Climate effects of high-speed solar wind streams

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Data

Solar wind data from OMNI-2 database (NASA/NSSDC).

Energetic electron (>30keV) fluxes measured by the MEPED instrument onboard the NOAA/POES-satellites at 800-900 km altitude from 1979 onwards.

Asikainen and Mursula, J. Geophys. Res., 118, 2013

Long-term analysis

SLP observations by the Hadley center since 1850, gridded in 5°×5° lat-long bins.

Surface temperature provided by GISS since 1880, gridded in 2°×2° lat-long bins.

Monthly Nino3.4 index of sea surface temperature (averaged over 5°N-5°S and 170°W-120°W) from NOAA, since 1856, is used to represent ENSO.

Volcanic activity is represented by stratospheric optical depth by NASA averaged over the Northern Hemisphere since 1850 (we have extended this series from the end of 2012 to the end of 2014 with zero values).

QBO at 30 hPa height is obtained from the long-term reconstruction by Brönnimann et al.(2007a), available since 1900.

Data

Analysis from 1980 onwards

Altitude profiles of zonal wind, temperature, ozone mixing ratio from ERA-Interim reanalysis data (2.5° horizontal resolution, 37 pressure levels from 1000 to 1 hPa) by European Centre for Medium-Range Weather Forecasts (ECMWF) from 1979 onwards.

QBO phase was calculated from zonal wind at 30 hPa averaged over 10°S-10°N and all longitudes.

Winters 1984/1985 and 2003/2004 were excluded due to unusually strong SSW.

Winters 1982/1983, 1983/1984, 1991/1992, 1992/1993 and 1993/1994 were excluded since these winters follow the large volcanic eruptions of El Chichon and Mount Pinatubo.

Methods

EEP and atmospheric data were first detrended using the LOWESS (locally weighted scatterplot smoothing) method with a 31-year window.

Regressions were computed separately for each latitude-pressure level grid-point and for each of the four winter months (December-March) using the Cochrane-Orcutt (CO) method which takes possible auto-correlation of residuals into account.

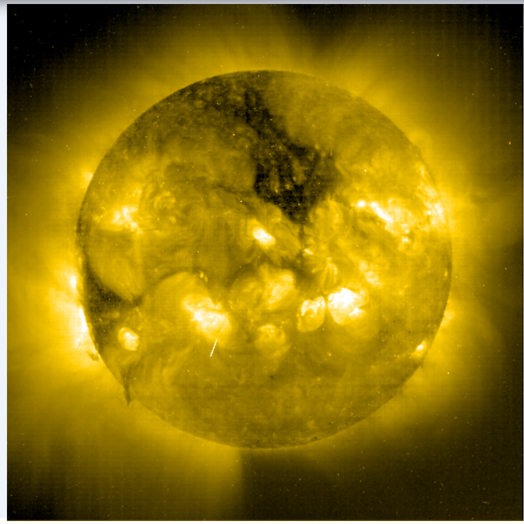
The significance of the response is estimated with the two-tailed Student´s t-test, which is appropriate for CO-method due to the way autocorrelation is incorporated into the model.

We used here a 1-month lag for EEP in February and March in order to account for the descent time of NOx from the upper atmosphere

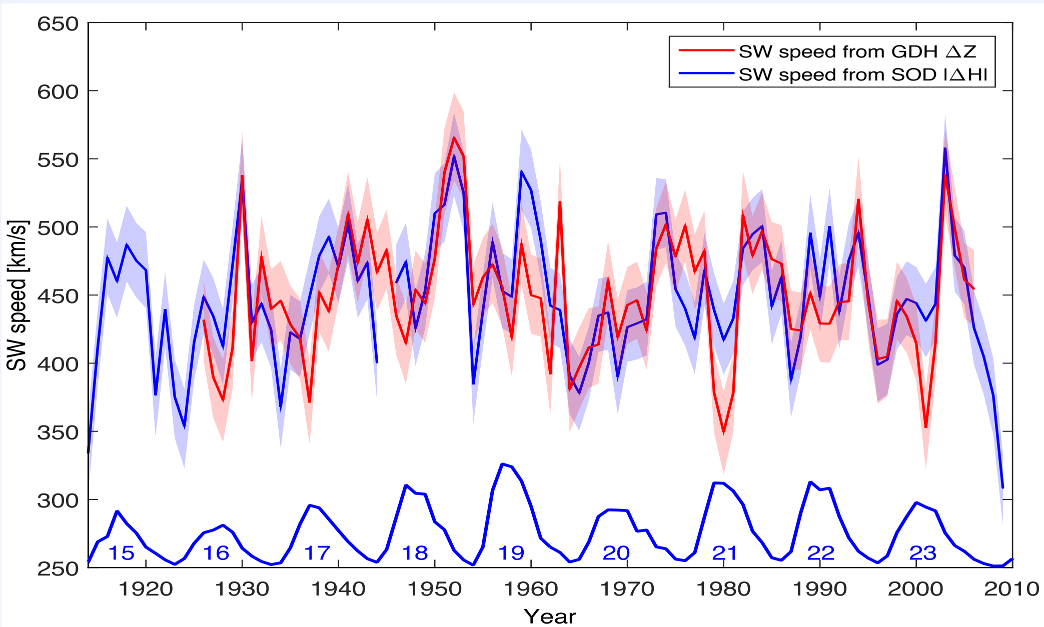
High-speed solar wind streams (HSS)

Solar cycle variation of solar wind speed

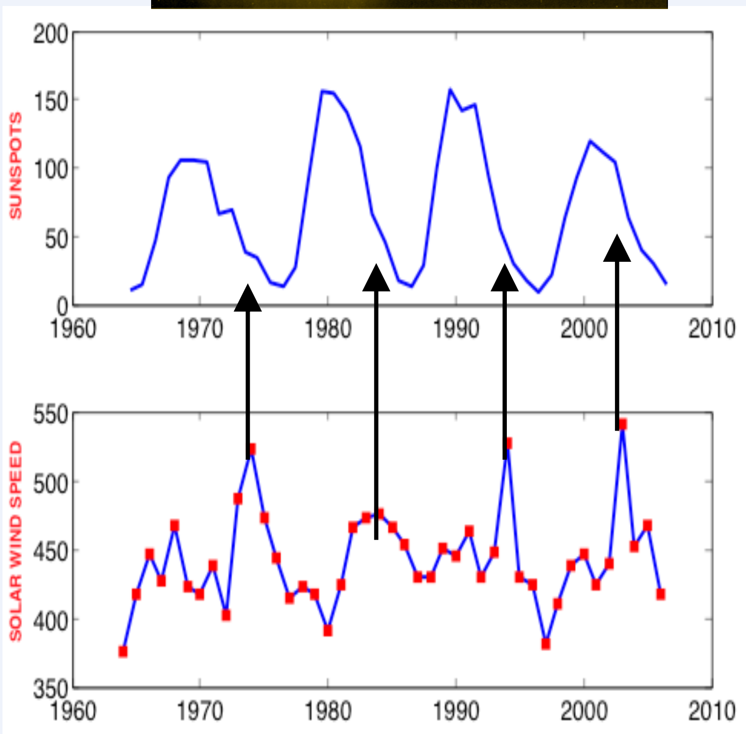
Solar wind speed observed at Earth has maximum in the declining phase of every sunspot cycle (above) due to high-speed streams (HSS) emanating from polar coronal holes with equatorial extensions.



