APPLICATION OF FACTOR SEPARATION TO HEAVY RAINFALL AND CYCLOGENESIS EVENTS: MEDITERRANEAN EXAMPLES

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Romu Romero

THE STUDY OF ATMOSPHERIC PHENOMENA

• Observations (limited in number, space and time)

• Theory (requires simplifications)

• Experimentation (Numerical Modeling)
- **Multiscale** perspective of the problem

- Realistic *physical processes* parameterized
**UNIQUE FEATURE OF NUMERICAL MODELS**

- Reasonably *good* control simulation of your case study

- Specifically *designed* simulations (by perturbing factors) (sensitivity studies / *factor separation* )

- Improved physical *understanding* of your case study
FACTOR SEPARATION (Stein and Alpert, JAS 1993)

2 FACTORS

<table>
<thead>
<tr>
<th>Run</th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{12}$</td>
<td>on</td>
<td>on</td>
</tr>
<tr>
<td>$F_1$</td>
<td>on</td>
<td>off</td>
</tr>
<tr>
<td>$F_2$</td>
<td>off</td>
<td>on</td>
</tr>
<tr>
<td>$F_0$</td>
<td>off</td>
<td>off</td>
</tr>
</tbody>
</table>

Unrelated with factors 1 and 2
Induced by the factor 1 (independent of 2)
Induced by the factor 2 (independent of 1)
Induced by the synergism of factors 1 and 2

* Generalization:

$$E_{i_1 i_2 i_3 \ldots i_k} = \sum_{m=0}^{k} (-1)^{k-m} \left( \sum_{\text{sort}} F_{j_1 j_2 j_3 \ldots j_m} \right) \quad 0 \leq k \leq n$$

where $\sum$ is over all groups of $m$ sorted indices $j_1 j_2 j_3 \ldots j_m$ chosen from $k$ indices $i_1 i_2 i_3 \ldots i_k$.

Part 1.- CASE STUDIES

2 FLASH FLOOD EVENTS OVER EASTERN SPAIN

2 FACTORS

Atlas Mountains (a boundary factor)
Latent heat exchange (a physical factor)
**GANDIA (3-4 Nov. 1987)**

MCS (33 h)
Circular shape (~200 km diameter)
1000 mm / 36 h in Gandia

**TOUS (20 Oct. 1982)**

MCC (>12 h)
>400 mm
Dam breaking in Tous

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**Location / Stationarity:** well
**QPF:** underestimated

**Algerian low / Mesolow**
**Convergence ahead of LLJ**

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**GANDIA**

Location / Stationarity: well
QPF: underestimated

**TOUS**

Location / Stationarity: well
QPF: underestimated

**Westward-moving low / ULJ**
**Embedded mesolow**
**Convergence over SE Spain**
Rainfall suppression
No inland structure
SLP appreciably modified
Shift Low / LLJ
Weak convergence SE Spain

**FULL SIMULATION**

**NO ATLAS**
**NO LATENT HEAT**

**TOUS**
Rainfall suppression
No inland structure
SLP appreciably modified
Shift Low / LLJ
Weak convergence SE Spain

**FACTOR SEPARATION STUDY**

Method of Stein and Alpert (1993)

\[ n \text{ factors} \rightarrow 2^n \text{ simulations} \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Atlas orography</th>
<th>Latent heat exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₀</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>F₁</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>F₂</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>F₁₂</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

a. **Effect of the Atlas Mountains** = F₁ - F₀
b. **Effect of the Latent heat** = F₂ - F₀
c. **Effect of the interaction Atlas/Latent heat** = F₁₂ - (F₁+F₂) + F₀
GANDIA
Extensive pressure decrease over the Mediterranean
Cyclogenesis / Enhancement of easterlies and convergence
Southward shift of the rainfall activity

EFFECT
ATLAS MOUTAINS

TOUS
Pressure decrease limited to the east of the Balearics
Northerly winds and offshore outflows over eastern Spain
General rainfall suppression

GANDIA
Mesolow over eastern Spain
Intense mesoscale cyclonic circulation / strong convergence
Focusing of rainfall over central Valencia

EFFECT
LATENT HEAT

TOUS
Mesolow over southeastern Spain
Intense vortex / strong convergence line
Substantial rainfall enhancement (elongated structure)
The numerical modeling of atmospheric circulations is the most powerful tool available to scientists to develop a better physical understanding of the responsible mechanisms and its relation to the weather or the environment.

