SENSITIVITY OF CYCLONES TO INITIAL CONDITIONS: A NUMERICAL APPROACH THROUGH POTENTIAL VORTICITY INVERSION

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INTRODUCTION- Lecture 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 **???**

↓

PIECEWISE PV INVERSION

FUNDAMENTALS PV- QG framework

1) Our starting point are the quasigeostrophic equations (in pressure coordinates):

*** Thermodynamic equation (adiabatic)**

$$\frac{\partial T}{\partial t} = -\vec{V}_g \cdot \vec{\nabla} T + \frac{p}{R_d}\sigma\omega \quad \xrightarrow[\text{Hydrostatic equation}]{T = -\frac{p}{R_d}\frac{\partial \phi}{\partial p}} \quad \frac{\partial}{\partial t}\frac{\partial \phi}{\partial p} = -\vec{V}_g \cdot \vec{\nabla}\frac{\partial \phi}{\partial p} - \sigma\omega$$

where for the static stability parameter we will assume: $\sigma = -\frac{\alpha}{\theta}\frac{\partial \theta}{\partial p} \approx \sigma_{ref}(p)$

and remember the expression for the geostrophic wind: $\vec{V}_g = \frac{1}{f_0}\hat{k} \times \vec{\nabla}\phi$

*** Vorticity equation (frictionless)**

$$\frac{\partial \zeta_g}{\partial t} = -\vec{V}_g \cdot \vec{\nabla}(\zeta_g + f) - f_0 D \quad \xrightarrow[\text{Continuity equation}]{D = -\frac{\partial \omega}{\partial p}} \quad \frac{\partial \zeta_g}{\partial t} = -\vec{V}_g \cdot \vec{\nabla}(\zeta_g + f) + f_0\frac{\partial \omega}{\partial p}$$

where the geostrophic relative vorticity is defined as: $\zeta_g = \frac{1}{f_0}\nabla^2 \phi$

FUNDAMENTALS PV- QG framework

2) Using the thermodynamic equation, let's find an expression for $f_0\frac{\partial \omega}{\partial p}$ **:**

$$f_0\frac{\partial \omega}{\partial p} = f_0\frac{\partial}{\partial p}\left[\frac{1}{\sigma}\frac{\partial}{\partial t}\left(-\frac{\partial \phi}{\partial p}\right)\right] - f_0\frac{\partial}{\partial p}\left\{\frac{1}{\sigma}\left[-\vec{V}_g \cdot \vec{\nabla}\left(-\frac{\partial \phi}{\partial p}\right)\right]\right\}$$

$$-\frac{\partial \vec{V}_g}{\partial p}\cdot\frac{1}{\sigma}\vec{\nabla}\left(-\frac{\partial \phi}{\partial p}\right) - \vec{V}_g \cdot \frac{\partial}{\partial p}\left[\frac{1}{\sigma}\vec{\nabla}\left(-\frac{\partial \phi}{\partial p}\right)\right]$$

Thermal wind: $\vec{V}_T \equiv -\frac{\partial \vec{V}_g}{\partial p} = \frac{R_d}{f_0 p}\hat{k} \times \vec{\nabla} T$ $\quad \propto T$ (from the hydrostatic relation)

resulting in the expression:

$$f_0\frac{\partial \omega}{\partial p} = f_0\frac{\partial}{\partial p}\left[\frac{1}{\sigma}\frac{\partial}{\partial t}\left(-\frac{\partial \phi}{\partial p}\right)\right] + f_0\vec{V}_g \cdot \frac{\partial}{\partial p}\left[\frac{1}{\sigma}\vec{\nabla}\left(-\frac{\partial \phi}{\partial p}\right)\right]$$

FUNDAMENTALS PV- QG framework

3) And now <u>substitute this expression</u> in the vorticity equation:

$$\frac{\partial \zeta_g}{\partial t} = -\vec{V}_g \cdot \vec{\nabla}(\zeta_g + f) - f_0 \frac{\partial}{\partial p}\left[\frac{1}{\sigma}\frac{\partial}{\partial t}\left(\frac{\partial \phi}{\partial p}\right)\right] - f_0 \vec{V}_g \cdot \frac{\partial}{\partial p}\left[\frac{1}{\sigma}\vec{\nabla}\left(\frac{\partial \phi}{\partial p}\right)\right]$$

$\sigma \approx \sigma_{ref}(p)$

$f = f(y)$

$$\frac{\partial}{\partial t}\left[\zeta_g + f + \frac{\partial}{\partial p}\left(\frac{f_0}{\sigma}\frac{\partial \phi}{\partial p}\right)\right] = -\vec{V}_g \cdot \vec{\nabla}\left[\zeta_g + f + \frac{\partial}{\partial p}\left(\frac{f_0}{\sigma}\frac{\partial \phi}{\partial p}\right)\right]$$

and therefore we can define the quantity: $QGPV \equiv \zeta_g + f + \frac{\partial}{\partial p}\left(\frac{f_0}{\sigma}\frac{\partial \phi}{\partial p}\right)$ **such that …**

(Quasigeostrophic potential vorticity)

FUNDAMENTALS PV- QG framework

a) Conservation principle: $\frac{D_g}{Dt}(QGPV) = 0$ In an adiabatic and frictionless atmosphere, it is conserved **following the geostrophic motion**

b) Invertibility principle: *QGPV field* + *Balance condition* + *Boundary conditions*

Function of ϕ | Geostrophic balance (**Requires *Ro* →0**) | On ϕ / ϕ_p

Linear operator (anomalies)

A balance flow can be calculated from the *QGPV* field: $\phi\,,\ \vec{V}_g\,,\ T$

