FACTORS SEPARATION BY NUMERICAL SIMULATIONS: BOUNDARY, MODEL PHYSICS AND DYNAMICAL FACTORS

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INTRODUCTION

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

FACTOR SEPARATION

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 !!!

STRUCTURE

1) Factors Separation Technique
- Traditional approach
- Stein and Alpert (*J. Atm. Sci.*, 1993)

2) Types of factors I (Case Studies)
- Boundary factors
- Model Physics factors

3) Types of factors II (Case Study)
- Dynamical factors

4) Conclusions

FACTORS SEPARATION (Traditional Approach)

1 FACTOR

Run	Factor		
F_1	*on*	Induced by the factor	$E_1 = F_1 - F_0$
F_0	*off*	Independent of the factor	$E_0 = F_0$

$(F_1 = E_0 + E_1)$

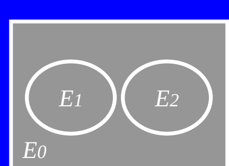
F_1

2 FACTORS

Run	Factor 1	Factor 2		
F_{12}	*on*	*on*	Induced by the factor 1	$E_1 = F_{12} - F_2$
F_1	*on*	*off*	Induced by the factor 2	$E_2 = F_{12} - F_1$
F_2	*off*	*on*	Independent of the factors	$E_0 = F_0$

F_{12}

* Ideally:



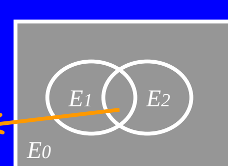
$(F_{12} = E_0 + E_1 + E_2)$

F_{12}

* But in nature:

Interaction

not isolated !!!

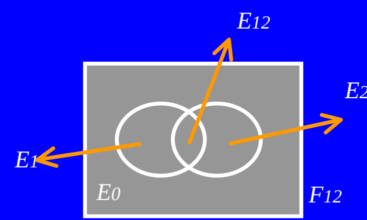


$(F_{12} \neq E_0 + E_1 + E_2)$

FACTORS SEPARATION (Stein and Alpert, *JAS* 1993)

2 FACTORS

Run	Factor 1	Factor 2	
F_{12}	*on*	*on*	$= E_0 + E_1 + E_2 + E_{12}$
F_1	*on*	*off*	$= E_0 + E_1$
F_2	*off*	*on*	$= E_0 + E_2$
F_0	*off*	*off*	$= E_0$



Unrelated with factors 1 and 2	$E_0 = F_0$
Induced by the factor 1 (independent of 2)	$E_1 = F_1 - F_0$
Induced by the factor 2 (independent of 1)	$E_2 = F_2 - F_0$
Induced by the synergism of factors 1 and 2	$E_{12} = F_{12} - (F_1 + F_2) + F_0$

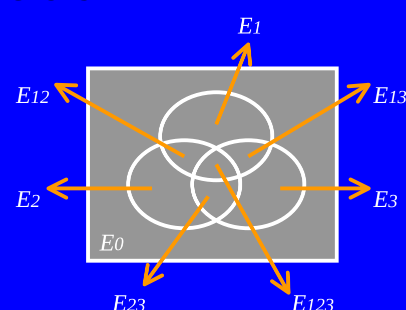
* Generalization: **n FACTORS** $\longrightarrow$ **2^n SIMULATIONS**

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

where $\sum_{sort}$ is over all groups of m sorted indices $j_1\, j_2\, j_3 \ldots j_m$ chosen from k indices $i_1\, i_2\, i_3 \ldots i_k$

FACTORS SEPARATION (Stein and Alpert, *JAS* 1993)

3 FACTORS



$E_0 = F_0$

$E_1 = F_1 - F_0$

$E_2 = F_2 - F_0$

$E_3 = F_3 - F_0$

$E_{12} = F_{12} - (F_1 + F_2) + F_0$

$E_{13} = F_{13} - (F_1 + F_3) + F_0$

$E_{23} = F_{23} - (F_2 + F_3) + F_0$

$E_{123} = F_{123} - (F_{12} + F_{13} + F_{23}) + (F_1 + F_2 + F_3) - F_0$

(8 simulations necessary)

