A METHOD FOR QUANTIFYING THE IMPACTS AND INTERACTIONS OF POTENTIAL-VORTICITY ANOMALIES IN EXTRATROPICAL CYCLONES: MEDITERRANEAN EXAMPLE

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A method for quantifying the impacts and interactions of potential-vorticity anomalies in extratropical cyclones

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ABSTRACT: The theory of potential vorticity (PV) allows us to describe the life cycle of mid-latitude baroclinic systems in terms of the individual impacts and interactions of distinct PV anomalies embedded in the background flow. PV anomalies associated with the undulating tropopause, the low-level thermal field, and key diabatic processes such as the latent-heat release within the cloudy systems of the cyclone, are often considered as evolving features regulated by their lateral and vertical mutual interactions and their interaction with the stratospheric high-latitude PV reservoir. Under some balance-flow assumptions, PV inversion can be used to quantify the contribution of the PV anomalies to the cyclone depth (or other attributes) at various stages of its life cycle (a *static* approach); but it is less clear how to diagnose with similar quantitative detail the various types of time-dependent interactions among the anomalies and mean flow that govern the processes of cyclogenesis and cyclolysis (a *dynamic* approach).

This paper presents a method that implements the concepts of 'PV thinking' quantitatively. The method first applies a piecewise PV-inversion scheme formulated according to the Charney nonlinear mass–wind-balance approximation. Then it combines a prognostic system of balance equations that are consistent with the applied inversion scheme with a factor-separation technique. By switching on and off the PV anomalies of interest, various flow configurations are generated, and

INTRODUCTION

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)

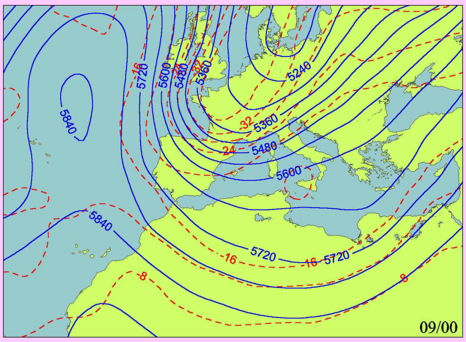
Beyond a qualitative analysis, **how** can these impacts and interactions be **quantified ???**

↓

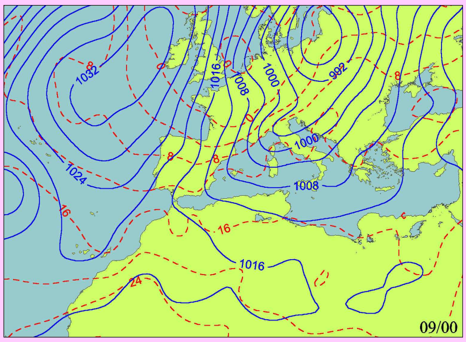
PV-BASED PROGNOSTIC SYSTEM + FACTOR SEPARATION

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

Mid-Upper levels (H 500 / T 500) ↓



Low levels (SLP / T 925) ↓



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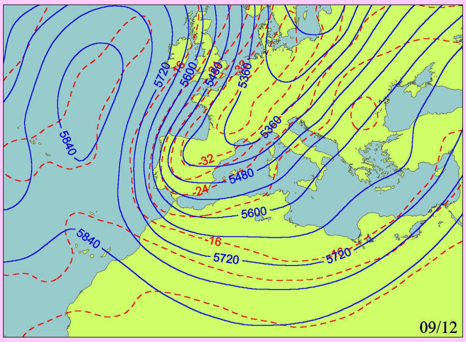

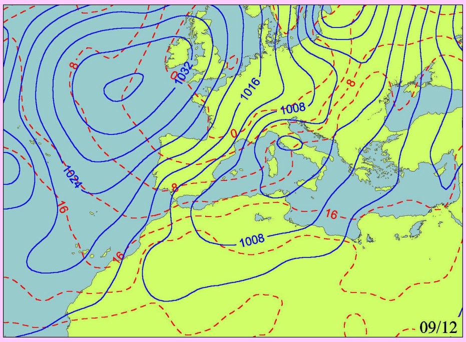

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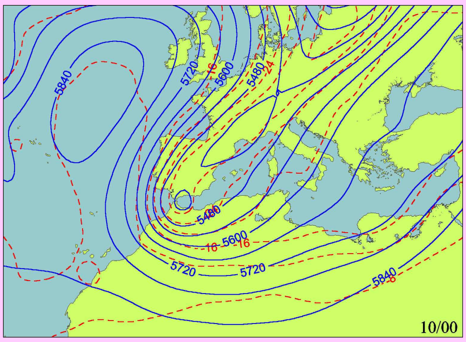

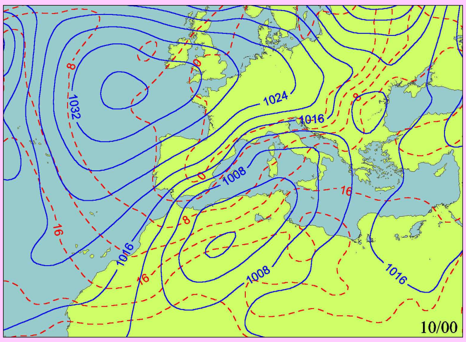

ALGERIA

- **Over 100 mm/6 h that led to catastrophic flooding**
- **737 people were killed and 23000 left homeless**

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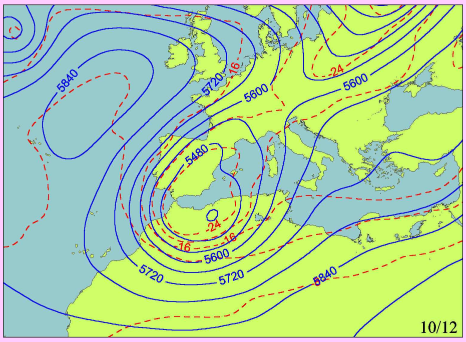

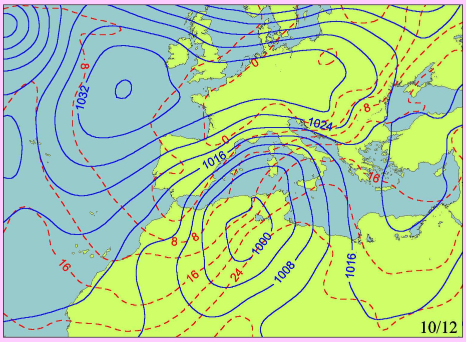

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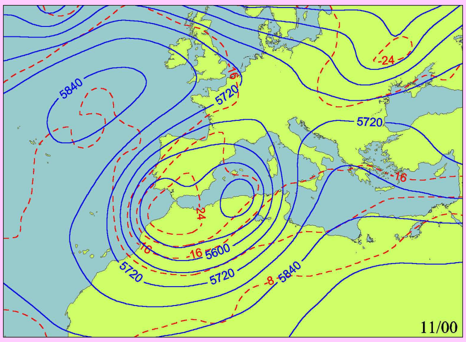

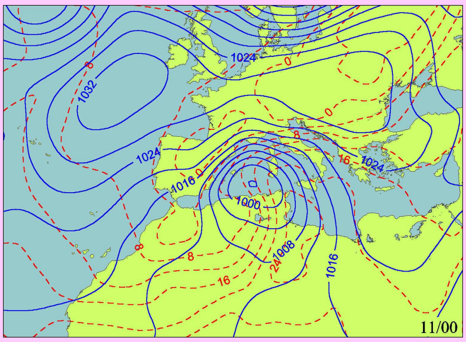

BALEARIC ISLANDS

- **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**

Some effects of the cyclone in the Balearics

Some effects of the cyclone in the Balearics

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

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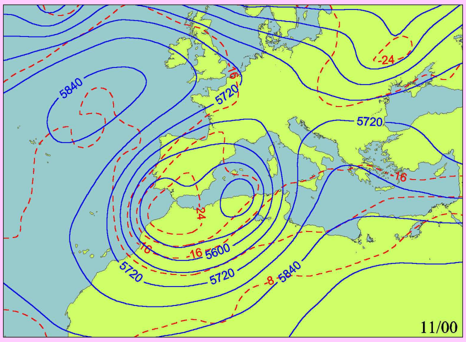

