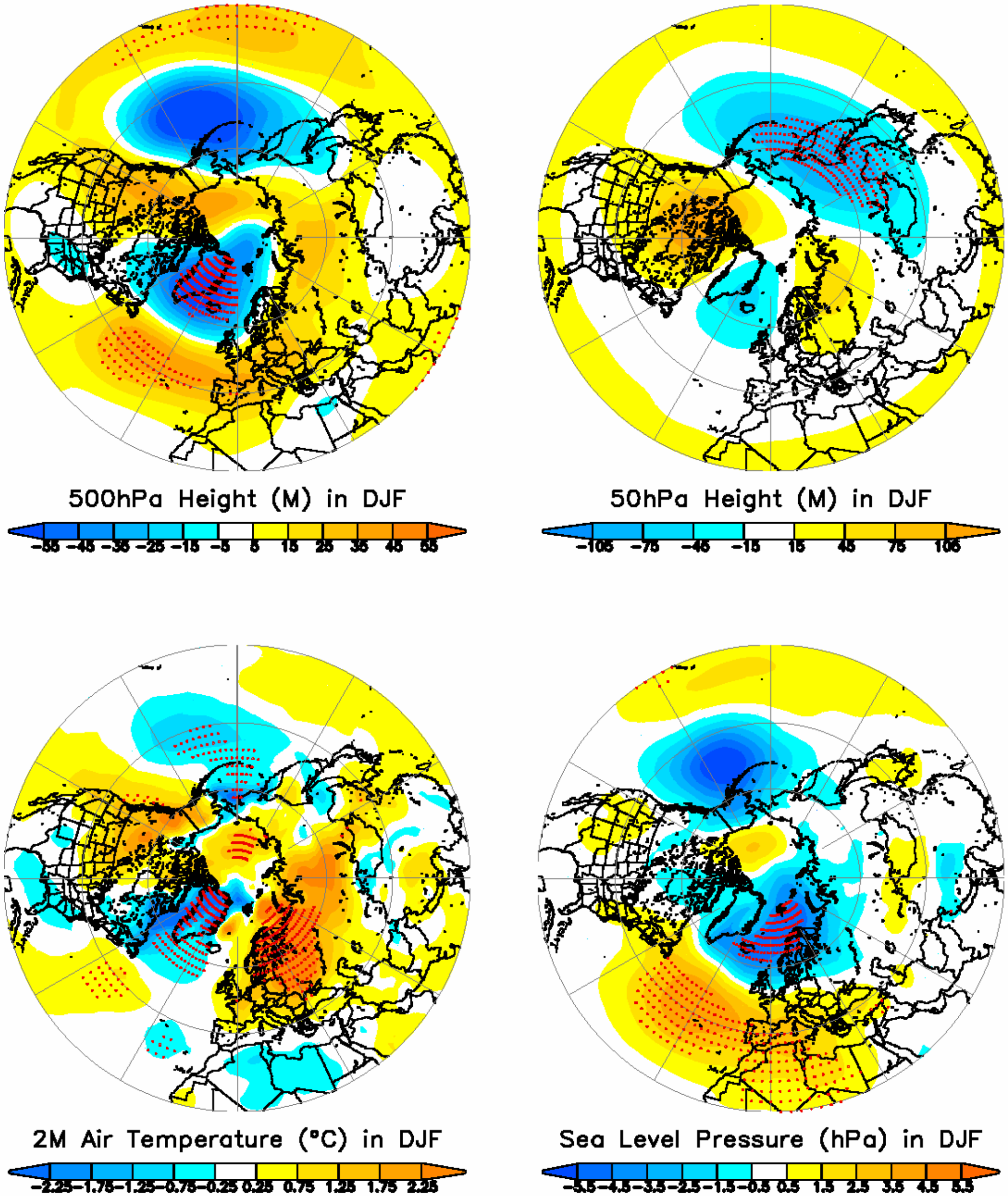


Circulation and temperature in previous winter

1958-1998

Composite of years with **high** JJAS Indian precipitation ***minus*** those with **low** JJAS Indian precipitation

- Significance from Monte Carlo tests



• 95% significance level

High Indian JJAS precip minus low Indian JJAS precip
Based on data from 1958 to 1998

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The Arctic Oscillation

Thompson and Wallace (1998)

Stronger polar vortex

Warm advection into Europe

Winter warming

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The Arctic Oscillation signature in the wintertime geopotential height and temperature fields (Fig. 1 maps)

