# Impacts and Interactions of Dry and Moist Potential-Vorticity Anomalies During the Life Cycle of an Intense Mediterranean Cyclone

5th EGS Plinius Conference on Mediterranean Storms
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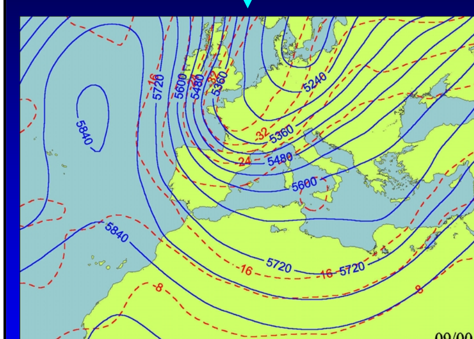
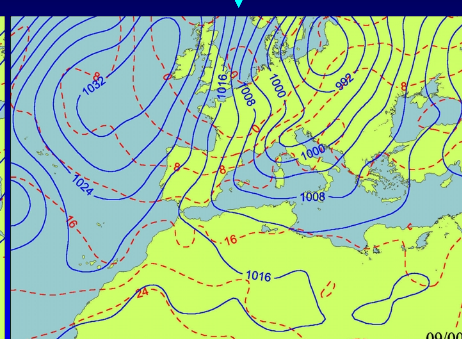
Universitat de les Illes Balears

## *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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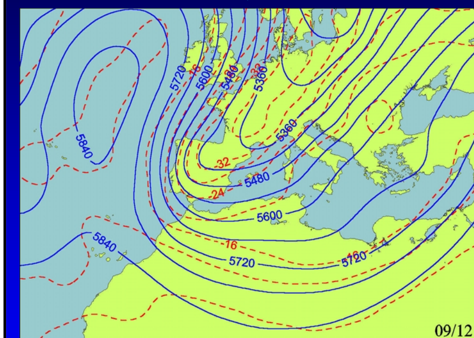


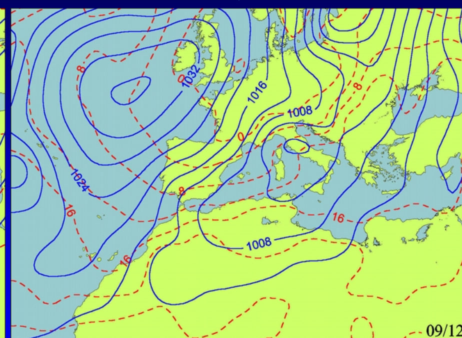


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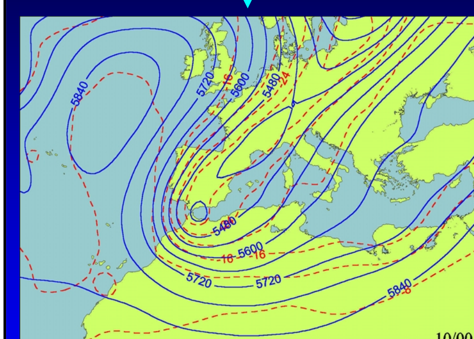


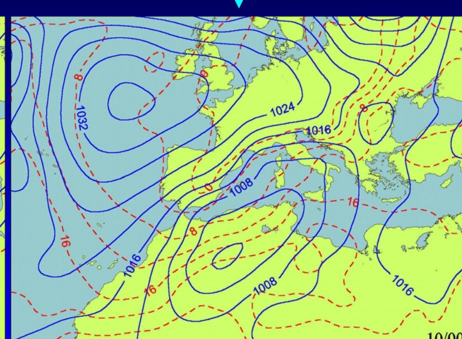


**ALGERIA**

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

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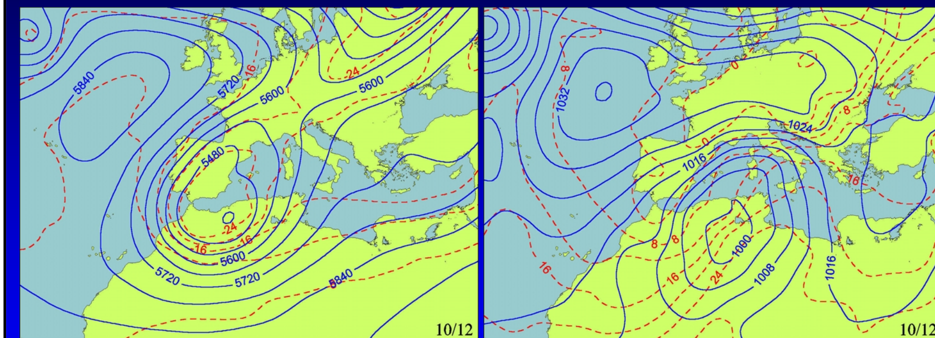



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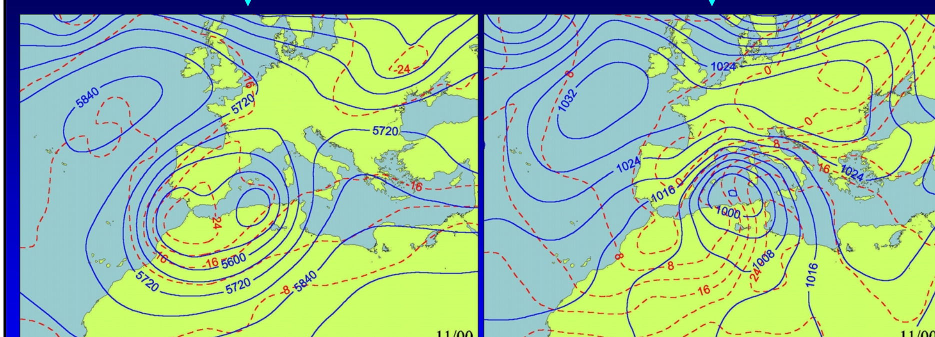


**BALEARIC ISLANDS**

- **Up to 400 mm/24 h, 150 km/h winds and 12 m sea waves**
- **4 casualties, 200000 trees uprooted, floods and severe damages on coasts**

