Volcanoes drive climate variability by

1. **emitting ozone weeks before eruptions,**
2. **forming lower stratospheric aerosols that cool Earth,**
3. **causing sustained ozone depletion, surface warming, and lower stratospheric cooling,**
4. **forming very large basaltic lava flows resulting in sudden erratic warming, and**
5. **causing rapid changes in regional ozone concentrations affecting temperature & pressure differences that drive atmospheric oscillations**

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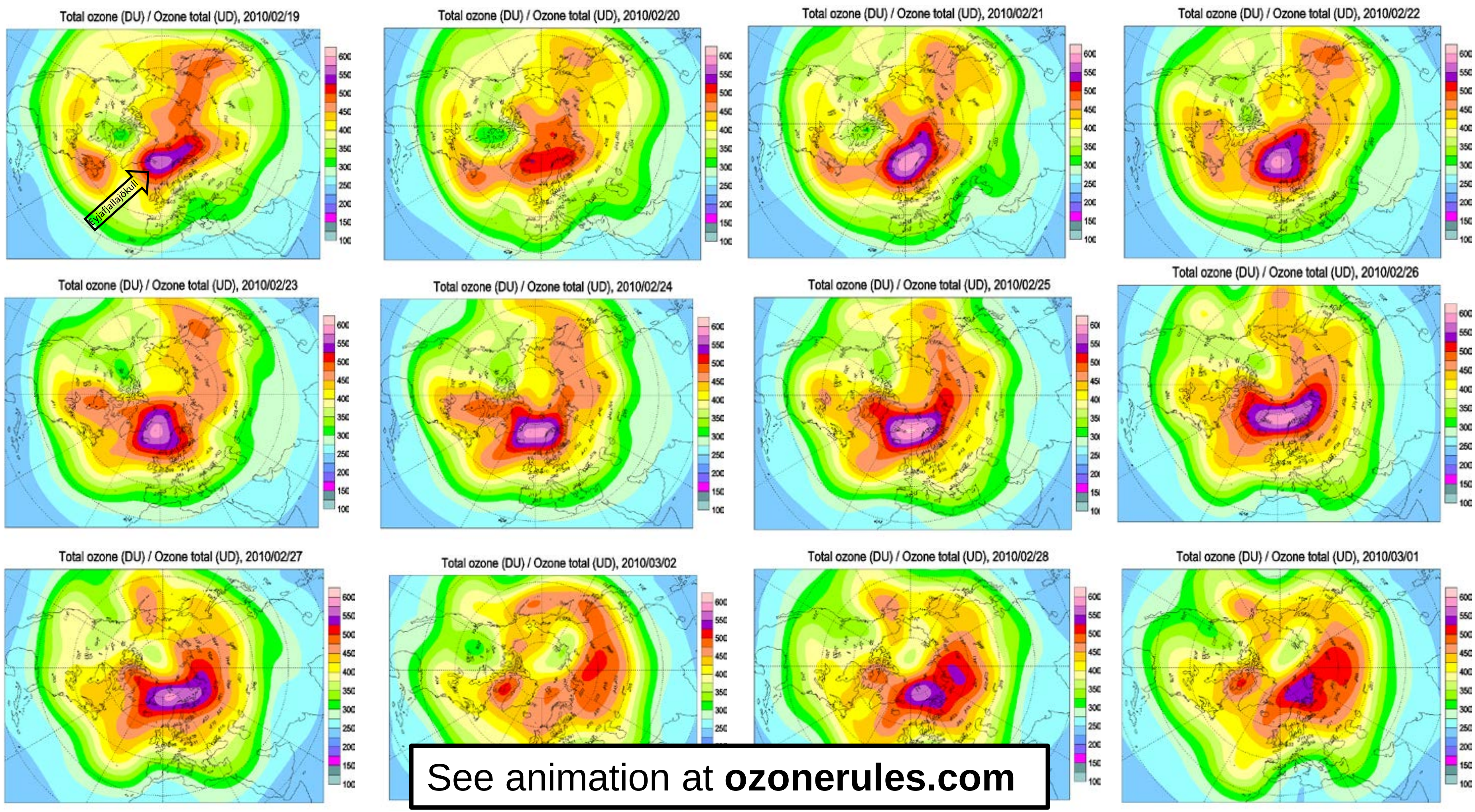
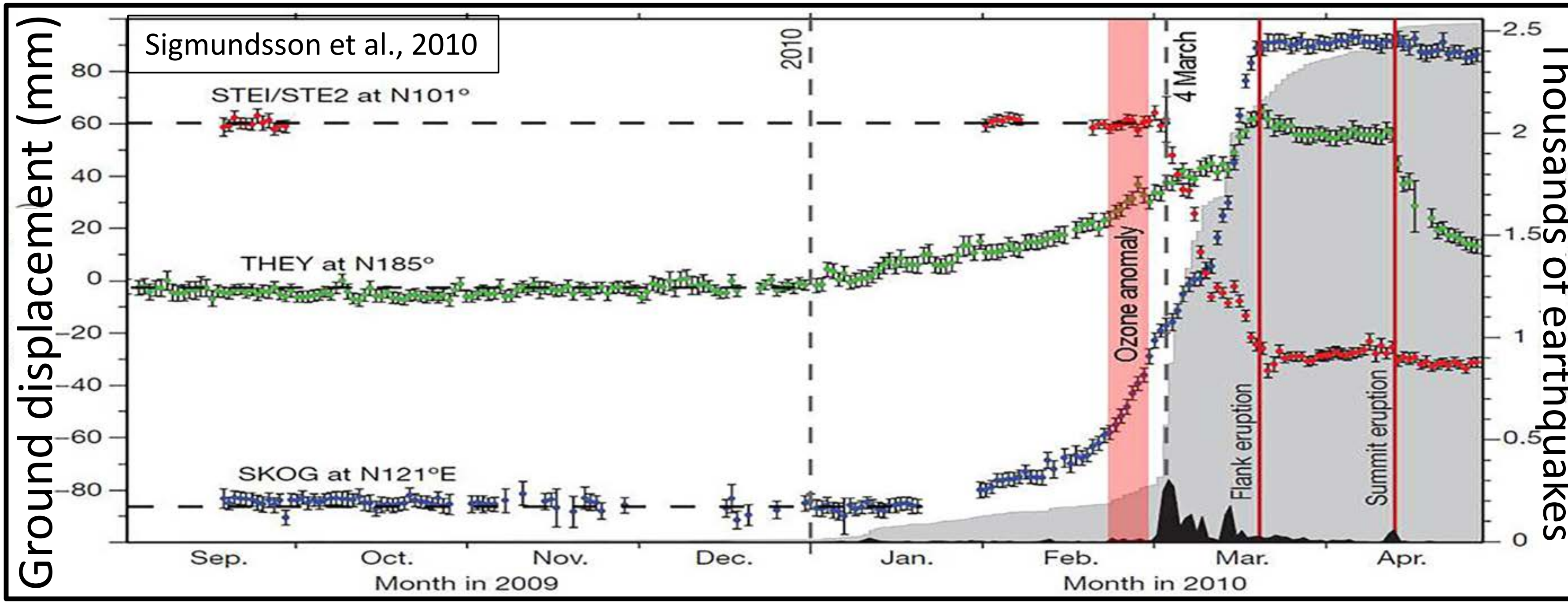
1. Emitting ozone weeks before eruptions

Daily total column ozone observed by satellite above **Eyjafjallajökull** volcano in southern Iceland suddenly increased by 70% starting on Feb. 19, 2010, ~4 weeks before the first effusive flank eruption of basalt starting on March 20 and ~7 weeks before the main explosive eruption on April 14 (increase from ~325 DU to >550 DU)



See animation at **ozonerules.com**

The ozone anomaly formed just as ground deformation and small earthquakes beneath Eyjafjallajökull showed fractures were probably forming above a magma sill 4 km deep



A substantial release of gas from the top of the magma body is highly likely to have occurred in late February as the roof of the intrusion fractured to the surface. Was this ozone from the magma, ozone created by very hot gases passing through the water table, or bogus measurements confused by SO_2? Not clear.

