The impact of moist processes on the large-scale extratropical circulation

Heatwave Europe July 2015

MSG IR satellite 12 UTC 1 July 2015, jetstream (2PVU@325K), blocking
Strongly ascending and precipitating airstream – associated with North Atlantic
cyclone - reaches into blocking region (MSLP 12 UTC 29 June 2015)
Outline

Moist processes & the large-scale circulation

1. Potential vorticity thinking
2. Diabatic influences on the large-scale circulation
3. Relevance for forecast error
4. Atlantic-European weather regime life cycles
Potential vorticity

\[ PV = \frac{1}{\rho} \vec{\eta} \cdot \nabla \Theta \]

unit: 1PVU = 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}

\[ \eta = f + \vec{k} \cdot \nabla \times \vec{v}_h \]

Absolute vorticity / horizontal flow

Vertical stratification of the atmosphere/stability

\[ \frac{dPV}{dt} = \frac{1}{\rho} \vec{\eta} \cdot \nabla \Theta + \frac{1}{\rho} \left( \nabla \times \vec{F} \right) \cdot \nabla \Theta \]

Total change in PV  
diabatic PV modification  
frictional processes

- PV is conserved under adiabatic frictionless flow (conservation principle)
- PV can be inverted given a balance condition and boundary conditions (inversion principle)
Warm conveyor belt

- rapidly ascending cross isentropic air flow (>600hPa/48h)
- diabatic heating of about 20K / 48h

see also WCB clim. by Madonna et al. (2014), *JCLI*, http://dx.doi.org/10.1175/JCLI-D-12-00720.1

\[
\frac{dPV}{dt} + \mu \frac{dPV}{dz}
\]

PV reduction

PV production

Wernli and Davies (1997), *QJRMS*, http://dx.doi.org/10.1002/qj.49712353811
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Diabatic outflow and upper-level flow

trajectories ($\Delta z/\Delta t > 8500\text{m}/48\text{h}$), pmsl, 3PVU@335K

Diabatic outflow and upper-level flow

335-K PV (shaded) and wind speed >50 m s\(^{-1}\) (dashed); SLP (solid)

- downstream ridgebuilding by downstream WCB
- Strongly amplified upper-level flow and downstream blocking

Diabatic outflow and upper-level flow

335-K PV (shaded) and wind speed >50 m s\(^{-1}\) (dashed); SLP (solid)

No TC

• diabatic outflow from different weather system categories jointly yield highly amplified midlatitude flow

Geopotential height 200hPa (1200 gpdm contour)

DS-WCB stage  T+84h

Downstream WCB outflow

335-K 2-PVU contours for Control and No TC, and Control minus No TC PV and wind

Diabatic outflow

Downstream WCB stage

Diabatic outflow

Downstream WCB stage

trjectories (dz/dt>8500m/48h), pmsl, 3PVU@335K

PV [PVU], Θ (solid, in K), windspeed

Downstream WCB outflow

250-150hPa wind speed (shading in m s\(^{-1}\)), irrot. wind (vectors), neg. PV advection by irrot. wind (red contours, PVU day\(^{-1}\)), total precip. water (gray shading, mm),
Outflow characteristics

- 3 stages of ET with diabatic outflow from different weather systems

<table>
<thead>
<tr>
<th>(p, Θ, PV: mean±stddev)</th>
<th>PRE</th>
<th>ET/TC</th>
<th>DS WCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>time of max. interaction</td>
<td>T+6h</td>
<td>T+45h</td>
<td>T+87h</td>
</tr>
<tr>
<td>max(−(\mathbf{v}_{irr} \cdot \nabla PV)) [PVU/h]</td>
<td>1.27</td>
<td>2.03</td>
<td>1.09</td>
</tr>
<tr>
<td>traj. ending at</td>
<td>T+12h</td>
<td>T+48h</td>
<td>T+108h</td>
</tr>
<tr>
<td>number of trajectories</td>
<td>1798</td>
<td>4727</td>
<td>4788</td>
</tr>
<tr>
<td>p[hPa] (outflow)</td>
<td>234 ± 36</td>
<td>183 ± 38</td>
<td>256 ± 40</td>
</tr>
<tr>
<td>Θ[K] (outflow)</td>
<td>345 ± 5</td>
<td>355 ± 6</td>
<td>334 ± 3</td>
</tr>
</tbody>
</table>

recent review paper on downstream impact of tropical cyclones:


Grams and Archambault (2016), MWR, doi: 10.1175/MWR-D-15-0419.1
Ridge composite YOTC period

$$\frac{\partial PV'}{\partial t} \bigg|_\theta = -v \cdot \nabla_{\theta} PV + \text{DIA}(\dot{\theta}, PV, v),$$  \hspace{1cm} (1)

**lifetime-integrated values \([10^{13} \text{ PVU m}^2]\):**
- near-tropopause: -0.6
- baroclinic growth: 1.4
- divergent: 3.0
- latent heat: 0.5
- radiation: -2.1


