Flow-dependent predictability of wintertime Euro-Atlantic weather regimes in medium-range forecasts

Mio Matsueda (University Tsukuba)
Outlines of my talk

1. my work for TIGGE and S2S
   - The TIGGE an S2S Museum
   - early warning product of severe weather events (TIGGE)

2. Predictability of Euro-Atlantic weather regime (NDJFM)
   - reanalysis (ERA-Interim)
     - pattern, frequency, duration & transition matrix
   - model performance (TIGGE models)
     - bias in regime persistence and transition
     - probabilistic verification of regime forecast
   - summary
My work for TIGGE and S2S

- Verification of grand ensemble: Matsueda & Tanaka (2009)
- NH Blocking: Matsueda (2009)
- Russian heatwave in 2010: Matsueda (2011)
- Madden-Julian Oscillation (MJO): Matsueda & Endo (2011)
- Early warning product for severe weather events: Matsueda & Nakazawa (2015)
  high/low T, heavy rainfall & strong winds
- Forecast verification in the Polar region: Jung & Matsueda (2016)
- Arctic cyclones: Yamagami et al., (2018a,b, 2019)
- TIGGE project summary: Swinbank et al. (2016)
- The TIGGE and S2S Museums → poster on Wednesday

→ poster on Tuesday
My work for TIGGE and S2S

Real spaghetti plot..
(analysis, CMC, JMA, NCEP)
Special thanks to Dr. Subramanian

Please see Matsueda et al. (2011, MWR) for the blocking event.
The TIGGE Museum (google “TIGGE Museum”)

Welcome to the TIGGE Museum
@University of Tsukuba, Japan

The THORPEX Interactive Grand Global Ensemble (TIGGE) is a key component of the THORPEX project, which provides operational global ensemble forecast data quasi-operationally (2-day delay). The TIGGE portals provide the TIGGE data freely only for research and education purposes. For details, visit the WMO THORPEX website or the TIGGE website.

The TIGGE Museum is operated for a promotion of utilization of the TIGGE data by Dr. Mio Matsueda (University of Tsukuba and University of Oxford). Forecast products in the TIGGE Museum are updated every day with a 2- or 3-day delay, and are available for non-commercial use.

If you want to use the TIGGE data, sample scripts (tar.gz. 48MB) (readme) would be helpful!

The S2S Museum has been just open! New!
The TIGGE Museum (google “TIGGE Museum”)  
The products are available for past forecast cases during the TIGGE period (from October 2006).

- Z500 Spaghetti & stamp maps
- **MJO (Madden-Julian Oscillation)**
- Atmospheric blocking
- Teleconnection indices
- EPS meteograms (UK&Europe)

- **Severe weather events (poster on Tuesday)**  
  (high/low T, heavy rainfall & strong winds)
- Forecast verifications  
  (daily and seasonal scores, MJO & blocking)
- Model biases

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**Fig. (top left)** Observed and (right 9panels) predicted **MJO indices** by BoM, CMA, CMC, CPTEC, ECMWF, JMA, KMA, NCEP, and UKMO, initialised on 1 April 2009 (Coloured line: individual members, black line: analysis).

**Occurrence probability of extreme 24hr precipitation**  
Valid: 2010.07.21.12UTC +6–7days

**Fig.** Occurrence probabilities (shading) of extreme 24-hr rainfall for the **2010 Pakistan floods**, by the (a) multicentre grand ensemble, (b) ECMWF, (c) JMA, (d) NCEP, and (e) UKMO, initialized at 1200UTC 21 July 2010, and valid at 1200UTC 27 – 28 July 2010. (f) Observed extremes.
Accurate prediction of the strength of North Pacific Subtropical High was important.

Heavy rainfall in Japan (7 July 2018)

Occurrence probability of extreme 24hr precipitation
valid time: 2018.07.06–07.12UTC

Contour: analysed SLP
Contour: ens. mean SLP

Matsunobu & Matsueda (submitted)
The TIGGE Museum (google “TIGGE Museum”)
The products are available for past forecast cases during the TIGGE period (from October 2006).

- Z500 Spaghetti & stamp maps
- MJO (Madden-Julian Oscillation)
- Atmospheric blocking
- Teleconnection indices
- EPS meteograms (UK&Europe)
- Severe weather events (poster on Tuesday) (high/low T, heavy rainfall & strong winds)
- Forecast verifications (daily and seasonal scores, MJO & blocking)
- Model biases

**Fig.** Anomaly correlation coefficient for 7-day forecasts of Z500 over the Northern mid-latitude (20-60N), valid in August 2018.