## Some effects of the cyclone in the Balearics

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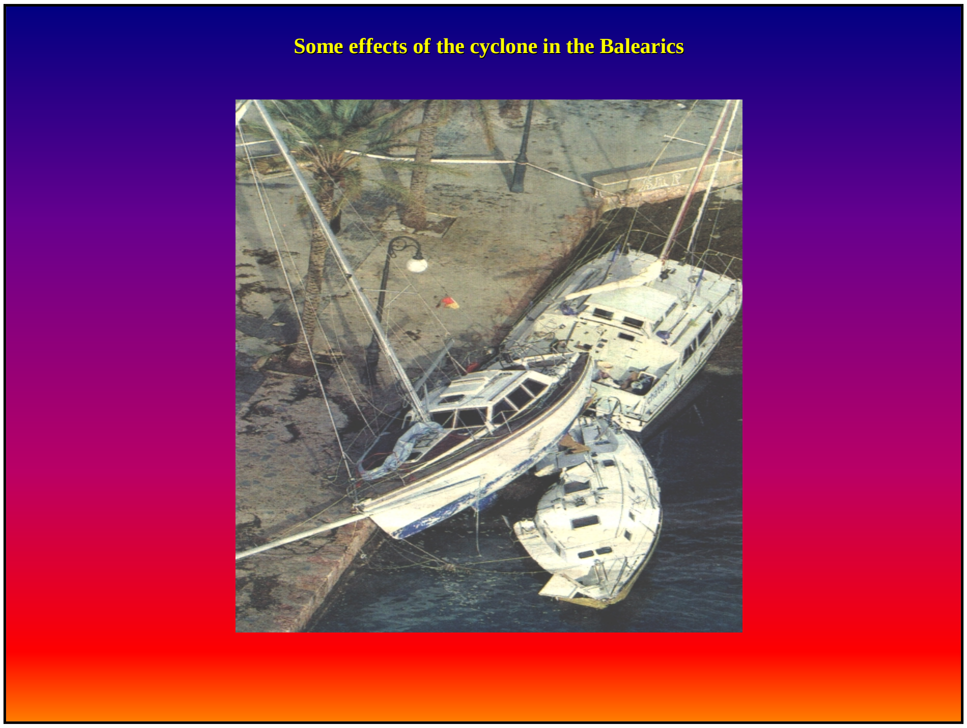
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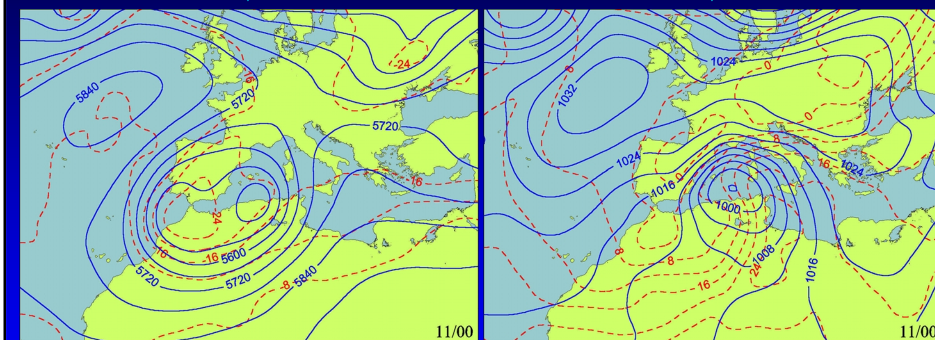


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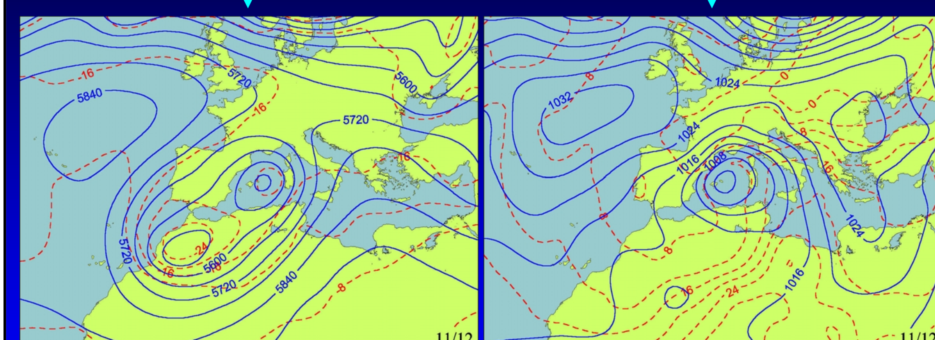

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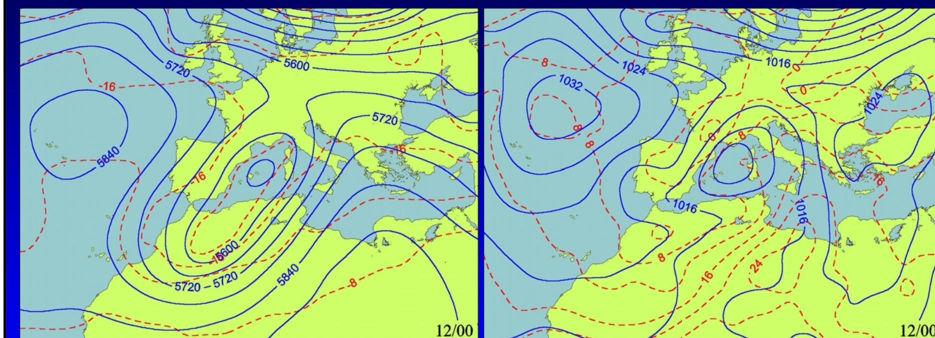


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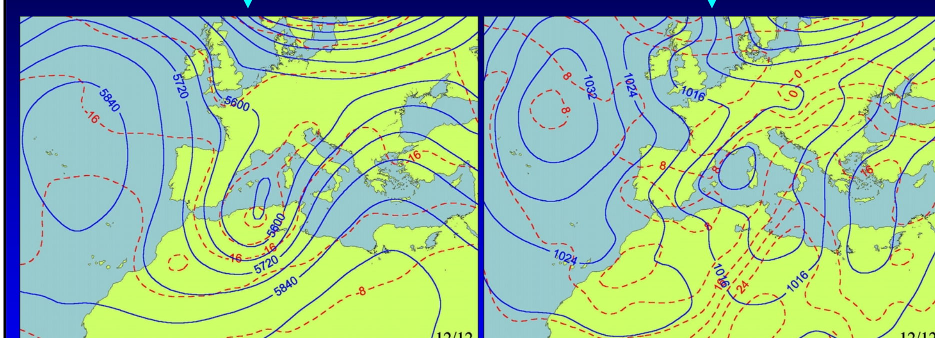