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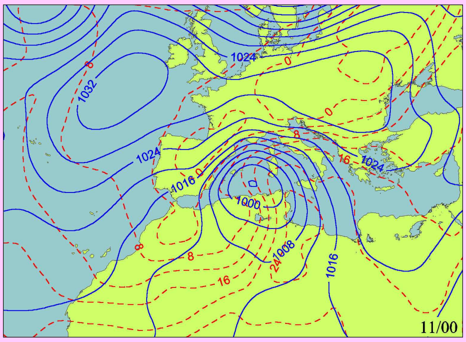

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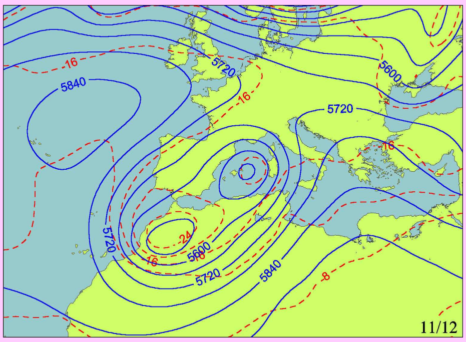

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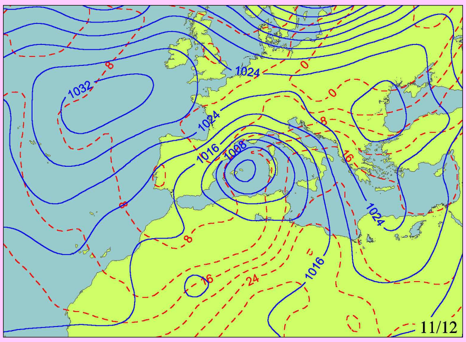

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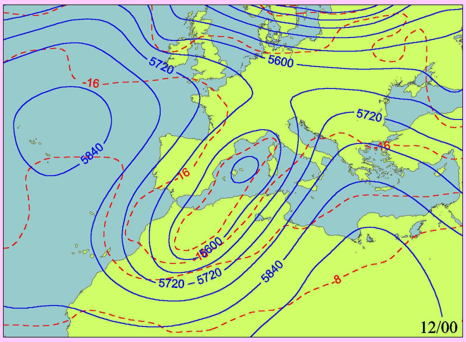

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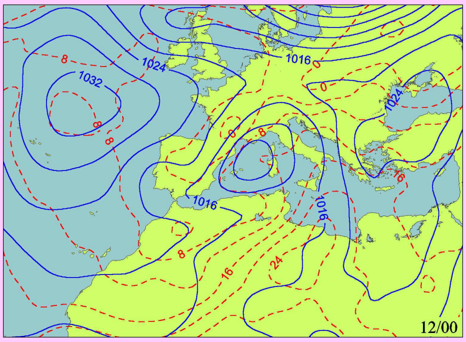

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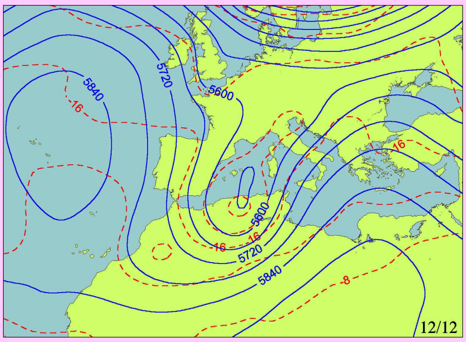

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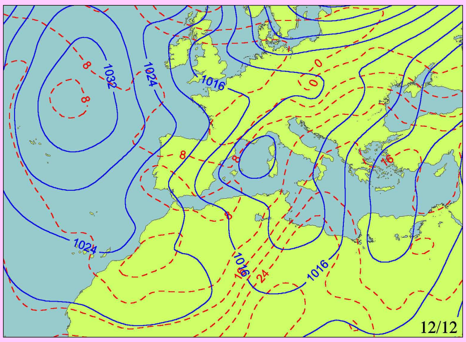
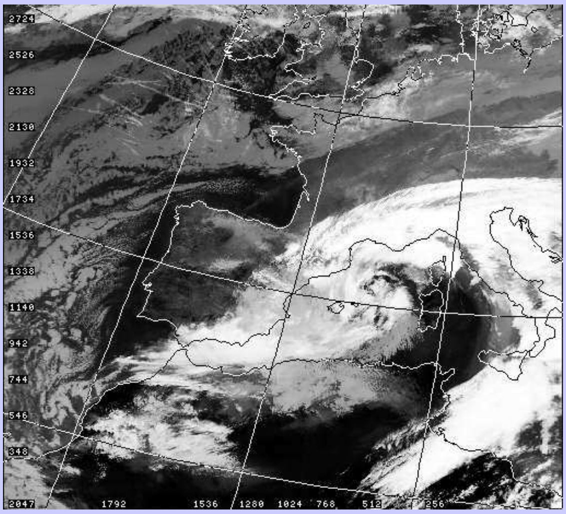


Strong baroclinic development

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



Diabatic contribution ?

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*

- *QGPV field*: Function of ϕ
- *Balance condition*: Geostrophic balance (**Requires** $\boldsymbol{Ro \to 0}$)
- *Boundary conditions*: 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:

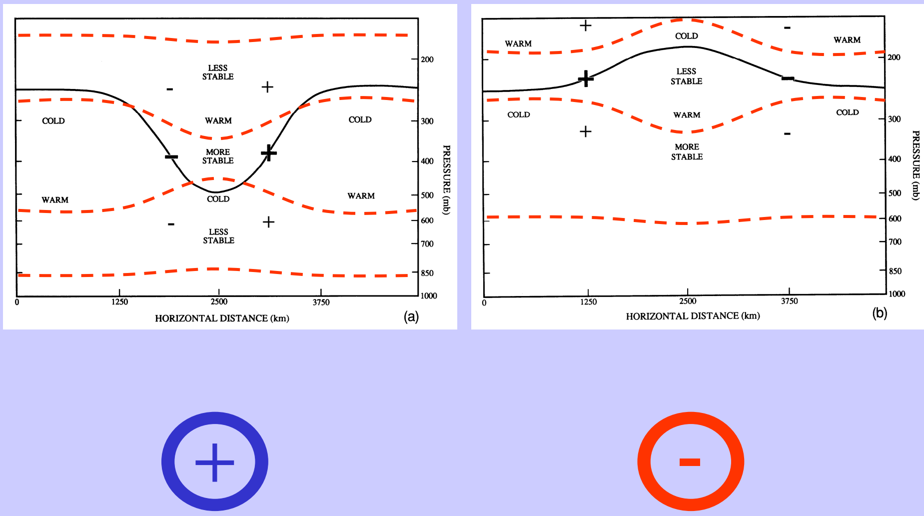
$$QGPV\begin{cases}\zeta_g+f \\ \frac{\partial}{\partial p}\left(\frac{f_0}{\sigma}\frac{\partial\phi}{\partial p}\right)=-\frac{\partial}{\partial p}\left(\frac{f_0R_d}{\sigma p}T\right)\approx-\frac{f_0R_d}{\sigma p}\frac{\partial T}{\partial p}\end{cases}$$

- ζ_g+f: Coriolis parameter increases with latitude
- $-\frac{f_0R_d}{\sigma p}\frac{\partial T}{\partial p}$: <0 in troposphere, >0 in stratosphere

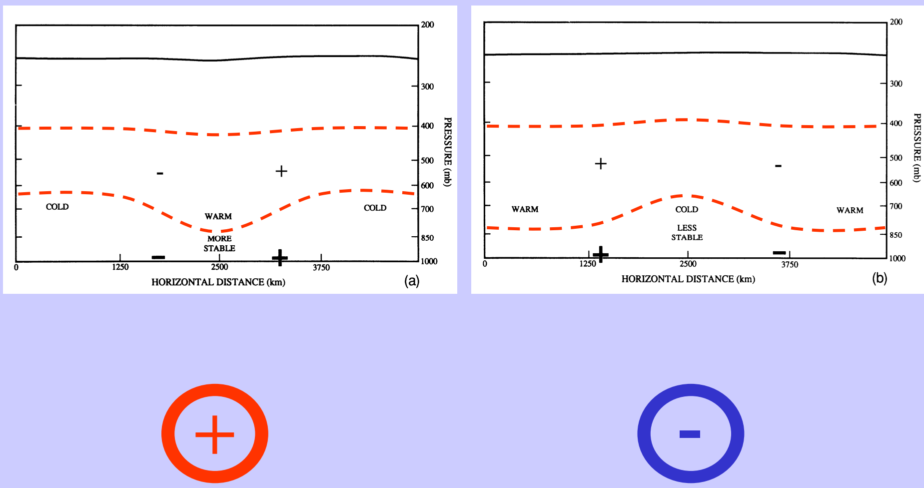
● *QGPV* is typically higher/lower in high/low latitude, stratospheric/tropospheric air: Source of +/- anomalies