A 40% increase in ozone was observed north of **Mt. Pinatubo** on March 15, 1991, before the first emissions of steam on April 2 and the first eruption on June 12.

We have much to learn to understand these observations.

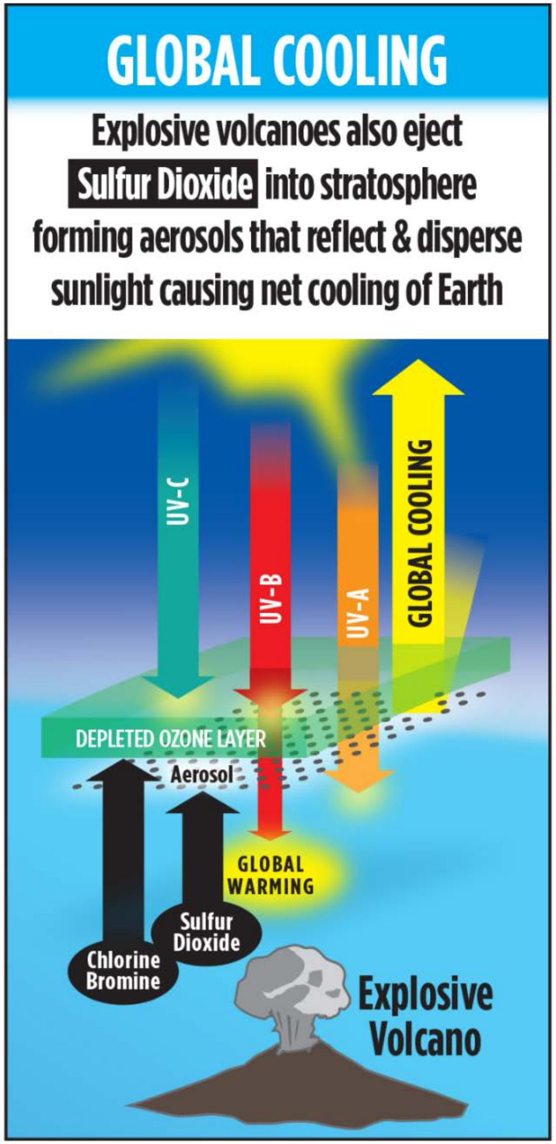
2. Forming lower stratospheric aerosols that cool Earth ~0.5^{o}C for ~3 years

The eruption of Mt. Pinatubo on June 15, 1991, ejected >490 Mt water and 17 Mt SO_2 forming, in the lower stratosphere, a sulfuric acid and water **aerosol** that spread around the globe in 21 days, covered 42% of the globe within 2 months, and lasted more than 3 years.

The aerosol droplets grew large enough to reflect and scatter sunlight, **reducing optical depth** to 0.4 within 3 months, cooling Earth ~0.5^{o}C for ~3 years.

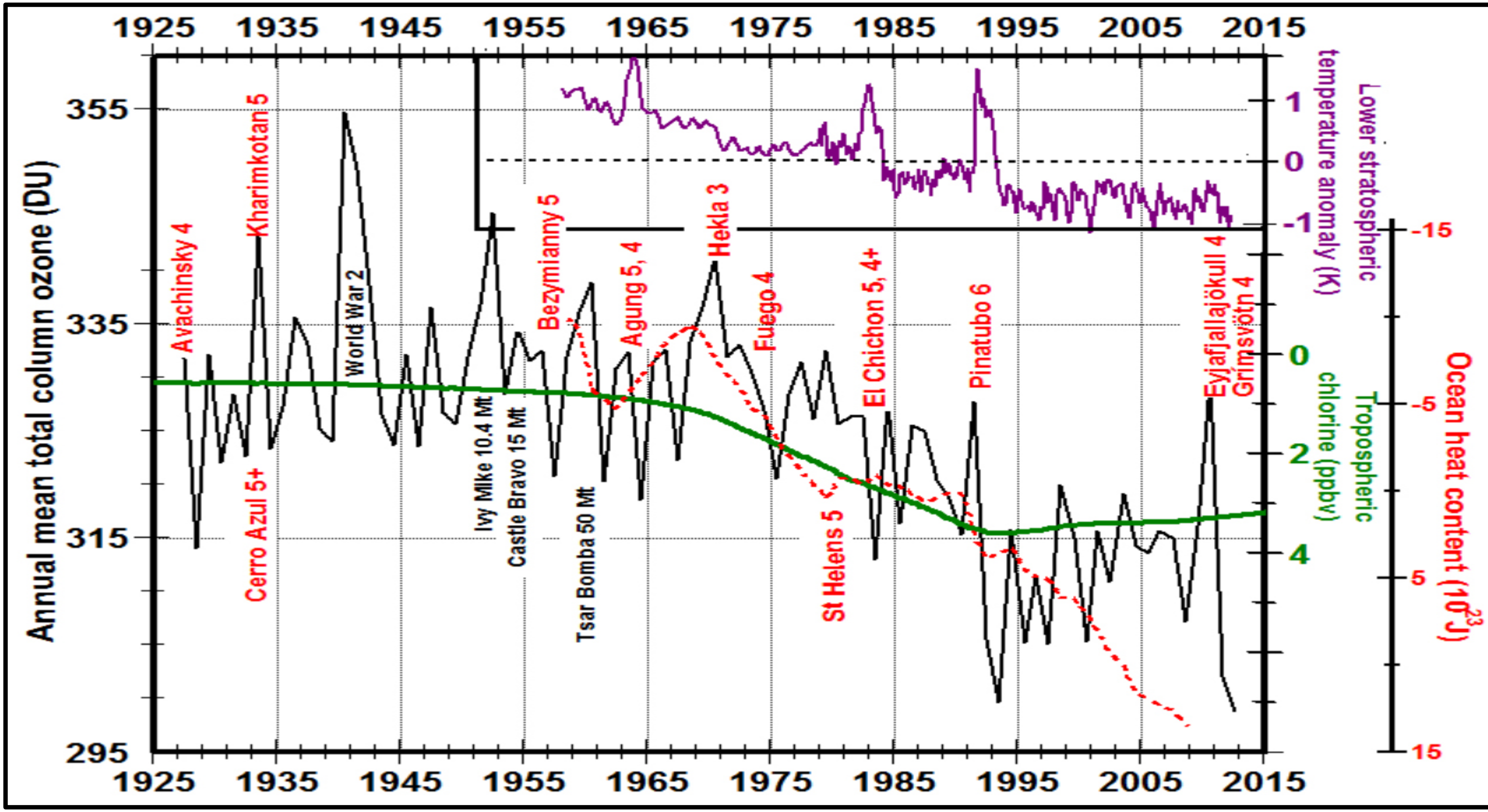
In 1992 and 1993, annual average **total column ozone** in northern mid-latitudes reached the lowest values observed since measurements began in 1927, most likely due to heterogeneous chemical reactions on the surfaces of the aerosol droplets caused by eruption of >3 Mt chlorine and bromine. This depletion caused **warming** of northern continental areas >3^{o}C during December 1991 through February 1992.