**Strong baroclinic development**

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

**Diabatic contribution ?**

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

**1) Balanced flow ($\phi$ , $\psi$) 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 $\quad$ $m$ 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 $\quad$ $g$ gravity $\quad$ $\kappa = Rd/Cp$ $\quad$ $\pi = Cp(p/po)^\kappa$

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

$\theta$ 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 ($\phi'$ , $\psi'$ , $q'$) 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 anomalies:** $q' = \sum_{n=1}^{N} q_n$

**5) Piecewise inversion: ($\phi_n$ , $\psi_n$ ) 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:

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

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

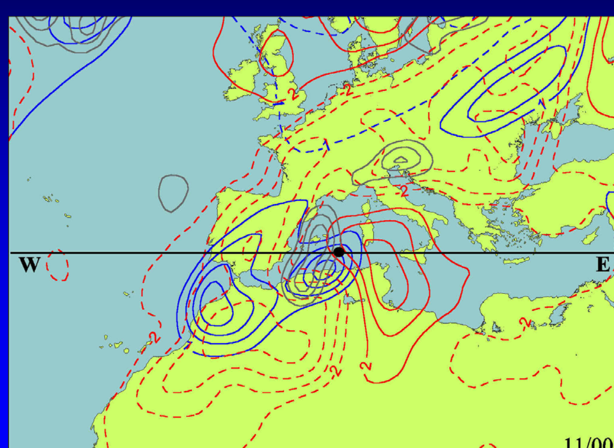
**where** $()^* = \overline{()} + \frac{1}{2}()'$

**B.C:** Lateral (Dirichlet with $\phi_n$ and $\psi_n$) / Top and bottom (Neumann with $\theta_n$)

*** In our case study:**
**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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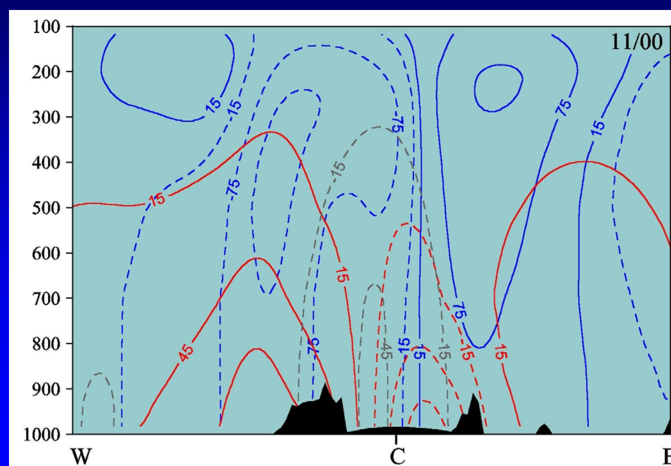
**Geopotential height perturbation**

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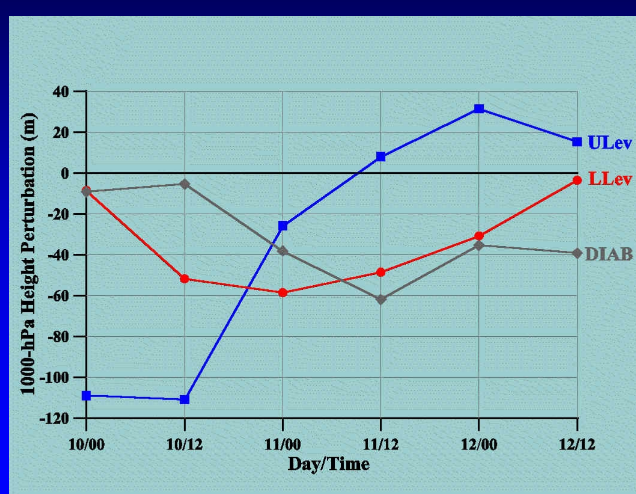
**Contribution to the surface cyclone height perturbation**



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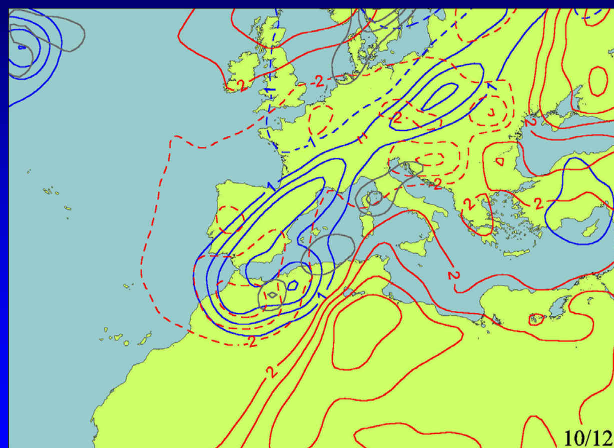
**Evolution of the PV anomalies**

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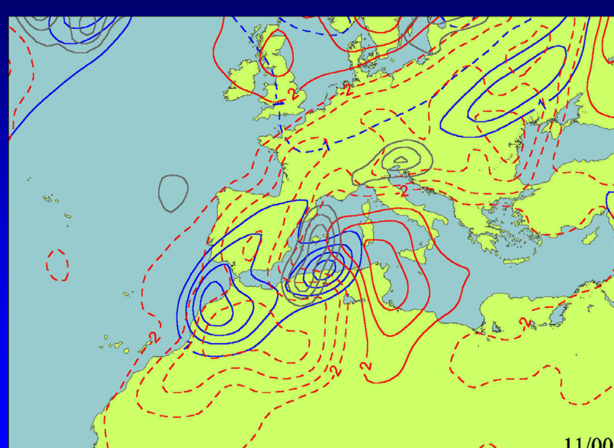