David W. J. Thompson and John. M. Wallace

Geophysical Research Letters, May 1, 1998

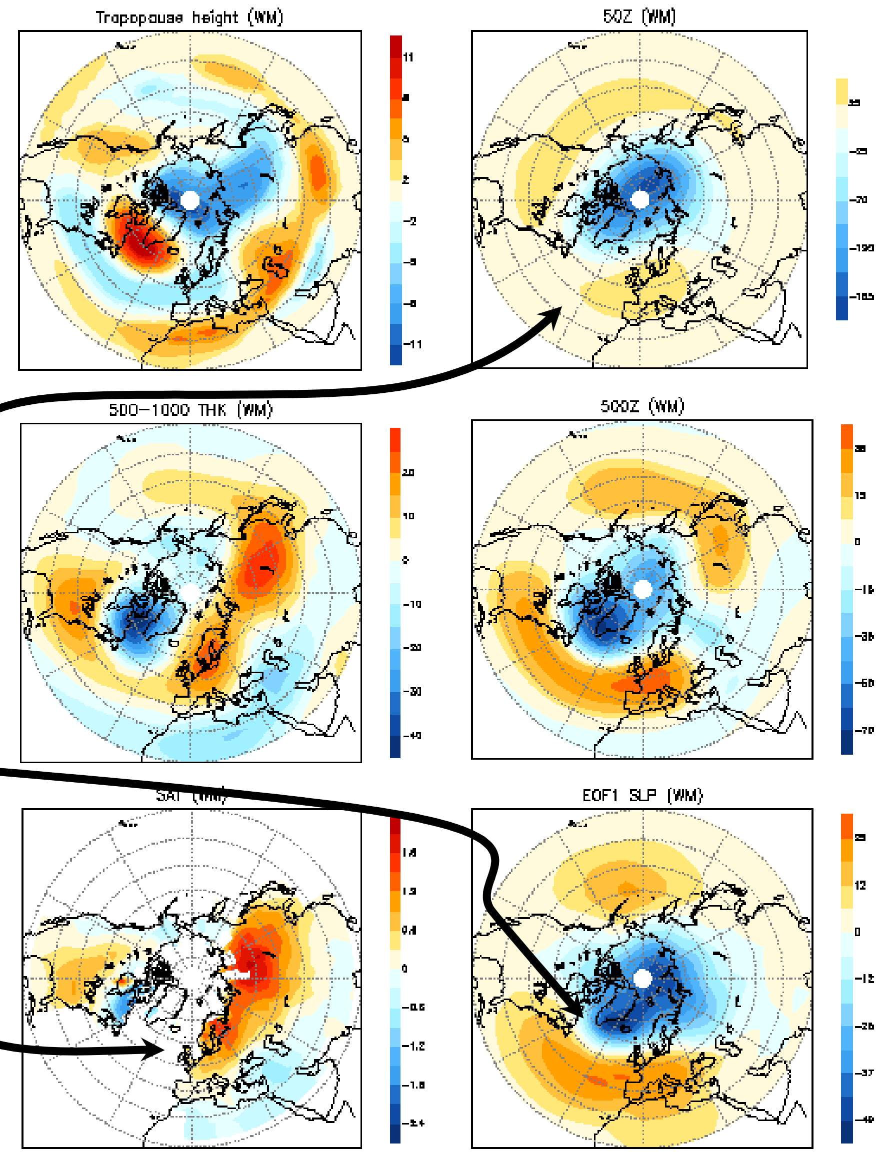
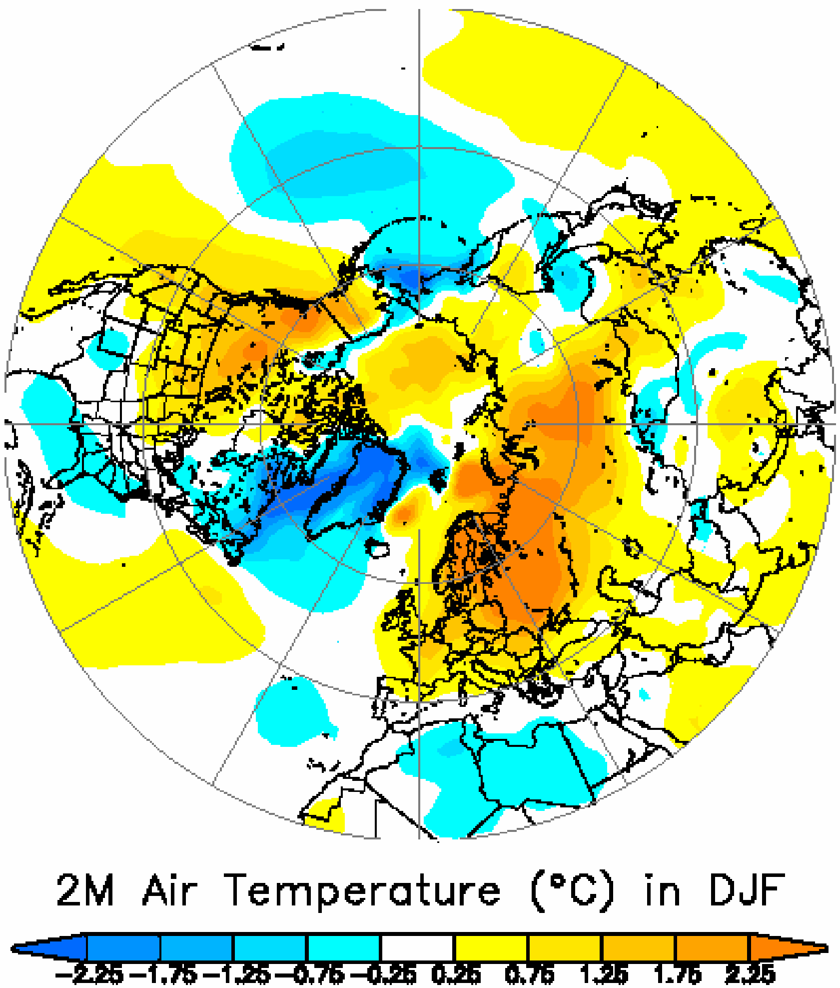
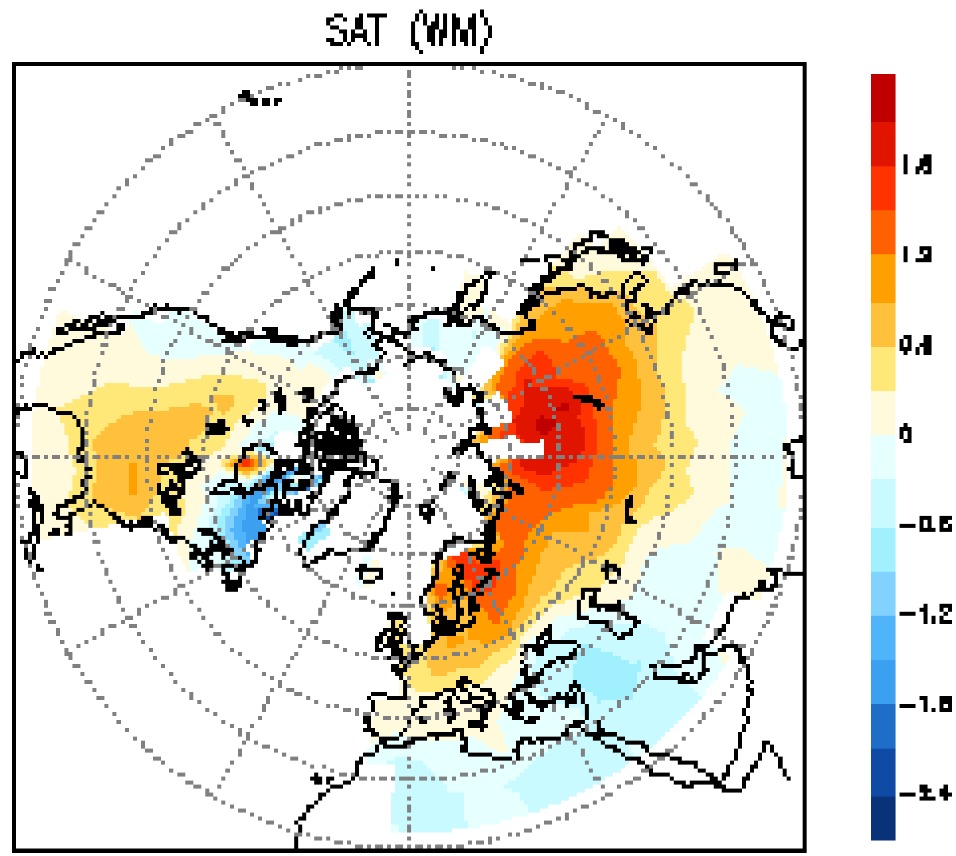


Figure 1. Regression maps for geopotential height (*meters*), tropopause pressure (*Pa*), 1000-500-hPa thickness (*m*), SLP (expressed as Z_{1000}: *m*) and surface air temperature (SAT-*K*) anomalies as indicated, based upon the AO index for 1947-1997. See text for details.