Similar cooling is observed after essentially all major explosive eruptions.



3. Causing sustained ozone depletion, surface warming, and lower stratospheric cooling

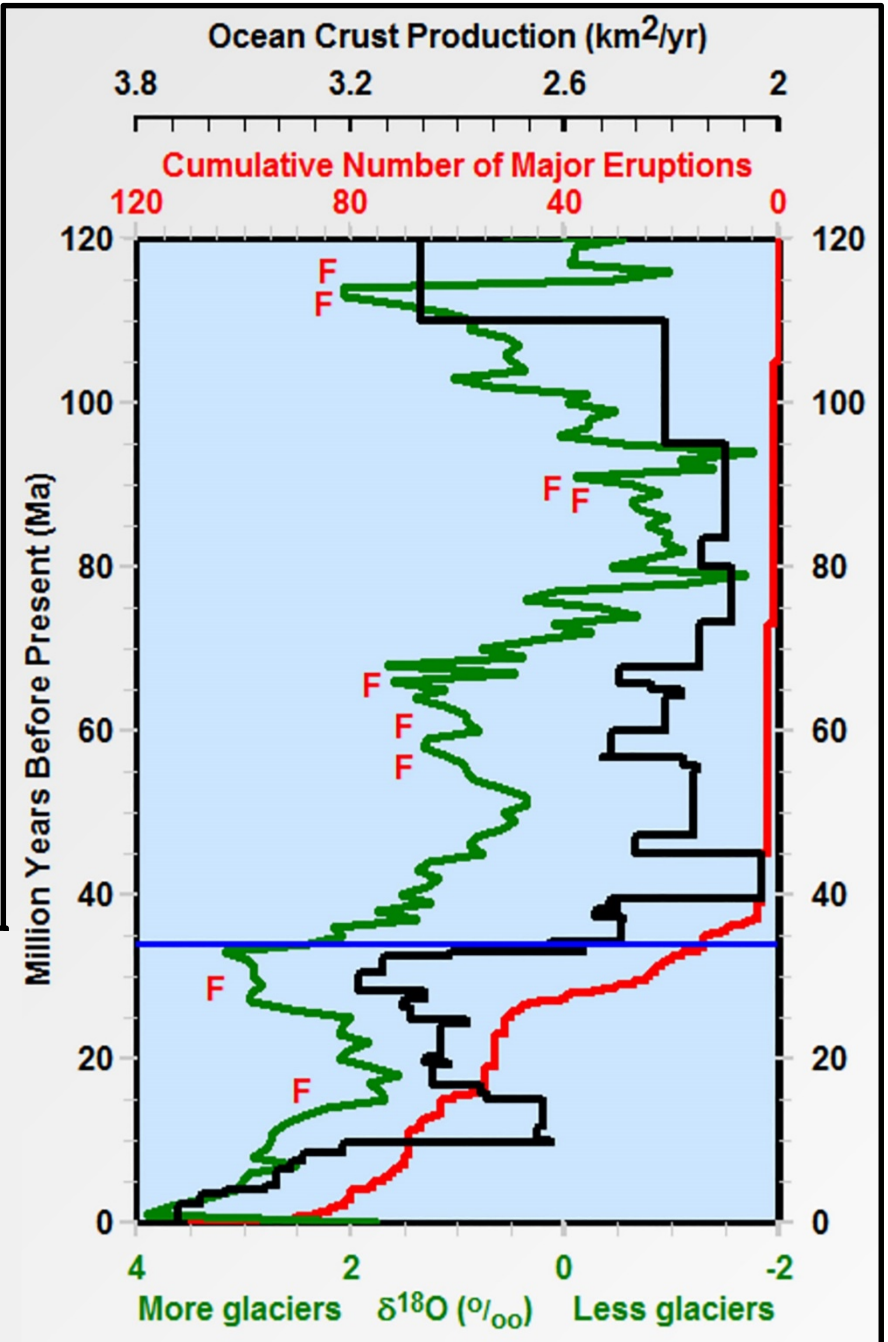
Annual average total column ozone measured at Arosa, Switzerland, is typically high the year of an eruption (shown in red with VEI) and much lower the first and second years after an eruption.



Note that the amount of ozone depletion following the eruptions of Eyjafjallajökull and Grímsvötn in 2010 was as large as depletion following the much larger eruption of Pinatubo in 1991.

Green line above shows tropospheric chlorine caused by emissions of human manufactured CFC gases, depleting the ozone layer since the 1960s.

Purple line above shows temperature of lower stratosphere. Note temperature peaks following eruptions, but overall decrease in temperature caused by increasing ozone depletion.