**Fig.** Seasonal-mean anomaly correlation coefficient for control and ensemble mean forecasts of Z500 over NH in JJA 2018.
Welcome to the S2S Museum
@University of Tsukuba, Japan

The Subseasonal to Seasonal Prediction (S2S) Project is a proposed WWRP/THORPEX/ WCRP joint research project.

The main goal of the S2S project is to improve forecast skill and understanding on the subseasonal to seasonal timescale, and promote its uptake by operational centres and exploitation by the applications community. Specific attention will be paid to the risk of extreme weather, including tropical cyclones, droughts, floods, heat waves and the waxing and waning of monsoon precipitation.

The S2S data portals provide the S2S data freely with a 3-week delay only for research and education purposes. For details, visit the S2S Project Office website or the ECMWF S2S website. Forecast products in the S2S Museum are updated everyday, with a 3-week delay, and are available for non-commercial use.
The S2S Museum (google “S2S Museum”)  
The products are available for past forecast cases during the S2S period (from January 2015).

- AO/AAO (Arctic/Antarctic Oscillations) index
- NAO (North Atlantic Oscillation) index
- Teleconnection indices (EA, PNA, WP & EU)
- SLP & Z500 anomalies (stamp maps)
- SSW (Sudden Stratospheric Warming)
- Stream function & Velocity Potential
- Wave Activity Flux at 200 hPa
- MJO (Madden-Julian Oscillation)
- SST (Sea Surface Temperature)
- Sea-ice cover

**Fig. NAO index forecasts by BoM, CMA, ECCC, ECMWF, HMCR, ISAC-CNR, KMA, METFR, NCEP and UKMO, initialised on 8 February 2018 (Coloured line: individual members, grey line: ensemble mean, black line: analysis).**

**Fig. Ensemble mean forecasts of sea surface temperature (colour bar at the lower-right corner) and sea ice cover (colour bar at the upper-right corner), initialised on 13 September 2018, valid on 4 – 10 October 2018 (Week 4).**
The S2S Museum (google “S2S Museum”)
The products are available for past forecast cases during the S2S period (from January 2015).

- AO-AAO (Arctic/Antarctic Oscillations) index
- NAO (North Atlantic Oscillation) index
- Teleconnection indices (EA, PNA, WP & EU)
- SLP & Z500 anomalies (stamp maps)
- SSW (Sudden Stratospheric Warming)

- Stream function & Velocity Potential
- Wave Activity Flux at 200 hPa
- MJO (Madden-Julian Oscillation)
- SST (Sea Surface Temperature)
- Sea-ice cover

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**Fig.** (top left) NCEP control analysis for real-time multivariate **MJO index** for the 90 days prior to the initial date of the forecast. (right 9 panels) Real-time multivariate MJO index forecasts, initialised on 11 January 2018. The black line correspond to the NCEP control analysis. The coloured lines indicate ensemble members. The colour changes reflect the lead-time of the forecasts.

**Fig.** Ensemble mean forecasts of 200hPa velocity potential by 10 S2S models, initialised on 11 January 2018, valid on 26 January – 1 February 2018 (Week 3). Observed 200hPa velocity potential (JRA55, bottom right) is also added when it becomes available. The contour and shading indicate full and anomaly fields, respectively.
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2. Predictability of Euro-Atlantic weather regime (NDJFM)
   - reanalysis (ERA-Interim)
     • pattern, frequency, duration & transition matrix
   - model performance (TIGGE models)
     • bias in regime persistence and transition
     • probabilistic verification of regime forecast
   - summary
Weather regimes are persistent and/or recurrent large-scale flow patterns and are associated with severe weather events. Accurate predictions of weather regimes are important in weather and climate.