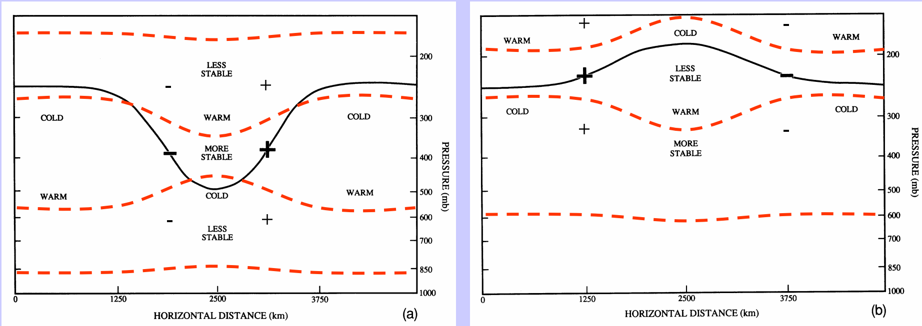
c) About the anomalies: *QGPV*

$\zeta_g + f$ — Coriolis parameter increases with latitude

$\frac{\partial}{\partial p}\left(\frac{f_0}{\sigma}\frac{\partial \phi}{\partial p}\right) = -\frac{\partial}{\partial p}\left(\frac{f_0 R_d}{\sigma p}T\right) \approx -\frac{f_0 R_d}{\sigma p}\frac{\partial T}{\partial p}$ — <0 in troposphere, >0 in stratosphere

- *QGPV* is typically higher/lower in high/low latitude, stratospheric/tropospheric air: Source of +/- anomalies
- +/- anomalies are consistent with positive/negative relative vorticity **and (or ?)** enhanced/reduced stability

FUNDAMENTALS PV - Upper Level PV Anomalies



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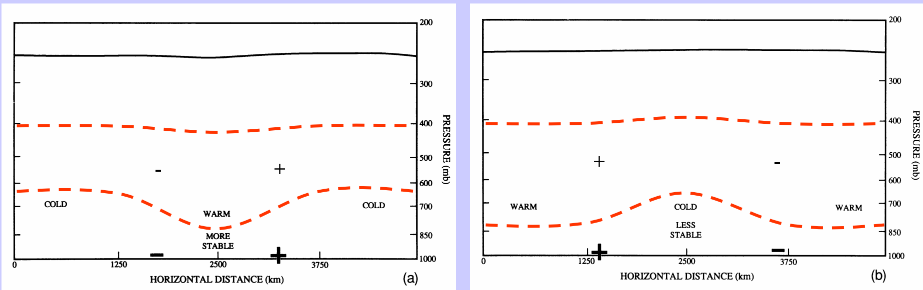
FUNDAMENTALS PV - Surface Thermal Anomalies



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COMPARISON – Ertel's Potential Vorticity

$$EPV \equiv \frac{1}{\rho}\vec{\eta}\cdot\vec{\nabla}\theta$$

a) Conservation principle: $\frac{D}{Dt}(EPV)=0$

In an adiabatic 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*

Balance condition: Nonlinear balance (very small irrot.wind) (**Accurate for** $Ro \rightarrow 1$)

EPV field: Under the same scale analysis

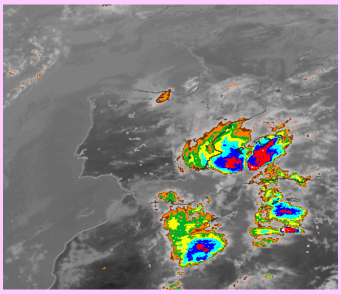
Nonlinear operator (anomalies !!!)

A balance flow can be calculated from the EPV field: $\phi\,,\ \vec{V}_{\psi}\,,\ T$

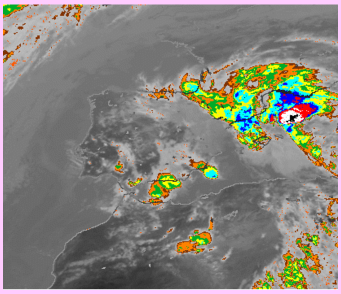
c) About the anomalies: Same qualitative picture as for the $QGPV$ anomalies

THE EVENT (28-29 Sept. 1994)

INFRARED METEOSAT

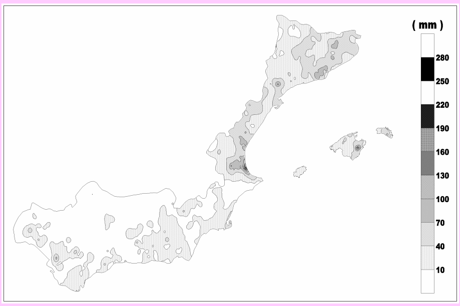


28th / 12 UTC



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

CONTROL NUMERICAL SIMULATION

* **PSU-NCAR mesoscale model (non-hydrostatic version MM5)**

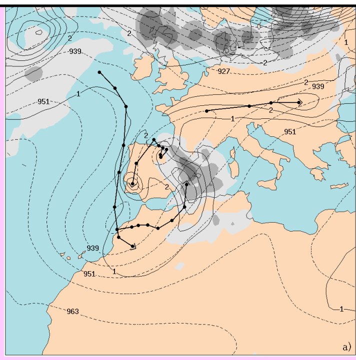
* **Simulation:**
  - **2 domains**: 82x82x31 (60 and 20 km)
  - **Interaction**: two-way
  - **I.C and B.C**: NCEP global analysis + Surface and Upper air obs.
  - **Period**: 48 h, from 00 UTC 28 September 1994

* **Physical parameterizations:**
  - **PBL**: Based on Blackadar (1979) scheme (Zhang and Anthes 1982)
  - **Ground temperature**: Force-restore slab model (Blackadar 1979)
  - **Radiation fluxes**: Considering cloud cover (Benjamin 1983)
  - **Resolved-scale microphysics**:
    Cloud water, rainwater, cloud ice and snow (Dudhia 1989)
  - **Parameterized convection**:
    60 km: Betts-Miller (1986)
    20 km: Kain-Fritsh (1990)