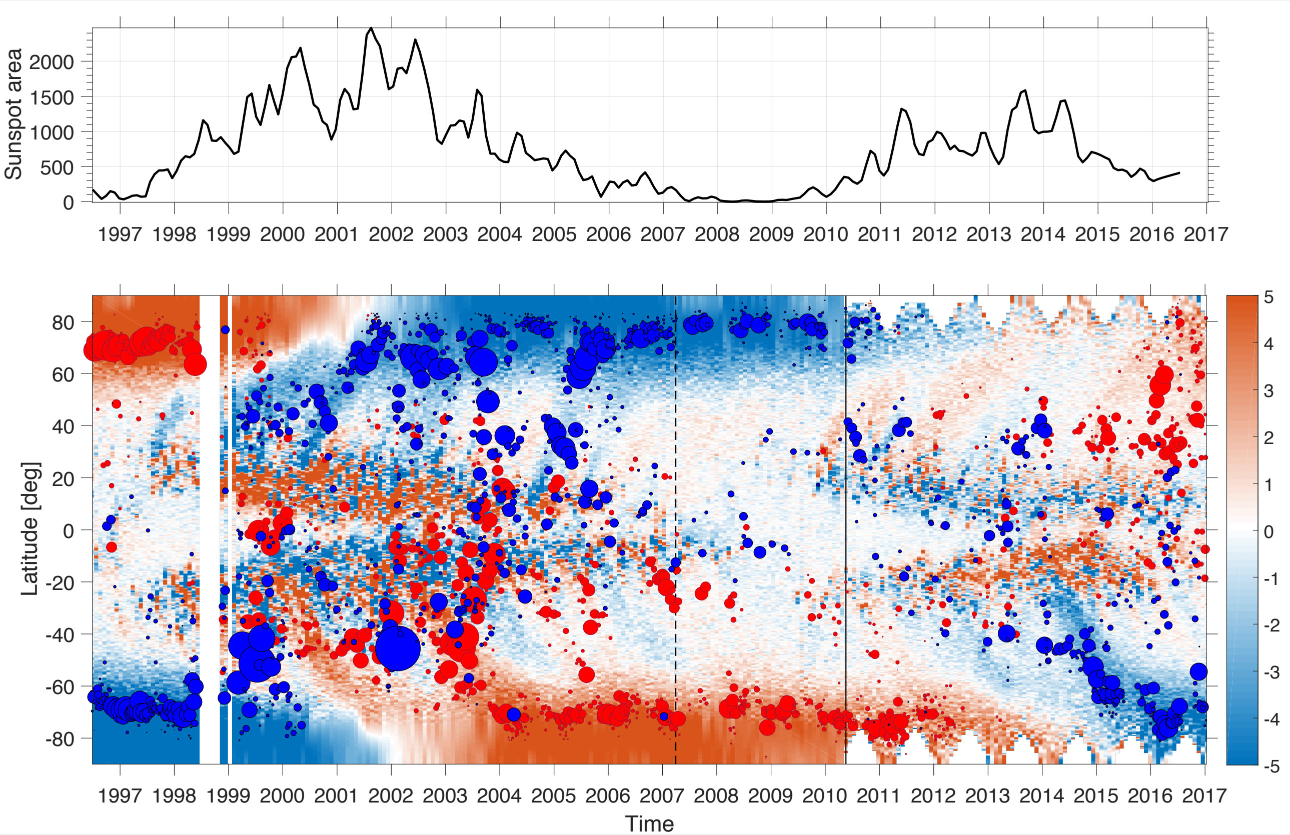
Solar wind has been directly observed during the satellite era since 1963. Before that, solar wind speed can be indirectly determined from geomagnetic activity.



Mursula, et al., Astrophys. J., 801, 1, 30, 2015



Structure and evolution of solar corona in SC23-SC24



Hamada et al., Solar Phys., 293:71, 2018

Background color (turquoise, orange) presents the two polarities of the solar photospheric magnetic field. Blue and red circles depict the centers of coronal holes with the corresponding polarity of magnetic field.

Coronal holes are seen to follow the surges of the magnetic field from mid-latitudes to the poles and form large unipolar regions at the poles during most of the solar cycle.

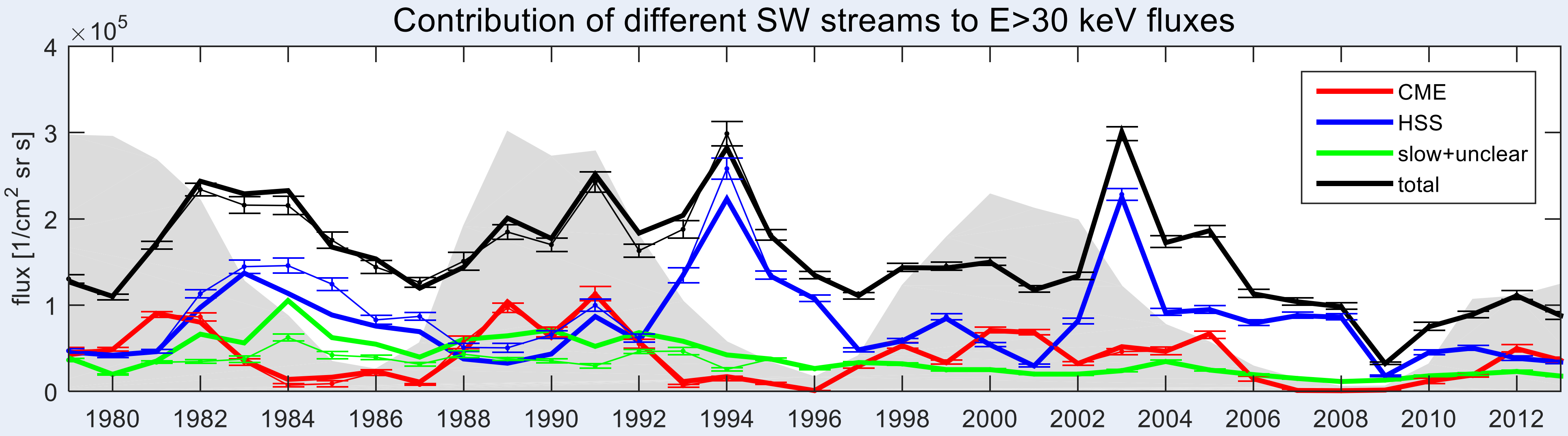
Solar wind drivers of energetic particles

High-speed solar wind streams are the dominant driver accelerating magnetospheric energetic particles (10-1000 keV protons, electrons, He+, O+) and auroral particles (1-30 keV electrons).

Energetic particle flux peaks in the declining phase of each solar cycle.

Asikainen and Ruopsa, J. Geophys. Res. 2016.

CMEs produce more energetic particles than HSS only during few years around sunspot maxima.



Contributions of the three SW patterns (CME, HSS, HCS) to produce energetic particles. Sunspots are depicted as grey area.

Chain of effects of energetic particles

Energetic particles precipitate from magnetosphere into the atmosphere mainly in the auroral oval and ring current regions.

Note the close proximity of the auroral oval with the Polar Vortex !

Enhanced atmospheric ionization

➔ Modified chemistry.

HOx and NOx production and descent.

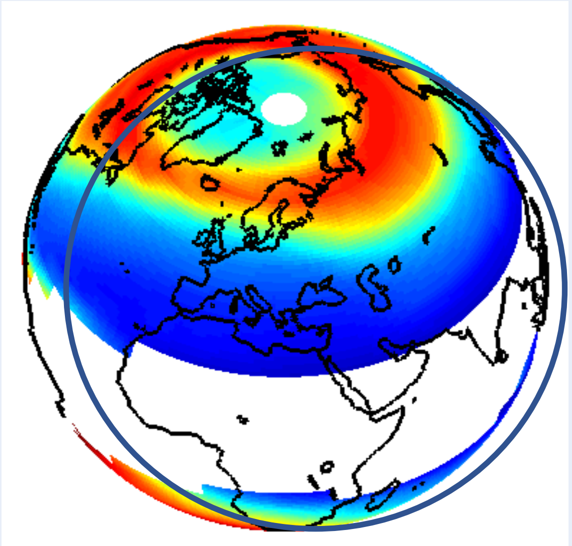
➔ Ozone destruction

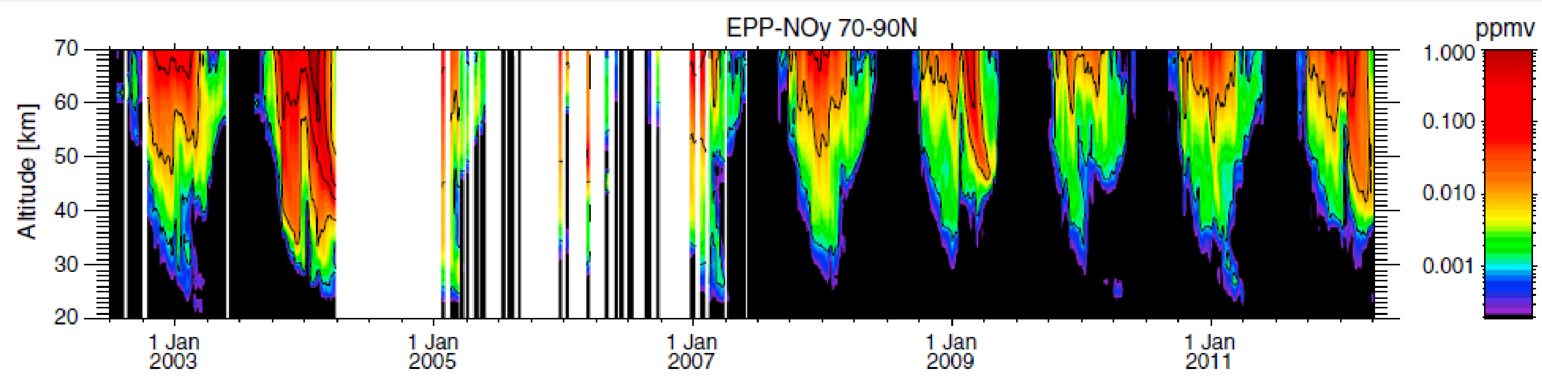
➔ Modified thermal balance and increased latitudinal temperature gradients