NAO+  
flooding (Oxford, 2014)

NAO-  
Heavy snow (UK, 2010)

blocking  
heatwave (Moscow, 2010)
Introduction — previous studies about weather regimes—

**Weather regimes in reanalysis**


**Weather regimes in weather and climate models**


**Weather regimes and extreme events**

Medium-range ensemble forecasts and reforecast

Centres: TIGGE (CMC, ECMWF, JMA, NCEP, and UKMO)
NOAA's GEFS reforecast v2 (fixed model & DA system)

Area: Euro-Atlantic sector: 30°-87.5°N, 90°W-40°E)

Period: NDJFM (TIGGE: 2006/07-2013/14, GEFS: 1985/86-2013/14)

Data availability

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initialised on every day

29 years
A k-means clustering

**Observed regimes:**
To define weather regimes in ERA-Interim (GEFS analysis), a k-means clustering (Jung et al., 2005; Dawson et al., 2012) has been applied to the leading 20 non-normalised principal components of Z500 anomalies (PCs, explained variance: 91.8%) over Euro-Atlantic sector in extended winters of 1979-2014 (1985-2014).

**Forecast regimes:**
Z500 forecast anomaly is defined as a departure from the observed climatology (ERA-Interim or GEFS analysis). Non-normalised forecast PCs are calculated by projecting the forecast anomaly onto the first 20 observed EOFs (ERA-Interim or GEFS analysis). Then, the observed cluster centroid closest to the forecast PC is regarded as a forecast regime.

Each calendar day is classified as a specific regime (i.e. no “no-regime” days).
Weather regimes (ERA-Interim, NDJFM) 99.8% significant, consistent with other studies (e.g. Ferranti et al. 2015, Dawson et al. 2012)
After 2009/10, many long-lasting NAO- events occurred:
- 28 days: Jan. - Feb. 1980
- 32 days: Dec. 2009 - Jan. 2010
- 47 days: Jan. - Mar. 2010
- 31 days: Mar. 2013

**Transition matrix**

\[
\begin{bmatrix}
0.83 & 0.03 & 0.07 & 0.08 \\
0.05 & 0.85 & 0.06 & 0.05 \\
0.09 & 0.05 & 0.77 & 0.10 \\
0.10 & 0.04 & 0.07 & 0.80 \\
\end{bmatrix}
\]
Frequencies of regime transition & regime in NWP models

Observed regime transition frequency (NDJFM)

- NAO+ → NAO- (0.03)
- NAO+ → ATLR (0.07)
- NAO+ → EABL (0.08)
- NAO- → NAO+ (0.05)
- NAO- → ATLR (0.06)
- NAO- → EABL (0.05)
- ATLR → NAO+ (0.09)
- ATLR → ATLR (0.77)
- ATLR → EABL (0.10)
- EABL → NAO+ (0.04)
- EABL → ATLR (0.07)
- EABL → EABL (0.80)
Forecast data verified in NDJFM are analysed. Some data are initialised in October.
Regime transition frequency in NWP models (NDJFM)

Transition frequency of Euro–Atlantic regimes (NDJFM)


(a) transition from NAO+

(b) transition from NAO−

(c) transition from ATL

(d) transition from EABL

Underestimate
Overestimate

Day 0 ➔ 1  Day 2 ➔ 3  Day 4 ➔ 5  Day 6 ➔ 7  Day 8 ➔ 9  Day 10 ➔ 11  Day 12 ➔ 13
Day 1 ➔ 2  Day 3 ➔ 4  Day 5 ➔ 6  Day 7 ➔ 8  Day 9 ➔ 10  Day 11 ➔ 12  Day 13 ➔ 14
Day 3 ➔ 4  Day 5 ➔ 6  Day 7 ➔ 8  Day 9 ➔ 10  Day 11 ➔ 12  Day 13 ➔ 14  Day 14 ➔ 15

analysed (each model)
Model bias in regime transition (NDJFM):

- More frequent than observations:
  - NAO+ to NAO-
  - ATLR to EABL

- Frequency similar to observations:
  - NAO+ to NAO+
  - ATLR to ATLR

- Less frequent than observations:
  - NAO- to NAO+
  - EABL to EABL
Models tend to prefer NAO- and ATLR to NAO+ with lead time.
Verification of probabilistic regime forecast

Probabilistic forecast of Euro–Atlantic regimes (ECMWF, initial: 2010.12.01.12UTC)
Verification of probabilistic regime forecast

Brier Score (BS) is calculated for

1. **single-category probabilistic forecast**
   (probabilistic forecast of each regime)

   \[ BS_r = \frac{1}{N} \sum_{i}^{N} (p_{i}^{r} - o_{i}^{r})^2 \]

2. **multi-category probabilistic forecast**
   (probabilistic forecast of all regimes)

   \[ BS = \frac{1}{N} \sum_{i}^{N} \sum_{r}^{R} (p_{i}^{r} - o_{i}^{r})^2 \]