By switching on / off some given factors in the numerical simulations, the role played by these factors on our meteorological or environmental problem can be isolated !!!
CONCLUSIONS (II) - Part 1

1) Factor separation technique (PROS):
- Numerical simulations can be utilized to obtain the pure contribution of any factor to any predicted field, as well as the contributions due to the mutual interactions among two or more factors.
- Easy to apply (algebraic combinations of model outputs).

2) Factor separation technique (CONS):
- \( n \) factors \( \rightarrow 2^n \) simulations
  (e.g. 10 factors would require 1024 simulations, but only 56 simulations would be needed to obtain double interactions only).
- The interactions can be complex and difficult to interpret

3) What about the nature of the factors?
- Boundary and physical factors, no problem!
- But … how to deal with dynamical factors (LC)?

INTRODUCTION - Part 2

HEAVY RAIN PRODUCING WESTERN MEDITERRANEAN CYCLONE

FACTORS
- Two embedded upper level disturbances (positive PV anomalies)
  (dynamical factors)

How can the internal features of the flow dynamics (jet streaks, troughs, fronts, etc…) present in the initial conditions be switched on/off without compromising the delicate 3-D dynamical balances that govern both the model and actual meteorological fields??
FUNDAMENTALS PV - QG framework

a) Conservation principle:

\[ \frac{D}{Dt} (QGPV) = 0 \]

In an adiabatic and frictionless atmosphere, it is conserved following the geostrophic motion.

b) Invertibility principle:

Function of \( \phi \) + Geostrophic balance (Requires \( Ro \to 0 \)) + Boundary conditions

Linear operator (anomalies)

A balance flow can be calculated from the QGPV field:

\[ \phi, \bar{V}, T \]

\( QGPV \) field

\( QGPV \) is typically higher/lower in high/low latitude, stratospheric/tropospheric air: Source of +/- anomalies

+/- anomalies are consistent with positive/negative relative vorticity and enhanced/reduced stability

\( Coriolis \) parameter increases with latitude

\( <0 \) in troposphere

\( >0 \) in stratosphere

\( \frac{\partial}{\partial \sigma} \left( \frac{f}{\sigma} \frac{\partial \phi}{\partial \sigma} \right) - \frac{\partial}{\partial \sigma} \left( \frac{f R_e}{\sigma} \frac{\partial T}{\partial \sigma} \right) = \frac{f R_e}{\sigma} \frac{\partial T}{\partial \sigma} \)

\( QGPV \) field

\( QGPV \) field

FUNDAMENTALS PV - Upper Level PV Anomalies

\[ + \]

\[ - \]
FUNDAMENTALS PV - Surface Thermal Anomalies

In an adiabatic and frictionless atmosphere, it is conserved following air-parcel motion (even if the atmosphere is nonhydrostatic).

COMPARISON – Ertel’s Potential Vorticity

\[ EPV = \frac{1}{\rho} \hat{\eta} \cdot \hat{\nabla} \theta \]

a) Conservation principle:

\[ \frac{D}{Dt} (EPV) = 0 \]

In a dry and frictionless atmosphere, it is conserved following air-parcel motion (even if the atmosphere is nonhydrostatic).

b) Invertibility principle:

Balance condition + EPV field + Boundary conditions

Charney nonlinear balance (very small irrot.wind) (Accurate for \( Ro \to 1 \))

Under the same scale analysis

Nonlinear operator (anomalies !!!)

A balance flow can be calculated from the \( EPV \) field:

\[ \phi, \ V_p, \ T \]

c) About the anomalies:

Same qualitative picture as for the QGPV anomalies
The cyclone progressed northwards during the episode. Main MCSs developed over the sea (strong QG forcing), and heavy precipitation and flash floods occurred in eastern Spain.
Lateral Interactions

Vortex-vortex interactions
Vortex retrogression
Background-flow advection of vortex

HORIZONTAL VIEW at 250 hPa
Mutual interactions among background flow and anomalies

VERTICAL VIEW along A-B
Anomalies felt throughout the entire atmospheric column
SENSITIVITY EXPERIMENTS

By adding and/or subtracting the PV-inverted balanced fields (geopotential, temperature and wind) into the model initial conditions

Sensitivity to the intensity
(One or both PV anomalies removed or doubled)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>SW anomaly</th>
<th>NE anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S^0_0$</td>
<td>Removed</td>
<td>Removed</td>
</tr>
<tr>
<td>$S^1_2$</td>
<td>Doubled</td>
<td>Doubled</td>
</tr>
<tr>
<td>$S^1_1$</td>
<td>Unchanged</td>
<td>Removed</td>
</tr>
<tr>
<td>$S^2_2$</td>
<td>Doubled</td>
<td>Removed</td>
</tr>
<tr>
<td>$S^0_1$</td>
<td>Removed</td>
<td>Unchanged</td>
</tr>
<tr>
<td>$S^2_1$</td>
<td>Doubled</td>
<td>Unchanged</td>
</tr>
<tr>
<td>$S^1_1$</td>
<td>Unchanged</td>
<td>Doubled</td>
</tr>
</tbody>
</table>

