Mechanisms of Forced Arctic Oscillation Response to Volcanic Eruptions

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Pinatubo
June 12, 1991

Three days before major eruption of June 15, 1991
After Pinatubo, Cubi Point Naval Air Station, 40 km from volcano

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

Temperature Anomalies (°C)


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

Satellite data courtesy of John Christy, University of Alabama, Huntsville

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Winter (DJF) 1992–93
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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)
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)
Winter Warming for largest eruptions of the past 120 years

Observed surface air temperature anomalies

Robock and Mao (1992)
The Arctic Oscillation

Thompson and Wallace (1998)

Stronger polar vortex

Winter warming

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

Figure 1. Regression maps for geopotential height (meters), tropopause pressure (Pa), 1000-500-hPa thickness (m), SLP (expressed as Z1000 m) and surface air temperature (SAT-Z) 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
“stratospheric gradient” mechanism
“tropospheric gradient” mechanism
“wave feedback” mechanism

Ways Volcanic Eruptions Force Positive AO Mode

Aerosol heating

Increased height gradient

Surface warming

Dynamic cooling

Stronger polar vortex

Decreased EP flux

Weaker temperature gradient

Surface cooling

O_3 cooling

North Pole 60°N 30°N Equator

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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
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

Aerosol Optical Depth ($\lambda=0.55 \, \mu m$)

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Ramachandran et al. (2000)
ECHAM4
5-ensemble mean
Heating rates (K/day)
for different wavelengths and total
(Stenchikov et al., 1998)
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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\[ \frac{dU}{dt} = -\frac{\langle U \rangle - U_{\text{clim}} - U_{\text{QBO}}}{\tau(p, \phi)} \]

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

\( U_{\text{Sing}} \) - smoothed deseasonalized monthly-mean Singapore zonal wind

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

\( \tau(p, \phi) > 5 \text{ day for } 0.01 \text{ mb} < p < 100 \text{ mb} \)

\( \langle U \rangle \) - zonal mean zonal wind

\( U_{\text{clim}} \) - climatological mean of zonal mean zonal wind
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

ΔT (K) ensemble (AQ−climqbo) at 50 hPa

ΔT (K) at 50 hPa, NCEP reanalysis

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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
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 ($\mu$g/g) as calculated using ozonesonde

Data provided by Jim Angell
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/s²) at 400 hPa; bars show one standard deviation calculated from 40-year control (in black).
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
SKYHI simulations of surface temperature anomaly (K) caused by aerosols only (A)

Winter 91/92

Hatching shows 90% significance

Winter 92/93
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
SKYHI simulations of surface temperature anomaly (K) caused by ozone changes only (O)

February-April 1992

Hatching shows 90% significance

February-April 1993
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

Alan Robock
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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.
For the details, see:


Available at [http://envsci.rutgers.edu/~robock](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
Blanford found a negative correlation between snow cover and Indian summer monsoon rainfall:


“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....”
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?
All-India JJAS precipitation anomaly with respect to 1958–1998 mean

* High Indian JJAS precip  * Low Indian JJAS precip
Correlation between All-India rainfall (1967–2000) and the previous winter and spring snow cover.
Detrended snow and precipitation - first SVD coupled mode, 1967-1998

SVD First Coupled Mode; Covariance=42%; Corr=0.62

SVD First Coupled Mode; Covariance=49%; Corr=0.60

Snow Cover (%) in DJF; Variance=20%

Snow Cover (%) in MAM; Variance=27%

Precipitation (mm) in JJAS; Variance=17%

Precipitation (mm) in JJAS; Variance=19%
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

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

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Department of Environmental Sciences
The Arctic Oscillation

Thompson and Wallace (1998)

Stronger polar vortex

Warm advection into Europe

Winter warming

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 Z1000 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

2M Air Temperature (°C) in DJF

Surface temperature same
Strong Indian Monsoon

Arctic Oscillation

Sea Level Pressure (hPa) in DJF

SLP same only in Atlantic

Alan Robock
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Strong Indian Monsoon

Arctic Oscillation

50 hPa not same at all
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.
Correlation between snow cover and NAO index in DJF (detrended)
Are the relationships we have found robust over the past 130 years? [No]
Correlation between DJF NAO and JJAS AIR, 11-year and 21-year sliding window

Blue: 11-year
Black: 21-year

Blanford (1884)
Interdecadal change of NAO pattern and SLP

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<table>
<thead>
<tr>
<th>Model Version</th>
<th>Modeling Group</th>
<th>Scenario</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFDL_R30_c</td>
<td>Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey</td>
<td>IS92d</td>
<td>Delworth et al. [2002]</td>
</tr>
<tr>
<td>ECHAM3/LSG</td>
<td>Max Planck Institute for Meteorology, Hamburg, Germany</td>
<td>IS92a</td>
<td>Cubasch et al. [1997]</td>
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<tr>
<td>HADCM2</td>
<td>Hadley Centre for Climate Prediction and Research, Bracknell, UK</td>
<td>IS92d</td>
<td>Johns et al. [1997]</td>
</tr>
<tr>
<td>NCAR1</td>
<td>National Center for Atmospheric Research, Boulder, Colorado</td>
<td>IS92a</td>
<td>Meehl et al. [1996]</td>
</tr>
</tbody>
</table>
Correlation between DJF NAO and JJAS AIR, with 21-year sliding window
Correlation between DJF NAO and JJAS AIR, with 21-year sliding window
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:


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)