SYNOPTIC ASPECTS

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

Strong low-tropospheric **warm advection**

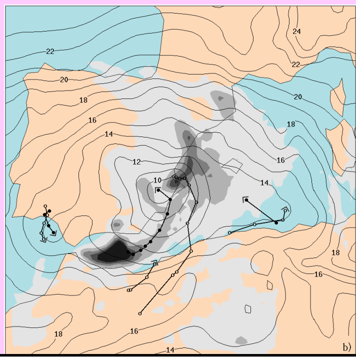


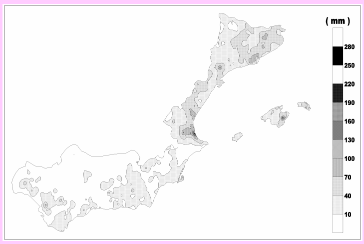
CONTROL SIMULATION

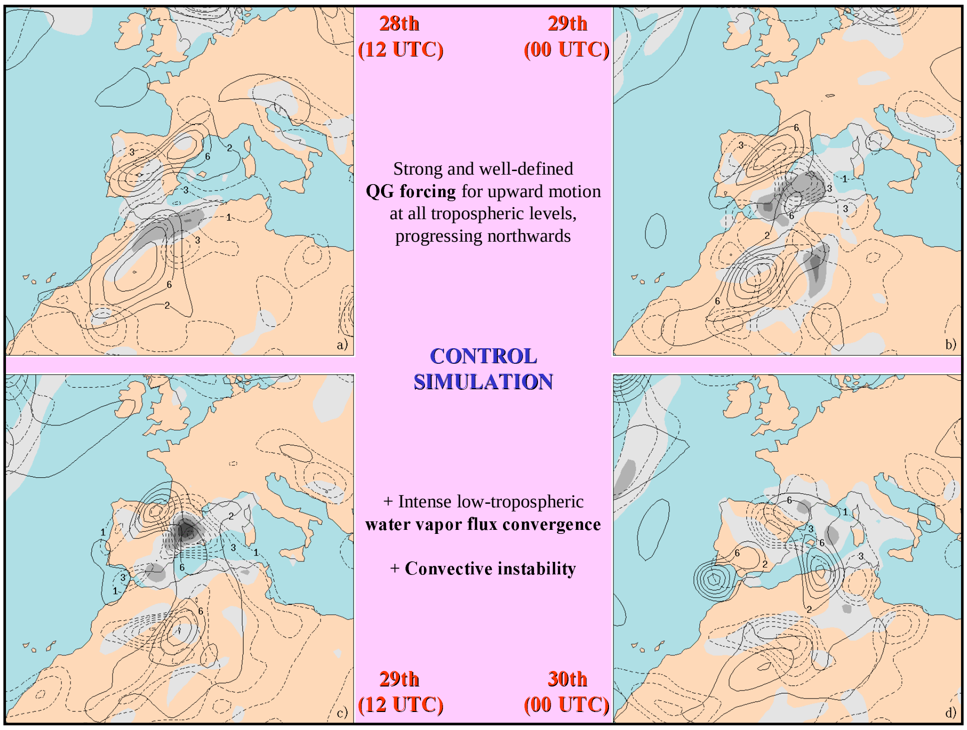
MESOSCALE FORECAST

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 spatial extent of the **surface cyclone**

* How a potential analysis 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**

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

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:** $\phi' = \sum_{n=1}^{N}\phi_n$ $\psi' = \sum_{n=1}^{N}\psi_n$

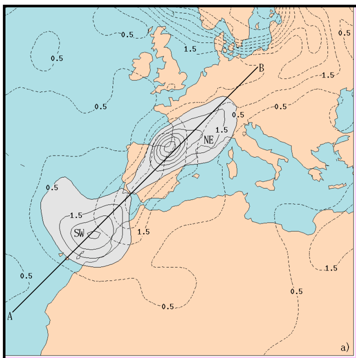
…After substitution of the above summations in the balance and PV equations and some rearrangements of the nonlinear terms:

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

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

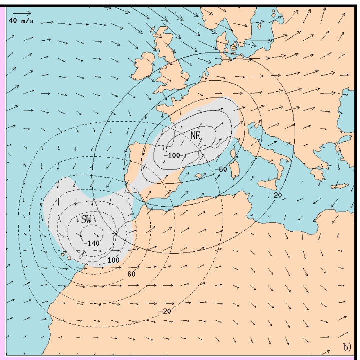
where $()^* = \overline{()} + \frac{1}{2}()'$ **Boundary conditions:** Lateral (homogeneous) / Top and bottom (using θ_n)