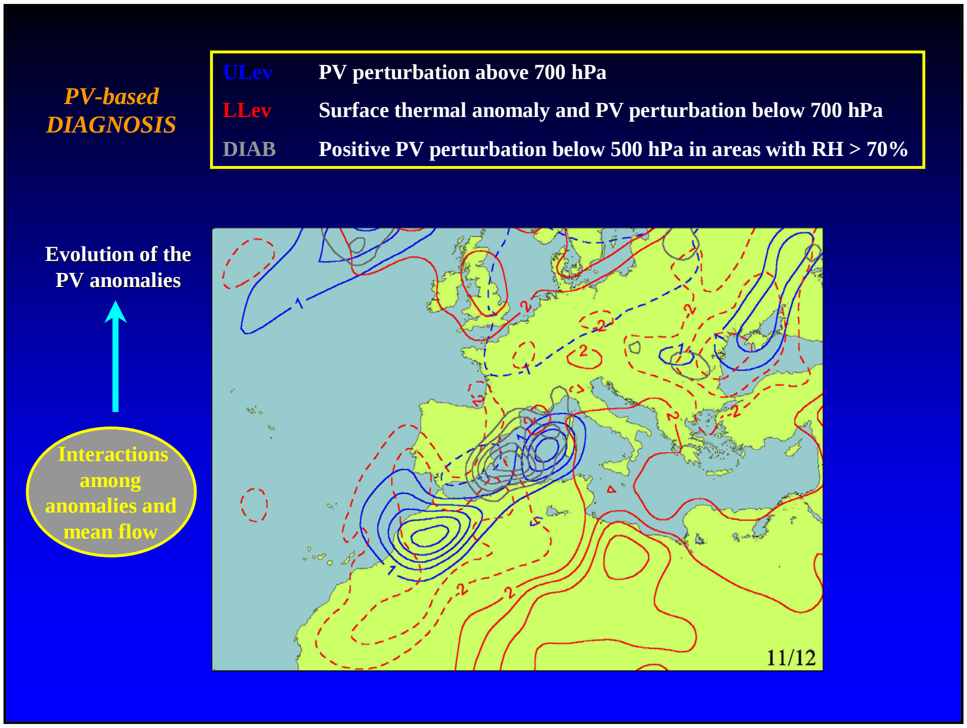
PV-based DIAGNOSIS
ULev PV perturbation above 700 hPa
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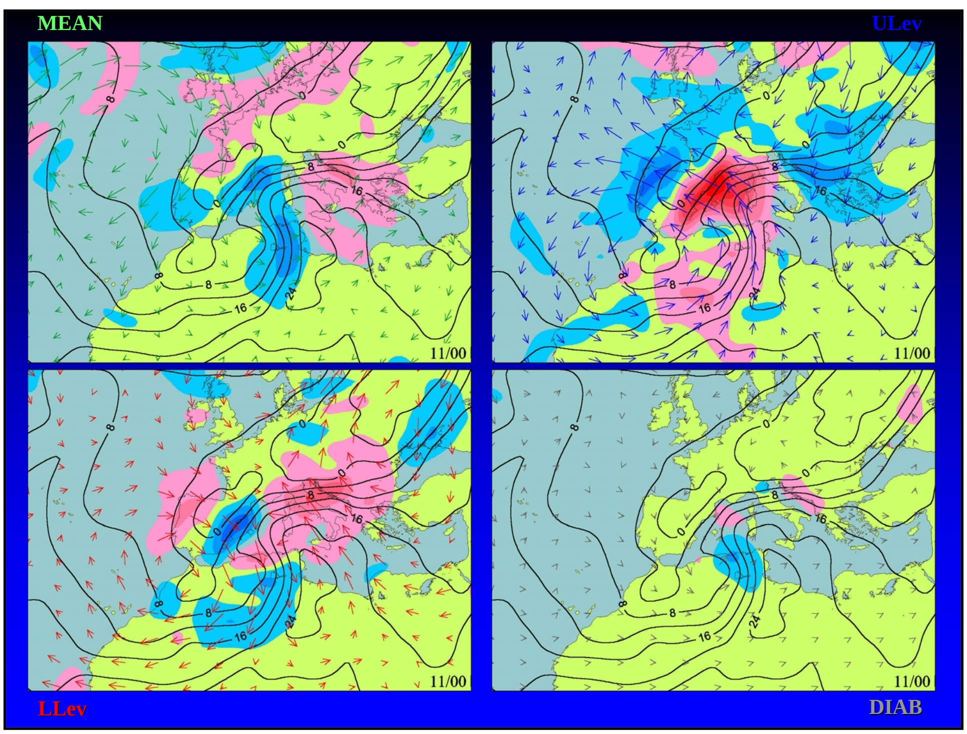
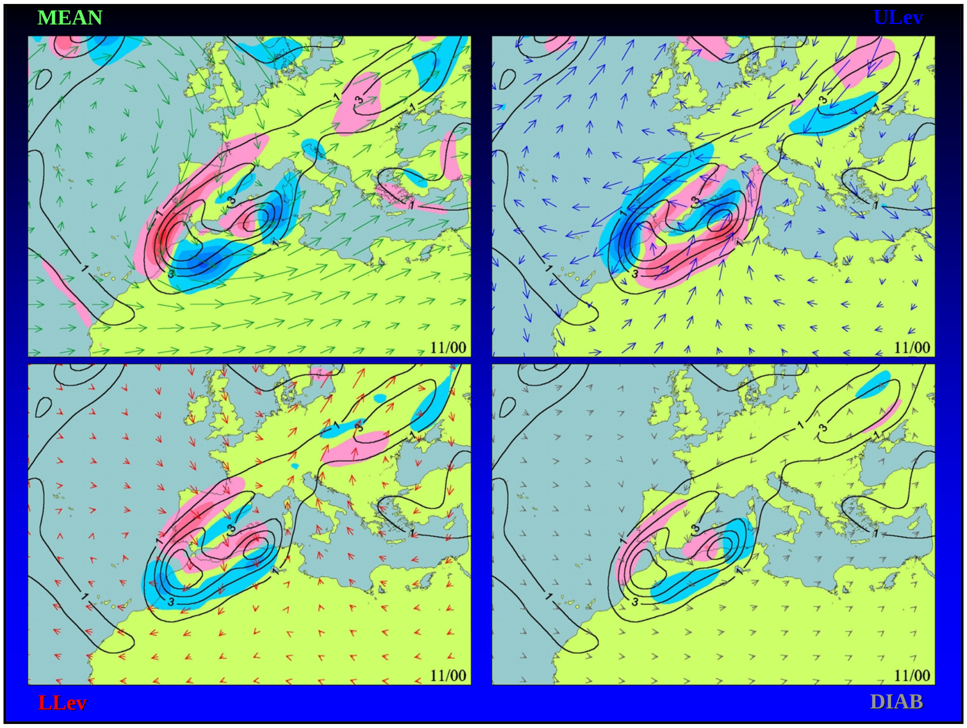
Evolution of the PV anomalies
Interactions among anomalies and mean flow
11/12