➔ Enhanced polar vortex

➔ Positive NAO

➔ Climate effect on surface





Winter climate in the 4 solar cycle phases

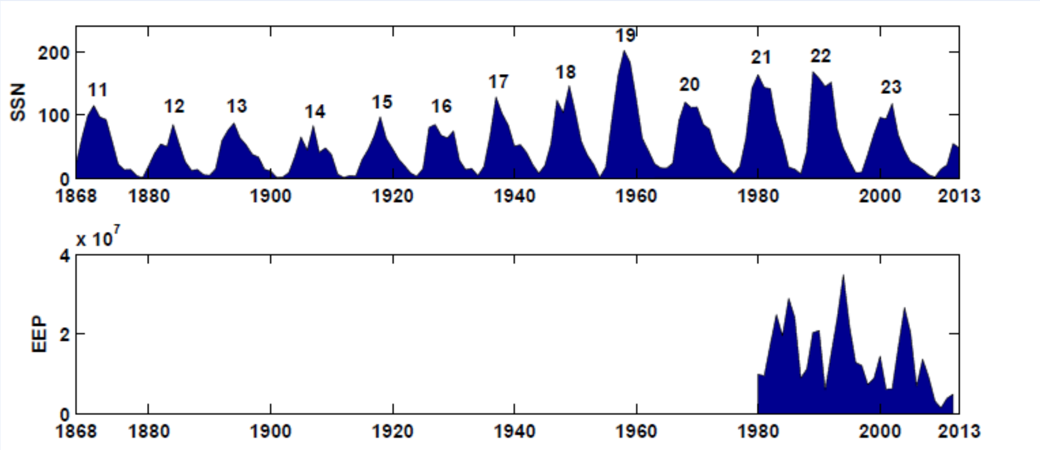
Solar cycle phases

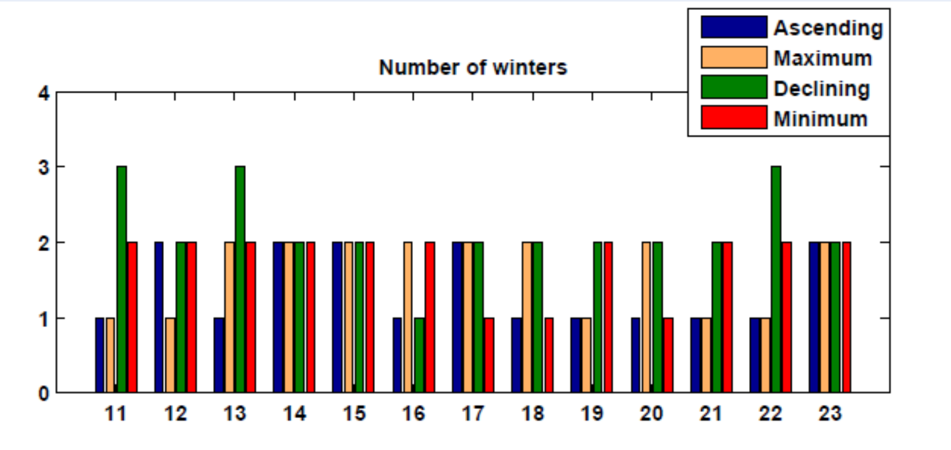
We study NAO in winters of 1880-2009 (solar cycles 11-23)

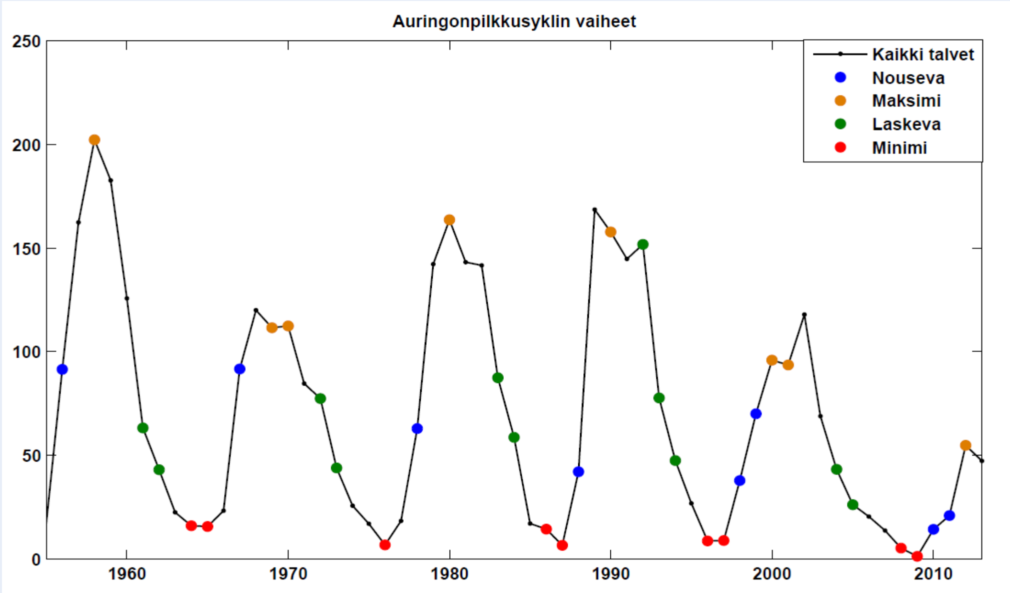
We divide years to four solar cycle phases:

Ascending, Maximum, Declining and Minimum
(60° wide window in the phase function)

- Ascending phase: 18 winters
- Maximum phase: 21 winters
- Declining phase: 28 winters
- Minimum phase: 23 winters





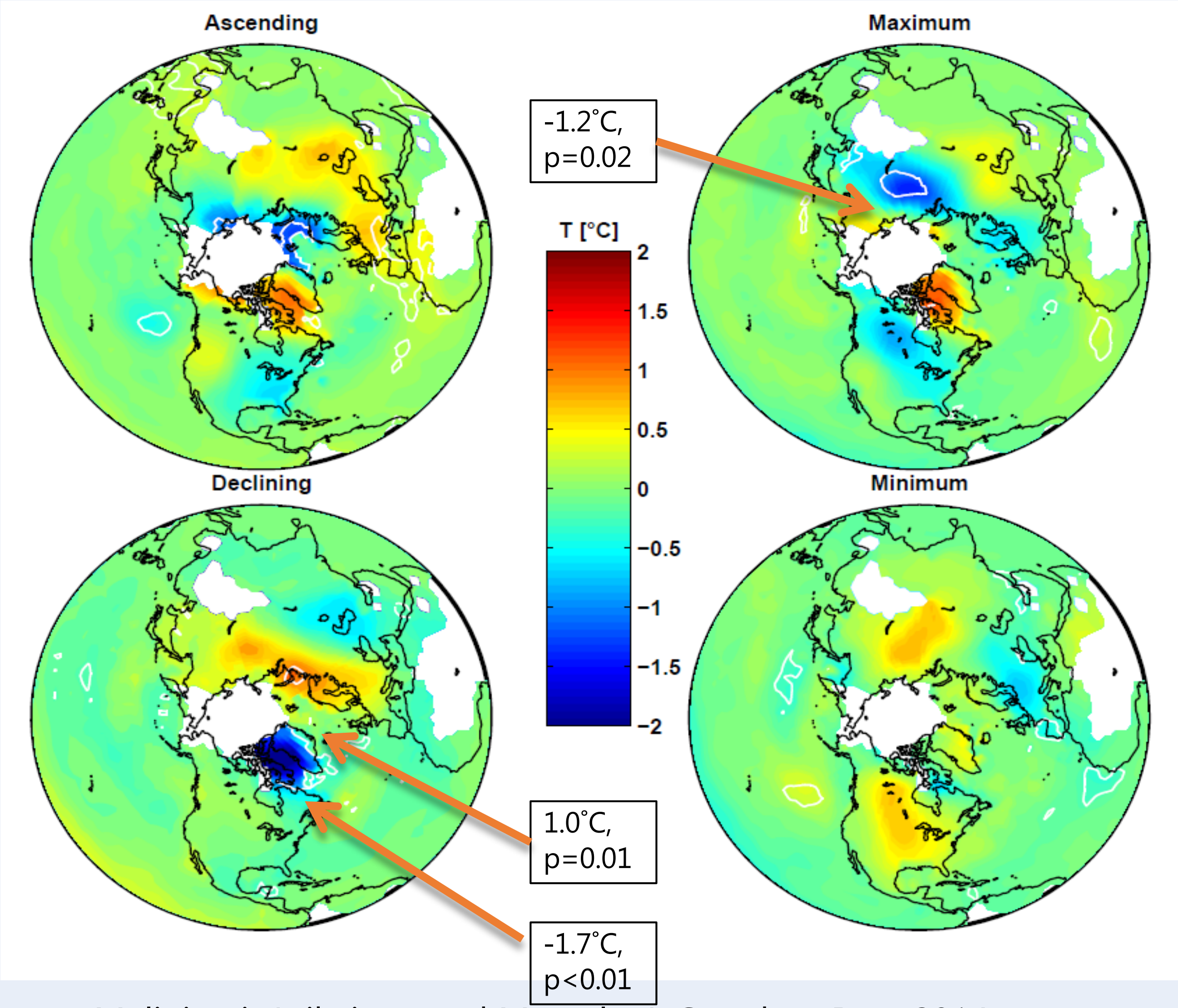


Maliniemi, Asikainen and Mursula, J. Geophys. Res., 2014.

