The role of the stratosphere for sub-seasonal to seasonal forecasting

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The stratosphere exhibits variability on all of these timescales:

- **WEATHER FORECAST**
  - 5 days

- **SUB-SEASONAL PREDICTION**
  - 2 weeks

- **SEASONAL PREDICTION**
  - 3 months

- **DECADAL PREDICTION**
  - 2 years

- **CLIMATE PROJECTION**
  - 20 years
  - 100 years

Internal stratospheric dynamics, tropical processes: ENSO and MJO influence on the stratosphere, tropospheric blocking, Arctic sea ice and snow cover influence, QBO influence on SSWs, Long-term changes in SSW events?
Limited prediction skill in midlatitudes

Prediction skill (ACC) for December - February

Model: Max-Planck-Institute Earth System Model (MPI-ESM-LR) [Baehr et al., 2015]

Initialization: November

Figure: Domeisen et al., 2015, J.Climate
WHAT HAPPENS IN THE STRATOSPHERE DOES NOT STAY IN THE STRATOSPHERE

Probably the most famous figure of stratosphere–troposphere coupling: “dripping paint”

“Wide acres of time”, Venice Biennale, 2017
Figure: elephant.art
The longer persistence of the stratosphere can leak through to the troposphere during months with an “active” stratosphere.

Figure: e-folding decorrelation time scales of the first EOF of deseasonalized NH/SH height variability (20–90N/S), i.e. the northern/southern annular mode

Figure: Kidston et al, 2015
ESTIMATE PREDICTABILITY FROM THE S2S PREDICTION DATABASE (VITART ET AL, 2017)

Figure 1. Schematic representation of model vertical resolution for all S2S prediction systems used in this study. Each block represents the pressure range indicated on the y-axis. The number of model levels in each range is shown numerically. The shading in each box is proportional to the average level spacing in km in that region of the atmosphere. The red number at the top of each bar shows the total number of levels in each model. The dashed line indicates the separation between high- and low-top models (see Table 1).

2.2 Skill Measures

In this study, skill is evaluated according to a range of measures that are commonly used in the literature. One common metric is the correlation coefficient $r$ given by

$$r = \frac{\sum_{t=1}^{T} (X_{mod} - C_{mod}) (X_{obs} - C_{obs})}{\sqrt{\sum_{t=1}^{T} (X_{mod} - C_{mod})^2 \cdot \sum_{t=1}^{T} (X_{obs} - C_{obs})^2}}$$

where $X$ is a time-dependent variable, and the subscripts $mod$ and $obs$ denote the model ensemble mean and the reanalysis dataset, respectively. $C_{mod}$ is the lead time dependent model climatology, over the same period of time as the observed climatology $C_{obs}$. $T$ is the number of events or time steps for which $r$ is being evaluated.
MODELS WITH A GOOD STRATOSPHERE MAKE BETTER PREDICTIONS FOR THE TROPOSPHERE

Figure 3. Scatter plot showing the predictability limit (the day for which the ACC crosses 0.6) of geopotential height (a-b) north of 30° N and (c-d) south of 30° S for each model at 50hPa vs. 500hPa for DJF (left) and JJA (right). The average for all prediction systems is shown as the black square. A linear fit to the data points is shown as the solid line. The correlation coefficient between the prediction skill at 50 hPa and 500 hPa is indicated in the upper-right corner of each panel.

Figure: H. Kim. From Domeisen et al., under review for the JGR special issue on S2S prediction.
CONTENTS

stratosphere
WHAT IS THE PREDICTABILITY LIMIT FOR SSW EVENTS?

In an idealized model:

Figure: Gerber et al (2009)
PREDICTABILITY LIMIT FOR STRATOSPHERIC EVENTS

Sudden stratospheric warming events are often not predictable on sub-seasonal timescales.

Strong vortex events and final warmings have a higher predictability.

Figure: A. Butler from Domeisen et al., under review for the JGR special issue on S2S prediction.
PREDICTABILITY OF SSW EVENTS IS LIMITED TO WEATHER TIMESCALES
But: there are precursors and teleconnections that can affect the frequency of stratospheric events on sub-seasonal to seasonal timescales.
Processes that alter wave propagation into the polar stratosphere can affect the strength of the polar vortex.
TROPOSPHERIC STRUCTURE BEFORE SSW EVENTS

Tropospheric precursors agree overall with reanalysis, except in strength and over Eurasia

Figure: Average Northern Hemisphere sea level pressure anomalies (hPa) 5 to 30 days before major SSW events between 1996-2010 in ERA-Interim. Areas enclosed by solid brown lines denote where the composite mean is significant.

