Investigating the Occurrence of Sudden Stratospheric Warmings with Non-linear Statistical Methods

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Motivation and Goals

Understanding the **frequency, dynamics and causes** of sudden stratospheric warmings (SSW).

Climate models (Charlton *et al.*, 2007) are able to simulate SSWs in principle, but evaluating contributions of **atmospheric variability factors** remains a difficult task.

Estimating the **non-linear impact** of factors like the QBO, ENSO, the Sun, the NAO, or stratospheric chlorine on wind and temperature data in the stratosphere (Labitzke *et al.*, 2006; Camp & Tung, 2007; Calvo *et al.*, 2009).

Evaluating non-linear contributions of these variability factors to the **probability of occurrence of SSWs**.

Data and SSW Criteria

Three Sets of Daily Data

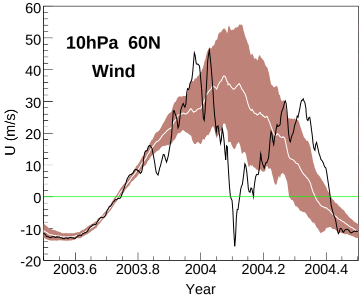
1. **ERA40** Reanalysis Extended from 1958 to 2008 (ERA40 + Operational ECMWF Analyses)
2. **NCEP**/NCAR Reanalysis from 1958 to 2008
3. **EMAC** CCMVal REF-B1 model output from 1960 to 2000 (Jöckel *et al.*, 2006; Morgenstern *et al.*, 2010)

The analyses were repeated with every time series starting at 1979 when the quality of data improved.

SSW Criteria at 10hPa (FUB)

$$U_{60\mathrm{N}} < 0$$
and
$$\Delta T := T_{90\mathrm{N}} - T_{60\mathrm{N}} > 0$$
and
Winter Period

$\longrightarrow$ Consider here: Nov. to Feb.



Idea

1. Non-linear regression on the time series $U_{60}(t)$, $T_{90}(t)$ and $T_{60}(t)$ with respect to the atmospheric factors

- EESC (Equivalent Effective Stratospheric Chlorine, 3 year age)
- MEI (Multivariate ENSO Index, NOAA)
- QBO (Equatorial zonal wind at 50hPa, FU Berlin)
- SFL (Solar Cycle, 10.7cm Radio Flux, NOAA)
- NAO (North-Atlantic Oscillation, NOAA)

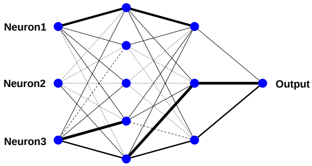
2. After regression, change the regressors and evaluate their **impacts** on the different time series

3. Look at the **change** in number of values that hold $U < 0$ $(\Delta T > 0)$ to estimate the influence of certain regressors on the occurrence of SSWs

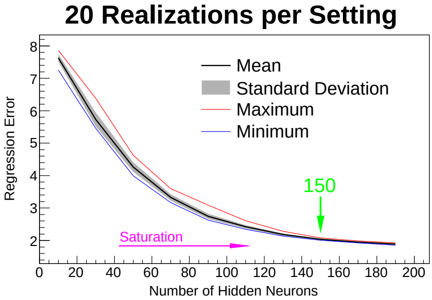
Statistical Model

A feed-forward **Artificial Neural Network** (ANN) performs the non-linear regression. (Bishop, 1995; Lu *et al.*, 2009)

Example Network



C++ Library at
http://root.cern.ch
Class: TMultiLayerPerceptron



In this analysis, the ANN has **5** normalized input neurons (regressors), **150** hidden neurons in one single hidden layer and **1** linear output neuron (response): **5,150,1**

⇒ The regression was successfully performed for both periods.