*** 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

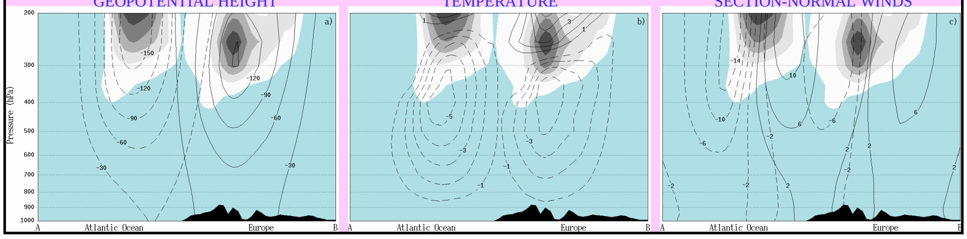
VERTICAL VIEW along A-B

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

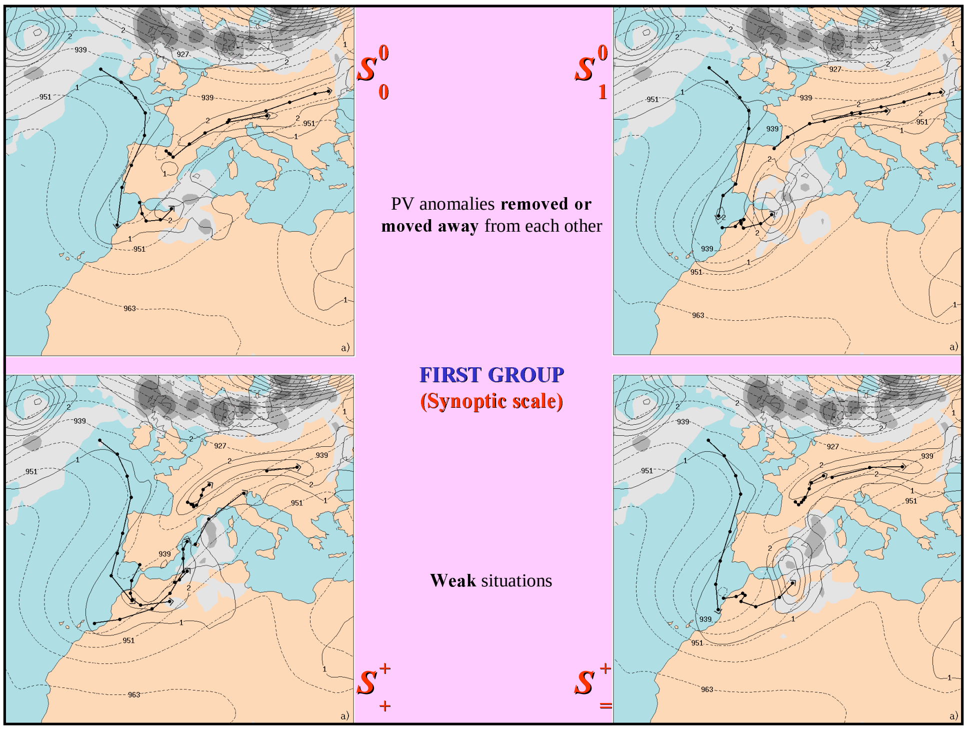
(One or both PV anomalies removed or doubled)

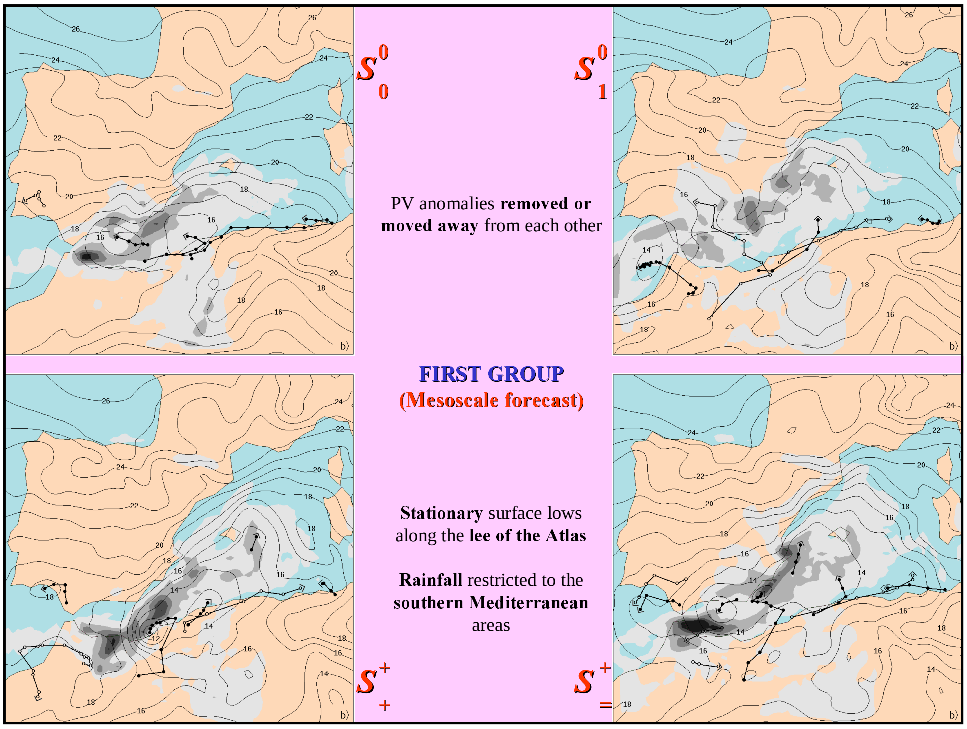
Experiment	SW anomaly	NE anomaly
S_0^0	Removed	Removed
S_2^2	Doubled	Doubled
S_1^0	Unchanged	Removed
S_2^0	Doubled	Removed
S_0^1	Removed	Unchanged
S_0^2	Removed	Doubled
S_2^1	Doubled	Unchanged
S_1^2	Unchanged	Doubled