Winter temperature anomalies during different cycle phases (1880-2009)

Temperature pattern in the declining phase greatly resembles the temperature pattern during positive NAO.

Field significance test yields a statistically significant result (92%) only in the declining phase

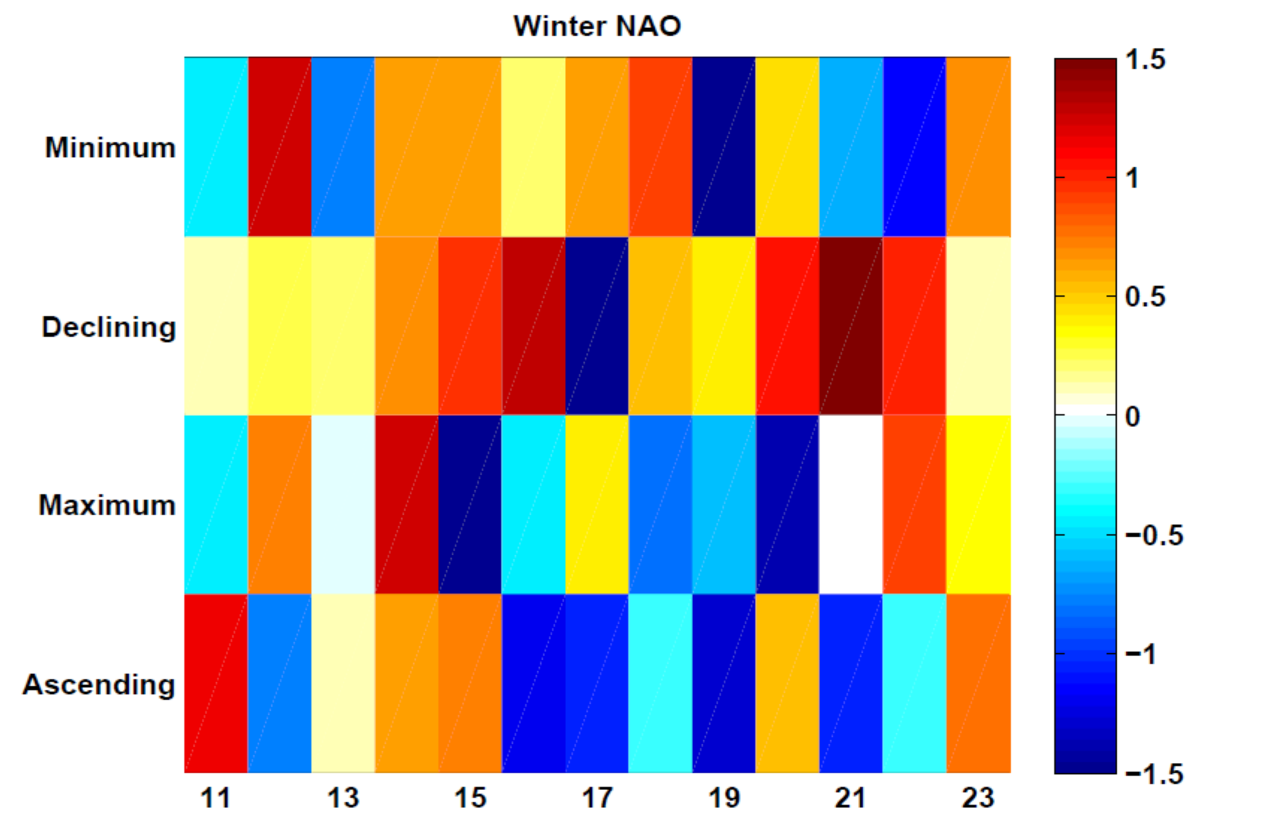


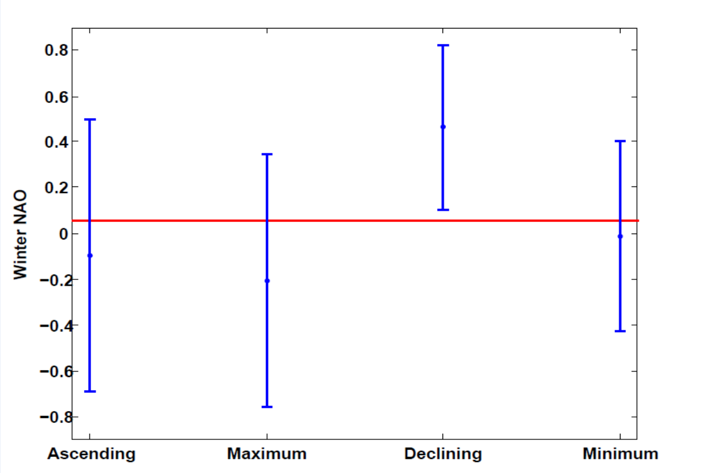
Maliniemi, Asikainen and Mursula, J. Geophys. Res., 2014.

NAO during different cycle phases (1880-2009)

Only the declining phase produces a systematically positive NAO

Wintertime NAO is significantly different (positive) from the long-term mean only in the declining phase.

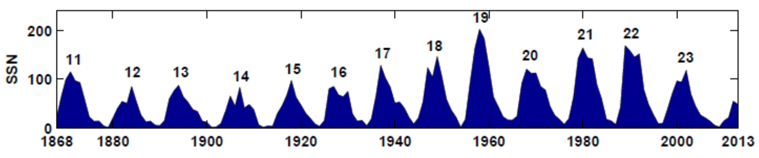




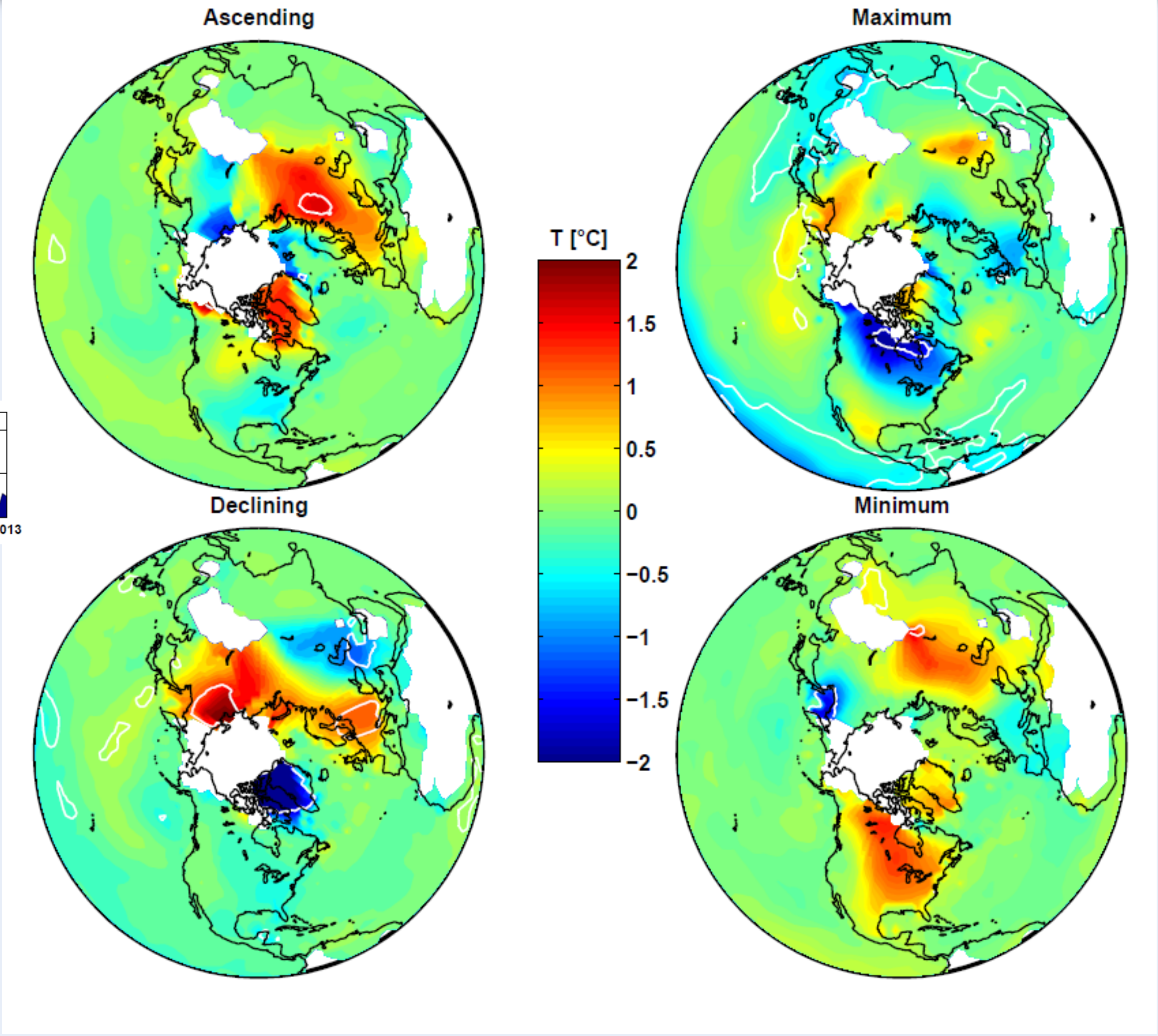
Maliniemi, Asikainen and Mursula, J. Geophys. Res., 2014.