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

FUNDAMENTALS PV - Upper Level PV Anomalies



FUNDAMENTALS PV - Surface Thermal Anomalies



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: Charney nonlinear balance (very small irrot.wind) (**Accurate for** ***Ro*** **→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

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**

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

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 $\kappa = Rd/Cp$ $\pi = Cp(p/po)^\kappa$

*** B.C** 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') defined through: $(q,\phi,\psi) = (\bar{q},\bar{\phi},\bar{\psi}) + (q',\phi',\psi')$

PIECEWISE PV INVERSION TECHNIQUE

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

5) <u>Piecewise inversion</u>: (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:

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

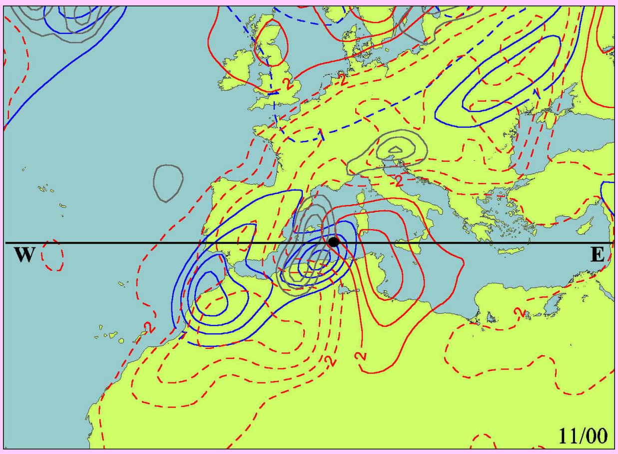
$$\begin{aligned} q_n \;=\; & \frac{g\kappa\pi}{p}\Bigg[(f+m^2\nabla^2\psi^*)\frac{\partial^2\phi_n}{\partial\pi^2}+m^2\frac{\partial^2\phi^*}{\partial\pi^2}\nabla^2\psi_n \\ & -m^2\left(\frac{\partial^2\phi^*}{\partial x\partial\pi}\frac{\partial^2\psi_n}{\partial x\partial\pi}+\frac{\partial^2\phi^*}{\partial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

where $()^* = \overline{()} + \frac{1}{2}()'$ **B.C:** Lateral (Dirichlet with ϕ_n and ψ_n) / Top and bottom (Neumann with θ_n)

*** <u>In our case study</u>:**
Time interval: 9/00 - 12/12 every 12 h, using the NCEP meteorological analyses
Reference state: 7-day time average for the period 7/00 - 14/00 (**MEAN**)
Anomalies: **ULev**, **LLev**, **DIAB**

PV-based DIAGNOSIS

ULev	**PV perturbation above 700 hPa**
LLev	**Surface thermal anomaly and PV perturbation below 700 hPa**
DIAB	**Positive PV perturbation below 500 hPa in areas with RH > 70%**



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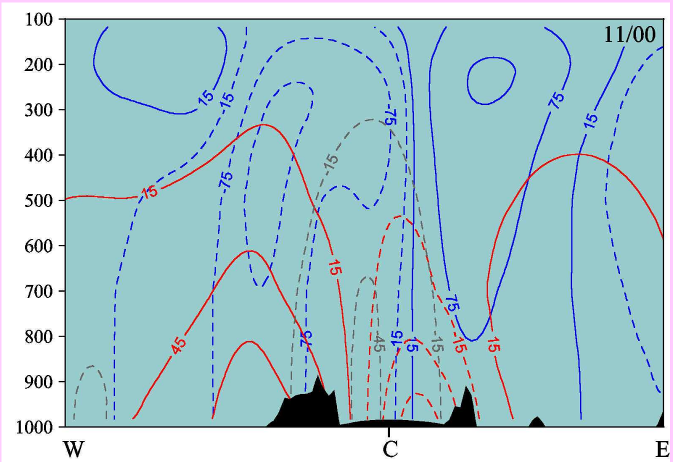
Geopotential height perturbation



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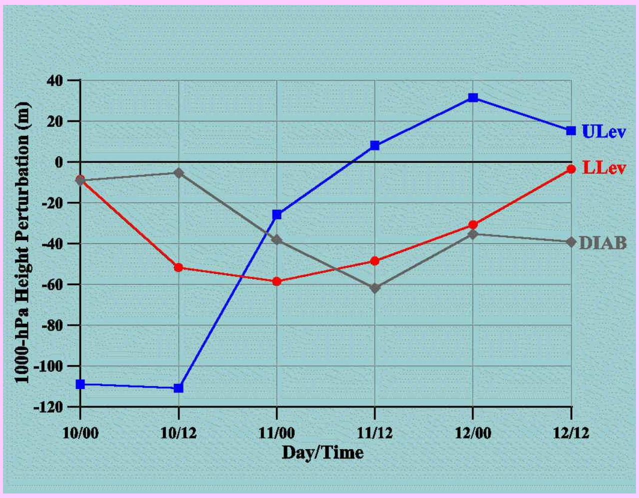
Contribution to the surface cyclone height perturbation



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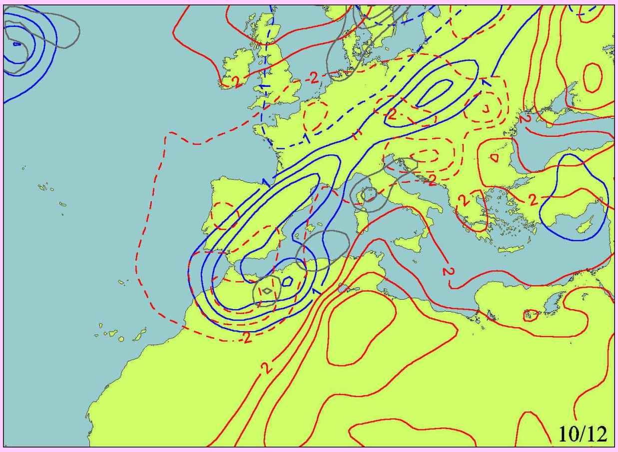
Evolution of the PV anomalies



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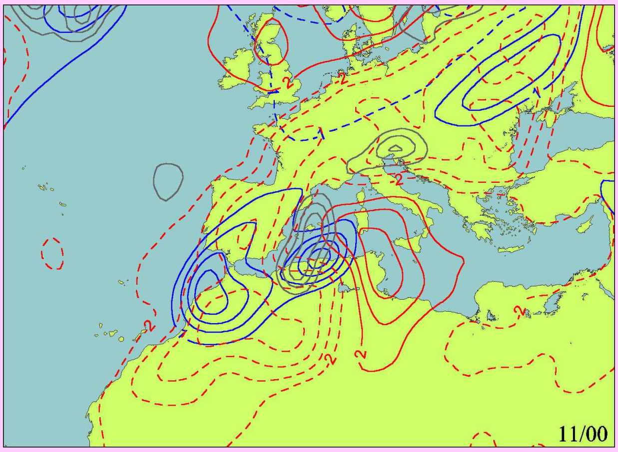