Impact of Input Neurons

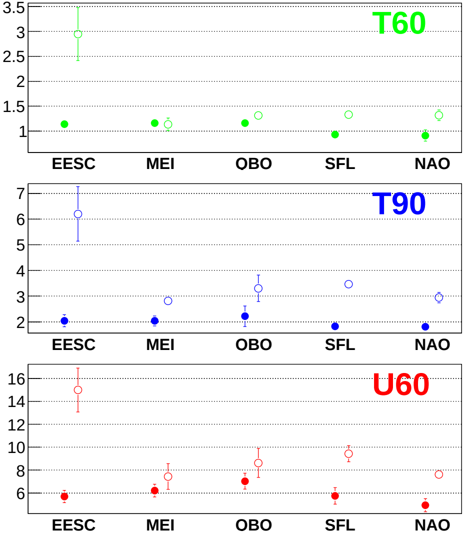
We define the **impact** P of one input neuron i on the ANN as

$$P_i(\gamma) = \frac{\sum_t |f - g_i(\gamma)|}{\sum_t f}$$

where

- γ denotes a **small disturbance** to each of the input neurons such that $x_i^*(\gamma) = x_i \cdot (1 + \gamma)$
- f denotes the **original fit**
- g denotes the **disturbed fit**

Impact (%) of Input Neurons for $\gamma = 0.1$



What is shown?

- Mean of the three data sets
- Shaded points: full time period (A)
- Hollow points: start at 1979 (B)

What does it mean?

- QBO and MEI make largest impact on ANN during (A)
- EESC, SFL and NAO make small impact during (A)
- During (B), SFL impact became large, QBO still important
- the largest impact makes EESC during (B) $\rightarrow$ Ozone loss

Change of SSW Occurrence in U_{60}

For reasons of simplicity, only U_{60} is considered in the following.

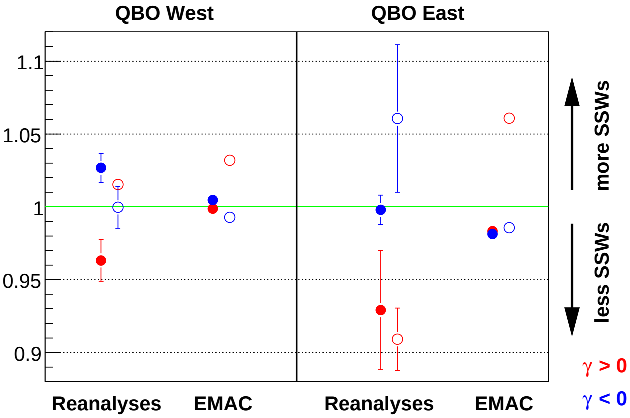
We define the **change of SSW Occurrence** C depending on the impact of the **phase** of one input neuron i as

$$C_i = \left\langle \frac{\sum_t g_i(\gamma)}{\sum_t f} \right\rangle_\gamma \qquad f, g < 0 \quad \text{(Easterlies)}$$

where

- γ denotes a **small disturbance** to each of the phases of the input neurons such that $x_i^*(\gamma) = x_i \cdot (1 + \gamma)$
- average over $\gamma \in \,]-0.1, 0[\,$ $(\gamma < 0)$ and $\gamma \in \,]0, 0.1[\,$ $(\gamma > 0)$
- f denotes the **original fit**
- g denotes the **disturbed fit**

Change of SSW Occurrence - QBO



Shaded points: full time period (A)

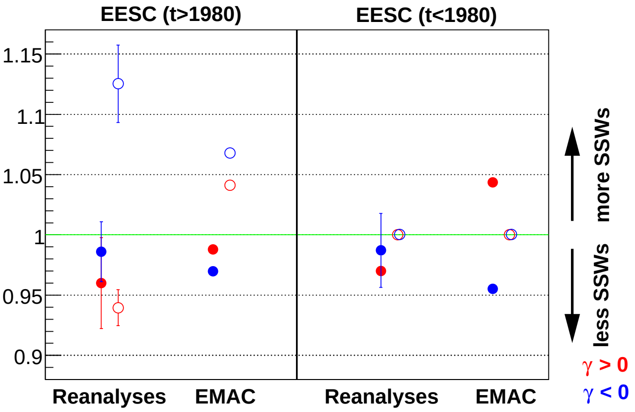
Hollow points: start at 1979 (B)

Increase of QBO East (A,B) ⇒ less SSWs
Decrease of QBO East (B) ⇒ more SSWs
Increase of QBO West (A) ⇒ less SSWs
Decrease of QBO West (A) ⇒ more SSWs

(Gray *et al.*, 2003) showed very similar results

Reanalyses and EMAC results differ significantly

Change of SSW Occurrence - EESC



Shaded points: full time period (A)

Hollow points: start at 1979 (B)

No big change on the full period.

