Predictability barriers and diabatic processes during NAWDEX campaign

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Introduction

- Uncertain representation of convective processes at forecast T+0 could become large errors at medium-range (e.g. ‘forecast bust’ of Rodwell et al. 2013)
- The dynamical mechanisms of error amplification are still debated

**NAWDEX Hypothesis:** Diabatic processes (1,2) have a major influence on the jet stream structure near North Atlantic, affecting the downstream development of Rossby waves (3) and eventually high impact weather (4) over Europe

**NAWDEX campaign:** Four aircraft observing diabatic processes and ridge development from 15/9 to 22/10 2016

[Top]: Sketch of NAWDEX main goals: Observation of diabatic process in WCB (1,2), ridge formation (3) and downstream effects (4). From Schäfler et al. (2018, BAMS)
Test the NAWDEX hypothesis in three steps

1. Seek evidence for flow-dependent predictability using MetOffice and ECMWF operational forecasts during the NAWDEX period (Sept-Oct 2016).

2. Quantify the diabatic influence on the balanced flow through the advection of potential vorticity mechanism, based on a Semi-Geotriptic (SGT) inversion model that provides the ageostrophic flow response to diabatic heating or dynamical sources.

3. Test whether or not the situations with lowest predictability are associated with strong diabatic influence.
Z500 RMSE rate of change ($\partial E / \partial f$): For all forecast start dates $s$ and forecast lead times $f$ over NAWDEX Period (15/9 to 15/10). validation time $t$ on diagonal lines.

There are times $t$ where error and spread grows rapidly (UM, IFS), error grows faster than spread (--); E.g. A (00Z 16th)
Predictability barriers (2)

Events with large increase of error growth at a similar validation time are defined as **predictability barriers (PB)**

- Similar for IFS and UM (HRES)
- Spread growth much smaller than EM error growth during PBs

[Top]: Table with Pearson correlation coefficients from left side Figure, all significant at 99% level

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[Top]: $\partial E / \partial f$ integrated across lead time for same validation time (diagonal lines)

PBs coincides with NAWDEX IOPs!
Semi-Geostrophic inversion tool (SGT)

SGT model able to solve pressure tendency, ageostrophic wind and balanced vertical wind (w). Source term is a linear combination of a dynamics only term and diabatic sources

- SGT w shows induced ascent on the upstream flank of a ridge for TC Ian (1) and downstream cyclone (2)
- Clear signal of diabatic process inducing vertical ascent and divergence over outflow region (d)

[Top]: SGT w (coloured), $v_{ag}$ (vectors) and $PV = 2$ PVU (think black line)
Diabatically influenced Ageostrophic Advection of PV (DIAA): PV advected as a result of diabatically induced SG ageostrophic winds.

Dynamic only (or geostrophic) induced ageostrophic advection of PV (SGAA)

- Diabatically influenced (DIAA) shows clearer ridge building action for upstream cyclone (2) (b,d) than SGAA (a,c)
- Degradation of ridge building with forecast lead time (a,b to c,d), domain average value ↓

[Right]: AAPV (coloured) $v_{ag}$ (vectors) and $PV=2$ PVU (thick black line).
Diabatic influence DIAA across different PB shows clear ridge building differences between T+24 and T+72

- **B**, Cyclone Vladiana
- **D**, Stalactite Cyclone
- **E**, Frontal cyclone
- **F**, Thor ridge and cut-off Sanchez

[Right]: DIAA (coloured), $v_{ag}$ (vectors) and $PV = 2$ PVU (thick black line). T+24 (left) T+72 (right). Mean value over box shown in bottom-left corner.
Diabatic influence and predictability barriers

Most of PB cases coincide with high domain averaged Diabatic influence (DIAA); e.g. A, C, E, G

Some PB cases occur 2 days after high diabatic influence; e.g. P-A, B-C, D-E, F-G ("preconditioning environment"?)