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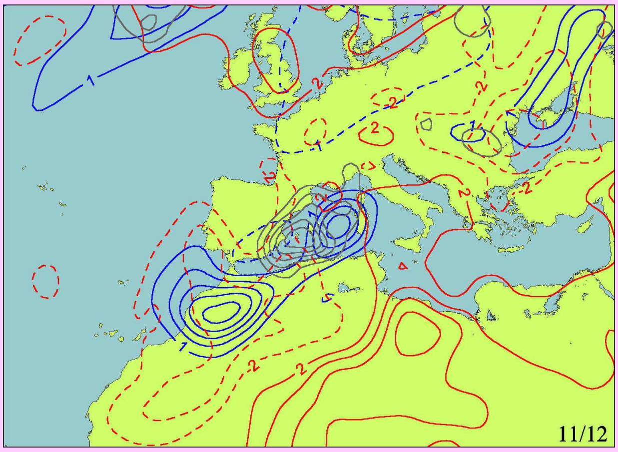
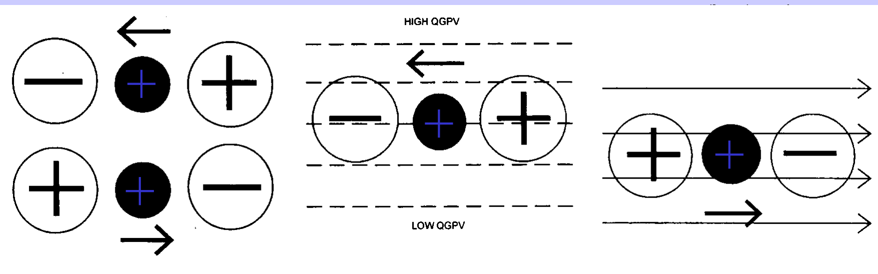
Evolution of the PV anomalies

Interactions among anomalies and mean flow



PV THINKING - Lateral Interactions

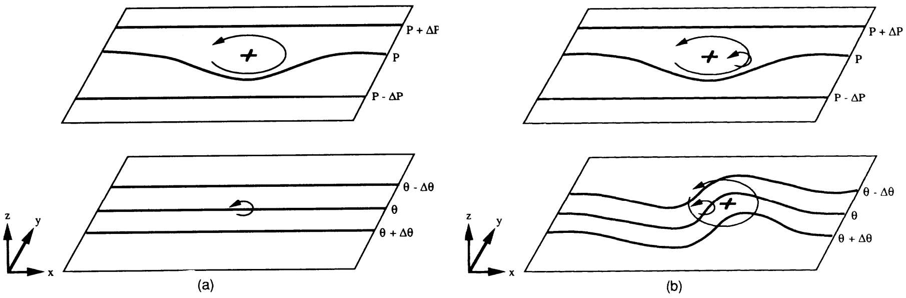


Vortex-vortex interactions

Vortex retrogression

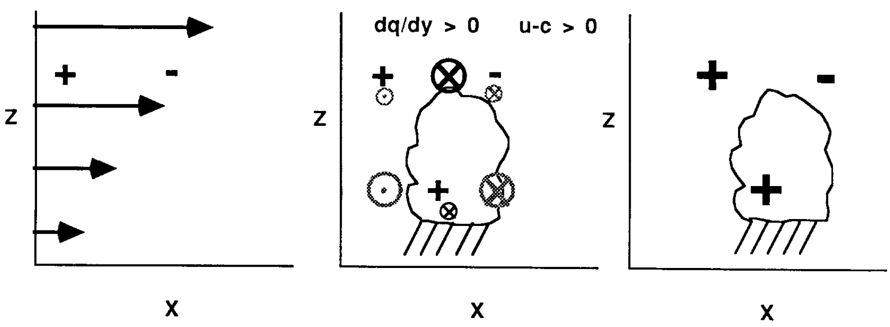
Background-flow advection of vortex

PV THINKING - Vertical Interactions

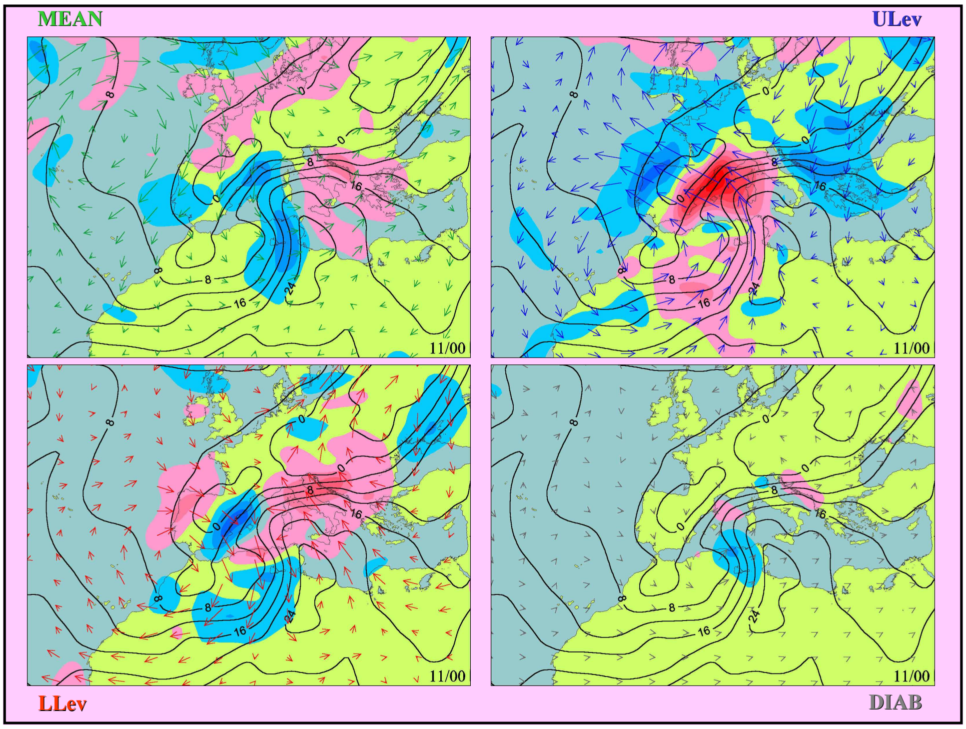


Growth of an idealized baroclinic wave-cyclone

PV THINKING - Vertical Interactions



Effects of diabatic processes (condensation)


MEAN
ULev
LLev
DIAB
11/00
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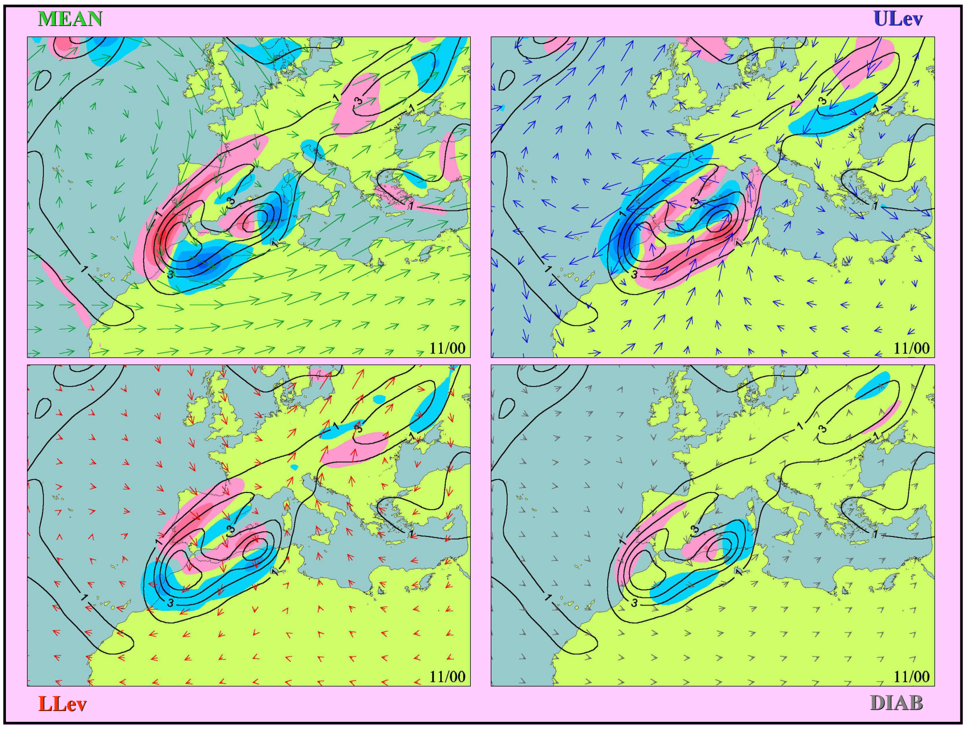
MEAN
ULev
LLev
DIAB
11/00
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PV-BASED PROGNOSTIC SYSTEM
(Davis and Emanuel; *MWR* 1991)

0) A balanced flow has been first found using the PV inversion technique: $\boldsymbol{q} \longrightarrow (\boldsymbol{\phi}, \boldsymbol{\psi})$