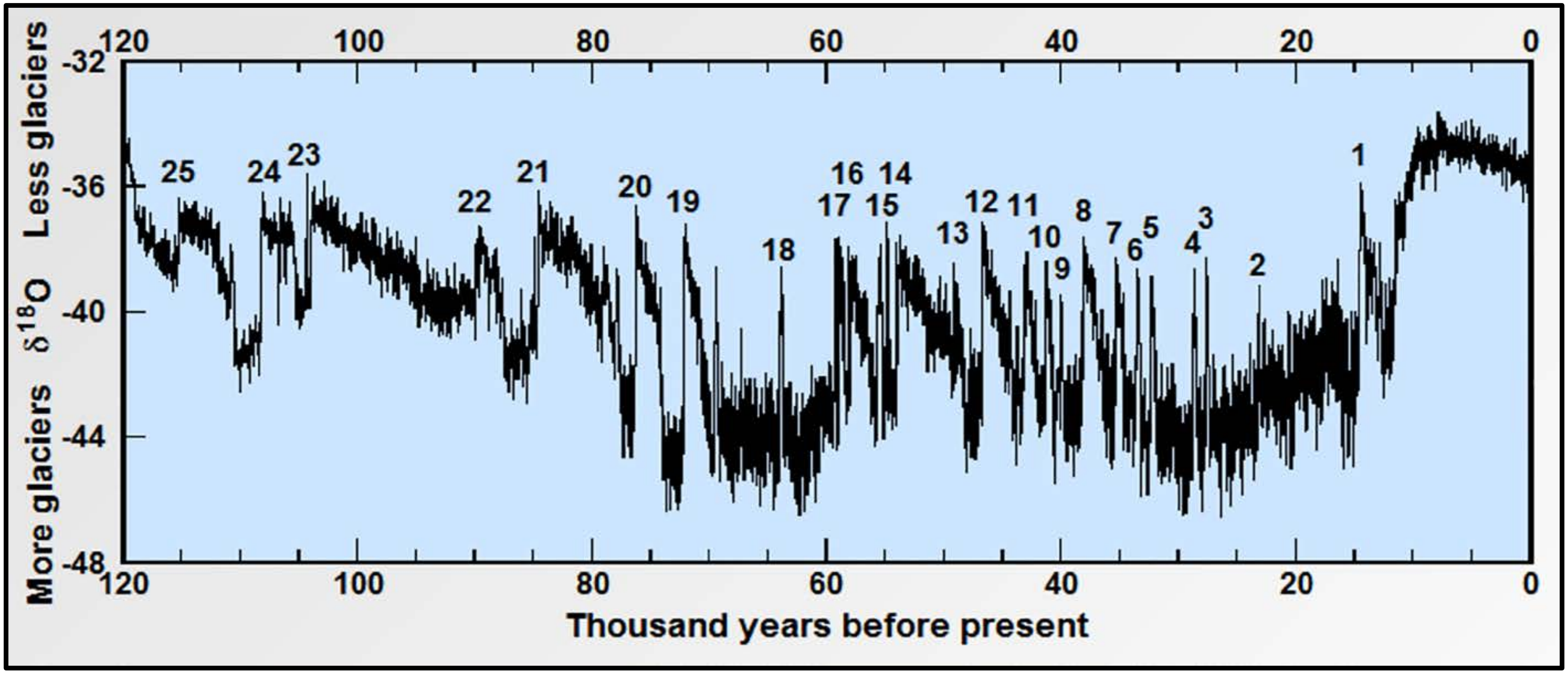


Increase in frequency of major explosive eruptions (red line) and in ocean crust production (black line) is associated with global cooling (green line). Blue line shows the onset of major glaciation in Antarctica around 34 Ma.

4. Forming very large basaltic lava flows resulting in sudden erratic warming

2016 is the hottest year on record apparently because Bárðarbunga volcano in central Iceland erupted basalt lavas covering 85 km^2 from Aug. 2014 to Feb 2015, the highest rate of basalt extrusion since 1783.

These 25 Dansgaard-Oeschger sudden warmings are contemporaneous with major basaltic, effusive volcanism under an ice sheet in Iceland. These warmings often occurred within years, while similar amount of cooling lasted centuries to millennia.



5. Causing rapid changes in regional ozone concentrations affecting temperature & pressure differences that drive atmospheric oscillations

Ozone is continually created and destroyed with an average molecule lasting about 8.3 days. This ongoing Chapman cycle dissociating oxygen to form ozone and then dissociating ozone heats the atmosphere regionally.

Ozone varies regionally all the time. On June 19, 2004, for example, total column ozone increased 20% (80 DU) over Toronto Canada in 5 hours while associated tropopause height dropped 5 km.

Maximum ozone is typically found in the rear of surface low-pressure areas while minimum ozone is typically found in the rear of surface high-pressure areas (Dobson, 1929, Reed, 1950).

Ozone depletion causes the polar vortex to become stronger, colder, and more persistent, increasing surface winds.

When the vortex weakens, the jet stream buckles causing significant outbreaks of cold air into lower latitudes.

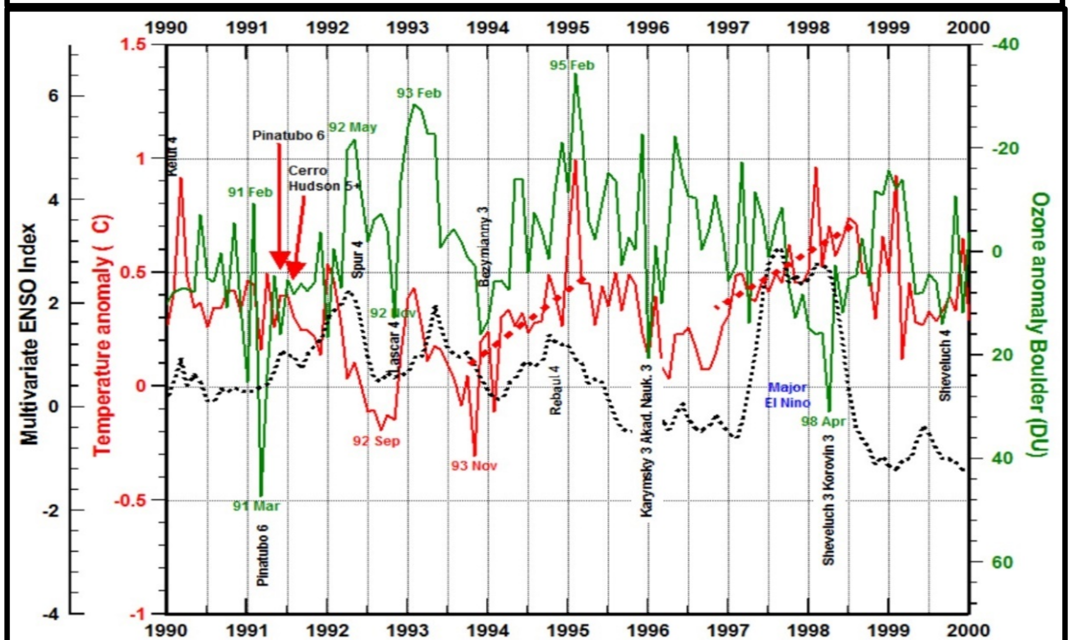
Regional changes in air pressure and temperature drive changes in atmospheric oscillations and ocean currents. Ozone variations are a mechanism for driving teleconnections.

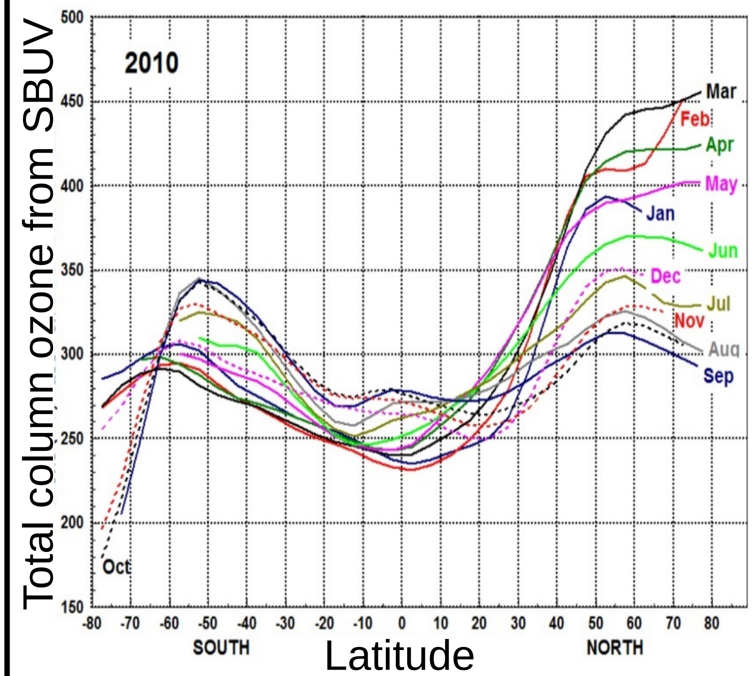
Variations of total column ozone as a function of latitude by month and by year