Temperature anomalies during weak cycles 12-15 (1880-1925)

- This relation is also true during weak sunspot cycles 12-15



- Field significance 93% in the declining phase (less than 70% in other phases)



Maliniemi, Asikainen and Mursula, J. Geophys. Res., 2014.

Declining phase is special

Above results verify that the declining phase of the solar cycle has particular relevance for climate !

Note:

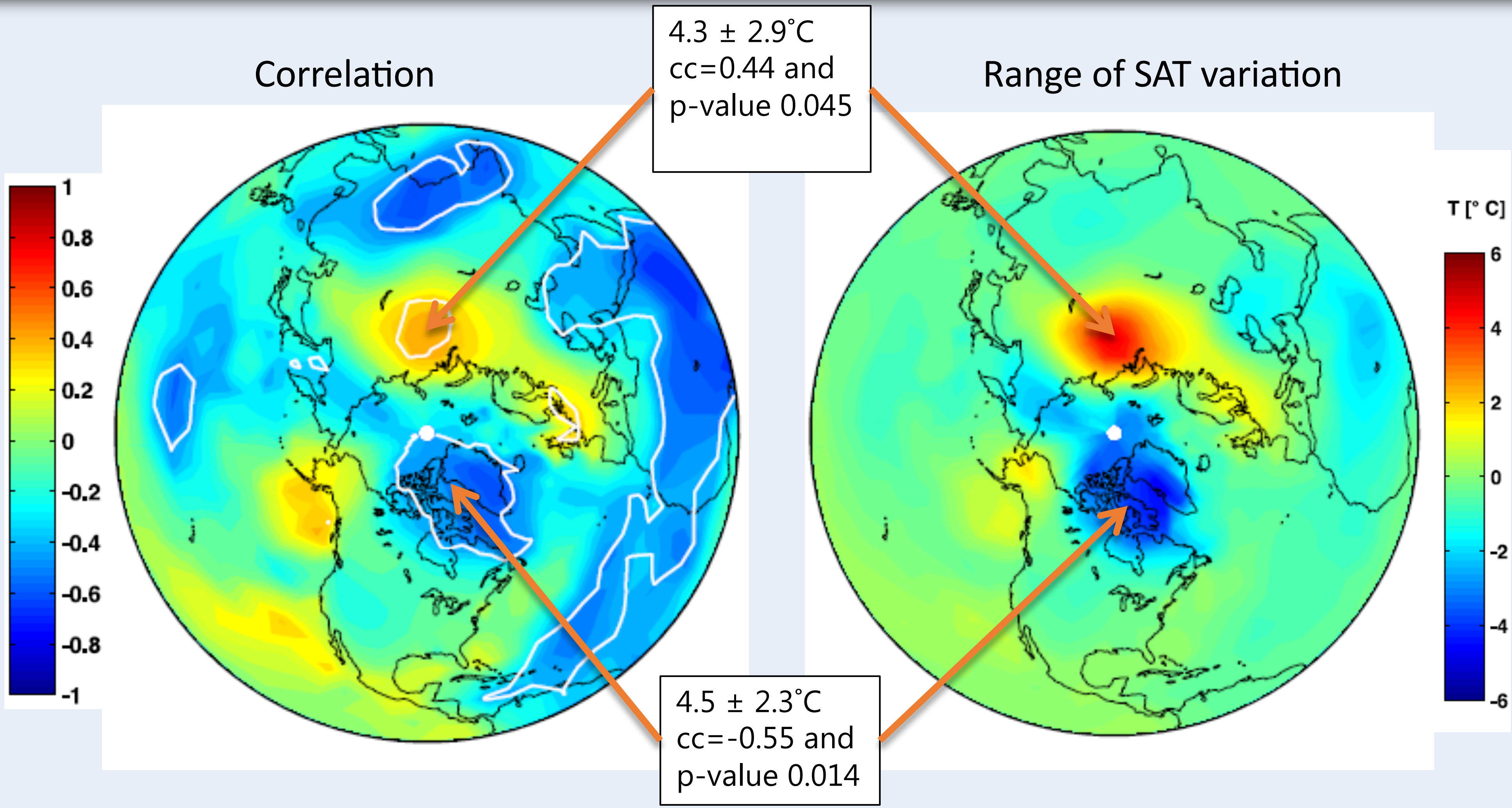
Above results need NO manipulation with the data, only appropriate sampling of data (selection of years).

So: There was systematic ordering within the data that was hidden within the "random" variation until proper understanding revealed the hidden order.

CONSEQUENCE:

Is there more similar orderings hidden in the climate data ?

SAT and EEP (1980-2010)



Measured EEP fluxes and SAT correlation produces the NAO pattern (even at a slightly higher confidence level than geomagnetic activity).

Maliniemi et al., J. Geophys. Res., 2013.

QBO dependence

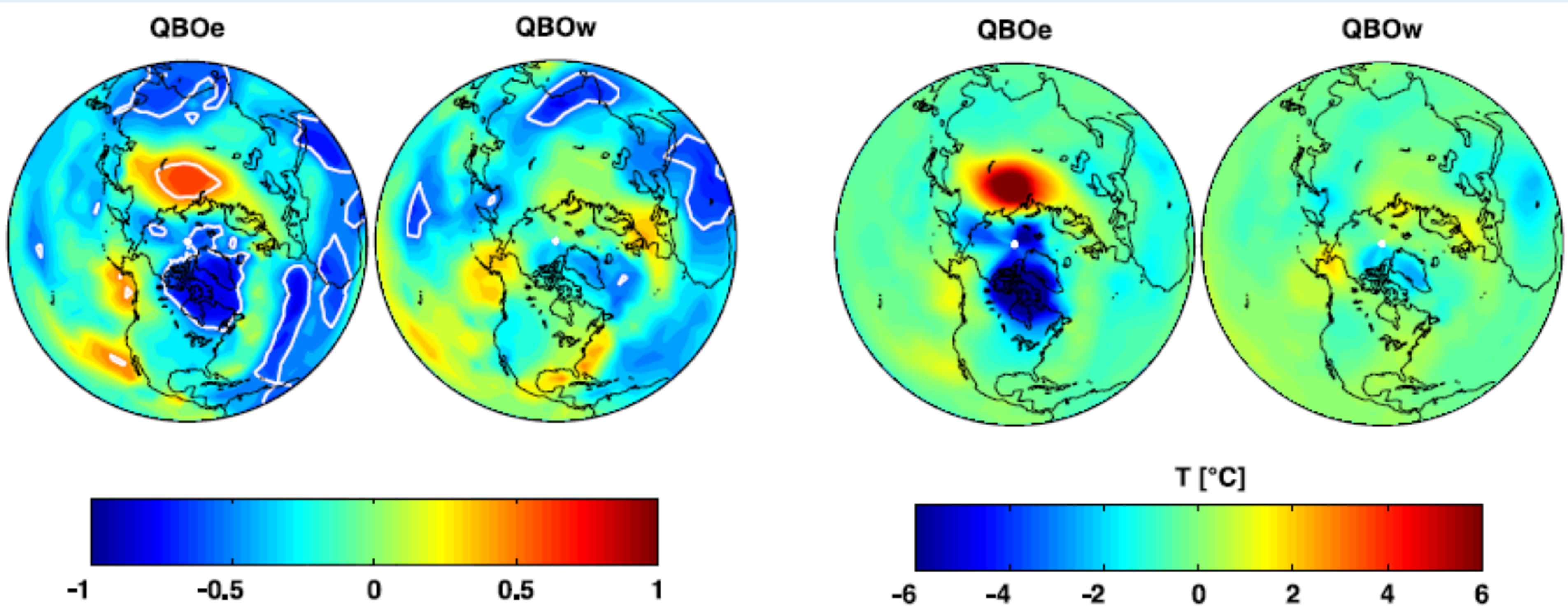
QBO phase separated EEP effect (1980-2010)

Data is divided into Easterly and Westerly QBO (30 hPa) phases.

EEP effect on winter temperatures is visible during Easterly QBO.
=> Global connection between equator and poles is obvious.