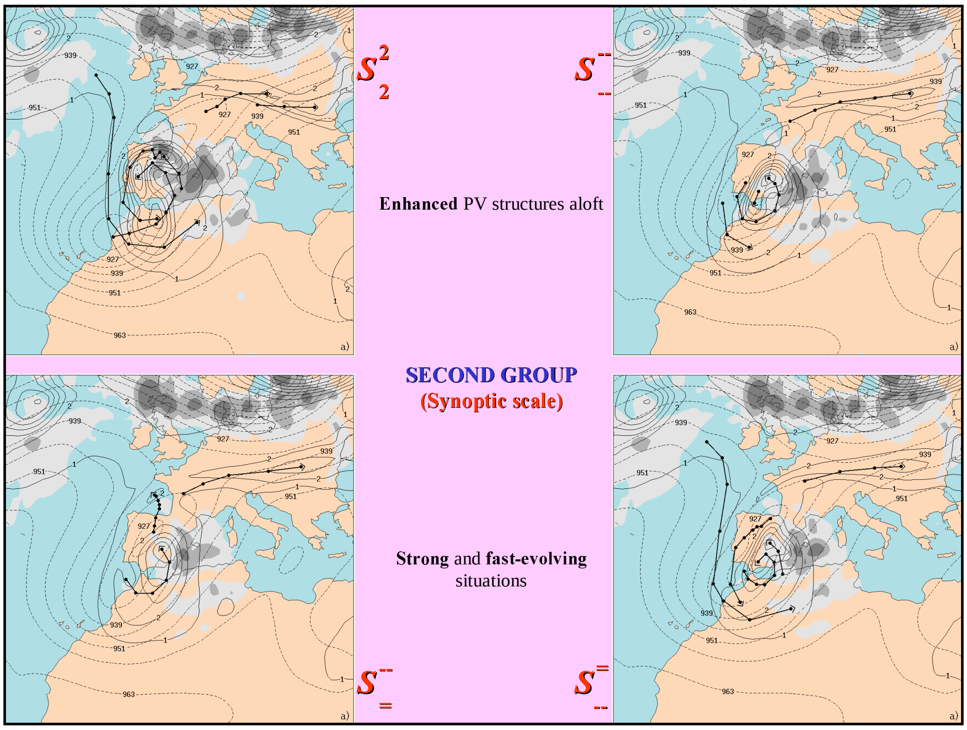
Sensitivity to the position

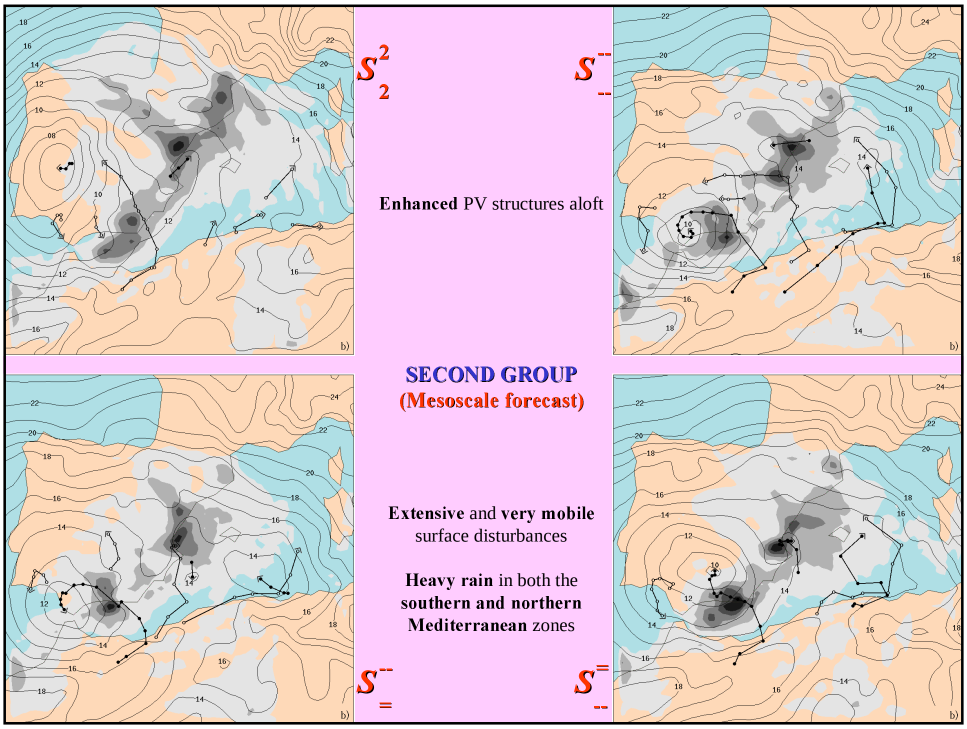
(One or both PV anomalies shifted 425 km along A-B)

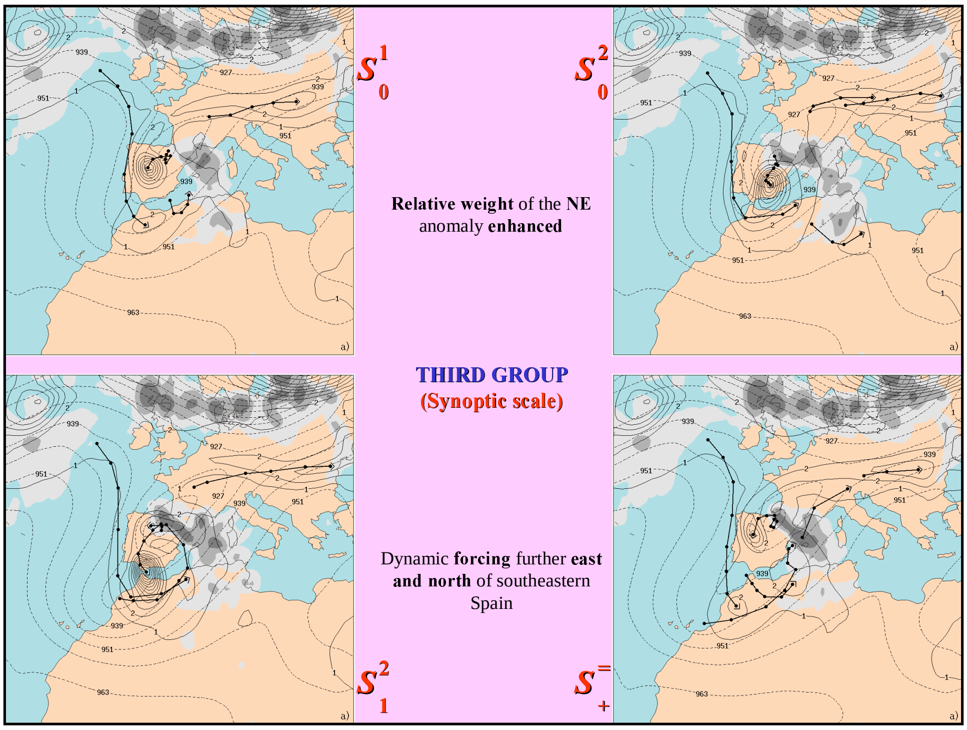
Experiment	SW anomaly	NE anomaly
S_-^-	Moved inwards	Moved inwards
S_+^+	Moved outwards	Moved outwards
$S_=^-$	Unchanged	Moved inwards
S_+^-	Moved outwards	Moved inwards
$S_-^=$	Moved inwards	Unchanged
S_-^+	Moved inwards	Moved outwards
$S_+^=$	Moved outwards	Unchanged
$S_=^+$	Unchanged	Moved outwards