[Left] Domain averaged Diabatic influence (DIAA) (coloured) and error growth rate (contoured)
Diabatic influence and predictability barriers (2)

Error growth rate (PB) and diabatic influence (DIAA) correlation significant, unlike SG influenced (SGAA)

DIAA stronger for high strong error growth (upper tercile of error growth timeseries), substantial drop when \( f > 60 \) hours

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Comparing EM error and spread for strong/weak (upper/lower terciles of timeseries) error growth (EG) and diabatic influence (DI):

- Spread matches error when diabatic influence is weak.
- Error grows 4/3 faster than spread after day 2 when DIAA is strong.
Conclusions

- Rapid error and ensemble spread growth was identified on particular dates, irrespective of lead times. Defined as **Predictability Barriers (PB)**
- The Diabatically Induced Ageostrophic Advection of PV (DIAA) from SGT model is strong and negative in the western flank of developing ridges -> ridge expansion
- Only DIAA is correlated with error growth rate, dynamics-only SGAA is not
- During strong error growth events (PB) :
  - DIAA is ~1.5x larger than average
  - DIAA halves beyond T+60
  - Error growth rate exceeds spread rate beyond T+48

**Unresolved questions:**

- What are the diabatic processes behind DIAA decrease on PB events?
- Are those processes misrepresented in the model? Are uncertainties in these processes not captured by the ensemble system?
Thanks for your attention!
(A): 16th-18th Sept. Ex-TC Ian. IOP 1
(B): 22nd-23rd Sept. Vladiana IOP 4
(C): 28-29th Sept. Walpurga + Ex-TC Karl. IOP 5

SEQUENCE A

(E): 4th-6th Oct. Downstream effects of Stalactite cyclone + blocking development. IOP 7

SEQUENCE B

(F): 11-13th Oct. PV cut off Sanchez + tropopause ridge Thor. IOP 9-10

SEQUENCE C

[Left] NAWDEX golden cases (aka Sequences)

Fig 6. Schaffler et al. 2018
Final conclusions and Future work

As hypothesized in NAWDEX campaign: Diabatic processes induce divergent outflow in ridges (2\textsuperscript{nd} stage of error growth of Baumgart et al. 2019), affecting the downstream development of Rossby waves, and thus leading to large forecast error growth (Predictability barriers)

To do …

• What processes are responsible for high values of DIAA over western flank of ridges (e.g. Joos and Wernli 2012)?
• Why DIAA declines after day 2?
• Are similar conclusions found in other areas or seasons (e.g. US west-coast)
SGT Inversion Model

$$\mathbf{BQ}'\left( \begin{array}{c} u - u_e \\ v - v_e \\ w \end{array} \right) + c_p d \frac{\partial}{\partial t} \left( \frac{1}{r \cos \phi} \left( \frac{\partial \pi}{\partial \lambda} - \frac{\partial \pi}{\partial r} \frac{\partial \lambda}{\partial r} \right) \right) = \mathbf{BH}'$$

SGT model able to solve pressure tendency ($d\pi/dt$), ageostrophic wind ($v - v_e$) and balanced vertical wind ($w$).

Source Matrix $H'$: linear comb. of geostrophic term plus friction and diabatic sources

SGT improves the Quasi-Geostrophic (QG) model:

- SGT model includes advection by the ageostrophic velocity
- The Ertel PV is conserved by SGT to the order of accuracy of the SGT model in adiabatic and frictionless conditions

SGT ~ SG at the tropopause level, as we do not include source friction in the SGT model and we are above BL
Semi-Geotriptic (SGT) Inversion Model

**UM eqs:**

\[
\frac{Du}{Dt} + c_{pd} \theta_v \nabla \pi + 2\Omega \times u = g + \frac{\partial}{\partial r} \left( K_m \frac{\partial u_i}{\partial r} \right) + S_u,
\]

\[
\frac{D\theta_{vd}}{Dt} = S_{\theta_{vd}}.
\]

\[c_{pd} \theta_v \nabla_h \pi - (f v_e - f u_e) = \frac{\partial}{\partial r} \left( K_m \frac{\partial u_e}{\partial r} \right)\]

\[c_{pd} \theta_v \frac{\partial \pi}{\partial r} = -g.
\]

\[
\begin{bmatrix}
  u - u_e \\
  v - v_e \\
  w
\end{bmatrix}
+ c_{pd} \theta_v \frac{\partial}{\partial t} \left( \begin{bmatrix}
  \frac{1}{r \cos \phi} \left( \frac{\partial \pi}{\partial \lambda} - \frac{\partial \pi}{\partial r} \frac{\partial \lambda}{\partial r} \right) \\
  \frac{1}{r} \left( \frac{\partial \pi}{\partial \phi} - \frac{\partial \pi}{\partial r} \frac{\partial \phi}{\partial r} \right) \\
  \frac{\partial \pi}{\partial r}
\end{bmatrix} \right) = BH'
\]

\[\Pi: \text{Exner pressure}
\]

\[K_m: \text{BL diffusion coef.}
\]

\[S: \text{Source terms}
\]

\[v_e: \text{Geotriptic wind}
\]

\[\text{SGT model able to solve pressure tendency (d\pi/dt), ageostrophic wind (v} - v_e\text{) and balanced vertical wind (w).}
\]