But, on the short period:
Increase of EESC (t>1980) ⇒ less SSWs
Decrease of EESC (t>1980) ⇒ more SSWs

Reanalyses and EMAC results differ again

Conclusions

- Non-linear regression successfully applied to wind and temperature data
- Stable learning algorithm, small spread in multiple realizations

- QBO and ENSO make largest impact during the full period
- EESC followed by SFL and QBO make largest impact during the period starting at 1979
- Reanalyses and model results for the change of SSW occurrence differ significantly, reason still unclear but the QBO influence towards higher latitudes might be underestimated in EMAC

- Increasing (decreasing) QBO East/West $\Rightarrow$ less (more) SSWs; in agreement with (Gray *et al.*, 2003)
- Increasing (decreasing) Chlorine fraction $\Rightarrow$ less (more) SSWs

Were less Warmings in the 90s caused by a strong loss of Ozone?

References I

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Supplement

ANN Details

- feed-forward network
- 5 normalized input neurons
- 150 hidden neurons in one single hidden layer
- the hidden neurons are Sigmoids
- 1 linear output neuron
- the BFGS algorithm is used to train the network
- 20 realizations per time series
- 1000 training epochs per realization
- ROOT Analysis Framework, Class: TMultiLayerPerceptron

Regression Results (%)

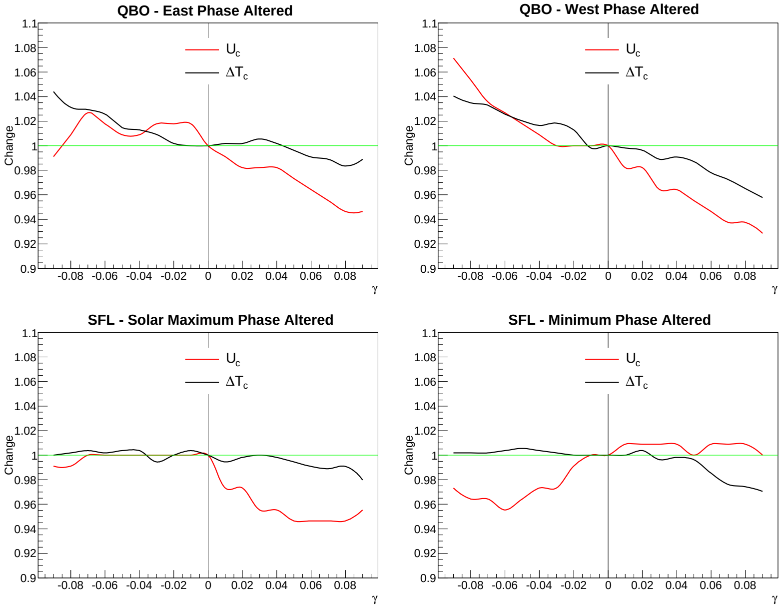
Black: full time period

Gray: starting at 1979

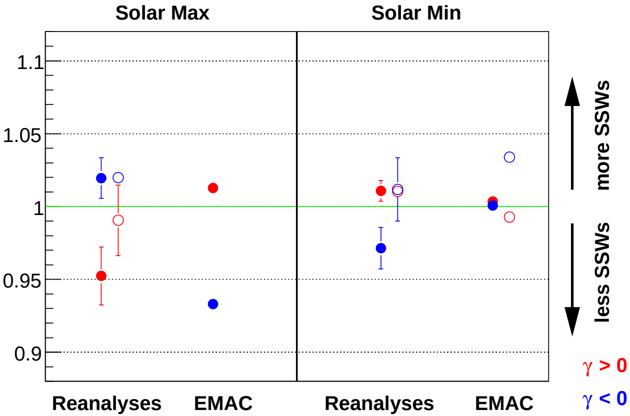
Data		R(Data,Fit)	$\hat{\sigma}(\mathrm{Res})$	t-Test	KS-Test
ERA40	U_{60}	99.8 99.9	5.5 3.7	97.7 99.9	99.9 99.6
	T_{90}	99.9 99.9	2.8 2.1	95.7 95.0	93.0 99.7
	T_{60}	99.9 99.9	1.1 0.9	97.0 96.3	100 100
NCEP	U_{60}	99.7 99.8	6.6 4.6	97.8 97.3	99.4 100
	T_{90}	97.6 99.8	1.4 0.7	96.3 95.0	55.0 97.8
	T_{60}	99.8 99.9	0.4 0.2	97.2 96.3	99.7 100
EMAC	U_{60}	99.9 99.9	4.9 3.5	97.7 97.3	100 100
	T_{90}	99.6 99.8	0.7 0.5	99.9 94.7	90.0 100
	T_{60}	99.8 99.9	0.2 0.2	93.8 95.8	100 100