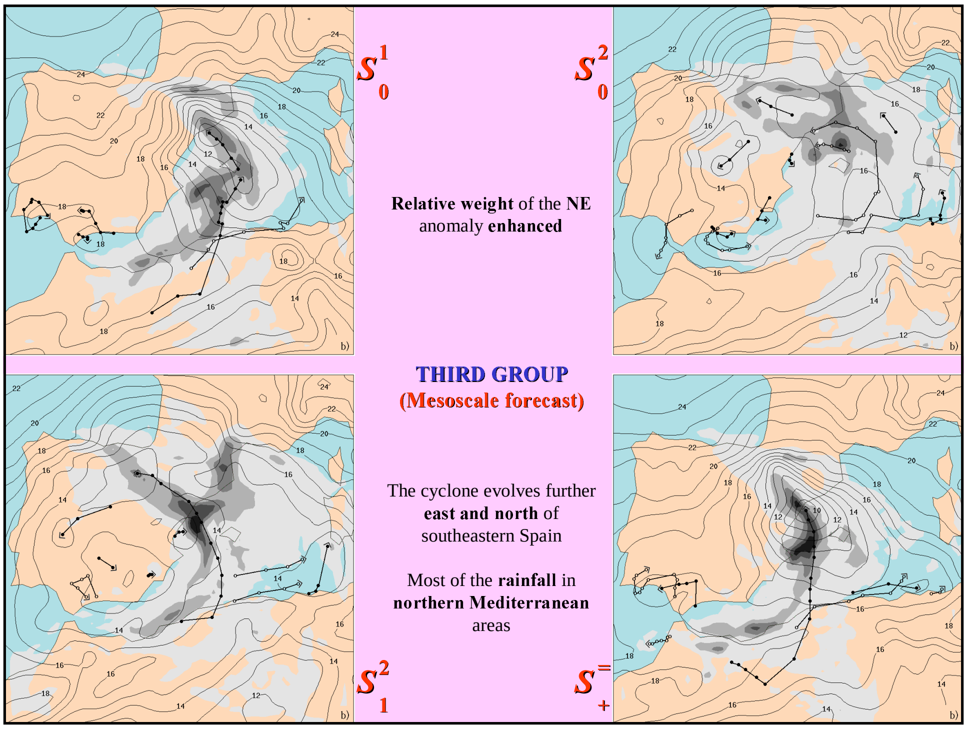

S_0^0
S_1^0
PV anomalies **removed or moved away** from each other
FIRST GROUP
(Synoptic scale)
Weak situations
S_+^+
$S_=^+$

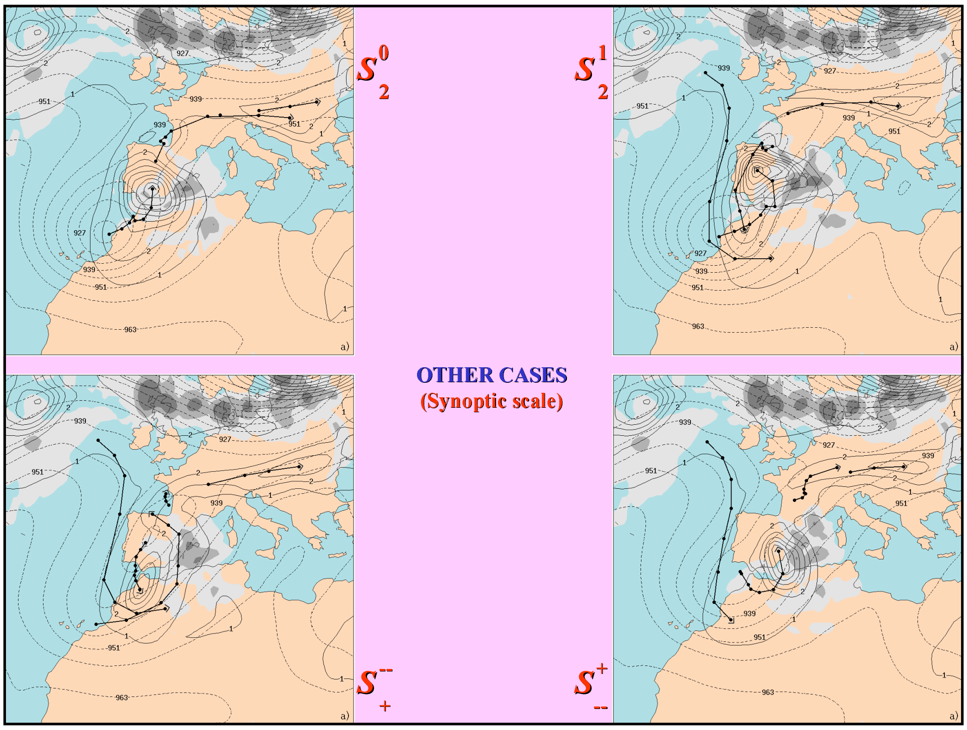

S_0^0
S_1^0
PV anomalies **removed or moved away** from each other
FIRST GROUP
(Mesoscale forecast)
Stationary surface lows along the **lee of the Atlas**
Rainfall restricted to the **southern Mediterranean** areas
S_+^+
$S_=^+$