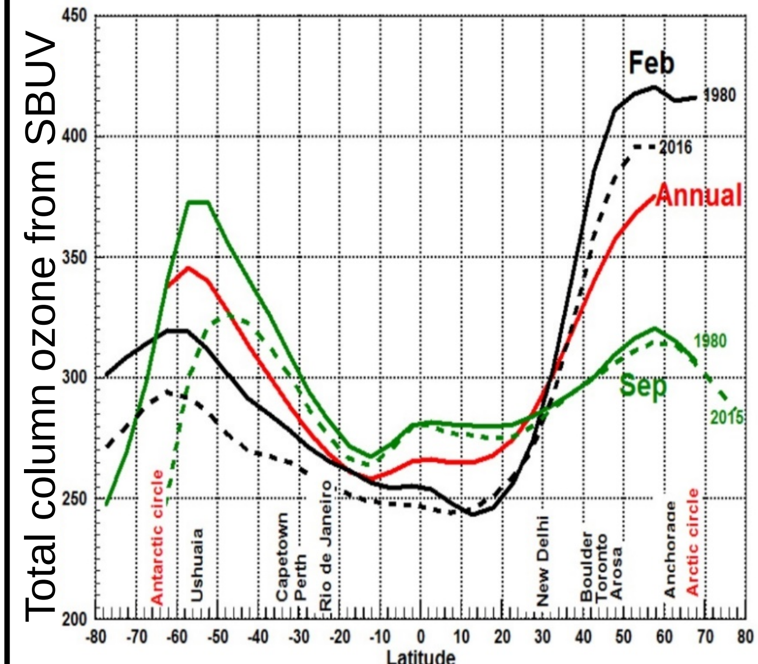
El Niños, for example, typically start around Christmas, a time of major change in ozone concentrations, especially in the northern hemisphere.

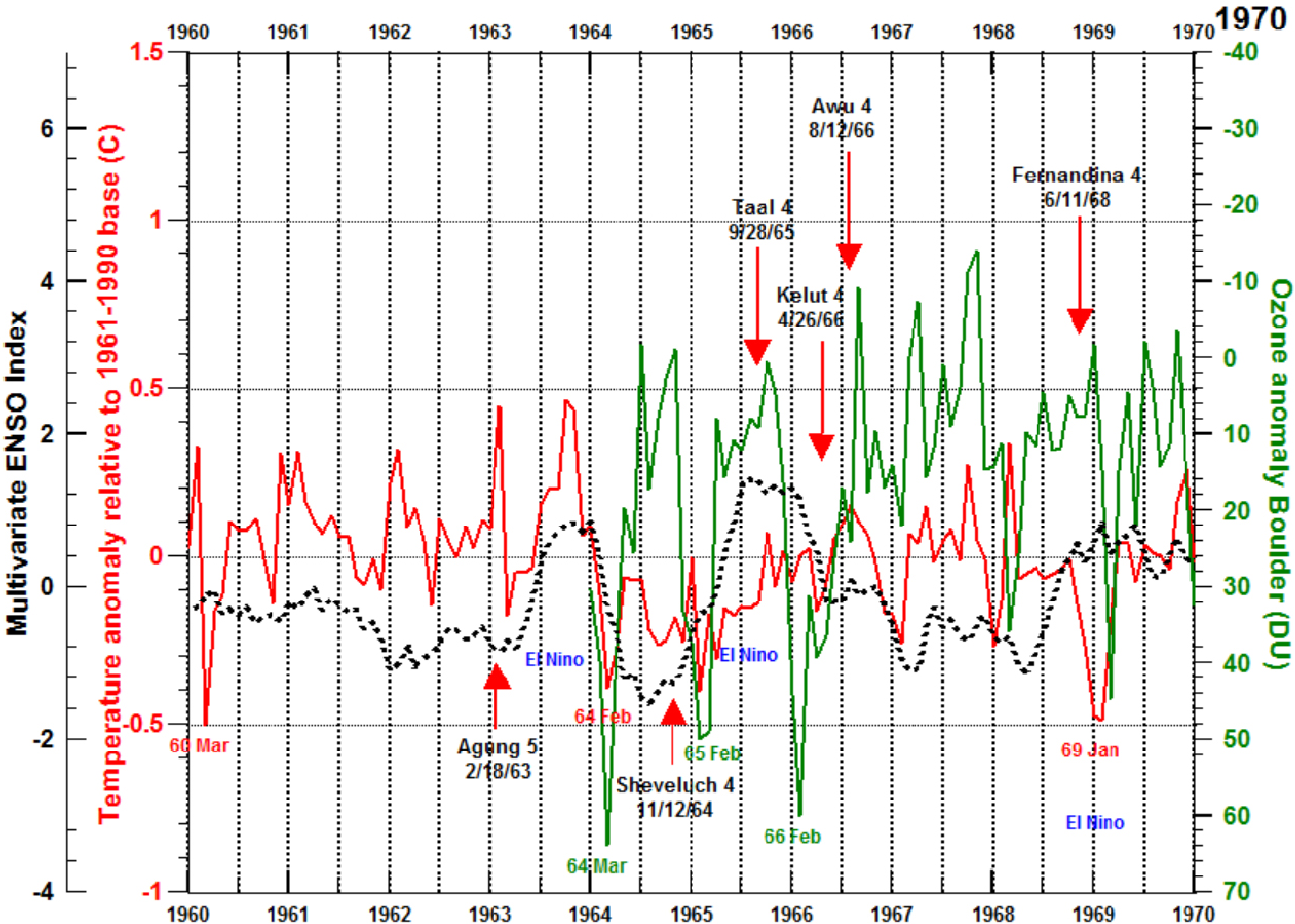
Major work is needed to sort out relationships between ozone concentrations, atmospheric oscillations, and ocean currents.