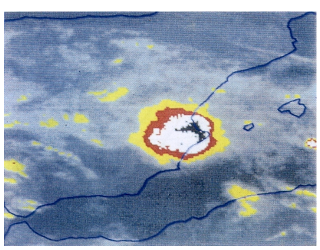
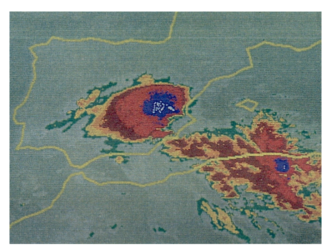
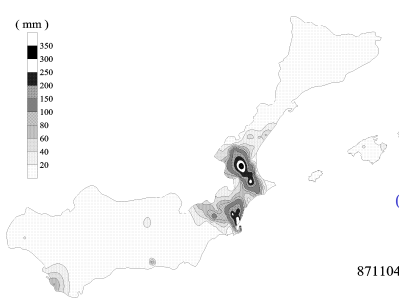
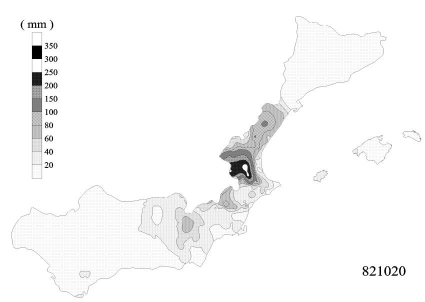
CASE STUDIES I

2 FLASH FLOOD EVENTS OVER EASTERN SPAIN

2 FACTORS

- Atlas Mountains (a boundary factor)
- Latent heat exchange (a model physics factor)

THE EVENTS

GANDIA (3-4 Nov. 1987)		**TOUS (20 Oct. 1982)**
MCS (33 h) Circular shape (~200 km diameter) 1000 mm / 36 h in **Gandia**		MCC (>12 h) >400 mm Dam breaking in **Tous**
	INFRARED METEOSAT	
	RAINFALL (SECOND HALF)	

GANDIA

Location / Stationarity: well
QPF: underestimated

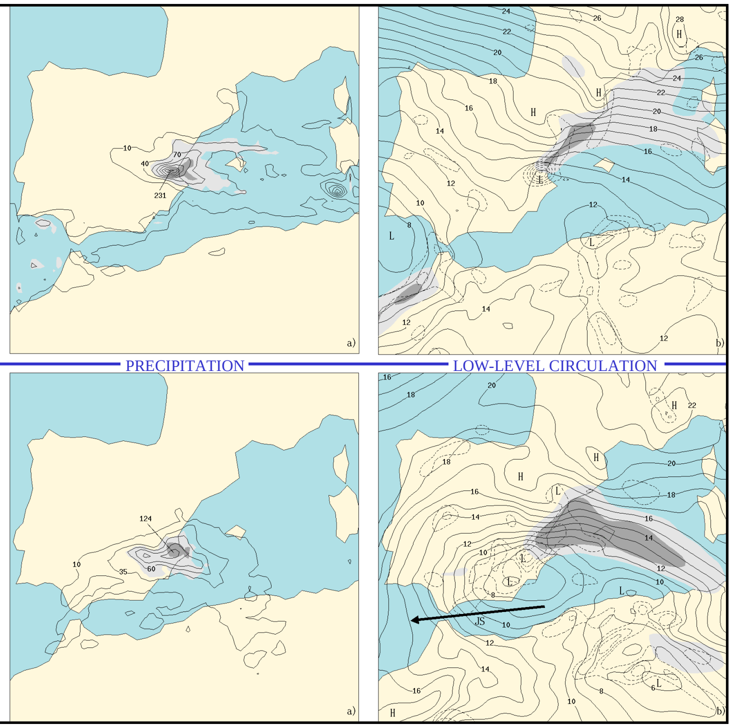
Algerian low / Mesolow
Convergence ahead of LLJ