\( p^r \): fcst prob. of regime \( r \) (0-1), \( N \): No. of forecasts
\( o^r \): obs prob. of regime \( r \) (0 or 1), \( R \): No. of regimes

**ECMWF (initial: 2010.12.01.12UTC)**

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Verification of probabilistic regime forecast

Brier Score (BS) is calculated for
1. single-category probabilistic forecast
   (probabilistic forecast of each regime)

\[ BS_r = \frac{1}{N} \sum_{i}^{N} (p_{ir}^r - o_{ir}^r)^2 \]

2. multi-category probabilistic forecast
   (probabilistic forecast of all regimes)

\[ BS = \frac{1}{N} \sum_{i}^{N} \sum_{r}^{R} (p_{ir}^r - o_{ir}^r)^2 \]

- \( p_r^r \): fcst prob. of regime r (0-1), \( N \): No. of forecasts
- \( o_r^r \): obs prob. of regime r (0 or 1), \( R \): No. of regimes
Verification of probabilistic regime forecast

Brier Skill Score (BSS)

\[ BSS = 1 - \frac{BS_{fcst}}{BS_{ref}} \]

BSS\(=1\): a perfect skill  
BSS\(=0\): a comparable skill to reference forecast  
BSS\(<0\): poorer skill than reference forecast

BSS is conventionally defined as the relative probability score compared with the probability score of a reference forecast. Here, a reference forecast is produced by considering a Markov chain with the initial regime (we know today's regime!) and the observed transition matrix (i.e. multiplying initial regime probability vector by the transition matrix). Therefore, the reference forecast has a higher skill than the climatological forecast, especially in the short forecast range.

If initial regime is NAO- (i.e. \(R_0=(0\ 1\ 0\ 0)\)), reference forecast \(R_x\) for Day \(X\) become

- \(R_1=R_0T=(0.05\ 0.85\ 0.06\ 0.05)\),
- \(R_2=R_1T=(0.09\ 0.73\ 0.10\ 0.09)\),
- \(R_3=R_2T=(0.12\ 0.63\ 0.13\ 0.12)\),

\(\vdots\)

- \(R_{15}=R_{14}T=(0.30\ 0.23\ 0.21\ 0.26)\). close to clim. Freq.
ECMWF has the highest skill

Skill dependency upon regimes

- the highest skills for NAO- (BSS>0 even after Day 15)
- the lowest skills for EABL (BSS<0 after Day 12)

NAO- forecast shows larger skill differences between the reforecast and TIGGE periods
Skill dependency upon forecast regime (GEFS)

**Brier Skill Score for GEFS regime forecasts (Euro-Atlantic region, NDJFM)**


(a) all forecasts (b) NAO+ forecasts (c) NAO− forecasts

Higher skill for the NAO- forecasts during the active NAO- periods

Long-lived (≥14 days) NAO- events

1985/86–1988/89: 16, 16, 16, 14 days
1989/90–1993/94: N/A
1994/95–1998/99: 22 days
1999/00–2003/04: 16, 15, 14, 14 days
2004/05–2008/09: 16, 15 days
2009/10–2013/14: 47, 33, 32, 31, 19, 14 days

ref. fcst base on obs. trans. matrix

single-category probabilistic forecast

BSref: trans. matrix–based
ECMWF has the highest skill

Dependency upon initial regimes

- higher skills for NAO-
  (BSS>0 even after Day 15, except GEFS)
- lower skills for ATLR
  (BSS<0 after Day 11)

GEFS (29yrs) shows smaller skill dependency upon initial regimes
(similar skill for forecasts from NAO± & EABL)
Regarding forecasts from NAO-, forecasts after 2009/10 show a much higher skill, compared with before 2009/10. Forecasts before 2009/10 become useless at Day 10-12 and show the lowest skill.

Forecasts from the other regimes show small skill dependency on verification periods.
Skill dependency upon regime duration (GEFS)

BSS for Euro-Atlantic regime forecasts (GEFS, NDJFM, 1985/86–2013/14)

Duration of obs regime starting at initial: D<7 7≤D 12≤D 17≤D

- The longer the NAO– events persist, the higher the skill of forecasts initialised on NAO–.
- The skill dependency on regime duration is less clearly observed for the other regimes.