Teubler and Riemer YOTC composite in preparation

slide provided by Michael Riemer
Diabatic influence on blocking

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RW characteristic of forecast error

- forecast error emerges along the midlatitude wave guide and propagates like RW

Figure 1 from Davies and Didone, 2013, *MWR*

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• contribution of model error to misrepresentation of WCB results in error of the large-scale flow

The March 2016 forecast bust

+144h Z500 ACC for HRES and ENS - Europe

forecast error 2m T

forecast of 2m T Germany at different init. times

Grams, Magnusson, and Madonna (2018), QJRMS, doi: 10.1002/qj.3353
IFS IPV315K analysis – ensemble mean & WCB intersection points (analysis)

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Grams, Magnusson, and Madonna (2018), QJRMS, doi: 10.1002/qj.3353
WCB activity during WR transition

ECMWF analysis

The PAL forecast metric

- Metric for quantifying the PV, Amplitude, and Location error of WCB outflow objects
  - **P** term: <0, too weak / >0, too strong negative PV anomaly in outflow
  - **A** term: <0, too few / >0 too many trajectories
  - **L** term: 0 good; close to 2 → objects in opposite corners

PAL diagram illustrates the three components, for different forecast members

Role of WCB in forecast bust

ECMWF ensemble initial time 20160307_00

focus on WCB starting 00 UTC 9 March (+48h) → ending 00 UTC 11 March (+96h)

Grams, Magnusson, and Madonna (2018), QJRMS, doi: 10.1002/qj.3353
Role of WCB in forecast bust

ECMWF ensemble initial time **20160307_00**

Focus on WCB starting **00 UTC 9 March (+48h)** → ending **00 UTC 11 March (+96h)**

- Southern branch too strong → maintained AR
- Northern branch too weak → missed BL onset

Initial condition error?

00 UTC 9 March

IPV@315K an/em, SLP ana, THE850 an-em, wind850-500hPa an-em

- error in upper-level cut-off induces → cyclonic flow anomaly and ill-forecast SLP
- enhanced and tilted baroclinic zone missed → wrong WCB ascent

Initial condition error?
• 3 stage error growth model (Zhang et al. 2007) confirmed in PV framework

Figure 7 from Baumgart et al., 2019, *MWR*

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Blocking and RWP in S2S models (J. Quinting)

Why are regimes relevant?

**Flow-dependent predictability**


![Anomaly correlation graph](image)

*Figure 3.* Anomaly correlation of the ensemble means over Europe (12.5°W–42.5°E, 35.0°N–75.0°N) for the four forecast categories as a function of forecast range. Red refers the BL regime, blue to the NAO+, green to the NAO− and violet to the AR regime. The bars, based on 1000 subsamples generated with the bootstrap method, indicate the 95% confidence intervals.

**ECMWF Roadmap to 2025:** “…we also aim to predict large-scale patterns and regime transitions up to four weeks ahead, …”
Why are regimes relevant?

Wind power variability

- Beerli et al. (2017) 10.1002/qj.3158
- Grams et al. (2017) 10.1038/nclimate3338

Modulation of heavy precipitation

- Pasquier et al. (2019) 10.1029/2018GL081194

Heat waves

- Quinting and Reeder (2017) 10.1175/MWR-D-17-0165.1

Cold air outbreaks

Year-round weather regimes

- **Atlantic trough (AT, 9.0%)**
- **Zonal Regime (ZO, 9.1%)**
- **Scandi. trough (ScTr, 10.3%)**
- **Atlantic ridge (AR, 9.0%)**
- **European blocking (EuBL, 10.1%)**
- **Scandi. blocking (ScBL 10.9%)**
- **Greenland blocking (10.1%)**
- **no regime (no, 31.5%)**

- quasi-stationary, persistent, recurrent flow patterns
- 70-80% of large-scale variability on sub-seasonal time scales
- here: year-round 7 regimes including a life-cycle definition

Weather regime life cycles

- **Weather regime Index** $I_{wr}$ (Michel and Rivière, 2011, *JAS*, doi:10.1175/2011JAS3635.1)
- Definition of *onset*, maximum, decay for individual weather regime life cycles
WCB activity during WR life cycles

- cyclone, WCB inflow & outflow, and blocking frequency anomalies during weather regime life cycle (Madonna et al. 2014, JCLI, Sprenger et al. 2017, BAMS)
- lagged composites in period around onset
Lagged composites at EuBL onset

→ WCB activity supports onset and maintenance of European blocking
Summary

- Diabatic outflow are key to upper-level midlatitude flow modification

- Predictability challenge for large-scale flow due to upscale error growth in WCBs

- WCB outflow important for onset and maintenance of blocked regimes

Outlook

- YIG SPREADOUT: relevance for subseasonal forecast skill?