MM5
FULL SIMULATION

TOUS

Location / Stationarity: well
QPF: underestimated

Westward-moving low / ULJ
Embedded mesolow
Convergence over SE Spain



GANDIA

Rainfall suppression
No inland peak

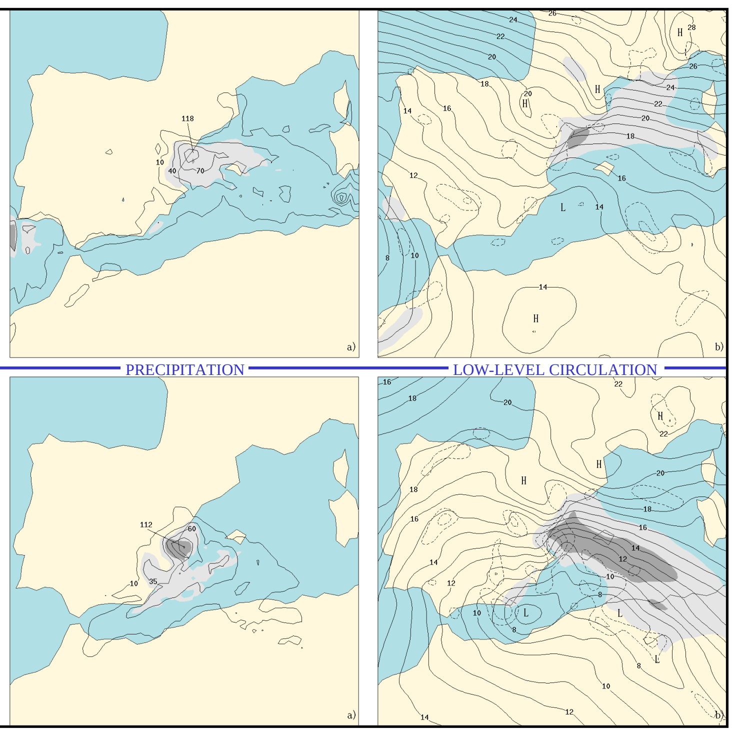
SLP appreciably modified
Less convergence / Shift LLJ

NO ATLAS
NO LATENT HEAT

TOUS

Rainfall suppression
No inland structure

SLP appreciably modified
Shift Low / LLJ
Weak convergence SE Spain



FACTOR SEPARATION STUDY

2 factors → **4 simulations**

Experiment	**Atlas orography**	**Latent heat exchange**
F_0	no	no
F_1	yes	no
F_2	no	yes
F_{12}	yes	yes

Effect of the Atlas Mountains = $F_1 - F_0$

Effect of the Latent heat = $F_2 - F_0$

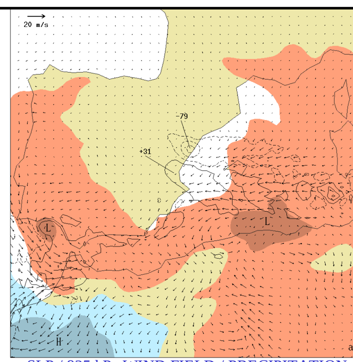
Effect of the interaction Atlas/Latent heat = $F_{12} - (F_1+F_2) + F_0$

GANDIA

Extensive pressure decrease over the Mediterranean

Cyclogenesis / Enhancement of easterlies and convergence

Southward shift of the rainfall activity



EFFECT
ATLAS MOUNTAINS

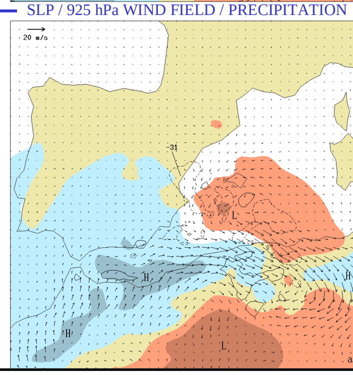
SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Pressure decrease limited to the east of the Balearics