Strong Indian Monsoon

Arctic Oscillation





Surface temperature same

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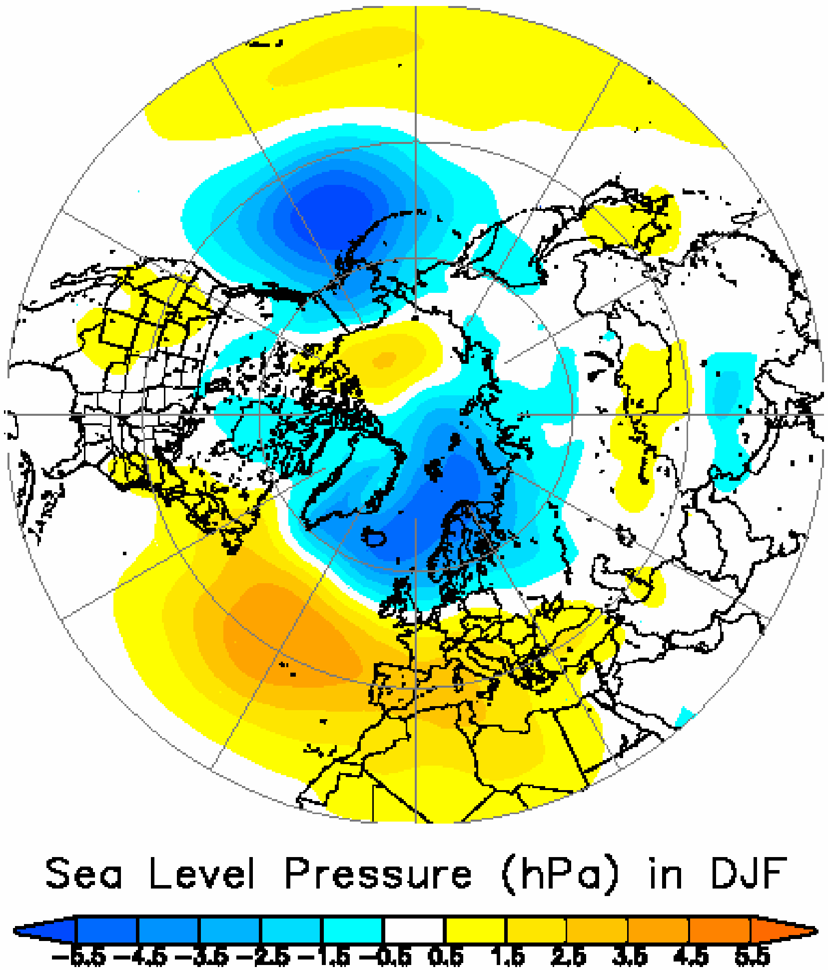
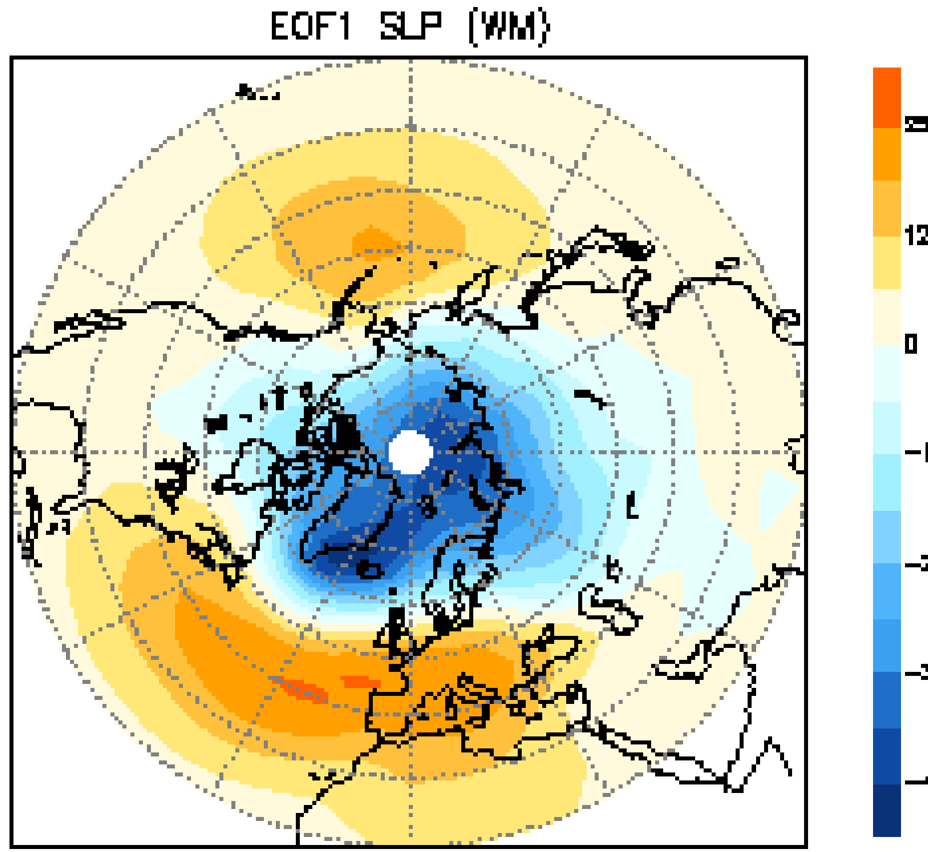
Strong Indian Monsoon