Figure: J. Furtado.
from: Domeisen et al., under review for the JGR special issue on S2S prediction
THERE ARE PRECURSORS AND TELECONNECTIONS THAT CAN AFFECT THE FREQUENCY OF SSW EVENTS

Processes that alter wave propagation into the polar stratosphere can affect the strength of the polar vortex.

- Extratropical tropospheric forcing, e.g. blocking
- ENSO
- MJO
- QBO
- Sea ice
- Solar forcing
- Snow cover
GLOBAL IMPACTS OF THE QUASI-BIENNIAL OSCILLATION

There are a range of remote impacts from the QBO

Figure: Gray et al., 2018
A CONNECTION BETWEEN THE TROPICAL AND THE EXTRATROPICAL STRATOSPHERE

HOLTON-TAN EFFECT

Westerly QBO winds in the lower stratosphere lead to a strengthening of the winter polar vortex through decreased refraction and reflection of waves towards the polar stratosphere, and vice versa for eQBO.

eQBO: easterly zonal winds in the lower equatorial stratosphere (commonly defined at 50 or 30hPa)

January, westerly – easterly QBO

stronger polar vortex

Data: ERAinterim

green lines: climatological winds

Figure: Anstey & Shepherd (2014), QJRMS
THERE ARE PRECURSORS AND TELECONNECTIONS THAT CAN AFFECT THE FREQUENCY OF SSW EVENTS

Processes that alter wave propagation into the polar stratosphere can affect the strength of the polar vortex.

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Domeisen | ECMWF Annual Seminar | 2019
THE EFFECT OF EL NINO ON THE STRATOSPHERE

Fig.: Domeisen, Garfinkel, and Butler, Rev. Geophys., 2019
MADDEN-JULIAN OSCILLATION IMPACT ON THE EXTRATROPICAL STRATOSPHERE

Sub-seasonal predictability of SSW events

Madden-Julian-Oscillation
see e.g.: Schwartz & Garfinkel, 2017, JGR

Figure: CPC NCEP NOAA
MADDOEN-JULIAN OSCILLATION IMPACT ON THE EXTRATROPICAL STRATOSPHERE IN THE S2S MODELS

ECMWF system:
increase in the probability for easterly winds by
66% for eQBO vs wQBO
30% for El Nino vs La Nina
139% for MJO phase 6 vs 2

see also:
Schwartz & Garfinkel, 2017, JGR

Figure: C. Garfinkel. from Domeiesen et al., under review for the JGR special issue on S2S prediction
THERE ARE PRECURSORS AND TELECONNECTIONS THAT CAN AFFECT THE FREQUENCY OF SSW EVENTS

Sub-seasonal predictability of SSW events

**Madden-Julian-Oscillation**
- Phase 6: weaker polar vortex
- Phase 2: stronger polar vortex
- See e.g.: Schwartz & Garfinkel, 2017, JGR

**Quasi-Biennial-Oscillation**
- eQBO
- wQBO
- See e.g.: Garfinkel et al., 2018, JGR

**El Nino Southern Oscillation**
- El Nino
- La Nina
- See e.g.: Domeisen, Garfinkel & Butler, 2018, Rev. Geophys.
  Ineson & Scaife, 2008, Nature Geoscience
PROBABILITY PREDICTABILITY OF SSW EVENTS ON S2S TIMESCALES

increased predictability due to precursors:
weeks to months

stratosphere

North Pacific

Tropical Pacific:
Predictability:
~ months

QBO:
Predictability:
months to years
CAN WE PREDICT THE RESPONSE TO STRATOSPHERIC EVENTS?

stratosphere: predictability: ~ days

North Atlantic: Predictability: ?
AFTER SUDDEN STRATOSPHERIC WARMINGS:
TOP-DOWN INFLUENCE ON OUR WEATHER

...and phone calls from journalists

Warming in the stratosphere leads to cold winters

29.01.2019 | News
By: Peter Rüegg | 1 Comment

In the first week of January, the Arctic stratosphere suddenly warmed up, an occurrence known as “sudden stratospheric warming” (SSW). This phenomenon results in cold winter weather, just the kind we are facing now – ETH researchers have visualised the event that was observed before the current one – in February 2018. Daniela Domeisen explains how this phenomenon occurs in an interview.
AFTER SUDDEN STRATOSPHERIC WARMINGS: TOP-DOWN INFLUENCE ON OUR WEATHER

After a stratospheric event: anomalies with respect to the long-term mean:

The average over 60 days after historical sudden stratospheric warming events. The stippling indicates regions that are significantly different from the climatology at the 95% level. 

Figure: Butler et al., 2017, ESSD
INFLUENCE OF THE STRATOSPHERE ON OUR WEATHER

After a stratospheric event, the jet stream over the North Atlantic often assumes a persistent wavy pattern, leading to extended cold air outbreaks in northern Europe.
HOW WELL DO WE PREDICT THE NAO ON WEATHER TIMESCALES?