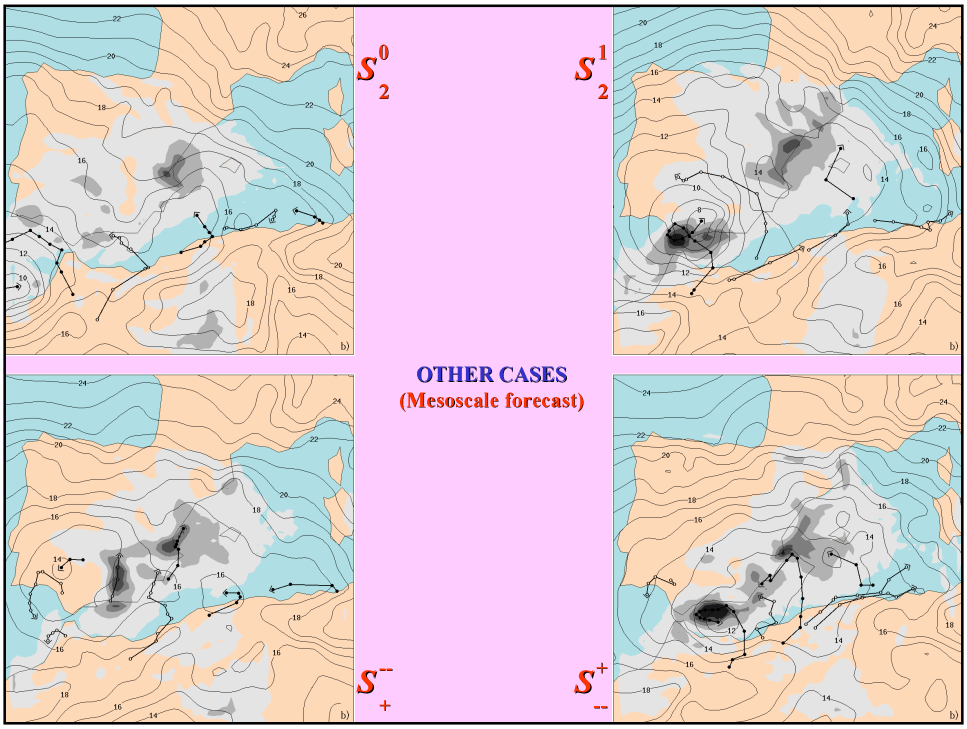

Enhanced PV structures aloft
SECOND GROUP
(Synoptic scale)
Strong and fast-evolving situations

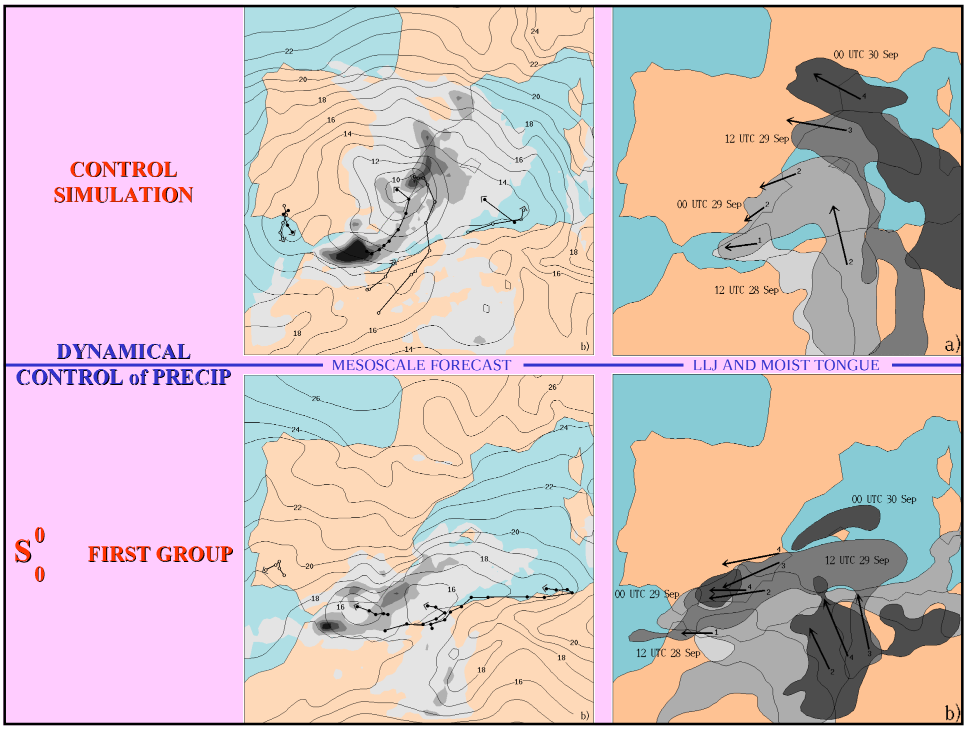

Enhanced PV structures aloft
SECOND GROUP
(Mesoscale forecast)
Extensive and very mobile surface disturbances
Heavy rain in both the southern and northern Mediterranean zones