Arctic Oscillation



SLP same only in Atlantic

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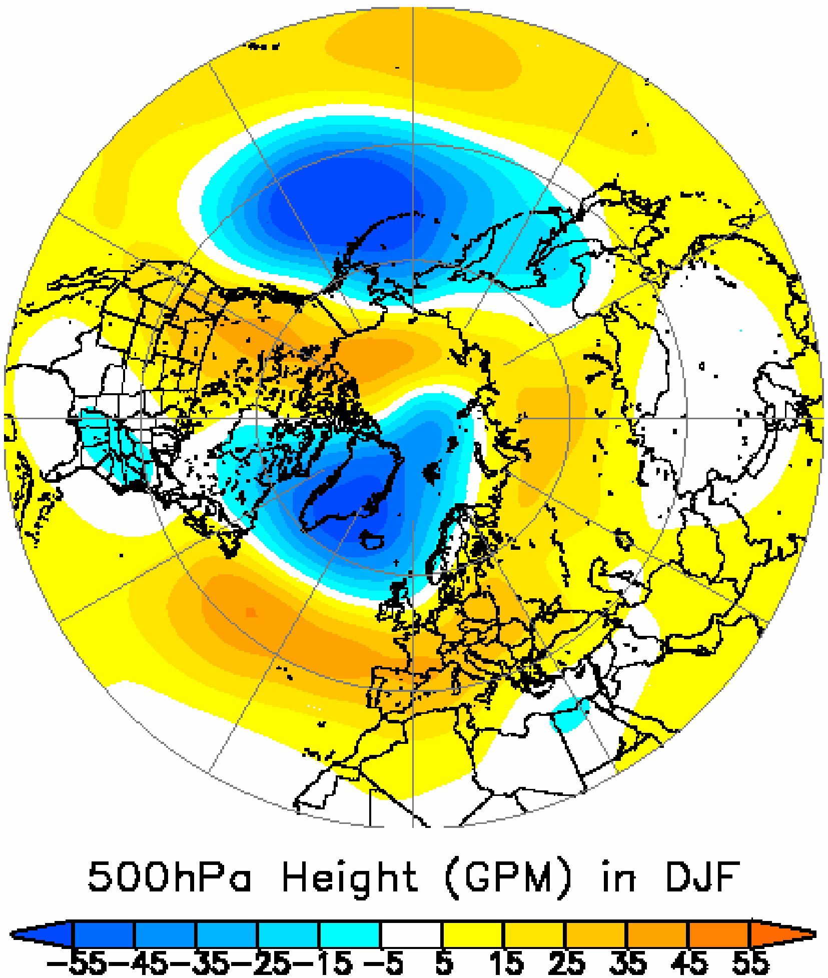
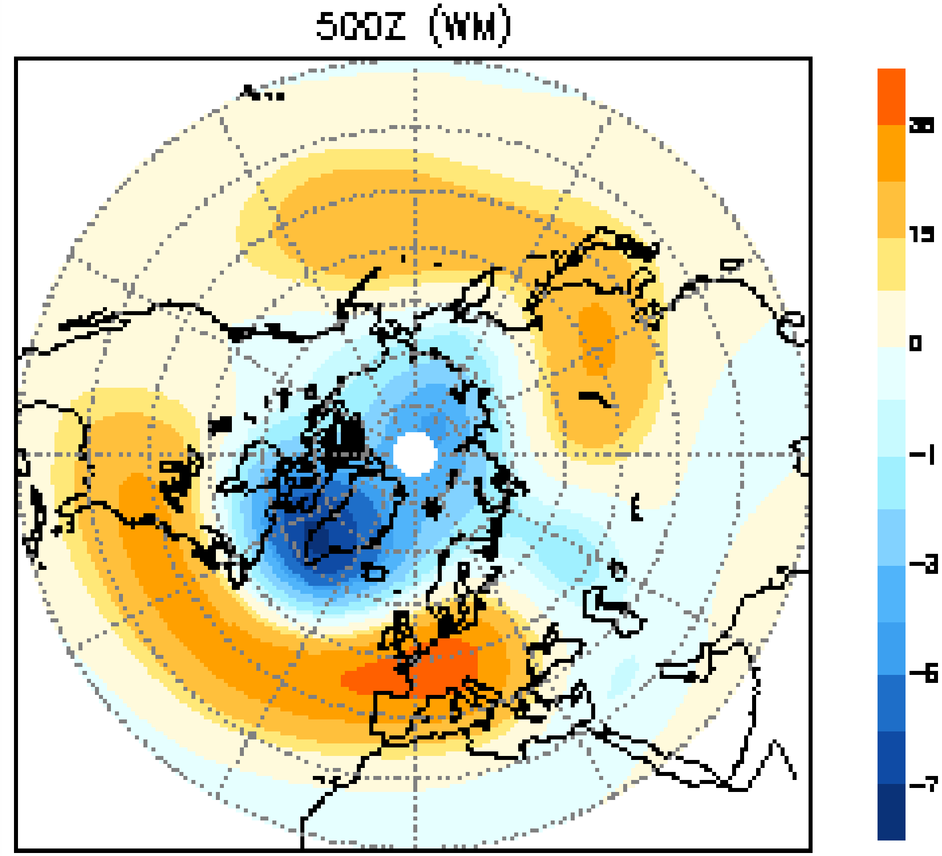
Strong Indian Monsoon