Sensitivity to the position
(One or both PV anomalies shifted 425 km along A-B)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>SW anomaly</th>
<th>NE anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S^0_-$</td>
<td>Moved inwards</td>
<td>Moved inwards</td>
</tr>
<tr>
<td>$S^1_-$</td>
<td>Moved outwards</td>
<td>Moved outwards</td>
</tr>
<tr>
<td>$S^0_+$</td>
<td>Unchanged</td>
<td>Moved inwards</td>
</tr>
<tr>
<td>$S^1_+$</td>
<td>Moved inwards</td>
<td>Moved inwards</td>
</tr>
<tr>
<td>$S^0_+$</td>
<td>Unchanged</td>
<td>Moved outwards</td>
</tr>
<tr>
<td>$S^1_+$</td>
<td>Unchanged</td>
<td>Moved outwards</td>
</tr>
</tbody>
</table>

FIRST GROUP
(Mesoscale forecast)

Stationary surface lows along the lee of the Atlas
Rainfall restricted to the southern Mediterranean areas

PV anomalies removed or moved away from each other
Enhanced PV structures aloft

SECOND GROUP (Mesoscale forecast)
Extensive and very mobile surface disturbances
Heavy rain in both the southern and northern Mediterranean zones

Relative weight of the NE anomaly enhanced

THIRD GROUP (Mesoscale forecast)
The cyclone evolves further east and north of southeastern Spain
Most of the rainfall in northern Mediterranean areas
INTRODUCTION - Part 3

LIFE CYCLE OF AN INTENSE MEDITERRANEAN CYCLONE

PV THINKING → An analysis of the cyclone event in terms of the impacts and interactions of dry and moist PV anomalies (and mean flow)

Beyond a qualitative analysis, how can these impacts and interactions be quantified ???

PV-BASED PROGNOSTIC SYSTEM + FACTOR SEPARATION
(without the need of numerical simulations !!!)

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PV THINKING - Vertical Interactions

Growth of an idealized baroclinic wave-cyclone
**PV THINKING - Vertical Interactions**

Effects of diabatic processes (condensation)

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**LIFE CYCLE OF THE CYCLONE (9-12 November 2001)**

Mid-Upper levels (H 500 / T 500)  
Low levels (SLP / T 925)
ALGERIA
- Over 100 mm/6 h that led to catastrophic flooding
- 737 people were killed and 23000 left homeless
LIFE CYCLE OF THE CYCLONE (9-12 November 2001)

Mid-Upper levels (H 500 / T 500)

Low levels (SLP / T 925)

BALEARIC ISLANDS
- Up to 400 mm/24 h, 150 km/h winds and 12 m sea waves
- 4 casualties, 500000 trees uprooted, floods and severe damages on coasts
LIFE CYCLE OF THE CYCLONE (9-12 November 2001)

Mid-Upper levels (H 500 / T 500)  Low levels (SLP / T 925)

LIFE CYCLE OF THE CYCLONE (9-12 November 2001)

Mid-Upper levels (H 500 / T 500)  Low levels (SLP / T 925)
LIFE CYCLE OF THE CYCLONE (9-12 November 2001)

Mid-Upper levels (H 500 / T 500)

Low levels (SLP / T 925)

Strong baroclinic development

Ch4-IR NOAA image (11 Nov / 13.29 UTC)

Diabatic contribution?
### PV-based DIAGNOSIS

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULev</td>
<td>PV perturbation above 700 hPa</td>
</tr>
<tr>
<td>LLev</td>
<td>Surface thermal anomaly and PV perturbation below 700 hPa</td>
</tr>
<tr>
<td>DIAB</td>
<td>Positive PV perturbation below 500 hPa in areas with RH &gt; 70%</td>
</tr>
</tbody>
</table>

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**Geopotential height perturbation**

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**Geopotential height perturbation**

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**Geopotential height perturbation**

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PV-BASED PROGNOSTIC SYSTEM
(Davis and Emanuel; MWR 1991)

0) A balanced flow has been first found using the PV inversion technique: \( q \rightarrow (\psi, \psi_b) \)