MEAN
ULev
LLev
DIAB
11/00
11/00
11/00
11/00




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

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

**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:**

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

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

**3) Ertel's PV tendency equation (frictionless and adiabatic):**

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

Horizontal wind    Vertical velocity $\longrightarrow q^t$

$$\boldsymbol{V}_\psi = m\boldsymbol{k}\times\boldsymbol{\nabla}\psi$$
$$\boldsymbol{V}_\chi = m\boldsymbol{\nabla}\chi$$

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

## PV-BASED PROGNOSTIC SYSTEM

**4) Omega equation:**

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

$\longrightarrow \omega^*$

**5) Continuity equation:**

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

$\longrightarrow \chi$

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

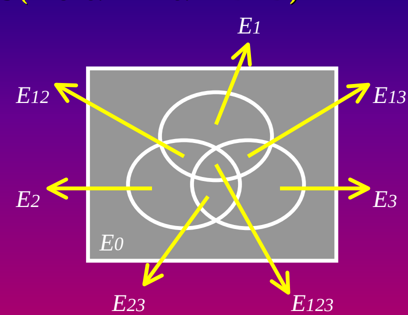
**Top-Bottom** B.C (Neumann) $\partial\phi^t/\partial\pi = f\partial\psi^t/\partial\pi = -\theta^t$