$\Rightarrow$ non-linear regression successful

Response Change for ERA40



Change of SSW Occurrence - SFL



Shaded points: full time period (A)

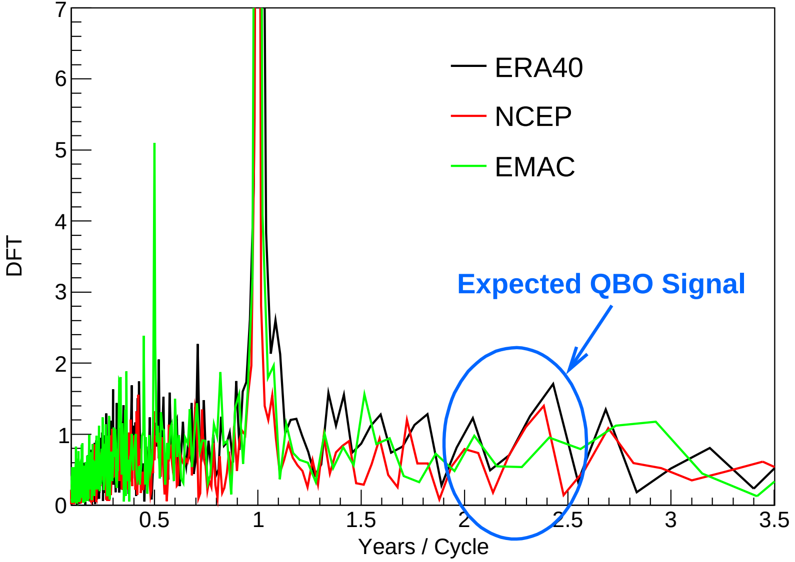
Hollow points: start at 1979 (B)

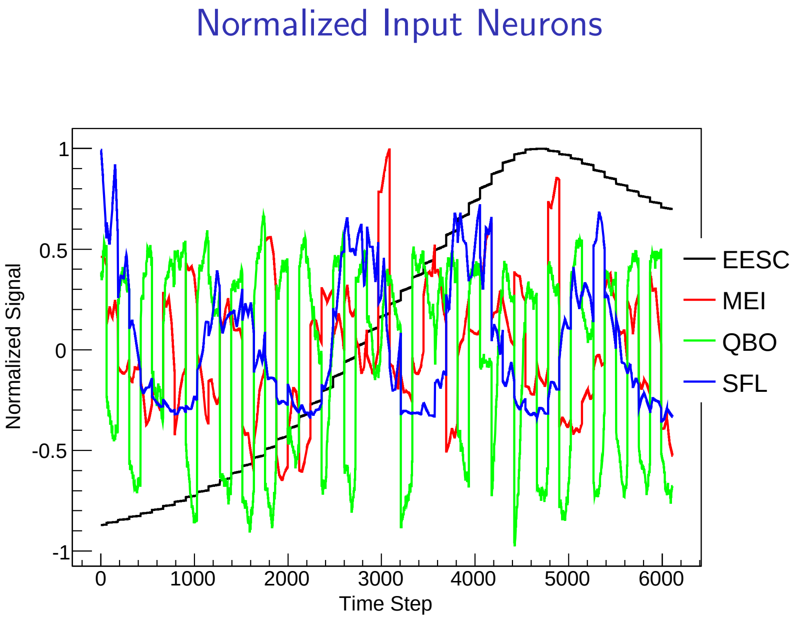
Increase of Solar Max (A) ⇒ less SSWs (?)
Decrease of Solar Max (A) ⇒ more SSWs (?)
Decrease of Solar Min (A) ⇒ less SSWs (?)

Reanalyses and EMAC results differ significantly

Also, ERA40 and NCEP results vary quite a lot here

Fourier Spectrum for U at 10hPa, 60N





Normalized Input Neurons
Normalized Signal
Time Step
1
0.5
0
-0.5
-1
0
1000
2000
3000
4000
5000
6000
EESC
MEI
QBO
SFL