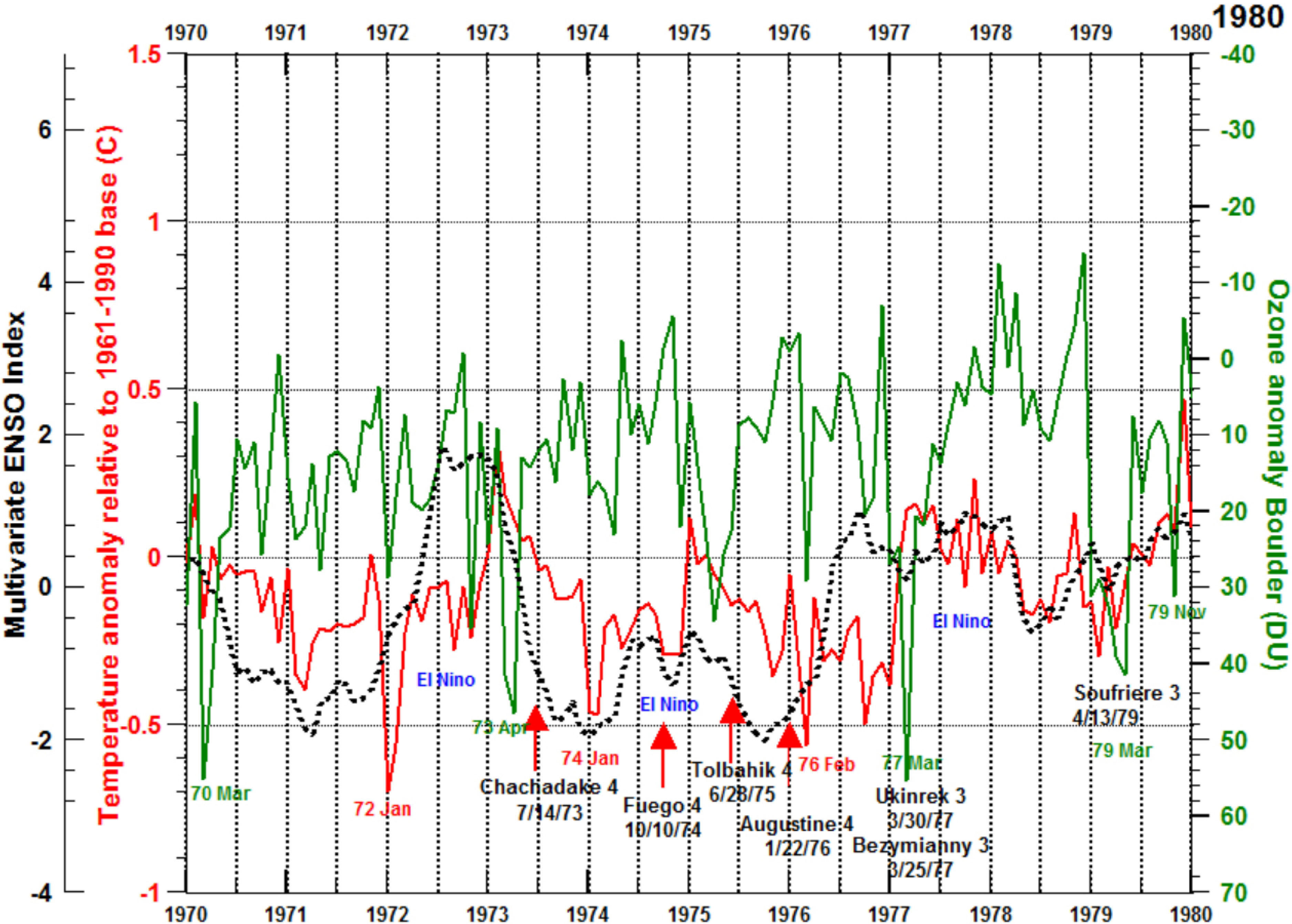
Ozone anomaly vs HadCRUT4 temp vs ENSO Index