Northerly winds and offshore outflows over eastern Spain

General rainfall suppression

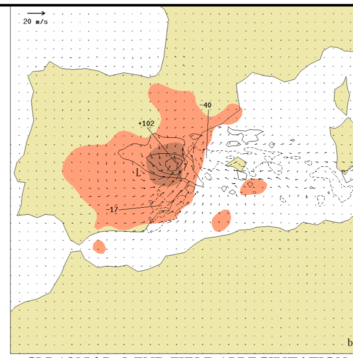


GANDIA

Mesolow over eastern Spain

Intense mesoscale cyclonic circulation / strong convergence

Focusing of rainfall over central Valencia



EFFECT
LATENT HEAT

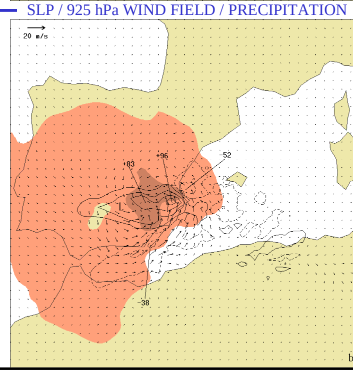
SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Mesolow over southeastern Spain

Intense vortex / strong convergence line

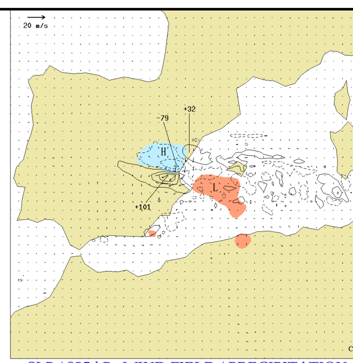
Substantial rainfall enhancement (elongated structure)



GANDIA

Complex pattern in space and time

Southward shift of the rainfall activity



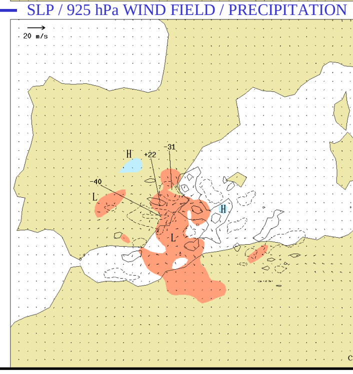
EFFECT
ATLAS MOUNTAINS / LATENT HEAT

SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Complex pattern in space and time

General rainfall suppression over land



CASE STUDY II

HEAVY RAIN PRODUCING WESTERN MEDITERRANEAN CYCLONE

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

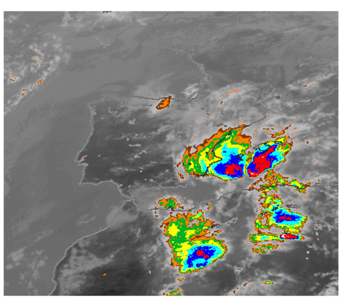
How can the internal features of the flow dynamics (jet streaks, troughs, fronts, etc...) be switched on / off without compromising the delicate 3-D dynamical balances that govern both the model and actual meteorological fields ???

↓

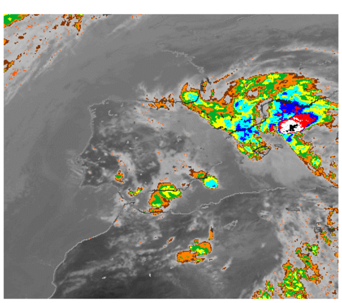
PIECEWISE PV INVERSION

THE EVENT (28-29 Sept. 1994)

INFRARED METEOSAT

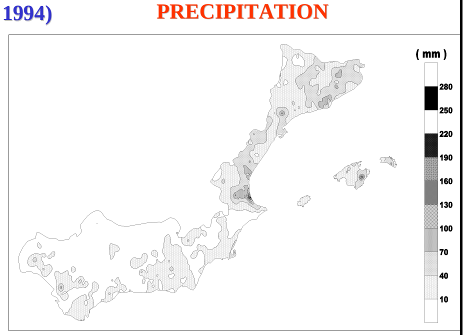


28th / 12 UTC



29th / 12 UTC

PRECIPITATION



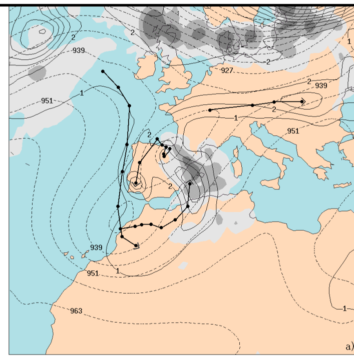
28th / 07 UTC → 30th / 07 UTC

The cyclone progressed northwards during the episode
Main MCSs developed over the sea (**strong QG forcing ?**)
Heavy precipitation and flash floods in eastern Spain