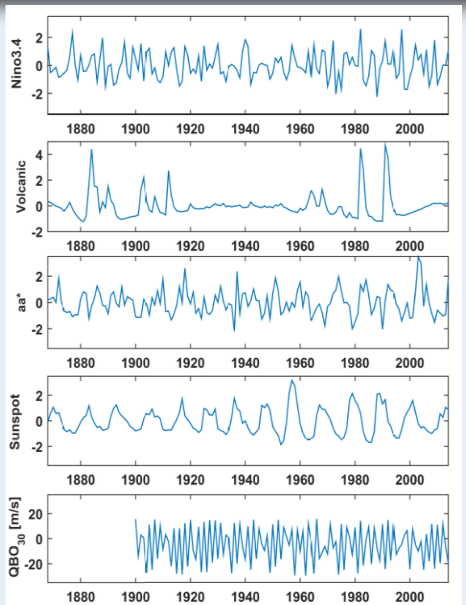
QBO regulates the solar wind effect on climate!
(Possibly by controlling meridional circulation)

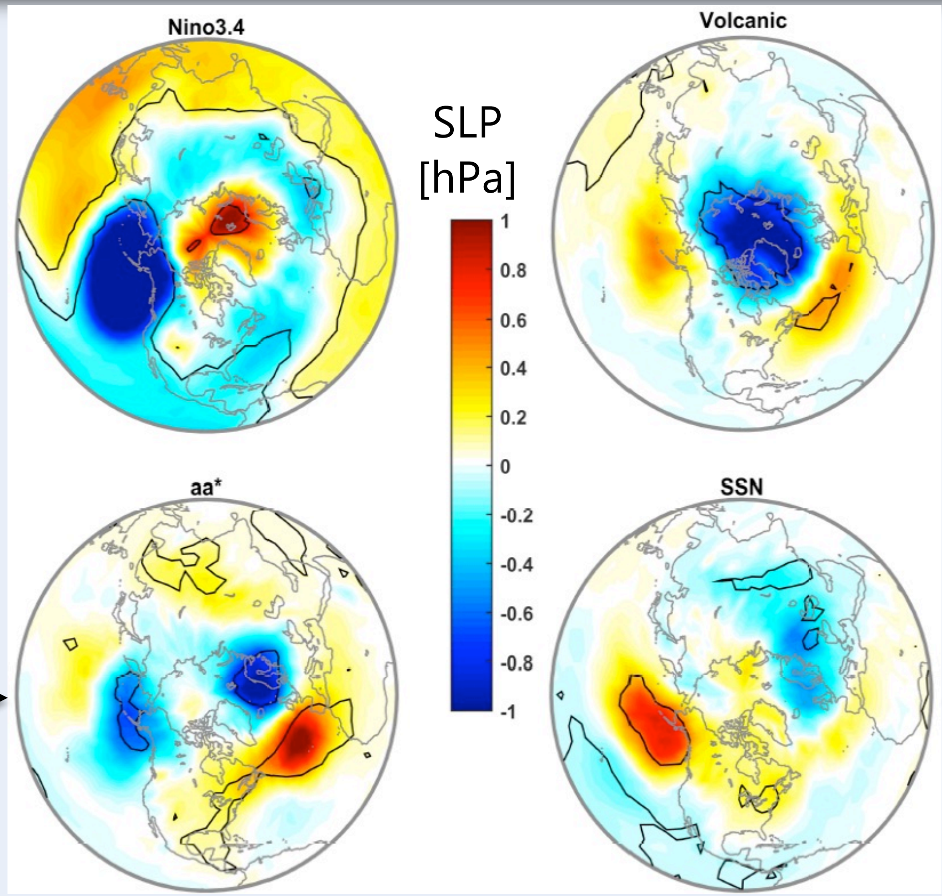
Maliniemi et al., J. Geophys. Res., 2013.



MLR analysis

SLP decadal variation in 1868-2014 related to ENSO, volcanic activity, GA/HSS and SSN





ENSO: Large effect in Pacific; Weak NAO<0 in Atlantic

Volcanic: NAO>0 effect due to equatorial heating by aerosols

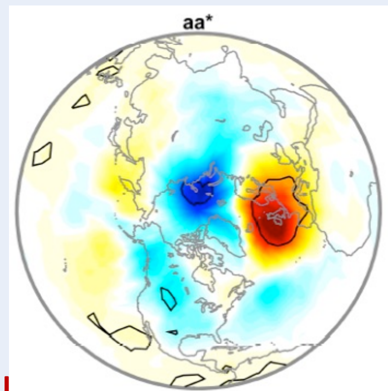
GA: positive NAO in early winter (Dec/Jan)

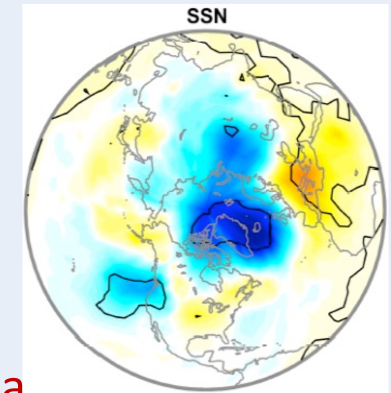
SSN: positive anomaly in Aleutian low in early winter (Dec/Jan)

Particle Top-down mechanism

Bottom-up mechanism

GA: positive NAO in late winter (Feb/Mar)





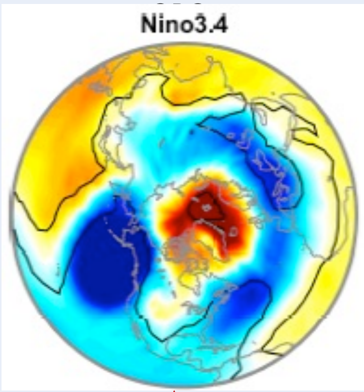
SSN: positive NAO in late winter (Feb/Mar)

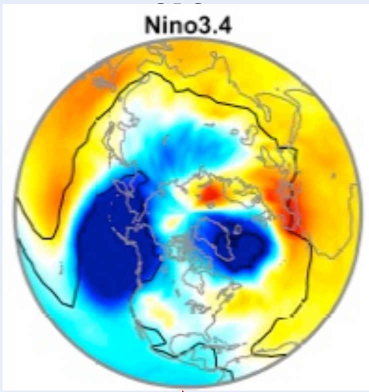
Top-down mechanism

Maliniemi et al., JASTP, 2018

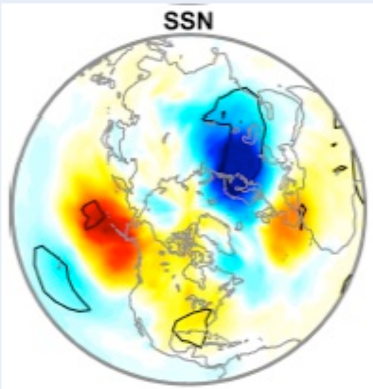
QBO phase separation (1900-2014) for SLP (early/mid-winter)

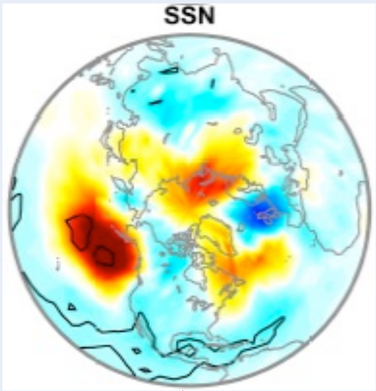
- Minor QBO (stratospheric) effect in the Pacific





Tropospheric ENSO forcing in Aleutian low region

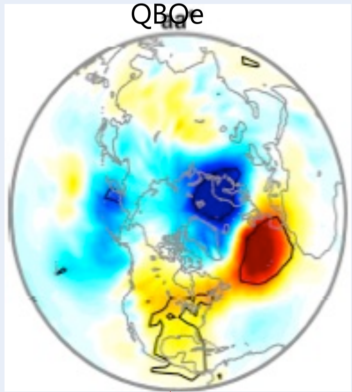


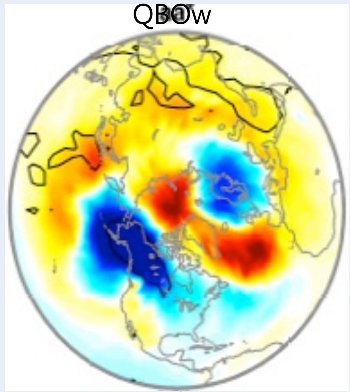


Bottom-up SSN mechanism in Aleutian low (unaffected by QBO)

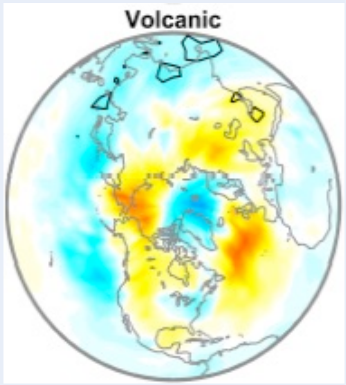
Maliniemi et al., JASTP, 2018

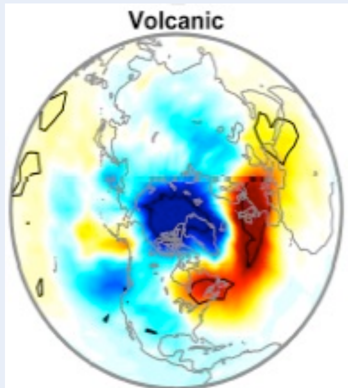
- Strong QBO (stratospheric) effect in the Atlantic





Particle top-down mechanism affected by QBO (stratospheric dynamics)





Volcanic forcing (aerosol injection into the atmosphere) affected by QBO

Altitude profiles

EEP effect on zonal wind, temperature, O3

EEP effect to zonal wind (1. row), temperature (2. row) and ozone (3. row) in Dec-Mar (columns 1-4).