Source Matrix $H'$: linear comb. of geostrophic term plus friction and diabatic sources
Semi-Geostrophic Inversion Model

Where

\[
\mathbf{BQ}' \left( \begin{array}{c}
u - u_e \\ \nu - v_e \\ w \\
\end{array} \right) + c_{pd} \theta_e \frac{\partial}{\partial t} \left( \begin{array}{c}
\frac{1}{r \cos \phi} \left( \frac{\partial \pi}{\partial \lambda} - \frac{\partial \pi}{\partial r} \frac{\partial \lambda}{\partial r} \right) \\
\frac{1}{r} \left( \frac{\partial \pi}{\partial \phi} - \frac{\partial \pi}{\partial r} \frac{\partial \phi}{\partial r} \right) \\
\frac{\partial \pi}{\partial r} \end{array} \right) = \mathbf{B}\mathbf{H}'
\]

Its form in momentum coordinates (Hoskins & Draghici, 1977) is:

\[
\nabla \cdot \left( r^2 \rho_d \frac{\partial \mathbf{V}}{\partial \eta} \mathbf{P}^{-1} \mathbf{G} \right) + \frac{1}{\cos \phi} \left( \frac{\partial}{\partial \lambda} \left( r \rho_d u_e \frac{\partial \eta}{\partial \eta} \right) + \frac{\partial}{\partial \phi} \left( r \rho_d v_e \cos \phi \frac{\partial \eta}{\partial \eta} \right) \right) \quad \text{(Elliptic equation for } \pi / \partial t \text{)}
\]

[Improvements to S-G omega equation …]

\[
\nabla \cdot \left( r^2 \rho_d \frac{\partial \mathbf{V}}{\partial \eta} \mathbf{P}^{-1} \mathbf{G} \right) + \frac{1}{\cos \phi} \left( \frac{\partial}{\partial \lambda} \left( r \rho_d u_e \frac{\partial \eta}{\partial \eta} \right) + \frac{\partial}{\partial \phi} \left( r \rho_d v_e \cos \phi \frac{\partial \eta}{\partial \eta} \right) \right) = H = \alpha \mathbf{w}^* , \quad \hat{Z} = \frac{N_0}{f_0} \mathbf{Z}
\]
Predictability barriers

Rate of change of ACC for IFS Z500 increases at particular validation times, defined as “predictability barriers”

Craig et al. (2018): Predictability barriers, NAWDEX 2018 workshop, Munich
SG and predictability barriers (+)

[Left]: Time series of PB, DIAA, and SGAA

[Left]: N768 EM RMSE ($E_\sigma$-) ad spread ($\sigma_--$), for High (Non) Non-Diabatic Influence or PB. Def as upper (lower) threshold in PB and DI-AAPV timeseries.
DIAA sketch

$$AAPV = -v_{ag} \cdot \nabla q$$

A,C,D,E: SG wind parallel to PV gradient (troposphere advecting towards stratosphere): DIAA negative

B,F: SG wind antiparallel to PV gradient, DIAA positive
Thoughts on Predictability Barriers

For a reliable forecast spread should match EM error for all lead times averaged over many forecast dates. Reasons why forecast error growth may be larger than ensemble spread during PB events:

1. Stochastic physics and ensemble design of initial condition uncertainty do not capture well major sources of model error that makes the rapid error growth during PB events
2. Very low predictability of PB events, flow may follow a very unlikely path
Methodology

Operational Models employed to spot Error growth:

- Met Office Unified Model (MetUM, H-Res) operational deterministic model (N768 ~18km, L70, GA6.1)
- Integrated Forecast System (IFS) operational deterministic model (O1280 ~9 km, L137, Cy41r2)
- Global MetUM operational Ensemble Prediction System (MOGREPS-G, N400,~35km, L70, GA6.1, 24 members)

H-Res re-run with the necessary diagnostics to run the Semi-Geotripctic inversion model 6 hourly up to T+120