Arctic Oscillation





500 hPa same only in Atlantic

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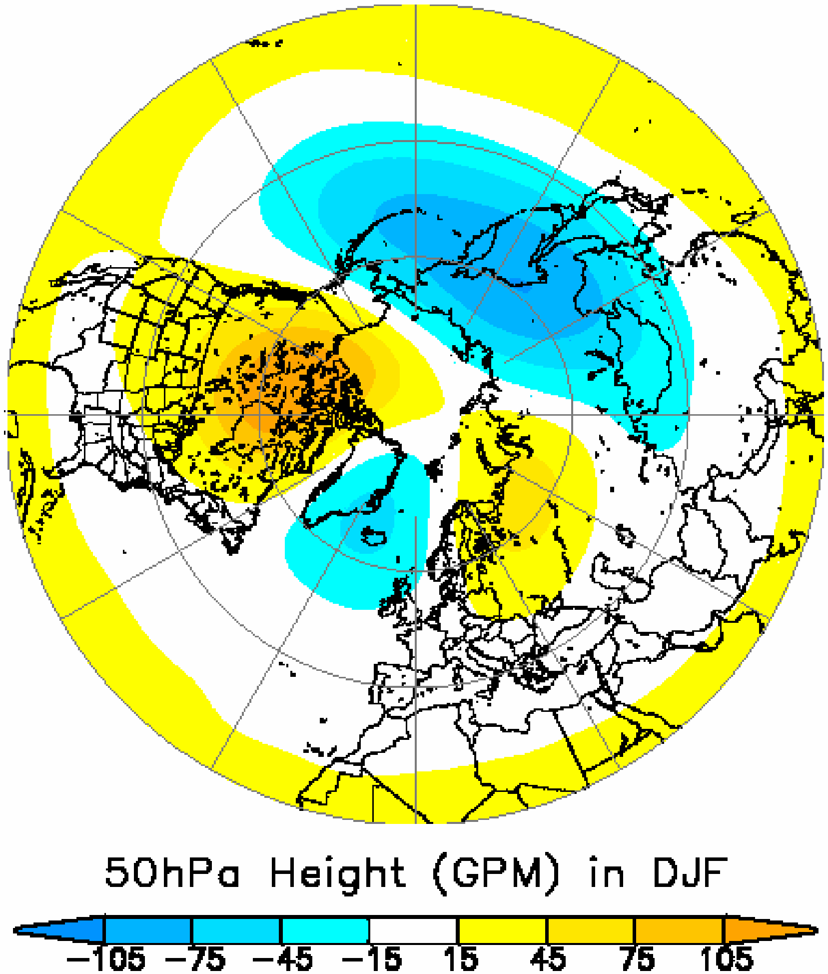
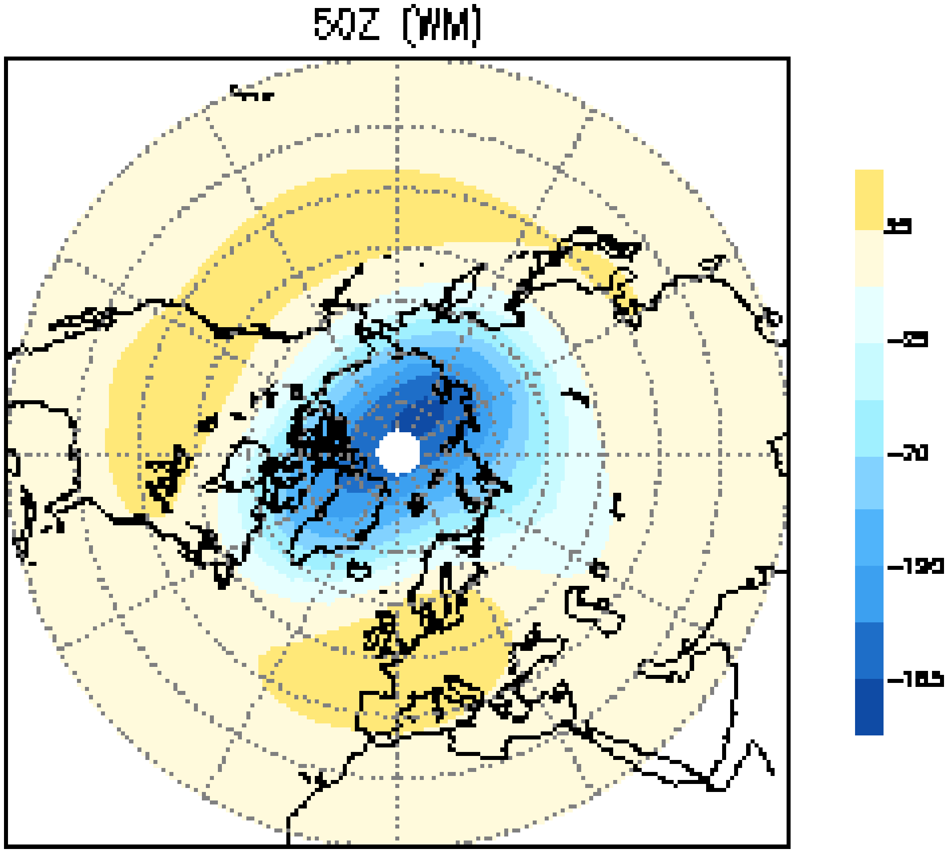
Strong Indian Monsoon

Arctic Oscillation





50 hPa not same at all

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So the circulation pattern that precedes strong Indian monsoon rainfall is associated with the North Atlantic Oscillation (NAO), and not with the AO. It is a tropospheric and not a coupled tropospheric-stratospheric circulation mode.

Let's see if we can use NAO as an index to examine the period before we have reliable snow cover data.

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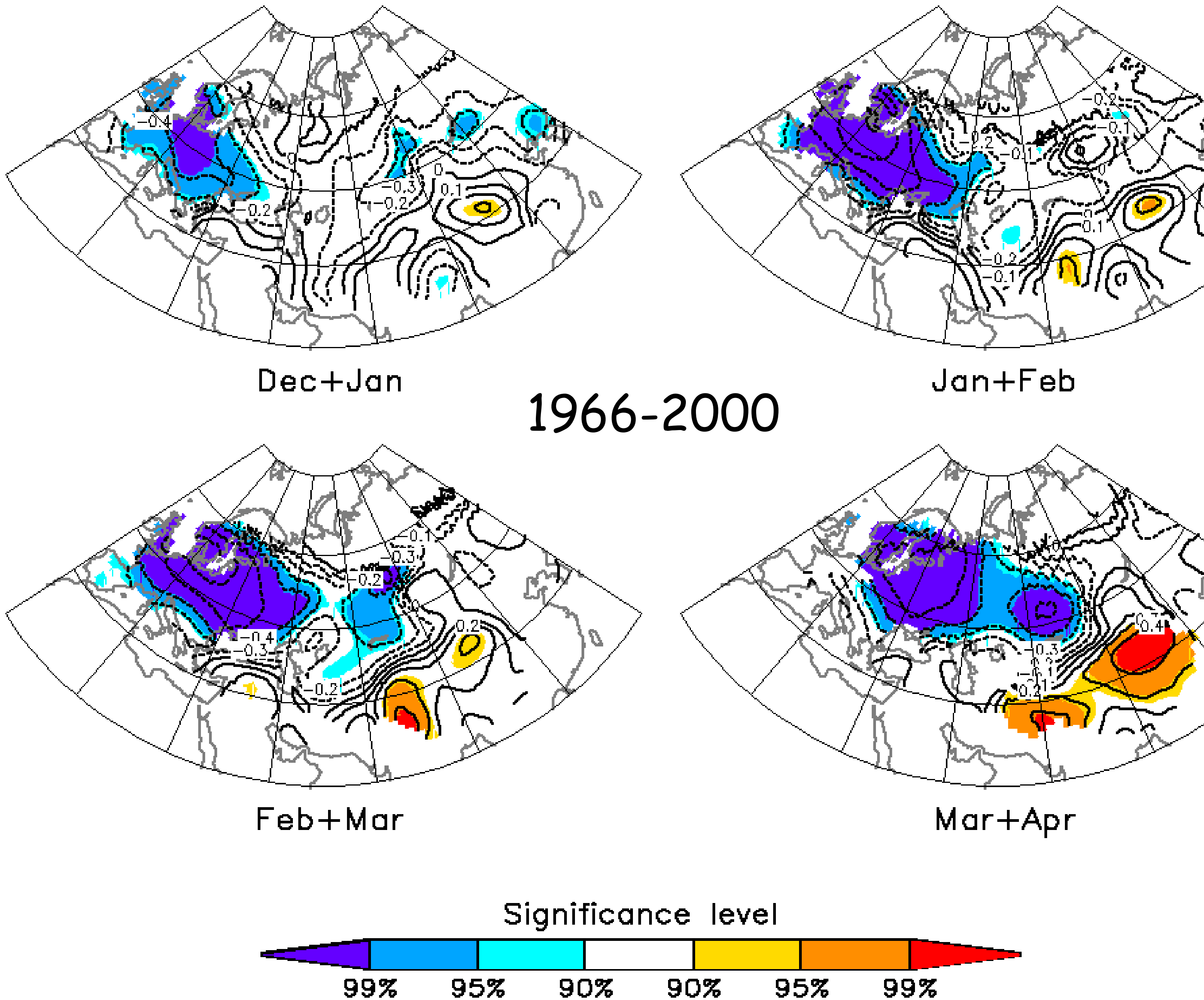