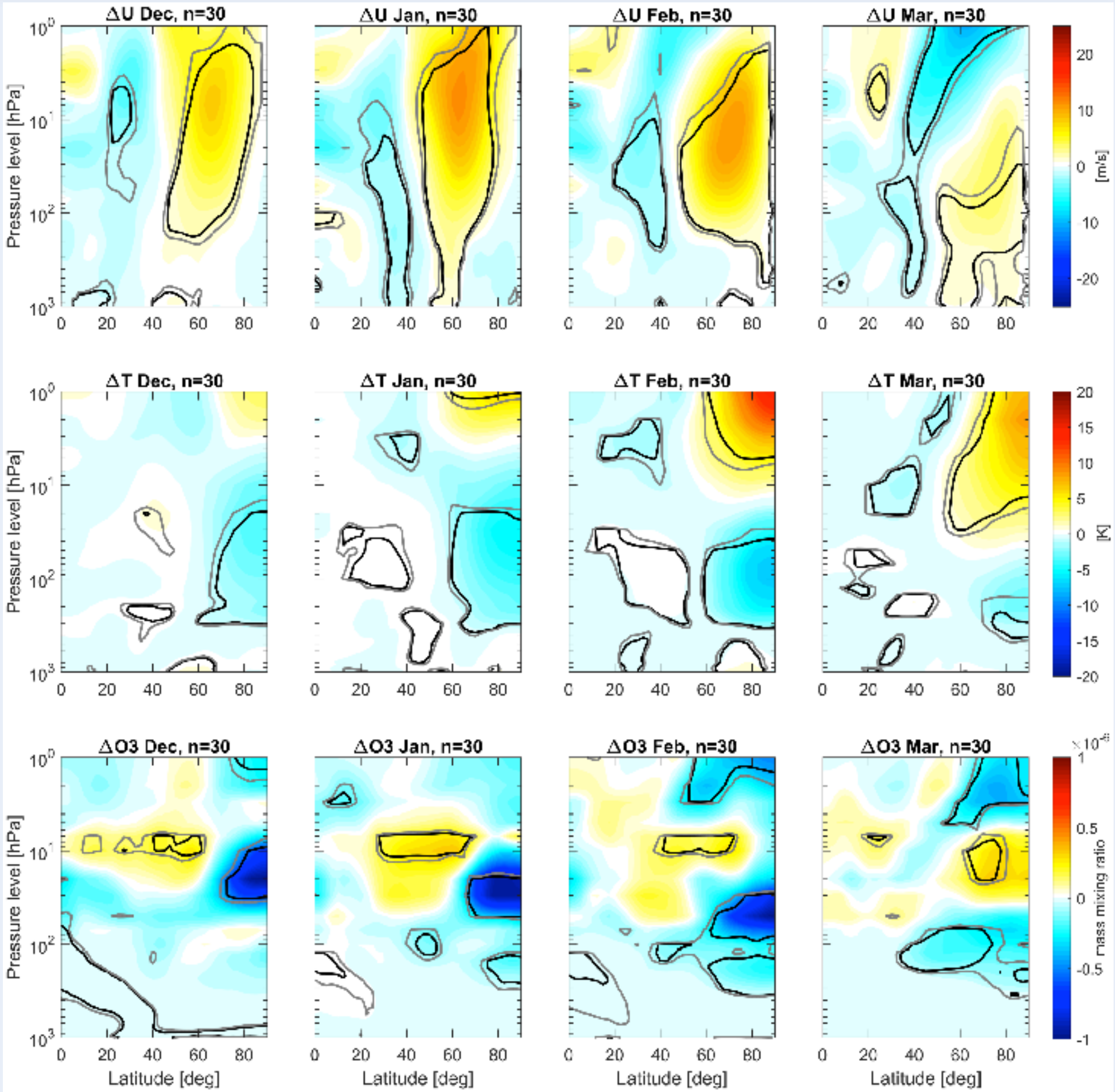
- Responses correspond to a change of one standard deviation in EEP.
- Black contours correspond to 95% significance level and grey contours to 90% level.

EEP **increases polar vortex** every month. Effect descends down during winter and extends to ground.

EEP **decreases (increases) temperature** in lower (upper) stratosphere.

EEP **decreases O3** in lower (and upper) stratosphere.

- Mid-lat O3 increase is probably an accumulation effect due to stronger PV.



Salminen et al., submitted, 2018.

EEP effect on zonal wind, temperature, O3 in QBO-E

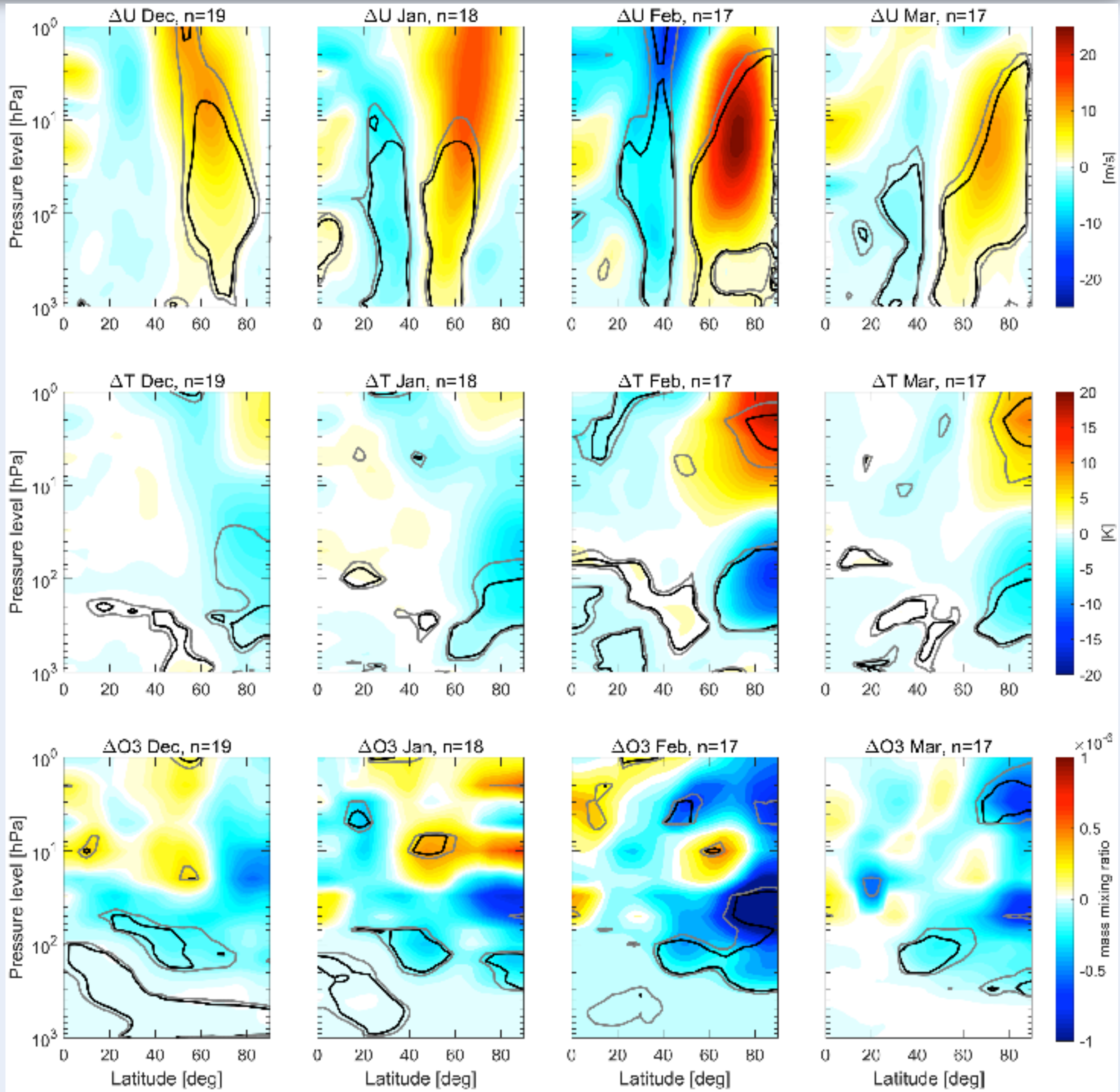
Method the same as for the overall effect, except that now a 6-month lag was used when dividing months to QBO phase.