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

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

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

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

(1) and (2) $\longrightarrow (\boldsymbol{\phi}^t, \boldsymbol{\psi}^t)$

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

$$q^t = -m(\boldsymbol{V}_\psi + \boldsymbol{V}_\chi) \cdot \boldsymbol{\nabla} q - \omega^* \frac{\partial q}{\partial \pi} + \frac{m}{\rho} \boldsymbol{\eta} \cdot \boldsymbol{\nabla} LH \longrightarrow \boldsymbol{q}^t$$

Horizontal wind: $\boldsymbol{V}_\psi = m\boldsymbol{k} \times \boldsymbol{\nabla} \psi$, $\boldsymbol{V}_\chi = m \boldsymbol{\nabla} \chi$

Vertical velocity: $\omega^* = \frac{d\pi}{dt} = \frac{\kappa\pi}{p} \omega$

PV-BASED PROGNOSTIC SYSTEM

4) Omega equation:

$$f\eta \frac{\partial}{\partial \pi} \left[\pi^{1-1/\kappa} \frac{\partial}{\partial \pi} (\pi^{1/\kappa - 1} \omega^*) \right] + m^2 \nabla^2 \left(\frac{\partial^2 \phi}{\partial \pi^2} \omega^* \right) - m^2 f \frac{\partial}{\partial \pi} \left(\frac{\partial \omega^*}{\partial x} \frac{\partial \psi}{\partial x \partial \pi} + \frac{\partial \omega^*}{\partial y} \frac{\partial \psi}{\partial y \partial \pi} \right) + \left(f \frac{\partial \eta}{\partial \pi} \frac{1/\kappa - 1}{\pi} - f \frac{\partial^2 \eta}{\partial \pi^2} \right) \omega^* = m^3 \nabla^2 [(\boldsymbol{V}_\psi + \boldsymbol{V}_\chi) \cdot \boldsymbol{\nabla} \theta] + mf \frac{\partial}{\partial \pi} [(\boldsymbol{V}_\psi + \boldsymbol{V}_\chi) \cdot \boldsymbol{\nabla} \eta] - m^2 \boldsymbol{\nabla} f \cdot \boldsymbol{\nabla} \left(\frac{\partial \psi^t}{\partial \pi} \right) - 2m^4 \frac{\partial}{\partial \pi} \left[\frac{\partial^2 \psi^t}{\partial x^2} \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial x^2} \frac{\partial^2 \psi^t}{\partial y^2} - 2 \frac{\partial^2 \psi}{\partial x \partial y} \frac{\partial^2 \psi^t}{\partial x \partial y} \right] - m^2 \nabla^2 LH$$

$\longrightarrow \boldsymbol{\omega}^*$

5) Continuity equation:

$$m^2 \nabla^2 \chi + \pi^{1-1/\kappa} \frac{\partial}{\partial \pi} (\pi^{1/\kappa - 1} \omega^*) = 0 \longrightarrow \boldsymbol{\chi}$$

$$\theta^t = -m(\boldsymbol{V}_\psi + \boldsymbol{V}_\chi) \cdot \boldsymbol{\nabla} \theta - \omega^* \frac{\partial \theta}{\partial \pi} + LH$$

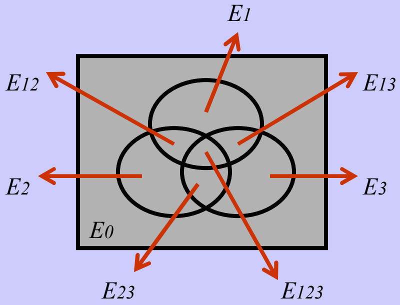
Lateral B.C (Homogeneous): $\phi^t = \psi^t = q^t = \omega^* = \chi = 0$

Top-Bottom B.C (Neumann): $\partial \phi^t / \partial \pi = f \partial \psi^t / \partial \pi = -\theta^t$

$\omega_T^* = 0$ $\omega_B^* =$ Topographic

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

0: MEAN + 3 FACTORS (*1:* ULev *2:* LLev *3:* DIAB)