Correlation between snow cover and NAO index in DJF (detrended)

Are the relationships we have found robust over the past 130 years? [No]

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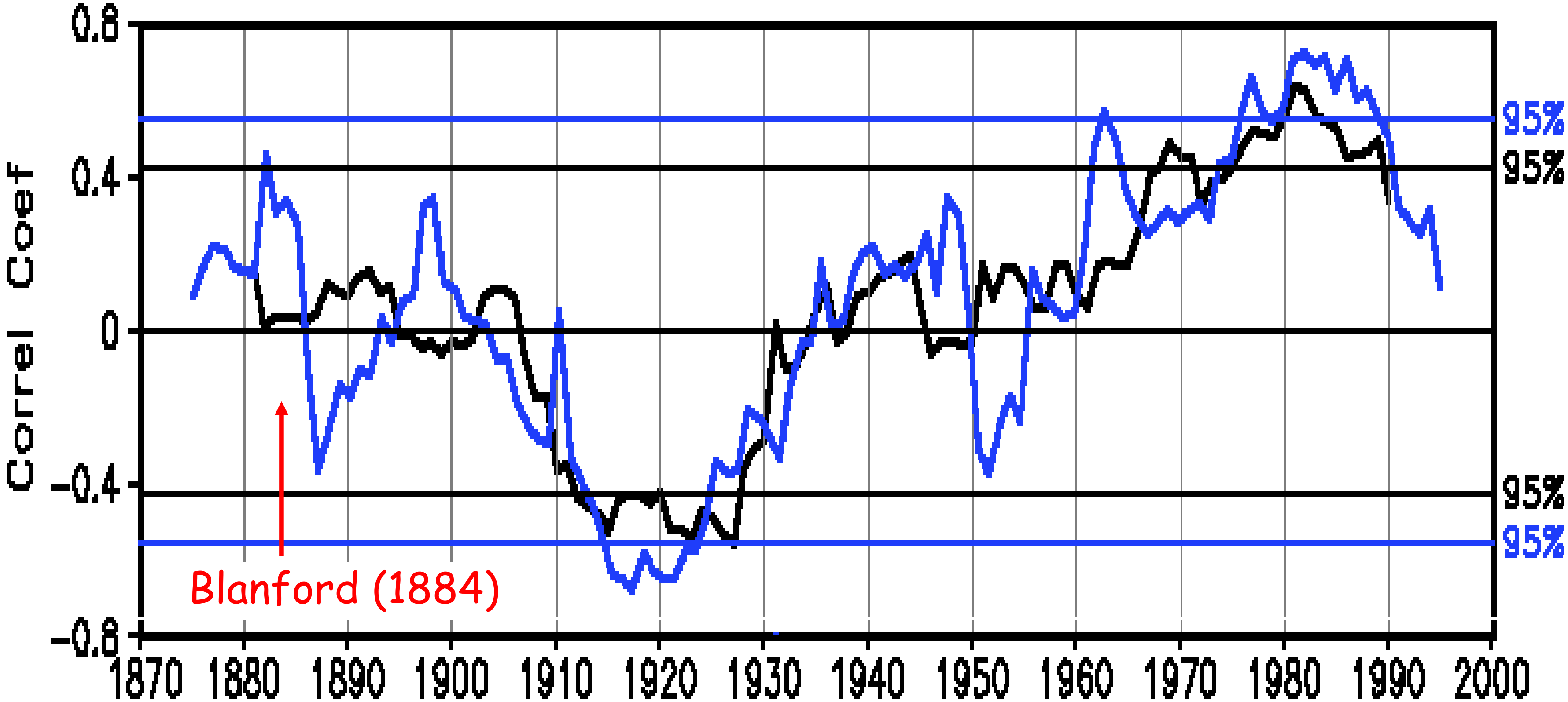