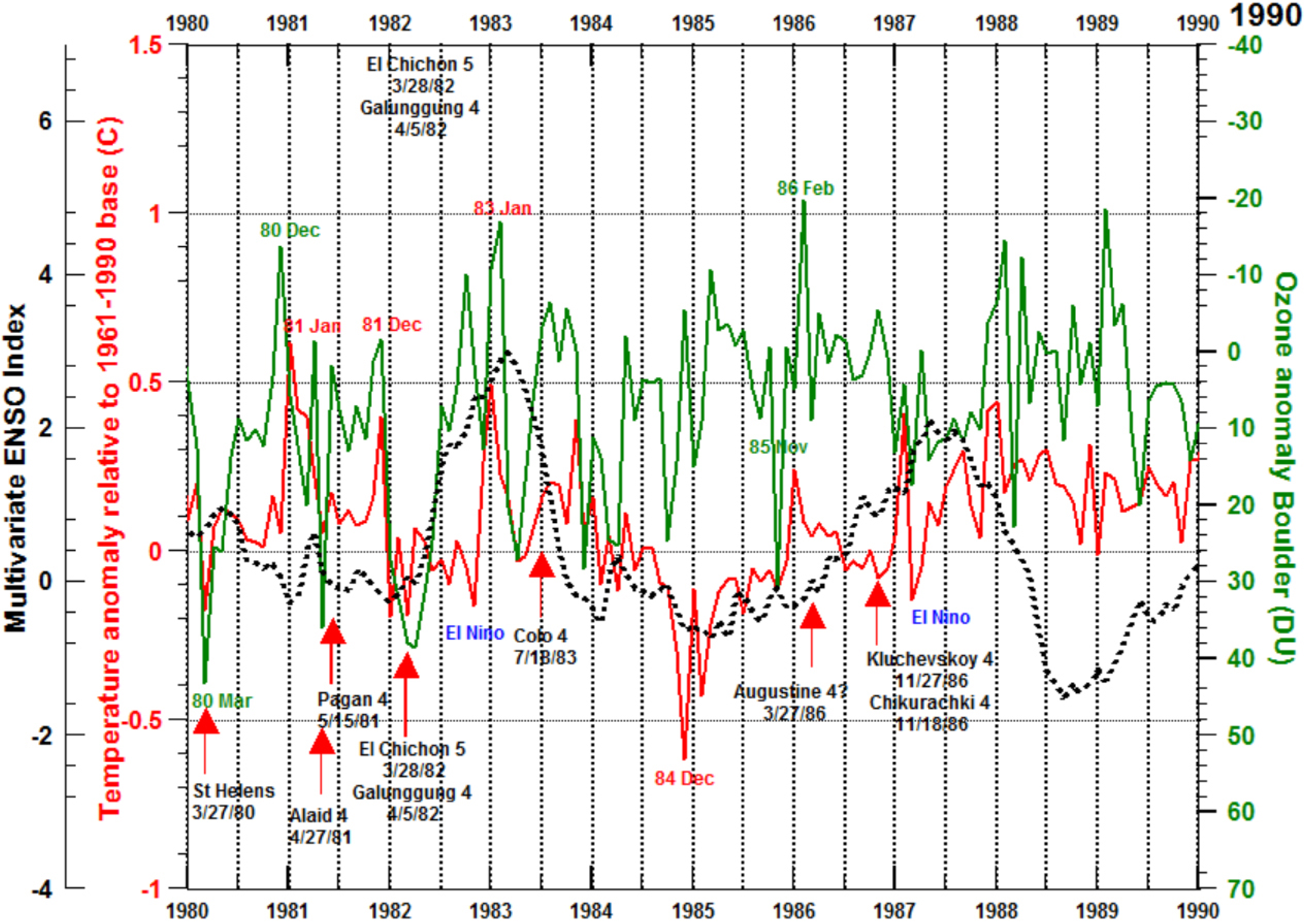




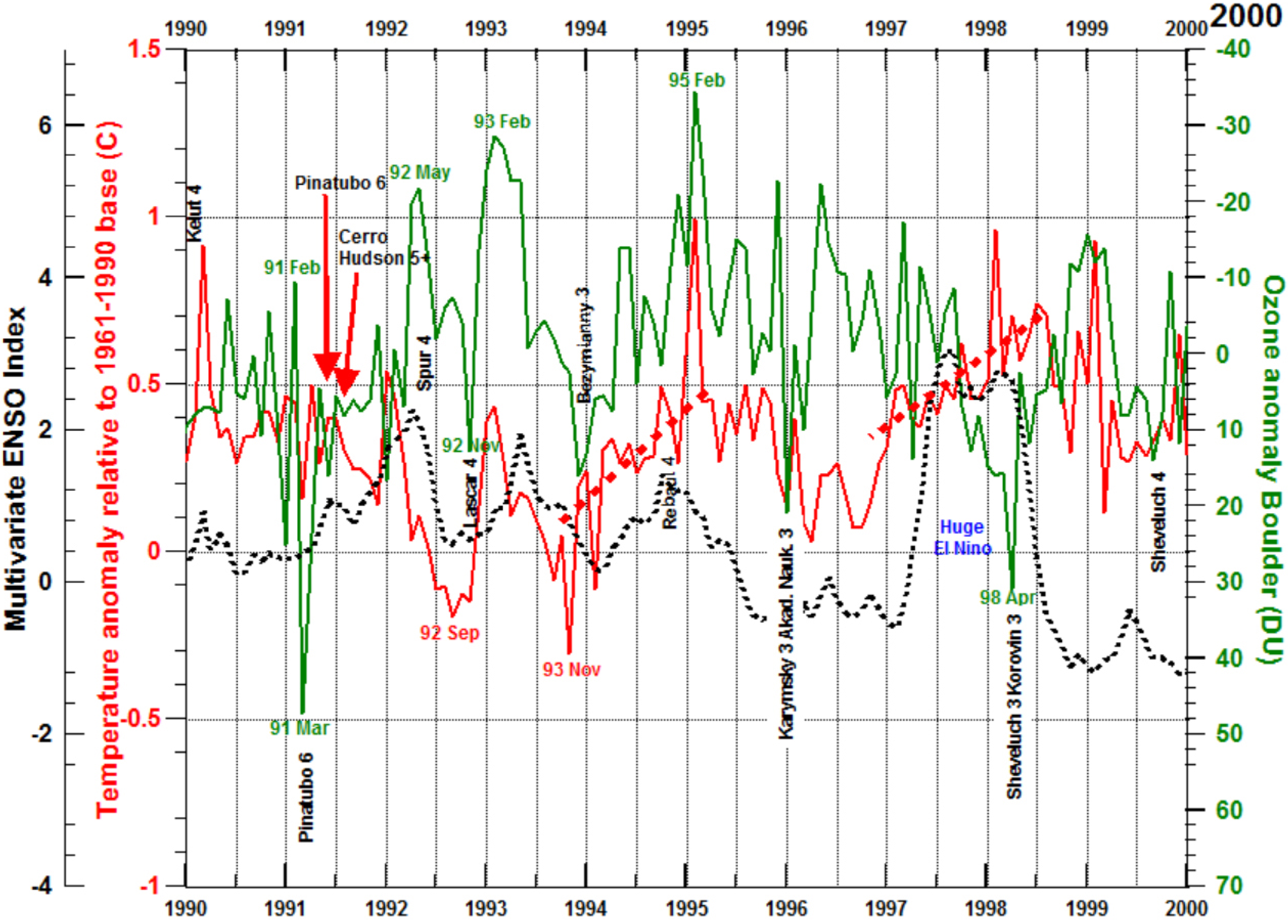

1970
Multivariate ENSO Index
Temperature anomaly relative to 1961-1990 base (C)
Ozone anomaly Boulder (DU)
Awu 4
8/12/66
Fernandina 4
6/11/68
Taal 4
9/28/65
Kelut 4
4/26/66
El Nino
El Nino
El Nino
64 Feb
60 Mar
Agung 5
2/18/63
65 Feb
Sheveluch 4
11/12/64
66 Feb
64 Mar
69 Jan



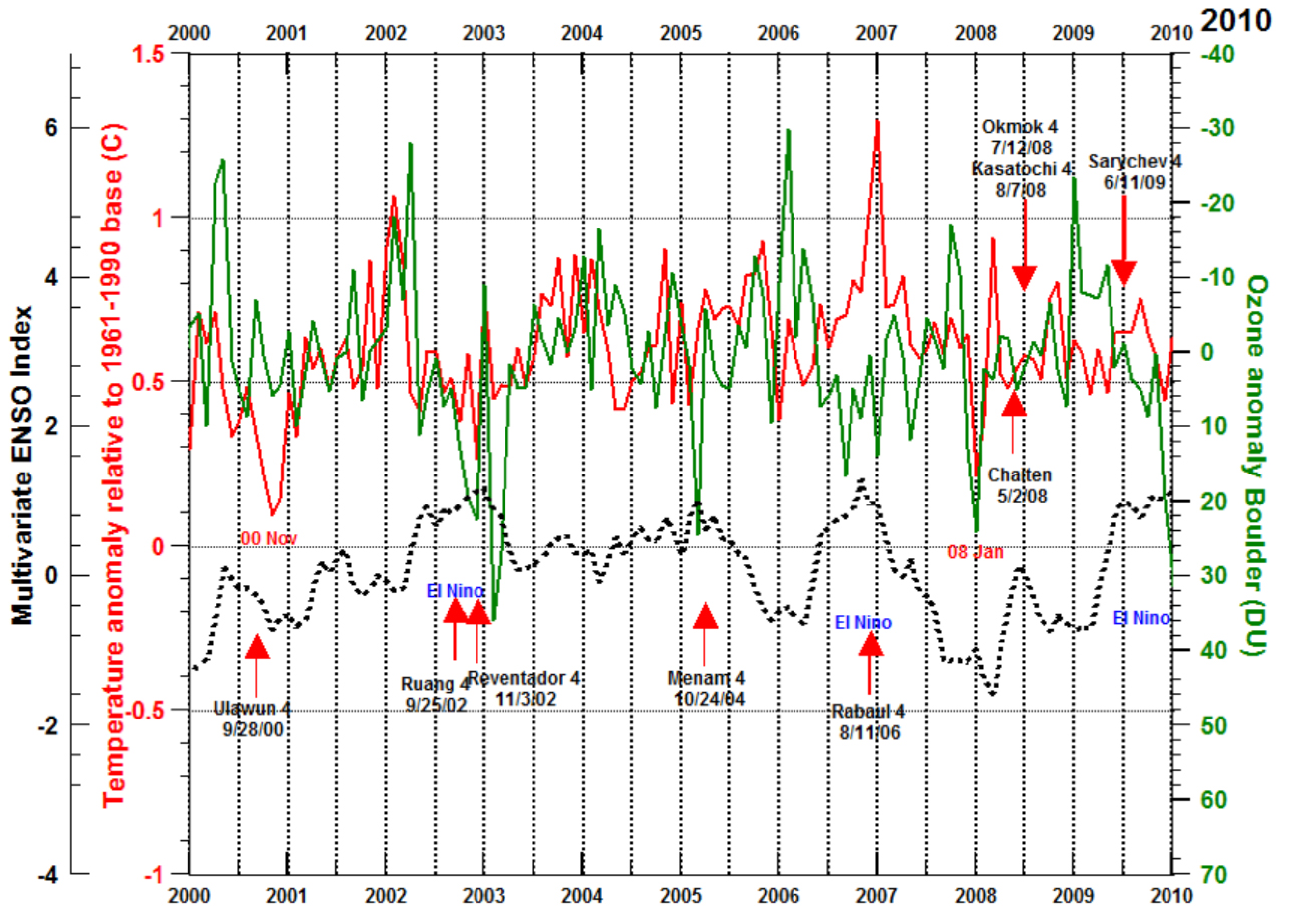
1980
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
Multivariate ENSO Index
Temperature anomaly relative to 1961-1990 base (C)
Ozone anomaly Boulder (DU)
El Nino
El Nino
El Nino
70 Mar
72 Jan
73 Apr
74 Jan
76 Feb
77 Mar
79 Mar
79 Nov
Chachadake 4
7/14/73
Fuego 4
10/10/74
Tolbahik 4
6/28/75
Augustine 4
1/22/76
Ukinrek 3
3/30/77
Bezymianny 3
3/25/77
Soufriere 3
4/13/79