1) Tendency of the Charney (1955) nonlinear balance equation:

\[
\nabla^2 \phi = \nabla \cdot f \nabla \psi + 2m^2 \left[ \frac{\partial^2 \phi}{\partial x^2} \frac{\partial \psi}{\partial y} + \frac{\partial^2 \phi}{\partial y^2} \frac{\partial \psi}{\partial x} - 2 \frac{\partial \phi \partial \psi}{\partial x \partial y} \right]
\]

2) Tendency of the approximate form of Ertel's PV:

\[
q' = \frac{g\epsilon}{\rho} \left[ (f + m^2 \nabla^2 \psi) \frac{\partial \psi}{\partial x} + m^2 \frac{\partial^2 \phi}{\partial x^2} \nabla^2 \psi \right] - m^2 \left( \frac{\partial^2 \psi \partial \phi}{\partial x \partial \xi} \frac{\partial \xi}{\partial x} + \frac{\partial^2 \phi \partial \psi}{\partial x \partial \xi} \frac{\partial \xi}{\partial x} + \frac{\partial^2 \phi \partial \psi}{\partial y \partial \xi} \frac{\partial \xi}{\partial y} + \frac{\partial^2 \phi \partial \psi}{\partial \xi \partial \xi} \right)
\]

3) Ertel's PV tendency equation (frictionless but with diabatic term included):

\[
q' = -m(V \cdot \nabla \psi) - \omega \frac{\partial \psi}{\partial x} + \frac{\eta}{\rho} \cdot \nabla L.H.
\]

Horizontal wind | Vertical velocity
--- | ---
\( V \psi = m \kappa \times \nabla \psi \) | \( \omega^* = \frac{\mu \pi}{\rho} \)

PV-BASED PROGNOSTIC SYSTEM

4) Omega equation:

\[
\begin{align*}
&f \eta \frac{\partial}{\partial \pi} \left[ \pi^{\prime-1} \kappa \frac{\partial}{\partial \eta} (\pi^{1/\kappa-1} \omega^*) \right] + m^2 \nabla^2 \left( \frac{\partial \phi}{\partial \pi^2} \omega^* \right) \\
&-m^2 f \frac{\partial}{\partial \pi} \left( \frac{\partial \omega^*}{\partial \eta} \kappa \frac{\partial \phi}{\partial \eta} + \frac{\partial \omega^*}{\partial \eta} \frac{\partial \phi}{\partial \eta} \right) \\
&\quad + \left( \frac{\partial \eta}{\partial \pi} \frac{\partial \psi}{\partial \eta} \right) \omega^* = m^2 \nabla^2 \left[ (V \cdot \nabla \psi) \cdot \nabla \theta \right] \\
&+m \frac{\partial}{\partial \pi} \left[ (V \cdot \nabla \chi) \cdot \nabla L.H. \right] - m^2 \nabla \cdot (\frac{\partial \psi}{\partial \pi}) - 2m^2 \nabla \cdot (\frac{\partial \psi}{\partial \pi}) - 2m^2 \nabla \cdot (\frac{\partial \psi}{\partial \pi})
\end{align*}
\]

5) Continuity equation:

\[
\nabla^2 \chi + \pi^{1-1/\kappa} \frac{\partial}{\partial \pi} (\pi^{1/\kappa-1} \omega^*) = 0
\]

Lateral B.C (Homogeneous) | Top-Bottom B.C (Neumann)
--- | ---
\( \psi' = \omega^* = \chi = 0 \) | \( \theta' = -m(V \cdot \nabla \psi) \cdot \nabla \theta - \omega^* \frac{\partial \theta}{\partial \pi} + L.H. \)

\( \omega^* = 0 \) | \( \omega^* = \text{Topographic} \)

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FACTOR SEPARATION (Stein and Alpert, JAS 1993)

$\text{MEAN} + 3 \text{ FACTORS (1: ULev 2: LLev 3: DIAB)}$

\[ E_0 = F_0 \]
\[ E_1 = F_1 - F_0 \]
\[ E_2 = F_2 - F_0 \]
\[ E_3 = F_3 - F_0 \]
\[ E_{12} = F_{12} - (F_1 + F_2) + F_0 \]
\[ E_{13} = F_{13} - (F_1 + F_3) + F_0 \]
\[ E_{23} = F_{23} - (F_2 + F_3) + F_0 \]
\[ E_{123} = F_{123} - (F_{12} + F_{13} + F_{23}) + (F_1 + F_2 + F_3) - F_0 \]

(8 flow configurations necessary)
This topic is now included as Chapter 7 in the BOOK.