Results are similar for other lags (0-9).

EEP responses are similar to those without QBO phase separation (or lag).

However, there is a stronger response in all three parameters in February and in polar vortex in Mar.

Even the decrease of zonal winds at mid-latitudes is more expressed for QBO-E, especially in Feb, during the strongest vortex.



Salminen et al., submitted, 2018.

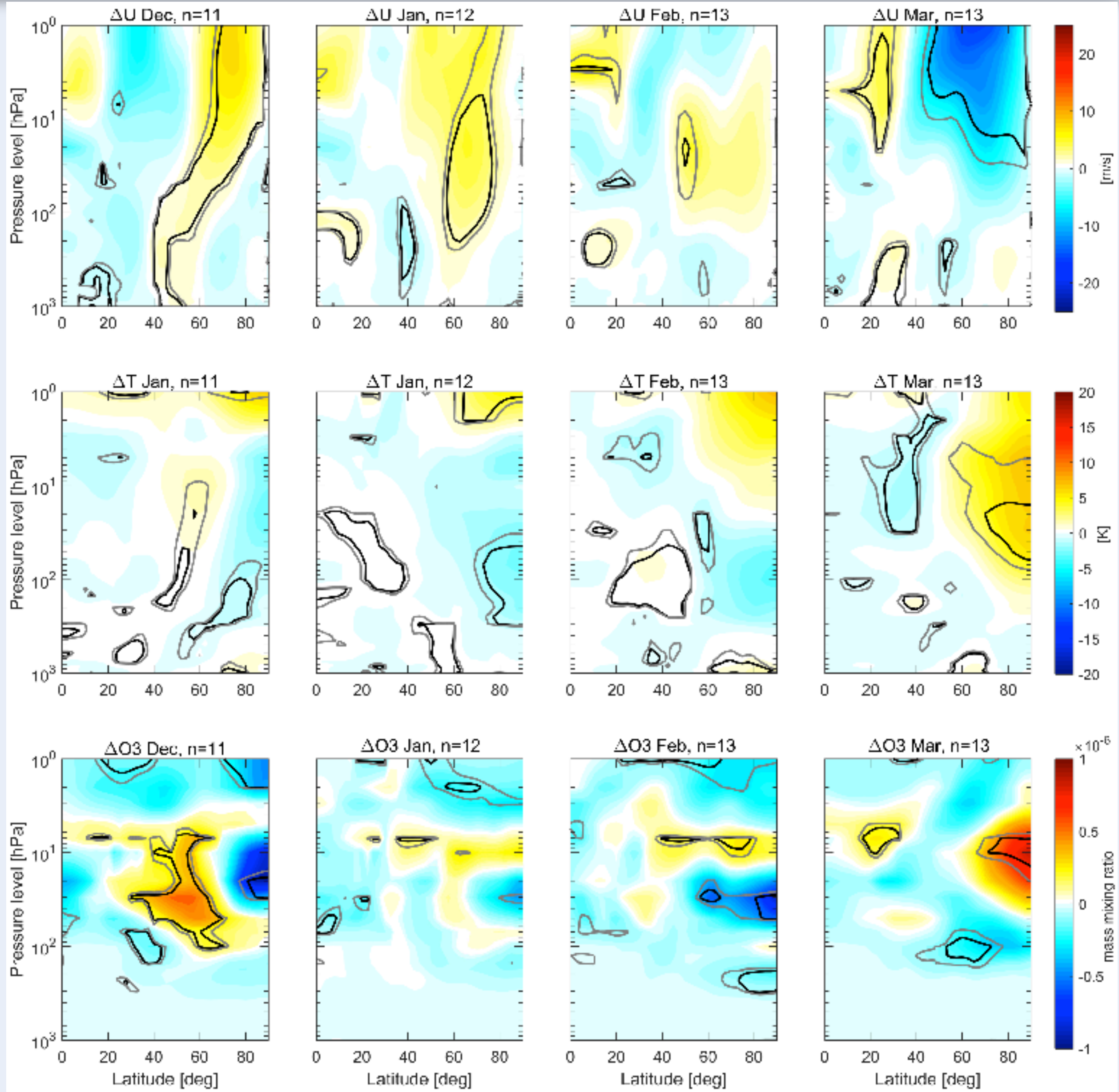
EEP effect on zonal wind, temperature, O3 in QBO-W

EEP responses are weaker, less persistent and less significant in QBO-W phase than in QBO-E, especially in late winter.

EEP strengthens polar vortex and decreases temperature only in early/mid-winter (Dec-Jan).

In March polar vortex weakens, and O3 and temperature increase.

Salminen et al., submitted, 2018.



Conclusions

Climate data includes hidden orderings. Go and find them !

Positive NAO is preferred in the declining phase of the solar cycle.
Other cycle phases have little preference for NAO phase.

HSS can naturally explain this dominance of positive NAO.

=> Particle top-down mechanism
=> Potential for long lead time weather/climate forecasting

HSS effect is found irrespective of possible simultaneous irradiance, ENSO, volcani etc effects.

QBO strongly modulates the solar wind effect to NAO.
This is related to its control of meridional circulation.

Meta-level conclusions

Solar wind is an (the most ?) important solar-related driver for winter climate at mid- to high latitudes of the Northern hemisphere.

This new climate driver needs to be taken into account in future IPCC reports.

Tribute to earlier works, e.g., by

- Andersson
- Arsenovic
- Baumgaertner
- Bochnicek
- Funke
- Kodera
- Labitzke
- Lam
- Lu
- Palamara
- Randall
- Rozanov
- Seppälä
- Sinnhuber
- Tinsley
- Van Loon
- Verronen

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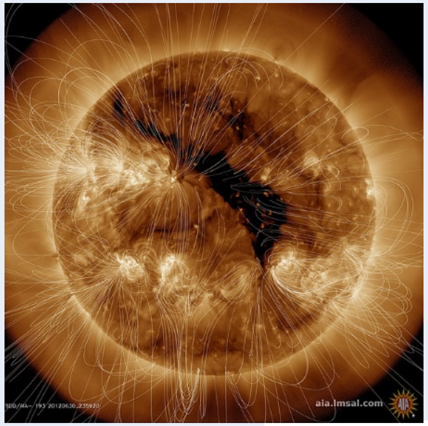
- Salminen, A., T. Asikainen, V. Maliniemi and K. Mursula, submitted, 2018.

Thank You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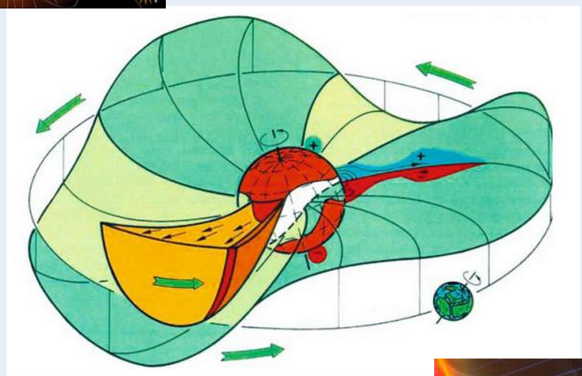

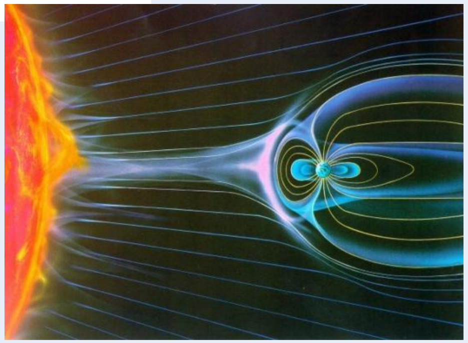

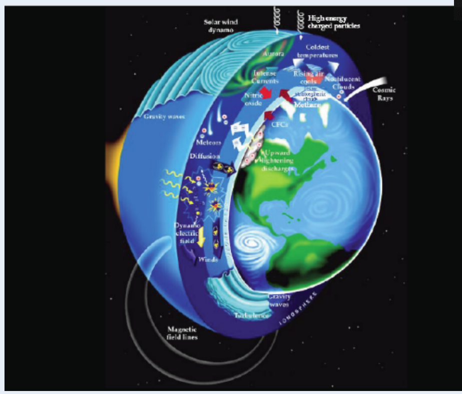

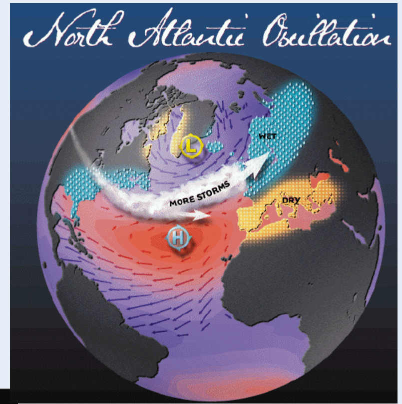
North Atlantic Oscillation
WET
DRY
MORE STORMS
L
H