$E_0 = F_0$

$E_1 = F_1 - F_0$

$E_2 = F_2 - F_0$

$E_3 = F_3 - F_0$

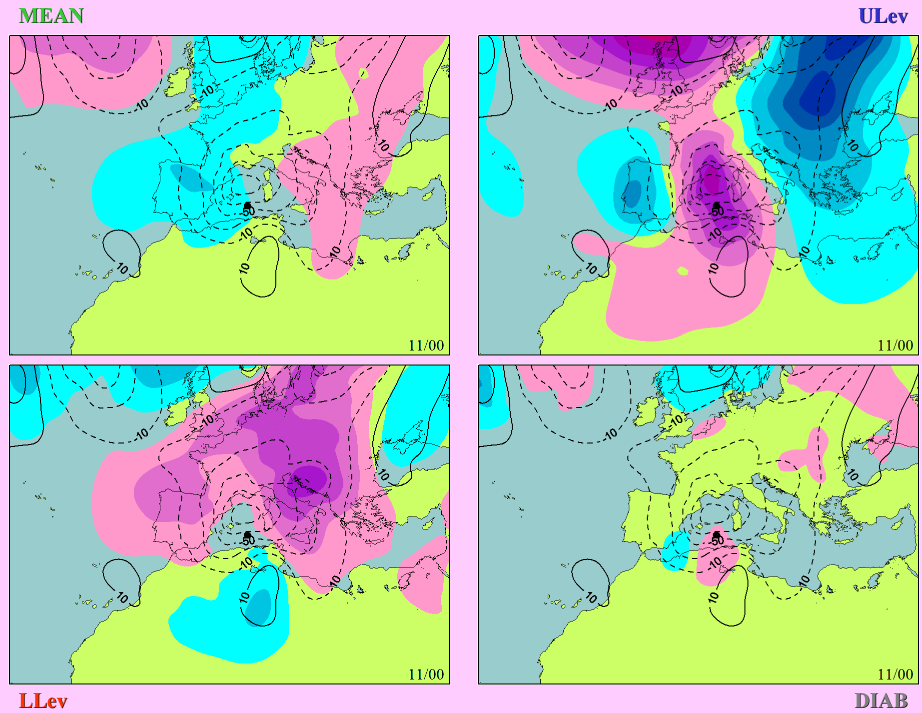
$E_{12} = F_{12} - (F_1 + F_2) + F_0$

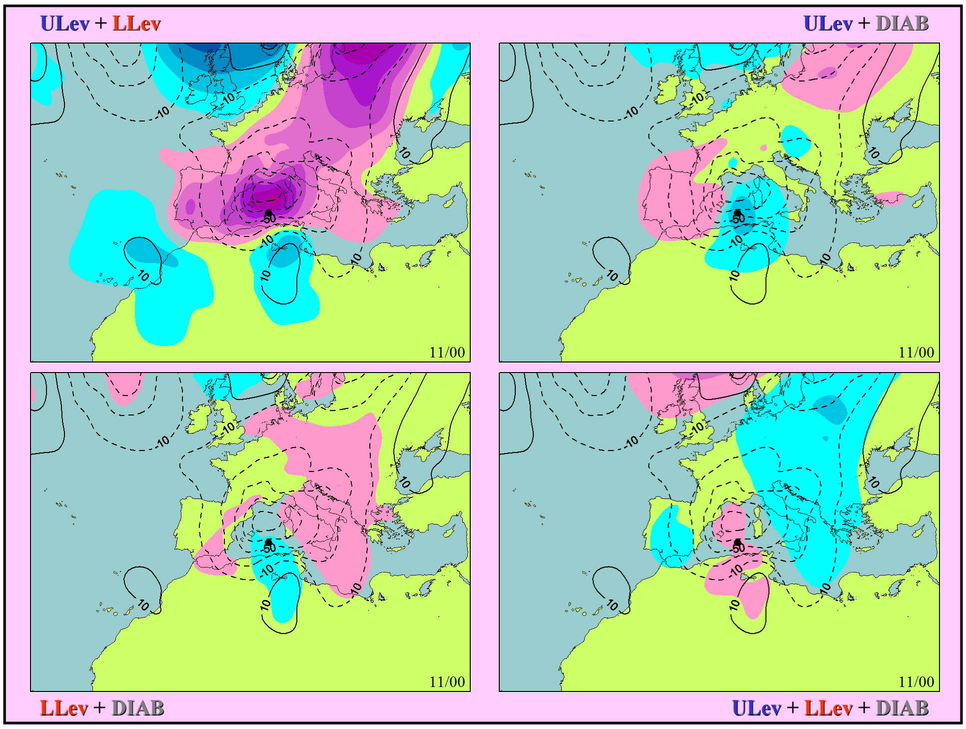
$E_{13} = F_{13} - (F_1 + F_3) + F_0$

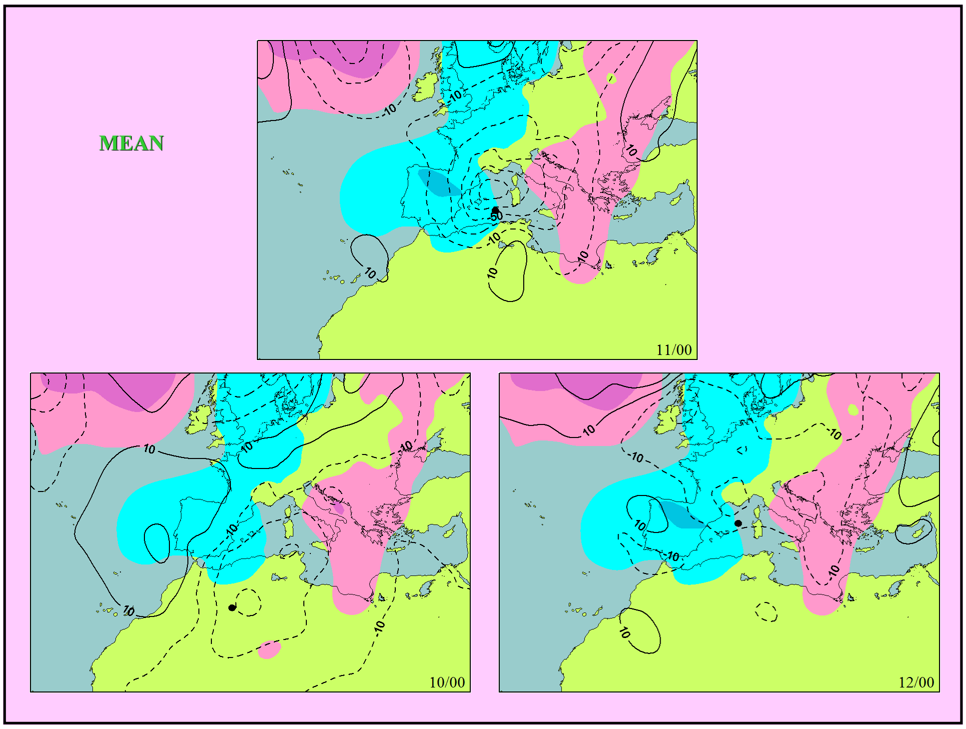
$E_{23} = F_{23} - (F_2 + F_3) + F_0$

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

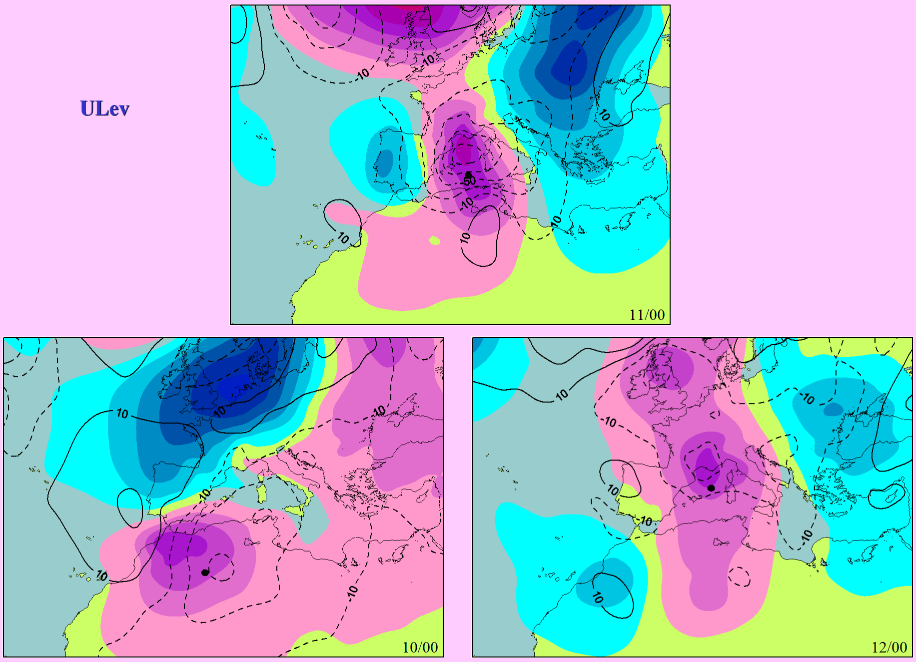
(8 flow configurations necessary)