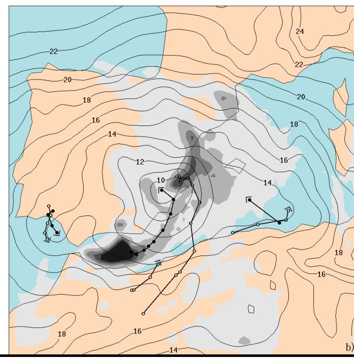
SYNOPTIC ASPECTS

Two **rotating** upper-level positive **PV anomalies**

Strong low-tropospheric **warm advection**



MM5 CONTROL SIMULATION



MESOSCALE FORECAST

Intense, broad and **mobile surface cyclone**

Heavy precipitation in agreement with observations

SENSITIVITY TO THE UPPER LEVEL PV ANOMALIES (motivation)

* The two embedded upper-level PV centres seem to be playing an important role for the evolution, intensity and areal extent of the surface cyclone

* How a potential analisis and/or forecast error in the representation of these PV anomalies might affect the mesoscale forecast ?

↓

* Sensitivity analysis based on additional simulations with perturbed initial conditions

* A balanced flow associated with each anomaly must be found that can be used to alter the model initial conditions in a physically consistent way without introducing any significant noise in the model ⟶ **Piecewise PV inversion**

PIECEWISE PV INVERSION TECHNIQUE
(Davis and Emanuel; *MWR* 1991)

1) Balanced flow (ϕ , ψ) given instantaneous distribution of Ertel's PV (q):

*** Charney (1955) nonlinear balance equation**

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

f Coriolis parameter m map-scale factor

*** Approximate form of Ertel's PV**

$$q = \frac{g\kappa\pi}{p}\left[(f + m^2\nabla^2\psi)\frac{\partial^2\phi}{\partial\pi^2} - m^2\left(\frac{\partial^2\psi}{\partial x\partial\pi}\frac{\partial^2\phi}{\partial x\partial\pi} + \frac{\partial^2\psi}{\partial y\partial\pi}\frac{\partial^2\phi}{\partial y\partial\pi}\right)\right]$$

p pressure g gravity $\kappa = Rd/Cp$ $\pi = Cp(p/po)^{\kappa}$

*** Bounday conditions** Lateral (Dirichlet) / Top and Bottom(Neumann): $\partial\phi/\partial\pi = f\partial\psi/\partial\pi = -\theta$

θ potential temperature

2) Reference state: Balanced flow ($\bar{\phi}$, $\bar{\psi}$) given time mean distribution of Ertel's PV ($\bar{q}$):

*** Same equations as in 1), except using time mean fields instead of instantaneous fields**

3) Perturbation fields (ϕ' , ψ' , q') given by the definitions: $(q,\phi,\psi) = (\bar{q},\bar{\phi},\bar{\psi}) + (q',\phi',\psi')$

PIECEWISE PV INVERSION TECHNIQUE

4) We consider that q' is partitioned into N portions or anomalies: $q' = \sum_{n=1}^{N} q_n$

5) Piecewise inversion: (ϕ_n , ψ_n) associated with q_n? **… and requiring:** $\phi' = \sum_{n=1}^{N}\phi_n$ $\psi' = \sum_{n=1}^{N}\psi_n$

…After substitution of the above summations in the balance and PV equations and some rearrangements of the nonlinear terms:

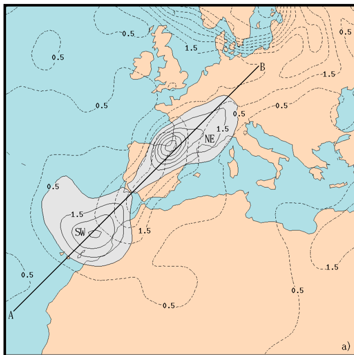
$$\nabla^2\phi_n = \boldsymbol{\nabla}\cdot f\boldsymbol{\nabla}\psi_n + 2m^2\left(\frac{\partial^2\psi^*}{\partial x^2}\frac{\partial^2\psi_n}{\partial y^2} + \frac{\partial^2\psi^*}{\partial y^2}\frac{\partial^2\psi_n}{\partial x^2} - 2\frac{\partial^2\psi^*}{\partial x\partial y}\frac{\partial^2\psi_n}{\partial y\partial x}\right)$$

$$\begin{aligned} q_n \;=\; & \frac{g\kappa\pi}{p}\left[(f + m^2\nabla^2\psi^*)\frac{\partial^2\phi_n}{\partial\pi^2} + m^2\frac{\partial^2\phi^*}{\partial\pi^2}\nabla^2\psi_n\right. \\ & \left. -m^2\left(\frac{\partial^2\phi^*}{\partial x\partial\pi}\frac{\partial^2\psi_n}{\partial x\partial\pi} + \frac{\partial^2\phi^*}{\partial y\partial\pi}\frac{\partial^2\psi_n}{\partial y\partial\pi}\right) - m^2\left(\frac{\partial^2\psi^*}{\partial x\partial\pi}\frac{\partial^2\phi_n}{\partial x\partial\pi} + \frac{\partial^2\psi^*}{\partial y\partial\pi}\frac{\partial^2\phi_n}{\partial y\partial\pi}\right)\right]\end{aligned}$$

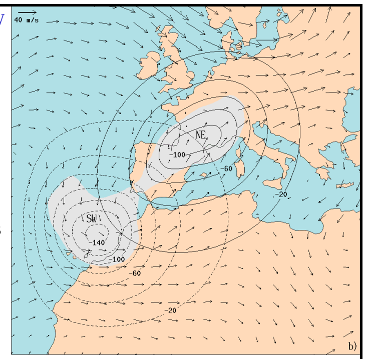
where $()^* = \overline{()} + \frac{1}{2}()'$ **Boundary conditions:** Lateral (homogeneous) / Top and bottom (using θ_n)

*** In our case study:** **At 00 UTC 28 September 1994**, using the NCEP-based isobaric analysis
Reference state: 6-day time average about 00 UTC 28 September
Anomalies: positive PV perturbations above 500 hPa **SW** and **NE** of Gulf of Cádiz

PV FIELD



FLOW



HORIZONTAL VIEW
at 250 hPa

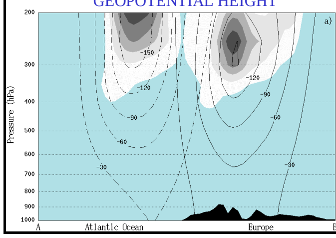
Mutual **interactions** among background flow and anomalies