Correlation between DJF NAO and JJAS AIR,
11-year and 21-year sliding window

Blue: 11-year
Black:21-year

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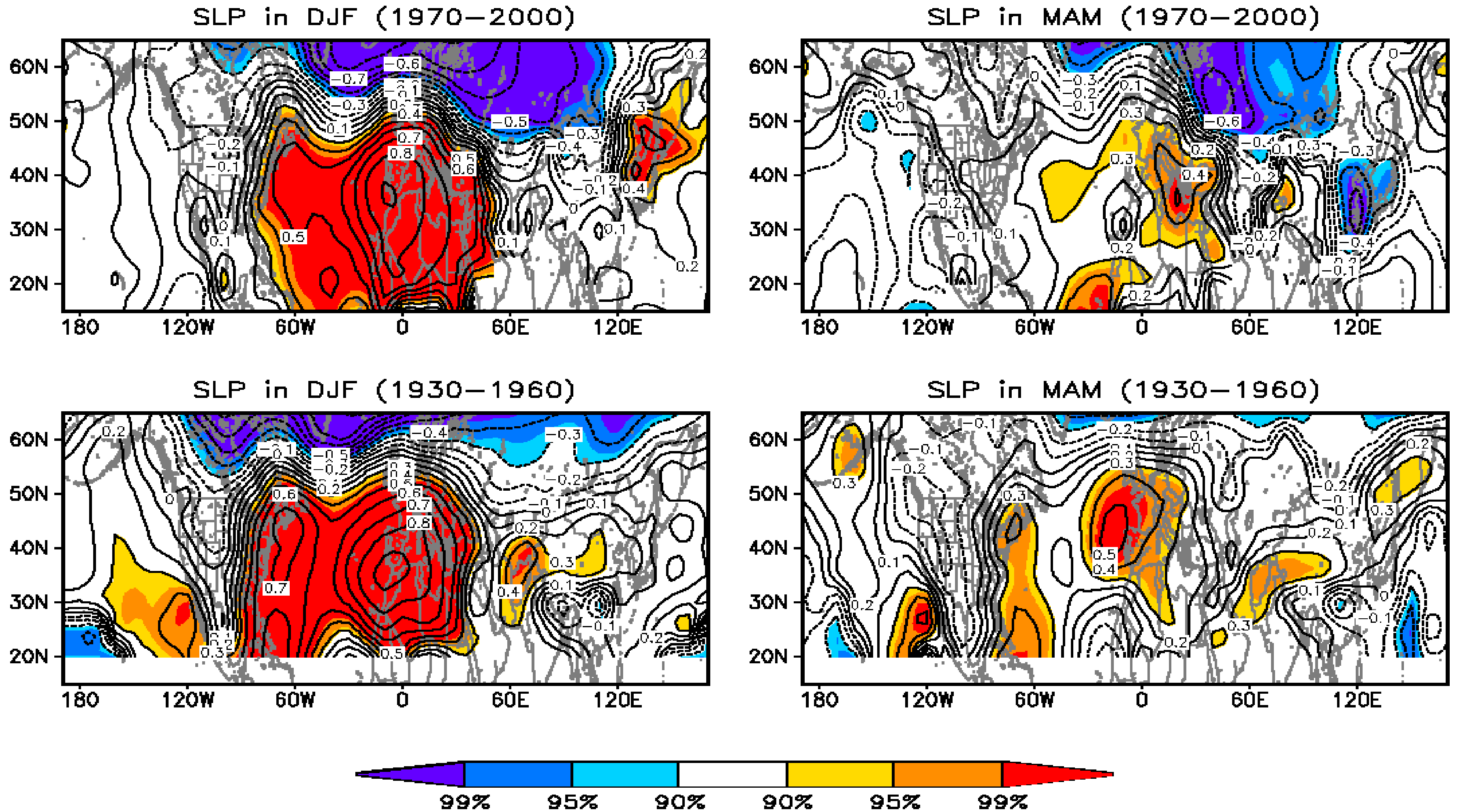

Correlation between NAO index in DJF and sea level pressure in DJF and MAM

Interdecadal change of NAO pattern and SLP

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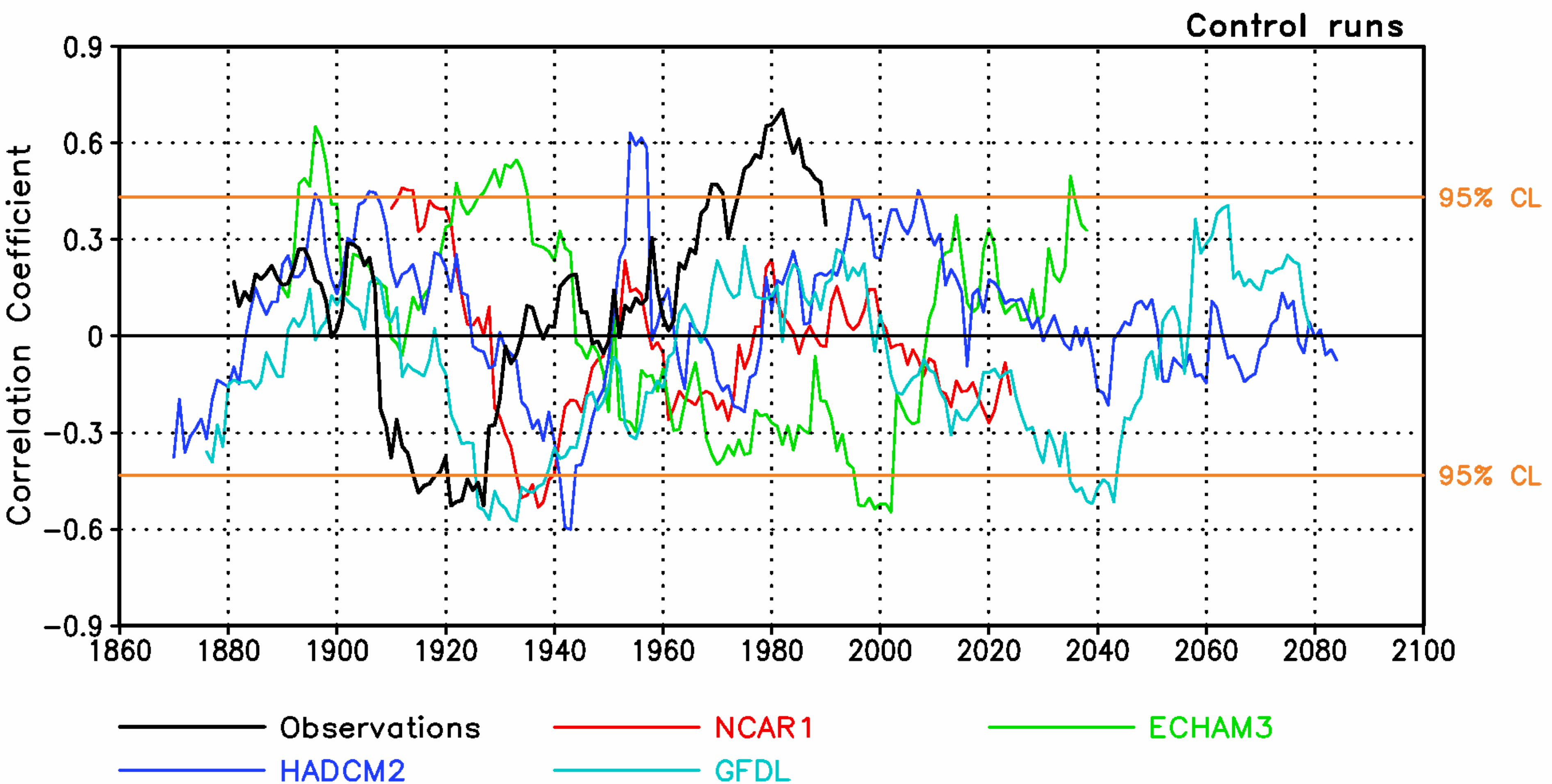
Model Version	Modeling Group	Scenario	Reference
GFDL_R30_c	Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey	IS92d	*Delworth et al.* [2002]
ECHAM3/LSG	Max Planck Institute for Meteorology, Hamburg, Germany	IS92a	*Cubasch et al.* [1997]
HADCM2	Hadley Centre for Climate Prediction and Research, Bracknell, UK	IS92d	*Johns et al.* [1997]
NCAR1	National Center for Atmospheric Research, Boulder, Colorado	IS92a	*Meehl et al.* [1996]