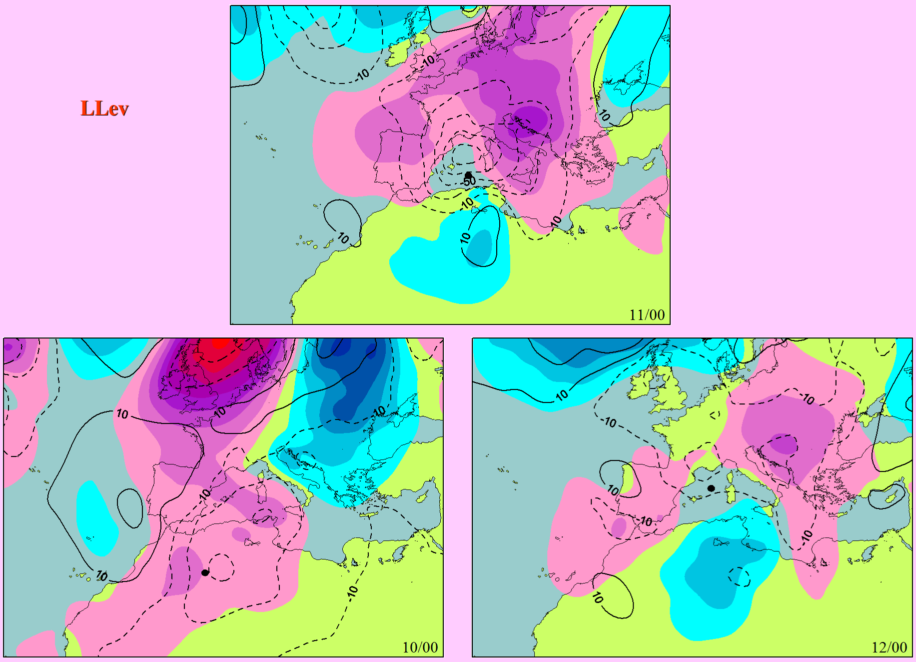

ULev + LLev
ULev + DIAB
11/00
11/00
11/00
11/00
LLev + DIAB
ULev + LLev + DIAB

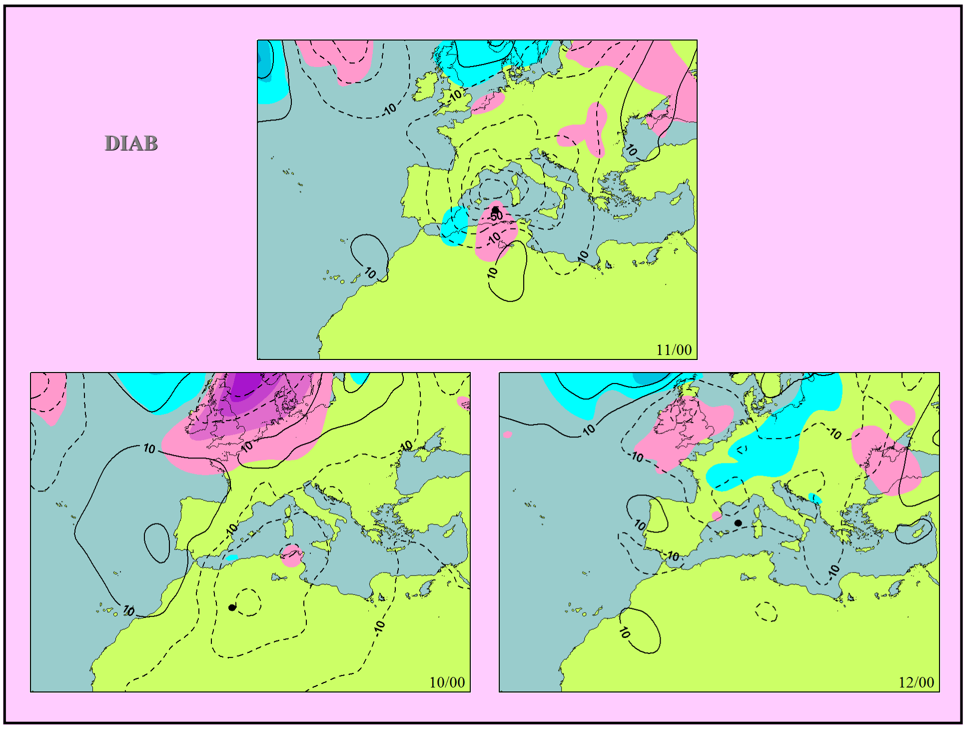

MEAN
11/00
10/00
12/00

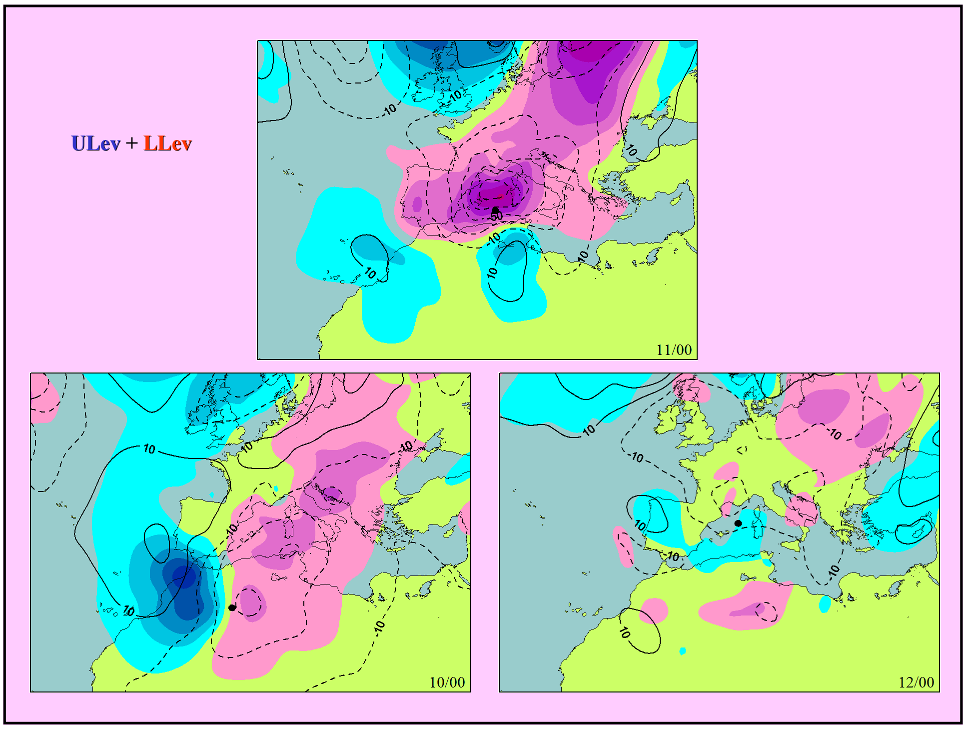
ULev

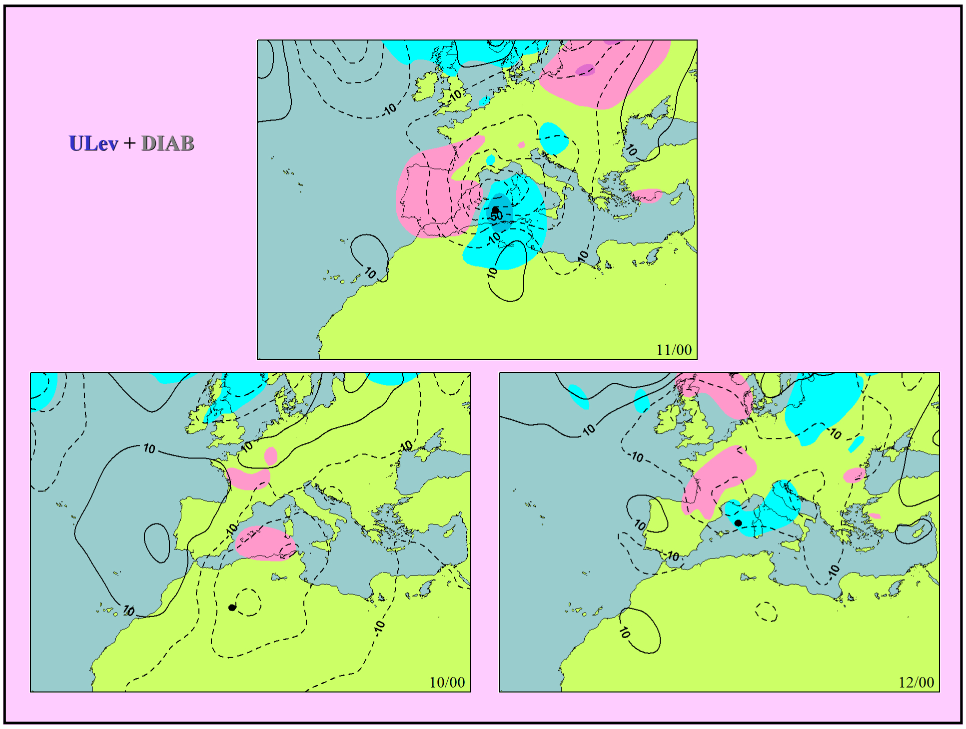


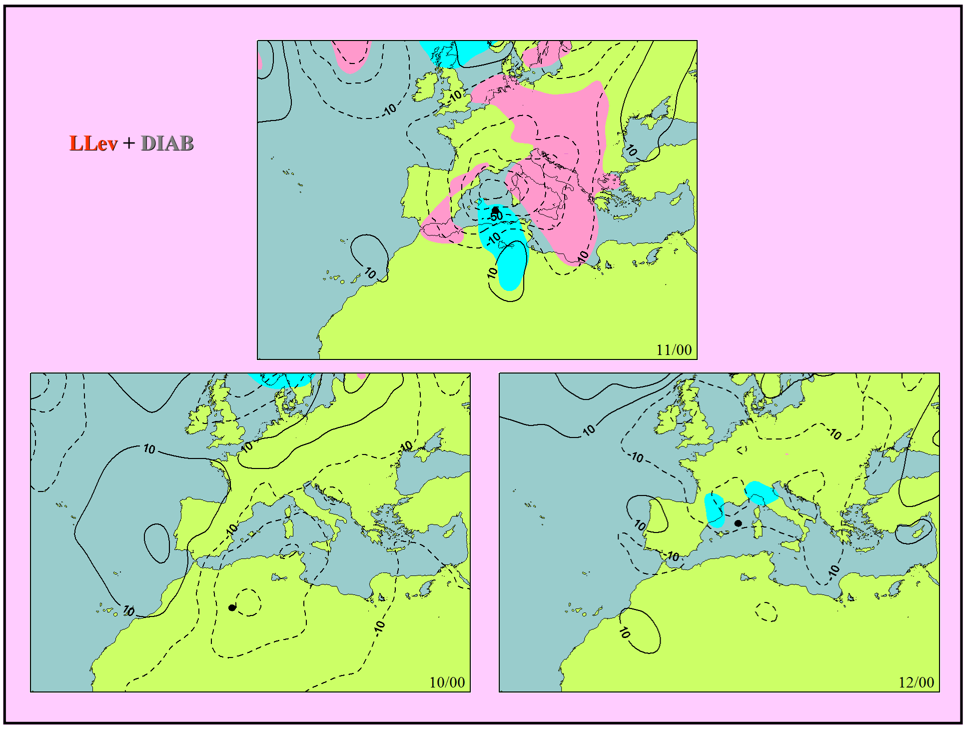
LLev

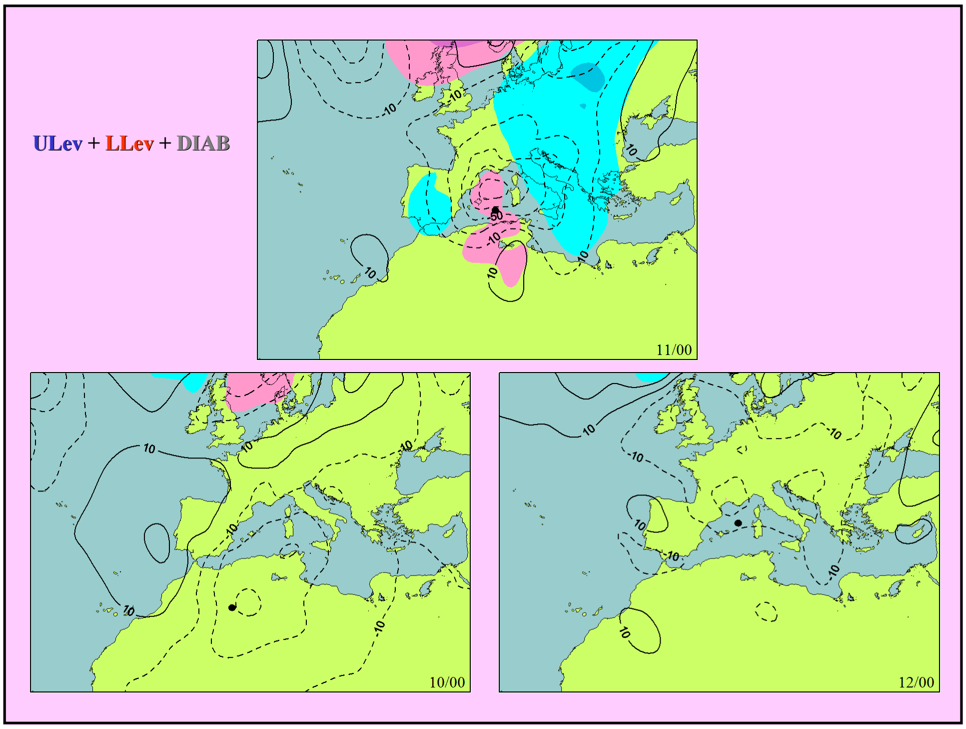


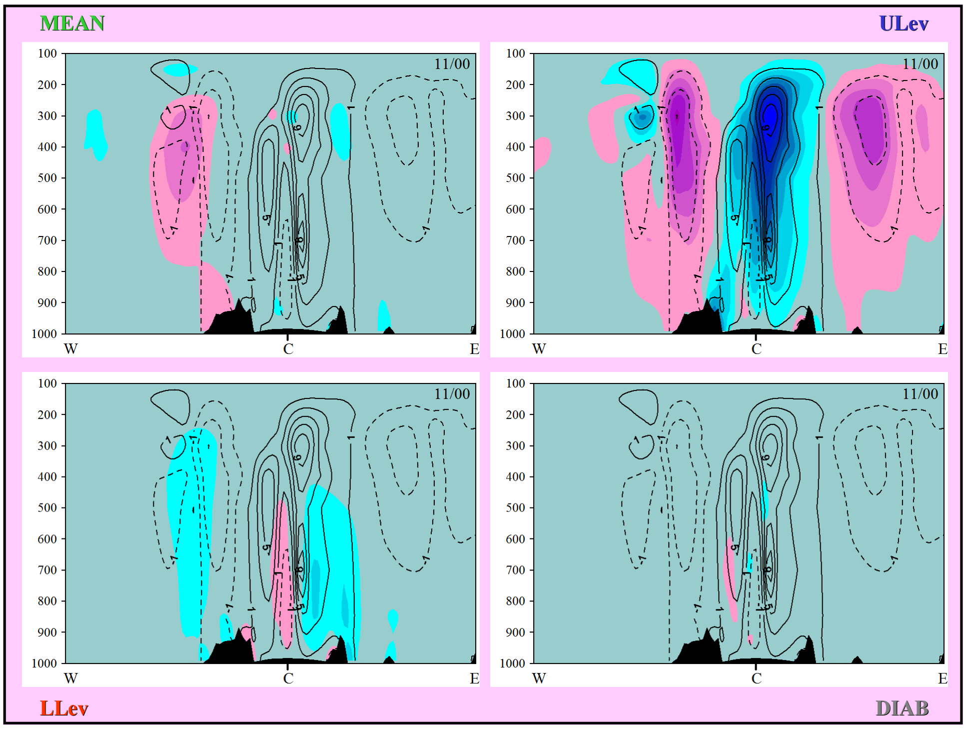

DIAB
11/00
10/00
12/00

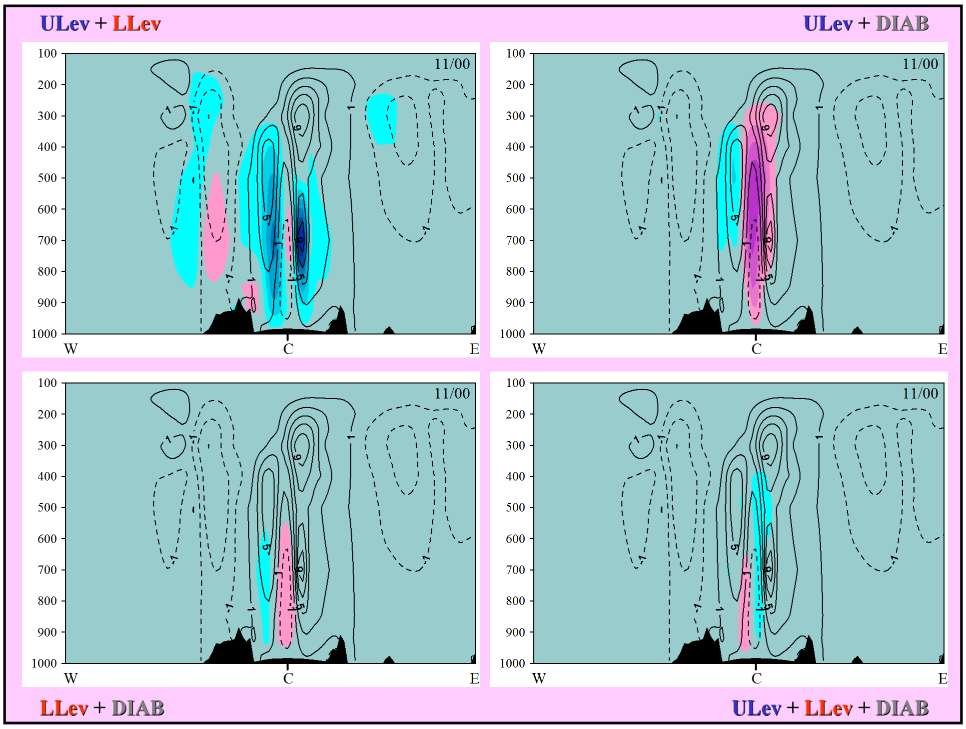

ULev + LLev
11/00
10/00
12/00


ULev + DIAB
11/00
10/00
12/00


LLev + DIAB
11/00
10/00
12/00


ULev + LLev + DIAB
11/00
10/00
12/00


MEAN
ULev
LLev
DIAB
11/00
100
200
300
400
500
600
700
800
900
1000
W
C
E



CONCLUSIONS

- **Extreme** cyclogenesis **event** in the western Mediterranean region (the worst storm affecting the Balearic Islands during the last decades)

- **Baroclinic** development + **Diabatic** contribution from condensation

- **PV-based diagnosis**:
  - Typical sequence of many extratropical cyclones: ULev → LLev → DIAB
  - Controlled by the mutual interactions among the anomalies and mean flow

- Quantification of the interactions (**PV thinking**):
  - **ULev** : Contribution during the whole life cycle of the cyclone
  - **LLev** : Contribution during the developing stage / Later NE movement
  - **ULev** + **LLev** : A leading factor, especially during the mature stage
  - **Other** : Most relevant during the mature stage, but **ULev** + **LLev** + **DIAB** during the developing stage !!!

- **Note**: Diabatic term in the equations and orography as a factor could also be considered

MOLTES GRÀCIES !!!