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

$\omega^*_T = 0$ $\qquad$ $\omega^*_B =$ Topographic

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

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




$E_0 = F_0$

$E_1 = F_1 - F_0$

$E_2 = F_2 - F_0$

$E_3 = F_3 - F_0$

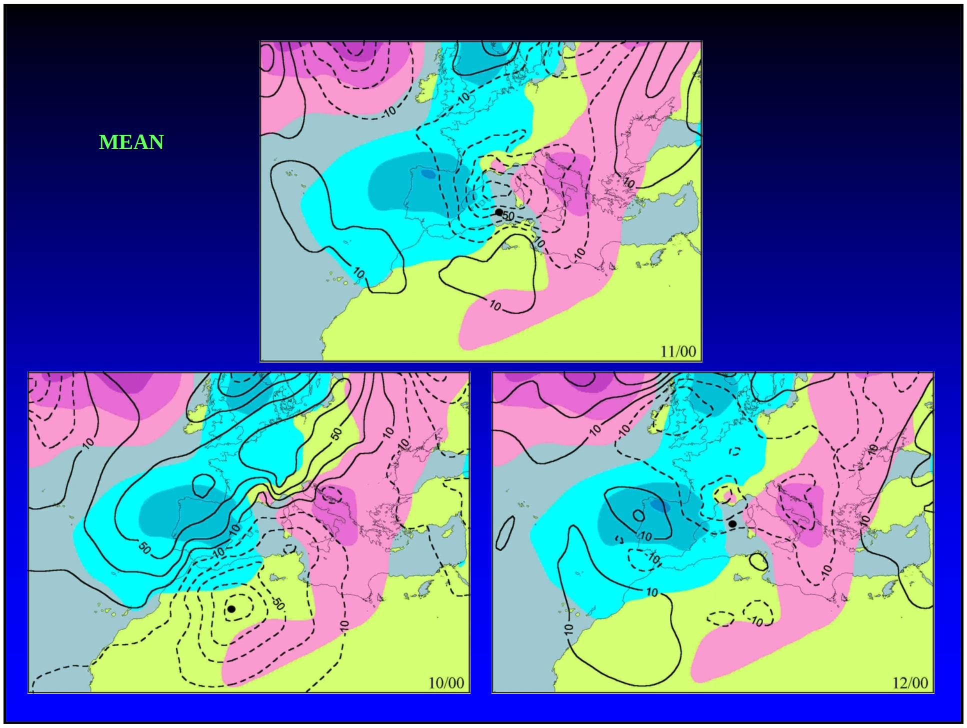
$E_{12} = F_{12} - (F_1 + F_2) + F_0$

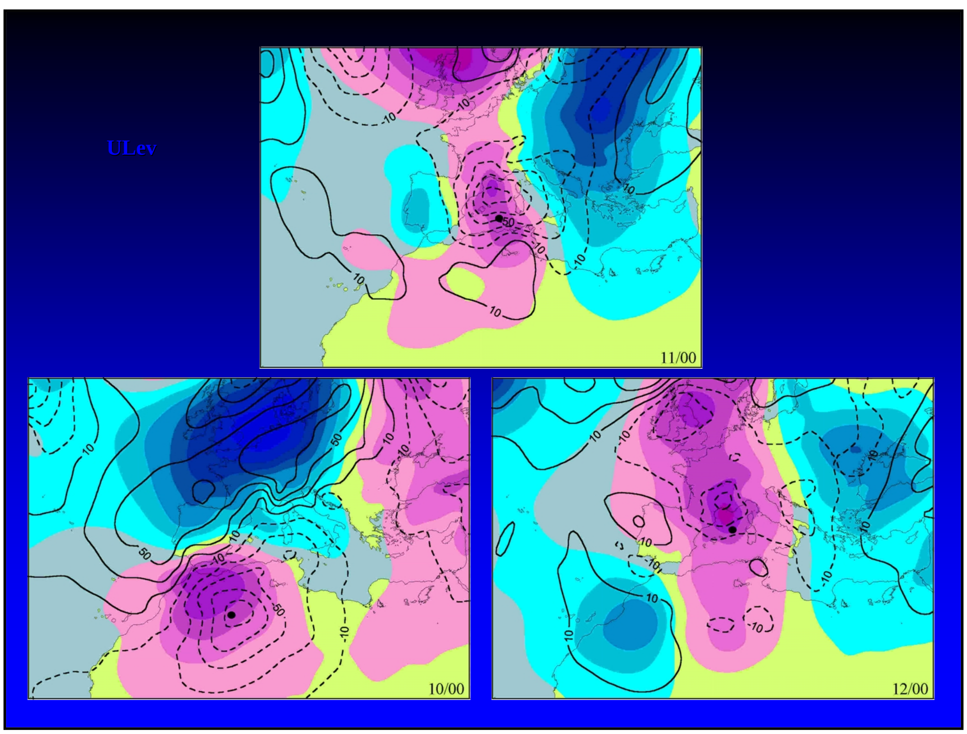
$E_{13} = F_{13} - (F_1 + F_3) + F_0$

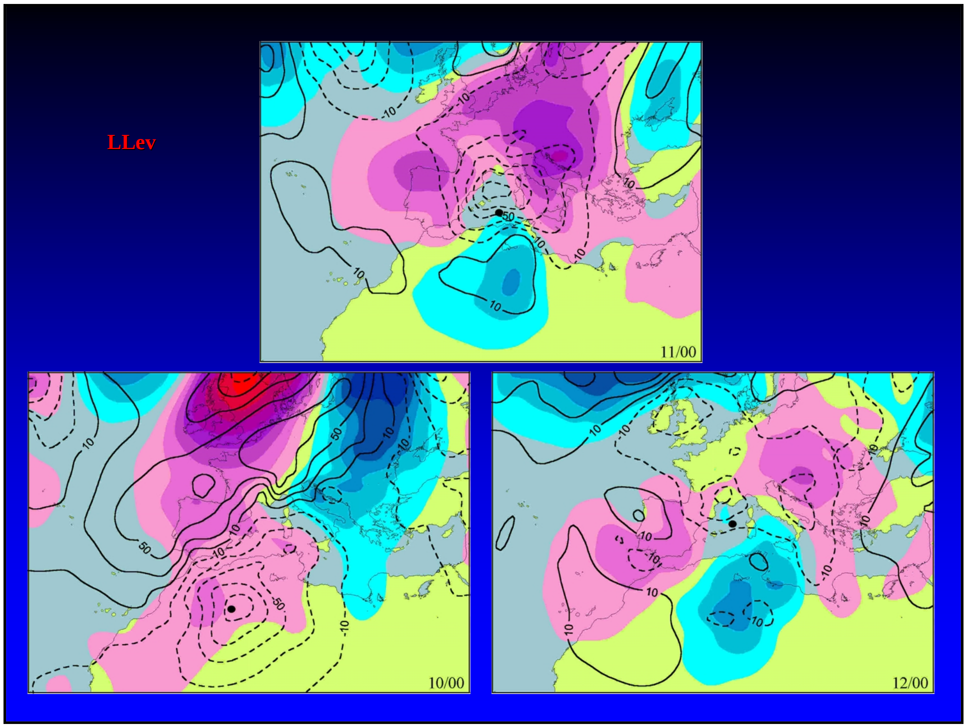
$E_{23} = F_{23} - (F_2 + F_3) + F_0$

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

( 8 flow configurations necessary )


MEAN
11/00
10/00
12/00


ULev
11/00
10/00
12/00


LLev
11/00
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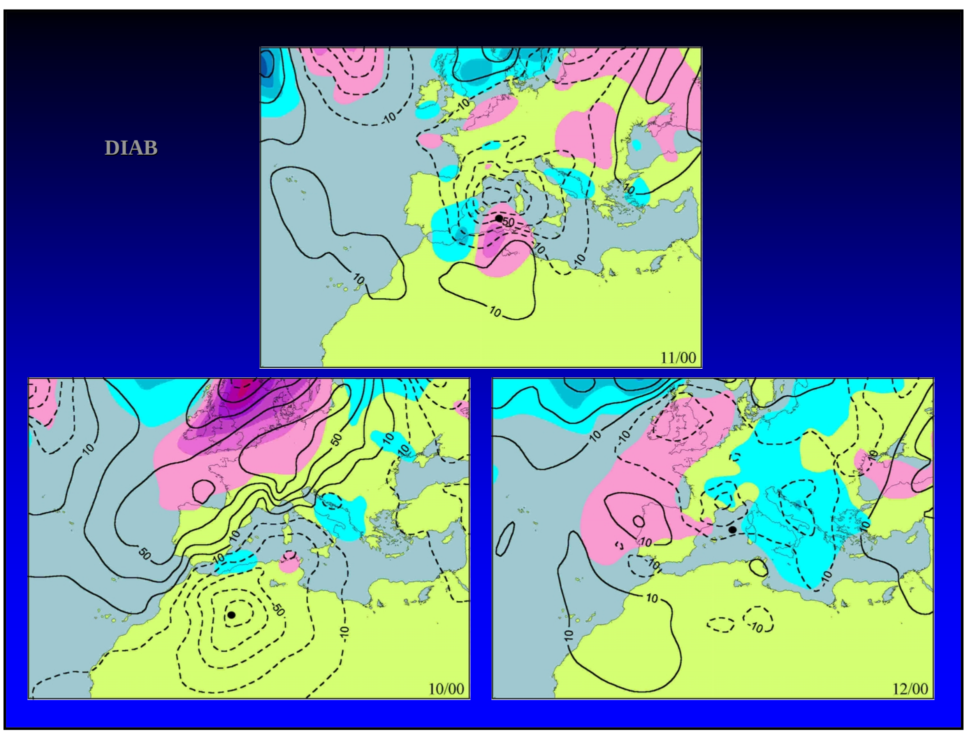
12/00