Long-lived (≥17 days) NAO- events
1994/95-98/99: 22 days
2009/10-13/14: 47, 33, 32, 31, 19 days

- The longer the NAO– events persist, the higher the skill of forecasts initialised on NAO–.
Models have common biases in regime persistence and transition, leading to more (less) frequent NAO- and ATLR (NAO+) with lead time.

The increased frequency of NAO– is not due to its excess persistence but due to more frequent transitions mainly from NAO+ and ATLR. In turn, NAO+ is under-persistent. A typical model bias is to underestimate regime persistence, as Strommen and Palmer (QJRMS) independently pointed out.

Probabilistic NAO- (EABL) forecasts show the highest (lowest) skill. In particular, NAO- forecasts show a higher skill during active NAO- years.

The models show the highest (lowest) probabilistic skill for forecasts from NAO- (ATLR) during the TIGGE period (NAO- was active) and the lowest skill for forecasts from NAO- before 2009/10 (NAO- was inactive).

The longer the NAO– events persist, the higher the skill of forecasts initialised on NAO–. The skill dependency on regime duration is less clearly observed for the other regimes.

Regime transition frequency in TIGGE models (NDJFM)

Transition frequency of Euro–Atlantic regimes (NDJFM)


(a) transition from NAO+
(b) transition from NAO–
(c) transition from ATL
(d) transition from EABL

- overestimate
- underestimate

Day 0 → 1, Day 1 → 2, Day 2 → 3, Day 3 → 4, Day 4 → 5, Day 5 → 6, Day 6 → 7, Day 7 → 8, Day 8 → 9, Day 9 → 10, Day 10 → 11, Day 11 → 12, Day 12 → 13, Day 13 → 14, Day 14 → 15
Regime transition frequency in S2S models (NDJFM)

Transition frequency of Euro–Atlantic regimes (NDJFM)


(a) transition from NAO+

(b) transition from NAO−

(c) transition from ATLR

(d) transition from EABL

- underestimate
- overestimate

Day 1 → 2, Day 3 → 4, Day 5 → 6
Day 6 → 7, Day 8 → 9, Day 10 → 11
Day 11 → 12, Day 13 → 14, Day 15 → 16
Day 17 → 18, Day 19 → 20, Day 21 → 22
Day 22 → 23, Day 24 → 25, Day 26 → 27
Regime transition frequency in all S2S models (NDJFM)

Transition frequency of Euro–Atlantic regimes (NDJFM)


(a) transition from NAO+

(b) transition from NAO−

(c) transition from ATL

(d) transition from EABL

Transition frequency [%]

Day 1 → 2
Day 2 → 3
Day 3 → 4
Day 4 → 5
Day 5 → 6
Day 6 → 7
Day 7 → 8
Day 8 → 9
Day 9 → 10
Day 10 → 11
Day 11 → 12
Day 12 → 13
Day 13 → 14
Day 14 → 15
Day 15 → 16
Day 16 → 17
Day 17 → 18
Day 18 → 19
Day 19 → 20
Day 20 → 21
Day 21 → 22
Day 22 → 23
Day 23 → 24
Day 24 → 25
Day 25 → 26

Underestimate?

Overestimate?
Thank you for your attentions.
Model bias in Z500 (against ERA-Interim/GEFS analysis)

Day 9

+216hr EA Z500 bias (NDJFM, 2006/07–2013/14, all members) against ERA-Interim (cint:120m)
(a) CMC
(b) ECMWF
(c) JMA
(d) NCEP
(e) UKMO
(f) GEFS_TIGGE
(g) GEFS

Day 15

+360hr EA Z500 bias (NDJFM, 2006/07–2013/14, all members) against ERA-Interim (cint:120m)
(a) CMC
(b) ECMWF
(c) JMA
(d) NCEP
(e) UKMO
(f) GEFS_TIGGE
(g) GEFS
“super” regimes – zonal vs wavy regimes -

**zonal regime**: NAO+, **wavy regime**: NAO-, ATLR&EABL

(a) regime transition (analysis)

0.84

\[ \text{zonal} \rightarrow \text{wavy} \]

0.16

\[ \text{wavy} \rightarrow \text{zonal} \]

0.92

(b) regime transition

(5 models' mean, +13-15days)

0.80

\[ \text{zonal} \rightarrow \text{wavy} \]

0.20

\[ \text{wavy} \rightarrow \text{zonal} \]

0.07

(c) potential well for regimes

models (+13-15days)

zonal

wavy