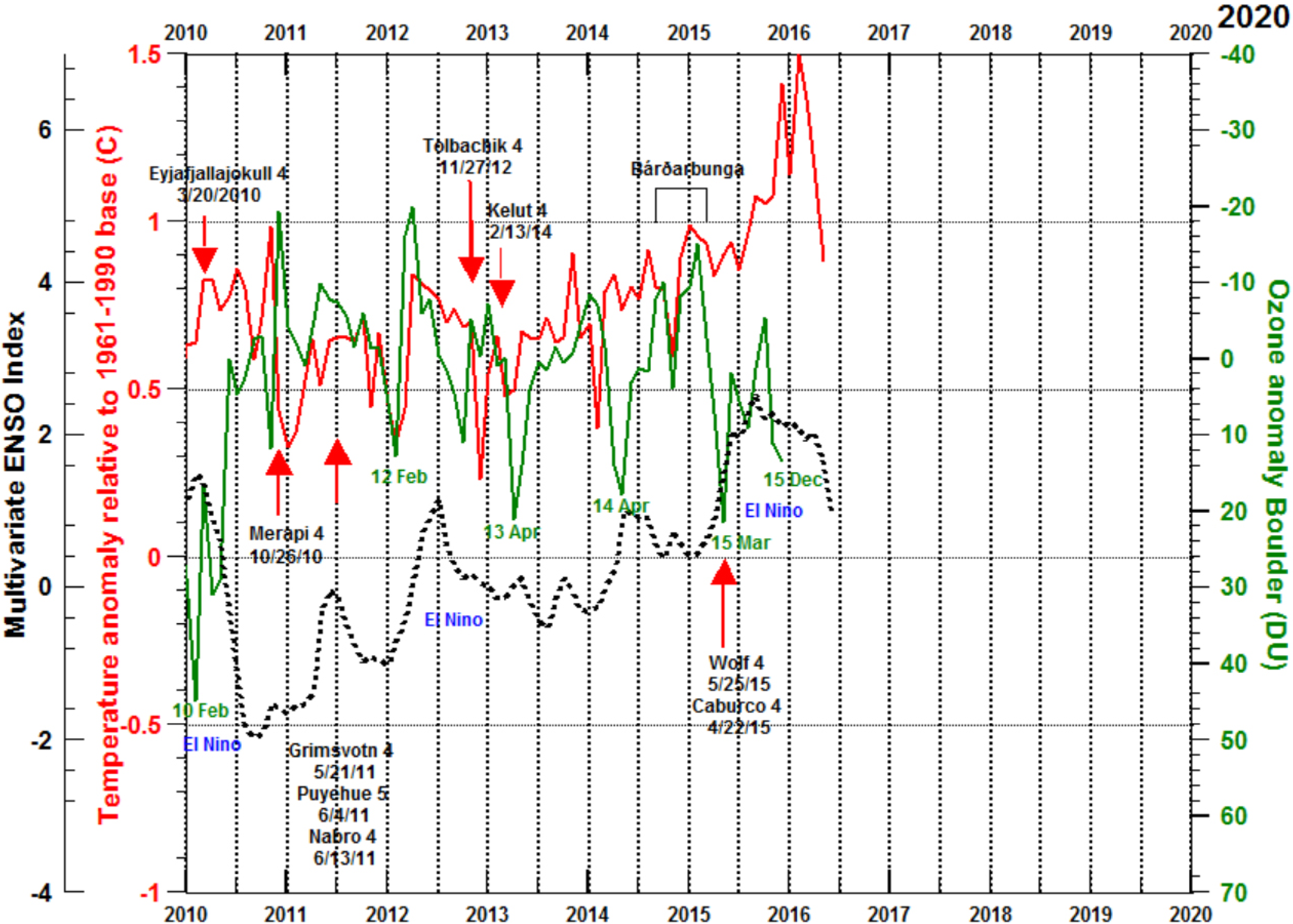
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
Multivariate ENSO Index
Temperature anomaly relative to 1961-1990 base (C)
Ozone anomaly Boulder (DU)
El Chichon 5
3/28/82
Galungguung 4
4/5/82
80 Dec
81 Jan
81 Dec
83 Jan
86 Feb
85 Nov
80 Mar
84 Dec
El Nino
El Nino
St Helens
3/27/80
Alaid 4
4/27/81
Pagan 4
5/15/81
Colo 4
7/13/83
Augustine 4?
3/27/86
Kluchevskoy 4
11/27/86
Chikurachki 4
11/18/86



2000
Multivariate ENSO Index
Temperature anomaly relative to 1961-1990 base (C)
Ozone anomaly Boulder (DU)
Kelut 4
Pinatubo 6
Cerro Hudson 5+
Spur 4
Lascar 4
Bezymianny 3
Rebaul 4
Karymsky 3 Akad. Nauk 3
Huge El Nino
Sheveluch 3 Korovin 3
Sheveluch 4
91 Feb
91 Mar
92 May
92 Nov
93 Feb
95 Feb
98 Apr
92 Sep
93 Nov



2010
Multivariate ENSO Index
Temperature anomaly relative to 1961-1990 base (C)
Ozone anomaly Boulder (DU)
Okmok 4
7/12/08
Kasatochi 4
8/7/08
Sarychev 4
6/11/09
Chalten
5/2/08
00 Nov
08 Jan
El Nino
El Nino
El Nino
Ulawun 4
9/28/00
Ruang 4
9/25/02
Reventador 4
11/3/02
Menam 4
10/24/04
Rabaul 4
8/11/06



2020
Multivariate ENSO Index
Temperature anomaly relative to 1961-1990 base (C)
Ozone anomaly Boulder (DU)
Eyjafjallajokull 4
3/20/2010
Merapi 4
10/26/10
Grimsvotn 4
5/21/11
Puyehue 5
6/4/11
Nabro 4
6/13/11
Tolbachik 4
11/27/12
Kelut 4
2/13/14
Bárðarbunga
Wolf 4
5/25/15
Calburco 4
4/22/15
10 Feb
12 Feb
13 Apr
14 Apr
15 Mar
15 Dec
El Nino
El Nino
El Nino