Limited operational predictability beyond about 1 week

The theoretical prediction limit of the NAO and the AO lies at 2-3 weeks. This is more predictable than numerical models tell us and reaches into sub-seasonal timescales.

Domeisen et al., 2018, J Clim; Eade et al. 2014, GRL; Buizza et al., 2015, QJRMS; Scaife et al., 2018, CAS; Zhang et al. 2019, JAS

Figure: modified from cpc.ncep.noaa.gov
PERSISTENCE OF NEGATIVE NAO EVENTS INCREASES AFTER SSW EVENTS

Persistent positive NAO phase is suppressed after SSW event

About two thirds of SSW events are followed by persistent NAO events

But: less than 25% of persistent NAO events in winter are preceded by SSW events

SSW = Sudden Stratospheric Warming
NAO = North Atlantic Oscillation

Figure: Domeisen, 2019. JGR-Atmospheres
2m temperature anomaly (week 3 + 4) after weak vortex event:


Figure: Isla Simpson.
from: Domeisen et al., in rev. for the JGR special issue on S2S prediction
CAN WE PREDICT THE RESPONSE TO STRATOSPHERIC EVENTS?

Data: S2S prediction database (Vitart et al, 2016)

Figure: Isla Simpson.
from: Domeisen et al., in rev. for the JGR special issue on S2S prediction

Figure 6. (left) ACC (equation 1) and (right) RMSE (equation 3) for 2m temperature for (top) the difference between WEAK vortex initializations and Control forecasts, (middle) the difference between STRONG vortex initializations and Control forecasts and (bottom) the difference between SSW initializations and Control forecasts. The regions considered (depicted by the green boxes in Fig. 5c) are as follows: NH = the area average from 30°-90°N, Russia = 80°-135°E, 50°-65°N, USA=250°-270°E, 30°-45°N, Middle-East=50°-80°E, 28°-40°N and Europe=0°-50°E, 45°-60°N. Red bars indicate an improvement and blue bars depict a degradation. The error bars indicate the 2.5th to 97.5th percentile range of the difference determined via bootstrapping for WEAK/STRONG/SSW forecasts and Control forecasts with replacement, 200 times to obtain 200 estimates of the skill difference. Asterisks indicate cases where this error bar does not encompass zero, i.e., cases where the difference is significant \( p < 0.05 \) using a 2-sided test.

\( \implies \) indicates high-top models.
stratosphere: predictability: ~ days

Predictability at the surface is generally increased after SSW events, but not necessarily over Europe.
MANY OPEN QUESTIONS REMAIN

One answer to the question “why is the skill of seasonal forecasts over Europe so low?”

many paths lead to Europe:

North Pacific – North Atlantic (via troposphere)
Jiménez-Esteve & Domeisen, 2018, J Clim

North Pacific – stratosphere
e.g. Ineson & Scaife, 2008, Domeisen et al., 2015,
Butler et al., 2016,
Iza & Calvo, 2015

Tropical Atlantic pathway
e.g. López-Parages & Rodríguez-Fonseca, 2012,
Wulff et al., 2017, GRL
MANY OPEN QUESTIONS REMAIN

One answer to the question “why is the skill of seasonal forecasts over Europe so low?”

nonlinearity
e.g. Frauen et al., 2014, Garfinkel et al., 2018, Jiménez & Domeisen, 2019

many paths lead to Europe
MANY OPEN QUESTIONS REMAIN

One answer to the question “why is the skill of seasonal forecasts over Europe so low?”

many paths lead to Europe

nonlinearity

teleconnections may not remain constant over time (non-stationarity)

e.g. Lopez-Parages et al., 2015, Woollings et al., 2018; Garfinkel et al, 2019, JGR
Many open questions remain

One answer to the question “why is the skill of seasonal forecasts over Europe so low?”

Many paths lead to Europe

Nonlinearity

Teleconnections may not remain constant over time (non-stationarity)

Additional drivers: sea ice, snow cover, etc

E.g. Sun et al., 2015, Dobrynin et al., 2018
MANY OPEN QUESTIONS REMAIN

One answer to the question “why is the skill of seasonal forecasts over Europe so low?”

- many paths lead to Europe
- nonlinearity
- teleconnections may not remain constant over time (non-stationarity)
- additional drivers: sea ice, snow cover, etc
- local feedbacks: e.g. soil moisture
  e.g. Fischer et al., 2007, Orth et al., 2016
MANY OPEN QUESTIONS REMAIN

many paths lead to Europe
nonlinearity
teleconnections may not remain constant over time (non-stationarity)
additional drivers: sea ice, snow cover, etc
local feedbacks
climate change

Thank you!  @Domeisen_D