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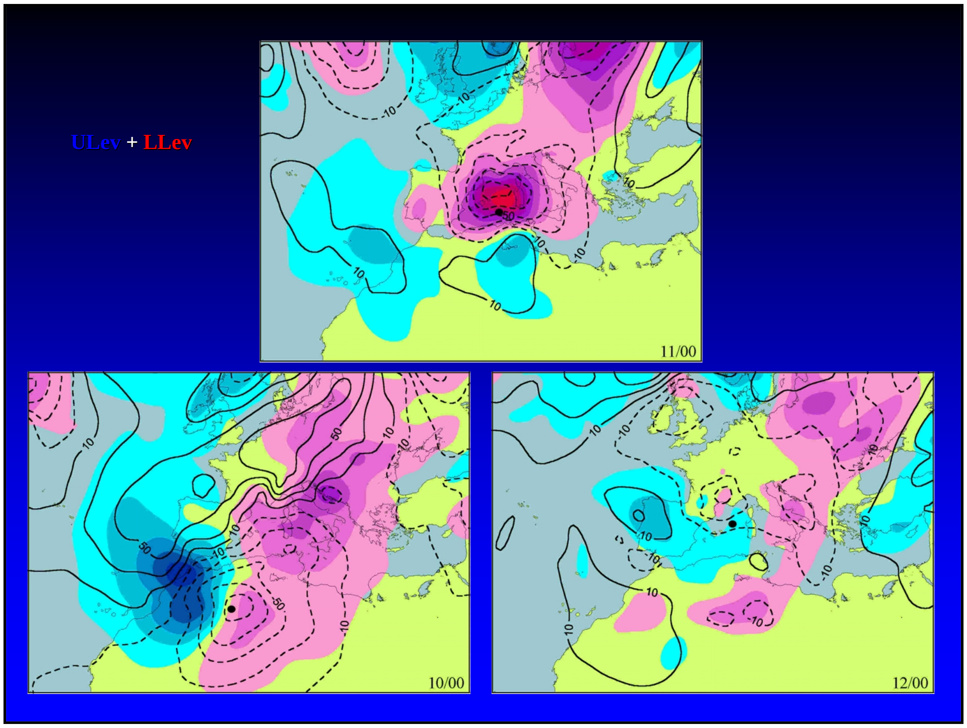
ULev + LLev
11/00
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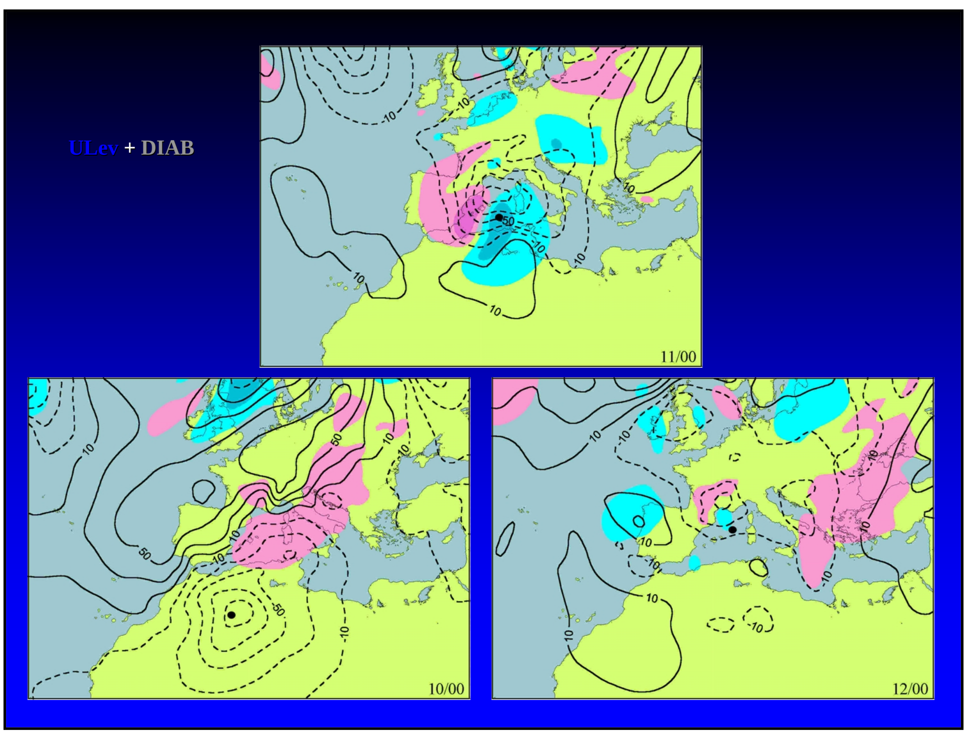
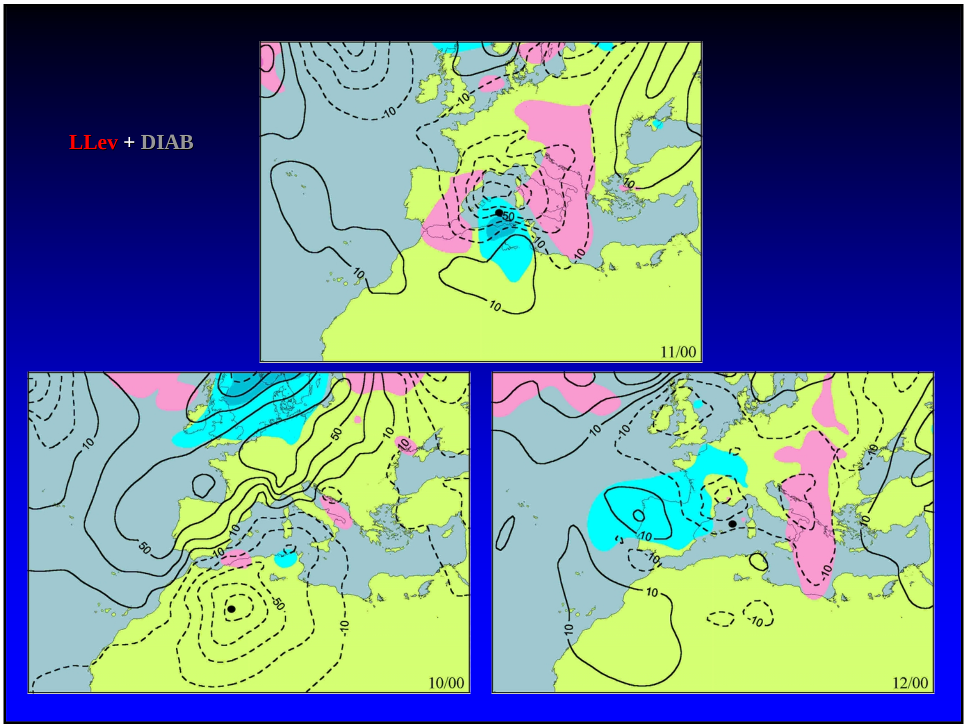