PV
INVERSION RESULTS

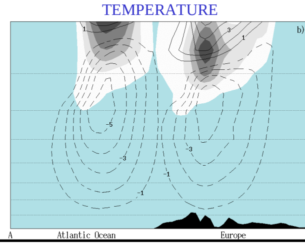
VERTICAL VIEW
along A-B

Anomalies felt throughout the **entire atmospheric column**

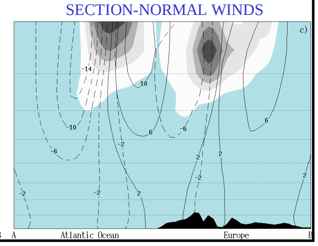
GEOPOTENTIAL HEIGHT



TEMPERATURE



SECTION-NORMAL WINDS



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

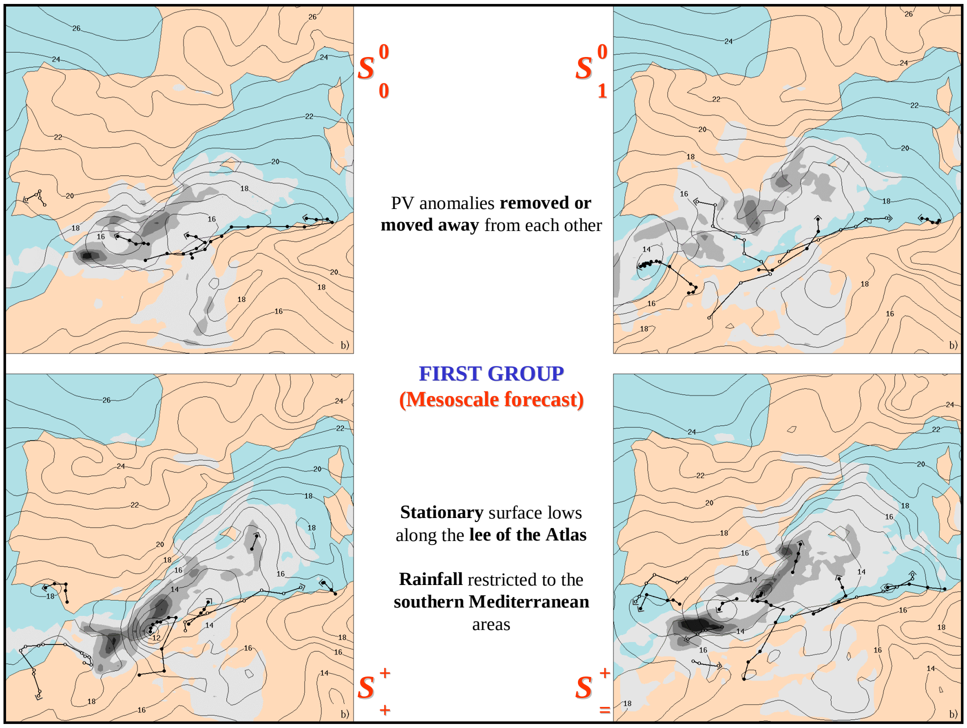
(One or both PV anomalies removed or doubled)

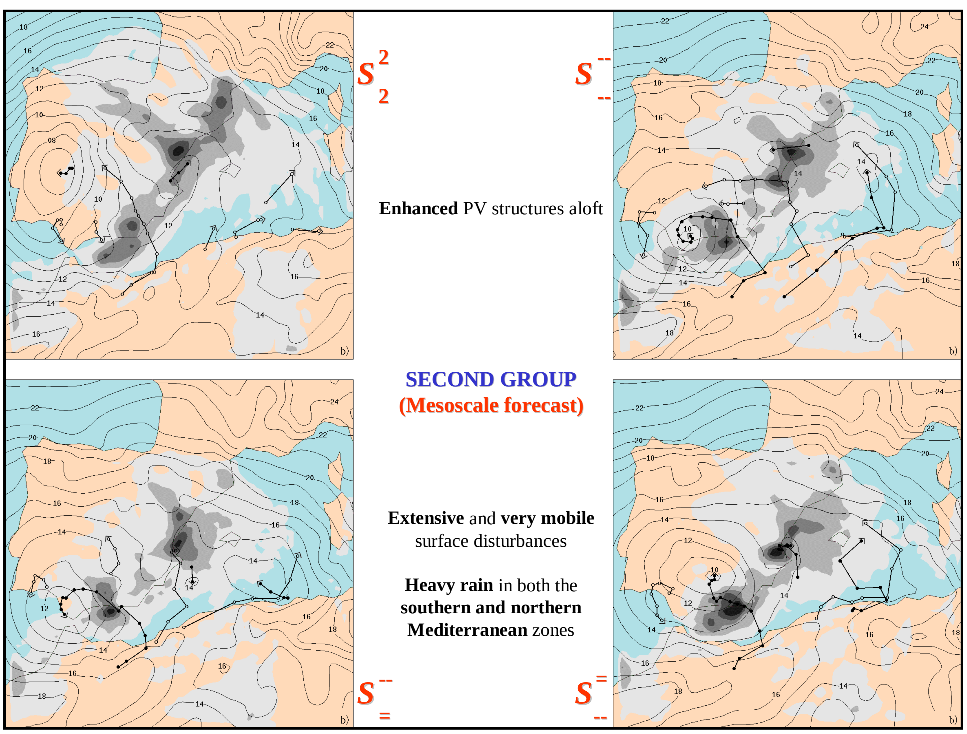
Experiment	SW anomaly	NE anomaly
S_0^0	Removed	Removed
S_2^2	Doubled	Doubled
S_1^0	Unchanged	Removed
S_2^0	Doubled	Removed
S_0^1	Removed	Unchanged
S_0^2	Removed	Doubled
S_2^1	Doubled	Unchanged
S_1^2	Unchanged	Doubled