Correlation between DJF NAO and JJAS AIR, with 21-year sliding window

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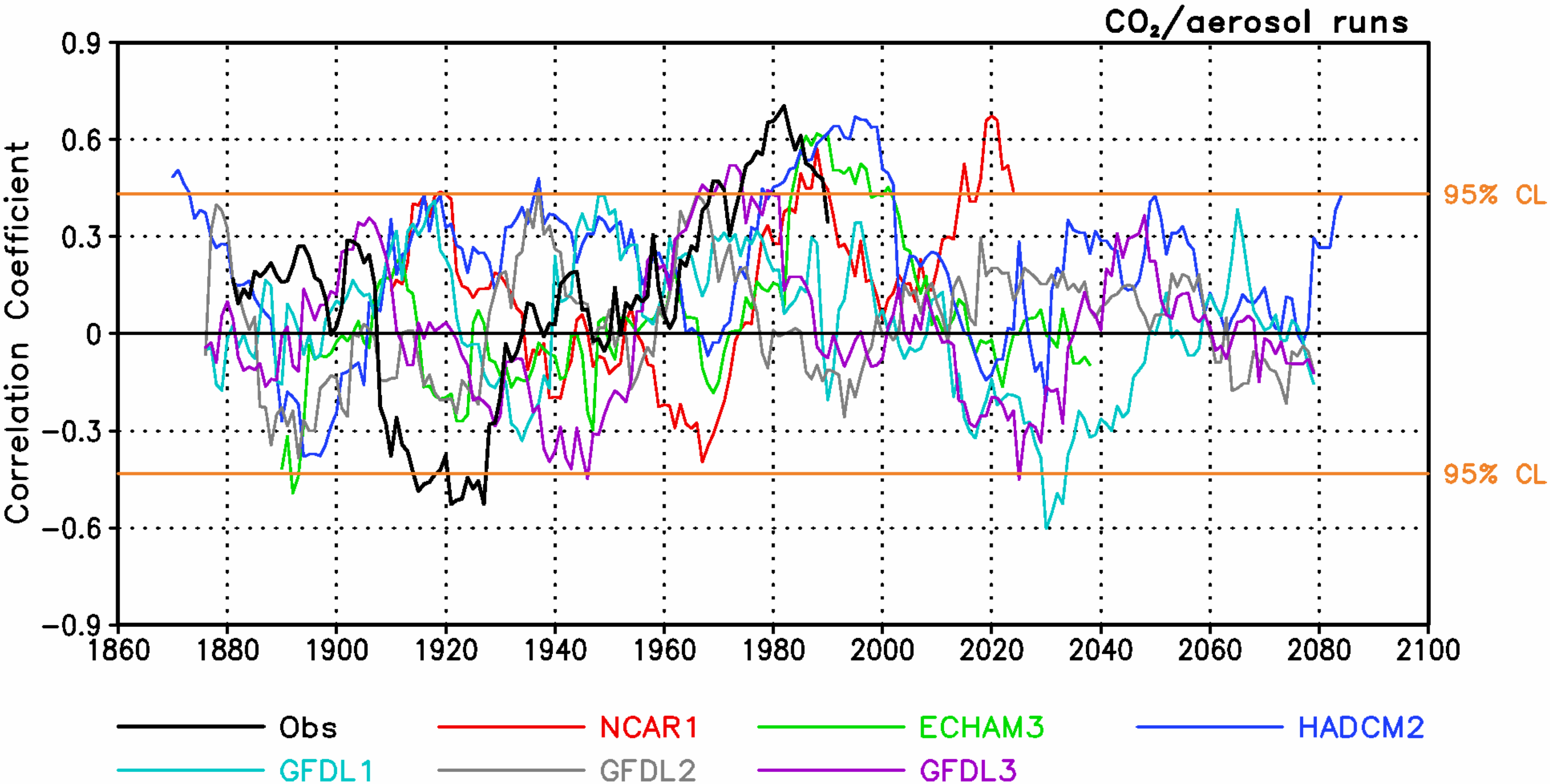

Correlation between DJF NAO and JJAS AIR, with 21-year sliding window

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Conclusions on Long-Term Relationships

1. For the past 130 years, we can explain JJAS AIR using the NAO index in the previous winter and the concurrent Niño 3.4 SST only for the periods around 1885 (about 25 years) and 1950-1995 (about 45 years), and this relationship is now gone.
2. These changing relationships appear to be random long-term climate variability and are similar to those simulated by the State-of-the-art GCMs. However, if these changes can be understood and predicted, then perhaps snow can be used to predict the Indian summer monsoon.

For the details, see:

Robock, Alan, Mingquan Mu, Konstantin Vinnikov, and David Robinson, 2003: Land surface conditions over Eurasia and Indian summer monsoon rainfall. *J. Geophys. Res.*, **108 (D4)**, 4131, doi:10.1029/2002JD002286.

Available at http://envsci.rutgers.edu/~robock

London Sunset After Krakatau
4:40 p.m., Nov. 26, 1883
Watercolor by Mr. W. Ashcroft
Figure from Symons (1888)