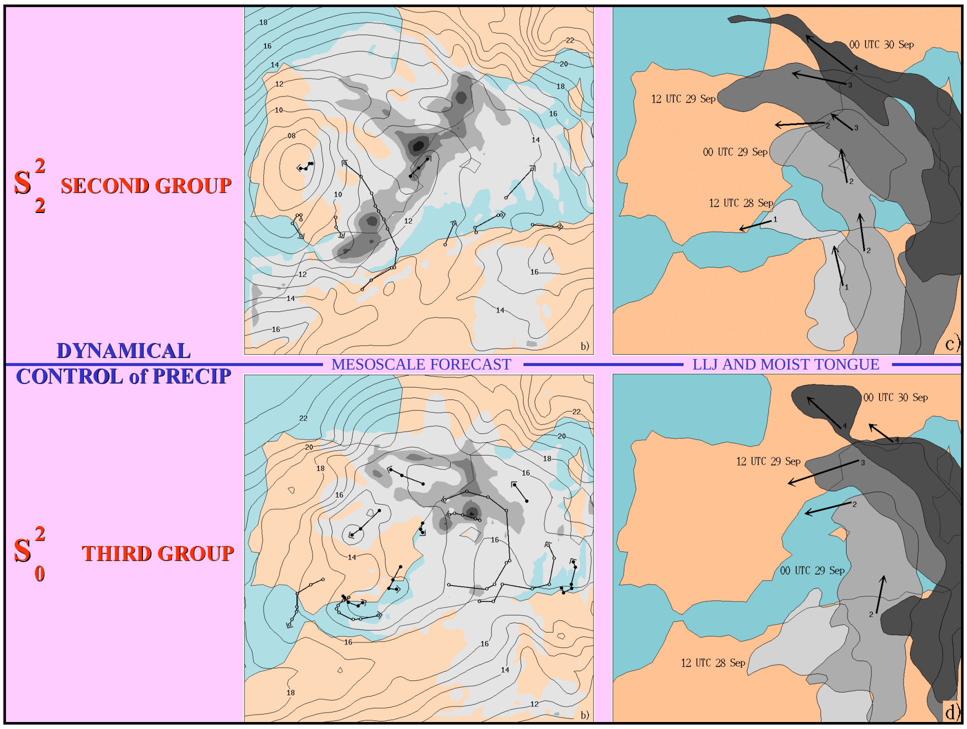

S_0^1
S_0^2
Relative weight of the NE anomaly enhanced
THIRD GROUP
(Synoptic scale)
Dynamic forcing further east and north of southeastern Spain
S_1^2
$S_+^=$


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
$S_+^=$


S_2^0
S_2^1
OTHER CASES
(Synoptic scale)
S_+^{--}
S_{--}^+


S_2^0
S_2^1
OTHER CASES
(Mesoscale forecast)
S_+^{--}
S_{--}^+


CONTROL SIMULATION
DYNAMICAL CONTROL of PRECIP
MESOSCALE FORECAST
LLJ AND MOIST TONGUE
00 UTC 30 Sep
12 UTC 29 Sep
00 UTC 29 Sep
12 UTC 28 Sep
a)
S 0 0
FIRST GROUP
b)

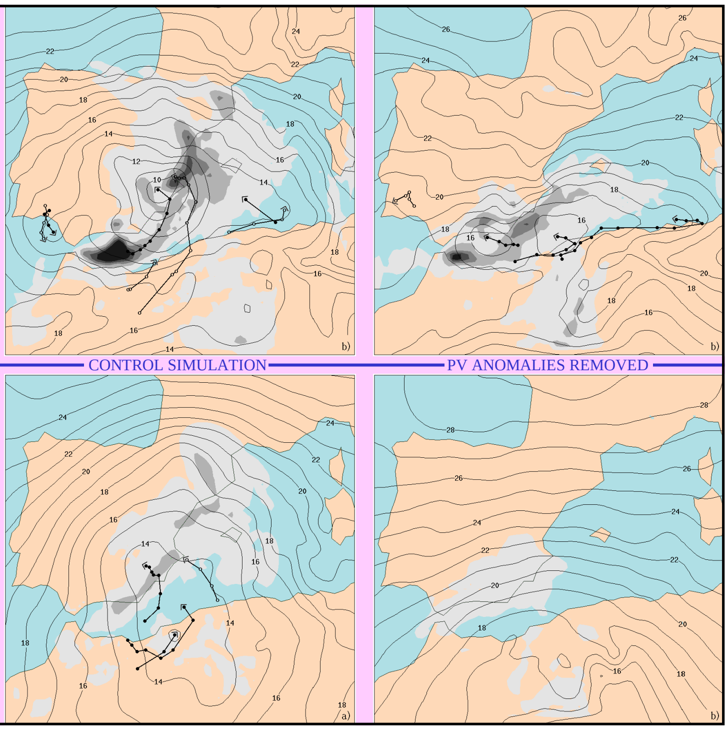

S 2 2
SECOND GROUP
DYNAMICAL CONTROL of PRECIP
MESOSCALE FORECAST
LLJ AND MOIST TONGUE
00 UTC 30 Sep
12 UTC 29 Sep
00 UTC 29 Sep
12 UTC 28 Sep
c)
S 2 0
THIRD GROUP
d)

ROLE EXTERNAL FACTORS

YES - Atlas Mountains
YES - Sea evaporation

NO - Atlas Mountains
NO - Sea evaporation

CONTROL SIMULATION | PV ANOMALIES REMOVED



CONCLUSIONS

* Track, shape and intensity of the **surface cyclone** and the corresponding **rainfall pattern** are very **sensitive** to the embedded upper-level **PV anomalies**

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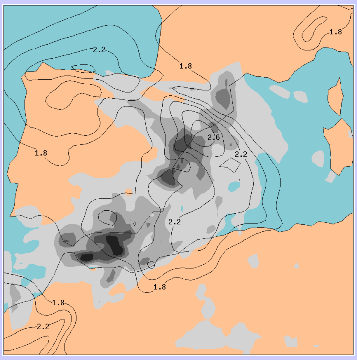
A potential **error** in the initial representation of the **anomalies** can be **critical**



SLP-TENDENCY and RAINFALL (STD)

* The **external factors** induced an **appreciable** modulation of the surface circulation and enhanced the efficiency of the system as a rainfall producer, **but** the cyclogenesis over the southern Mediterranean and its progression to the north must be attributed **mostly** to the action of the upper-level **PV anomalies**

* The combined application of **piecewise PV inversion + numerical simulation** offers a **valuable framework** from which the effects of **dynamical features** of the flow can be studied

INTRODUCTION- Lecture 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