ULev + DIAB
11/00
10/00
12/00


LLev + DIAB
11/00
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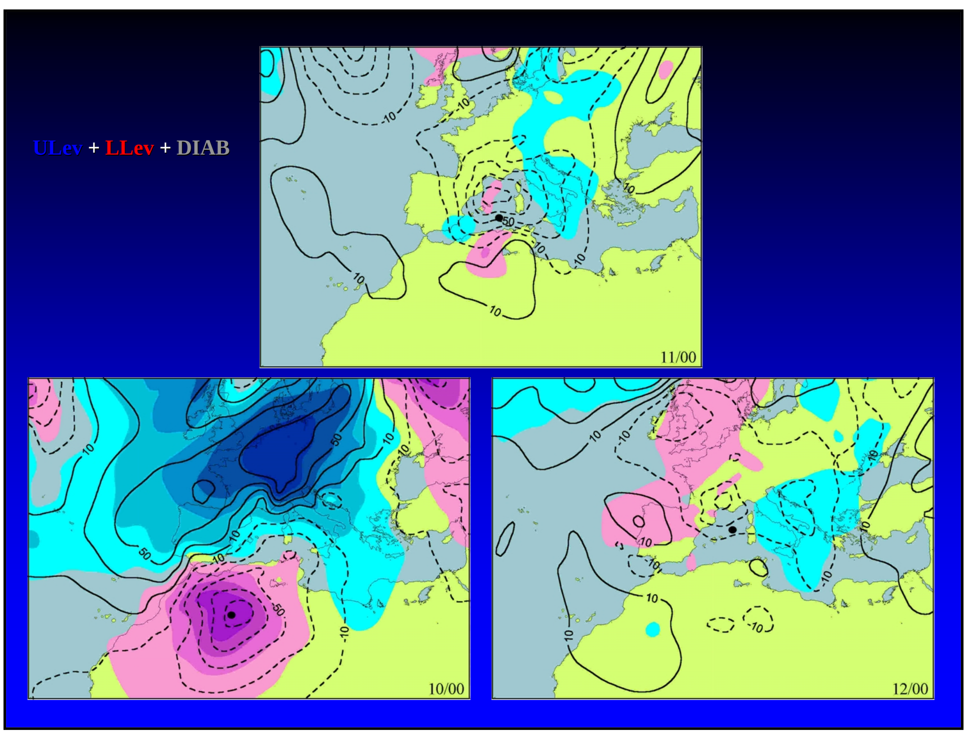
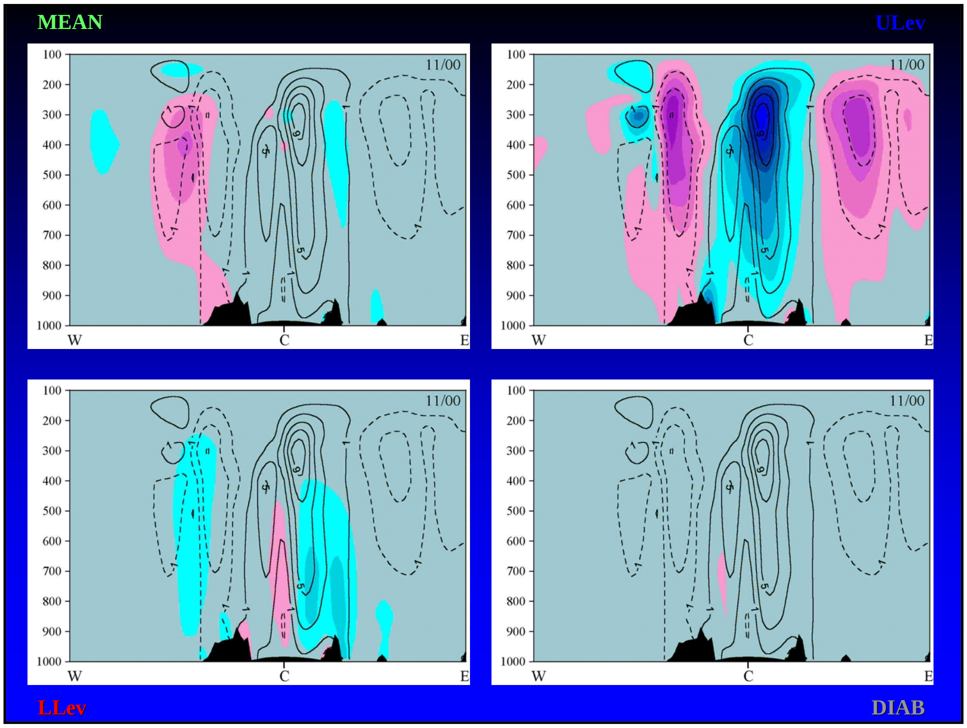

ULev + LLev + DIAB
11/00
10/00
12/00


MEAN
ULev
LLev
DIAB
11/00
100
200
300
400
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900
1000
W
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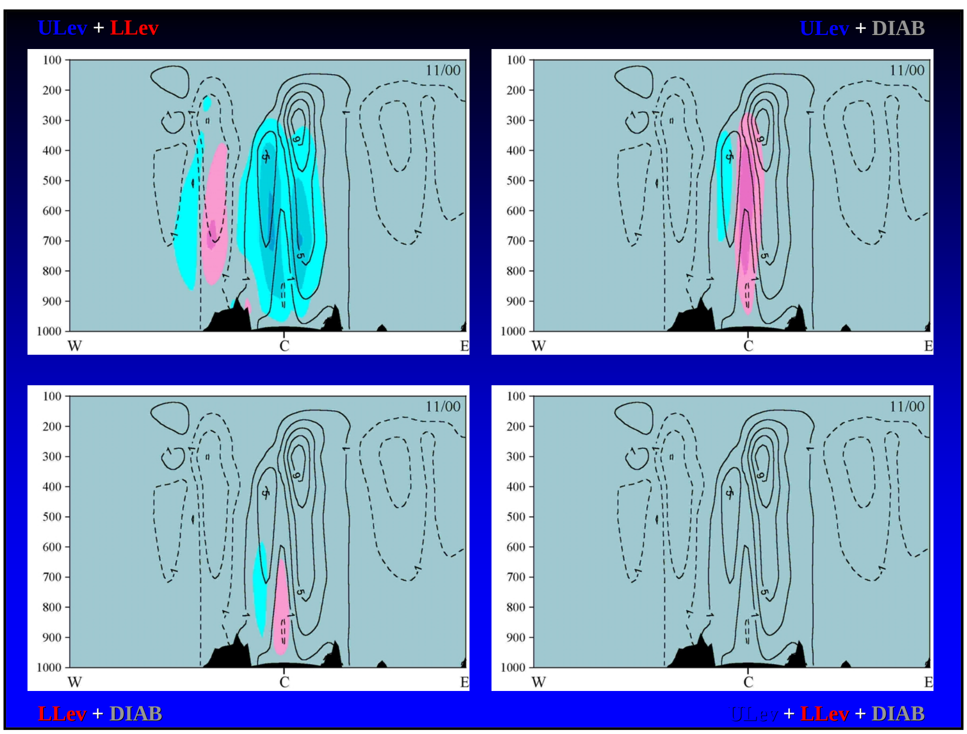
E


ULev + LLev
ULev + DIAB
LLev + DIAB
ULev + LLev + DIAB
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1000
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C
E

## SOME 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 !!!

- Future: Diabatic term will be included in the PV-based prognostic system