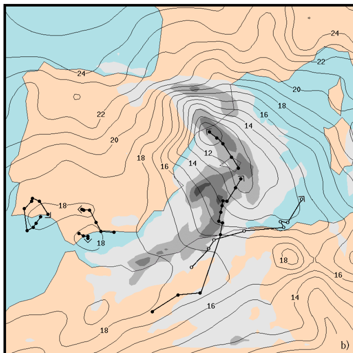
Sensitivity to the position

(One or both PV anomalies shifted 425 km along A-B)

Experiment	SW anomaly	NE anomaly
S_-^-	Moved inwards	Moved inwards
S_+^+	Moved outwards	Moved outwards
$S_=^-$	Unchanged	Moved inwards
S_+^-	Moved outwards	Moved inwards
$S_-^=$	Moved inwards	Unchanged
S_-^+	Moved inwards	Moved outwards
$S_+^=$	Moved outwards	Unchanged
$S_=^+$	Unchanged	Moved outwards

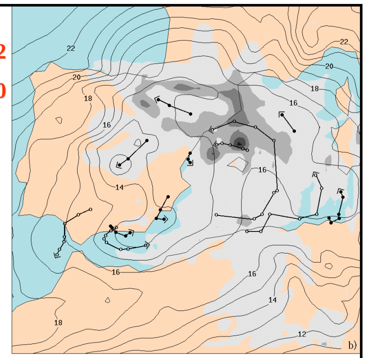

S_0^0
S_1^0
PV anomalies **removed or moved away** from each other
FIRST GROUP
(Mesoscale forecast)
Stationary surface lows along the **lee of the Atlas**
Rainfall restricted to the **southern Mediterranean** areas
S_+^+
$S_=^+$


S_2^2
S_{--}^{--}
Enhanced PV structures aloft
SECOND GROUP
(Mesoscale forecast)
Extensive and **very mobile** surface disturbances
Heavy rain in both the **southern and northern Mediterranean** zones
$S_=^{--}$
$S_{--}^=$



S_0^1

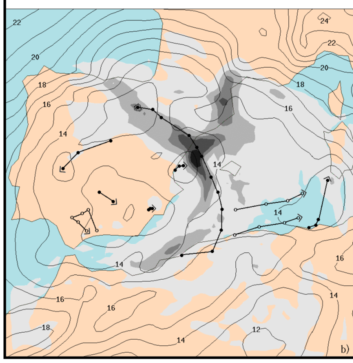
S_0^2



Relative weight of the **NE** anomaly **enhanced**

THIRD GROUP

(Mesoscale forecast)

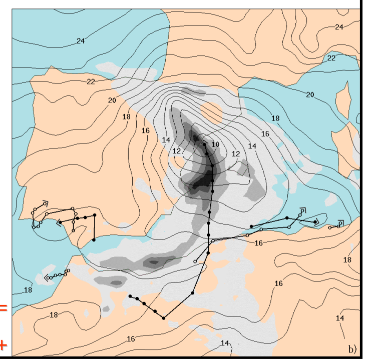


The cyclone evolves further **east and north** of southeastern Spain

Most of the **rainfall** in **northern Mediterranean** areas

S_1^2

$S_+^=$



CONCLUSIONS

1) Factor separation technique: 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. But remember:

- n factors ⟶ 2^n simulations
- The interactions can be complex and difficult to interpret

2) The combined application of piecewise PV inversion and numerical simulation offers a valuable and unique framework from which the effects of dynamical features of the flow can be studied in a practical and physically consistent way

Note: The piecewise PV inversion code for MM5 / Vis5D is available from the author by e-mail (Romu.Romero@uib.es)