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

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STRUCTURE

- **Introduction:** The ***Factor Separation*** technique
- **Part 1:** ***Boundary*** factors and ***Model Physics*** factors

  Romero, R., Doswell, C. A. III and Ramis, C., 2000: Mesoscale numerical study of two cases of long-lived quasistationary convective systems over eastern Spain. *Mon. Wea. Rev.,* 128, 3731-3751.

- **Part 2:** ***Dynamical*** factors - Piecewise ***PV inversion***

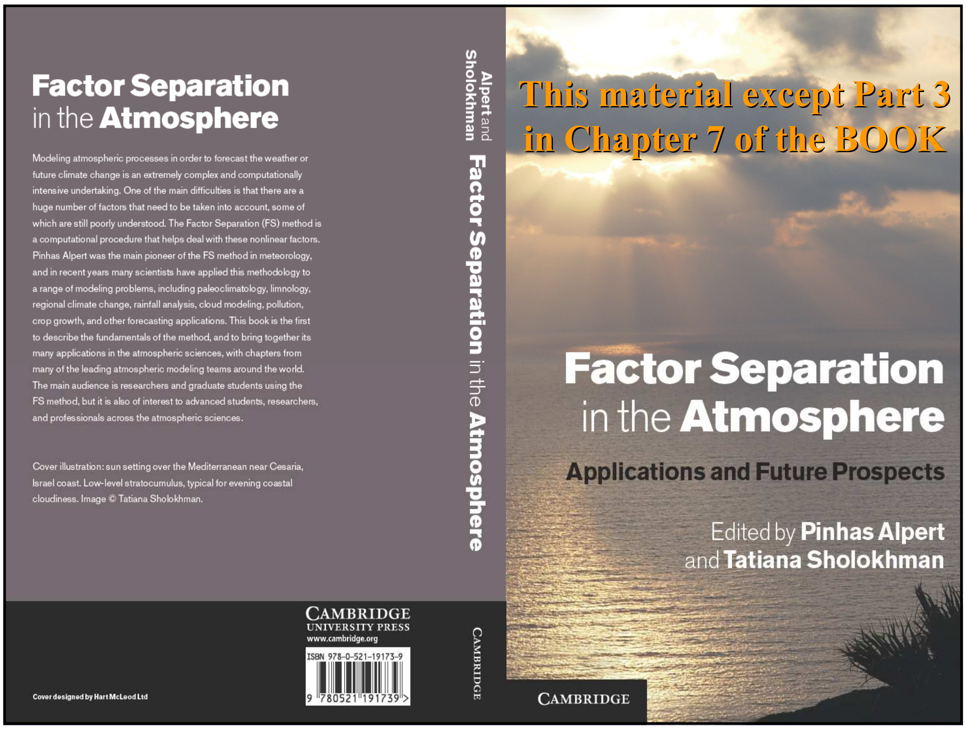
  Romero, R., 2001: Sensitivity of a heavy rain producing Western Mediterranean cyclone to embedded potential vorticity anomalies. *Quart. J. R. Meteorol. Soc.,* 127, 2559-2597.

- **Part 3:** ***Ensemble*** Prediction - ***PV-error*** climatology

  Vich, M., R. Romero, and H. E. Brooks/V. Homar, 2011: Ensemble prediction of Mediterranean high-impact events using potential vorticity perturbations. *Atmos. Res.*, 102, 224-241 (Part I) and 311-319 (Part II).

- **Part 4:** Quantitative implementation of ***PV-thinking***

  Romero, R., 2008: A method for quantifying the impacts and interactions of potential-vorticity anomalies in extratropical cyclones. Quart. J. R. Meteorol. Soc., 134, 385-402.



This material except Part 3 in Chapter 7 of the BOOK

Factor Separation
in the **Atmosphere**

Modeling atmospheric processes in order to forecast the weather or future climate change is an extremely complex and computationally intensive undertaking. One of the main difficulties is that there are a huge number of factors that need to be taken into account, some of which are still poorly understood. The Factor Separation (FS) method is a computational procedure that helps deal with these nonlinear factors. Pinhas Alpert was the main pioneer of the FS method in meteorology, and in recent years many scientists have applied this methodology to a range of modeling problems, including paleoclimatology, limnology, regional climate change, rainfall analysis, cloud modeling, pollution, crop growth, and other forecasting applications. This book is the first to describe the fundamentals of the method, and to bring together its many applications in the atmospheric sciences, with chapters from many of the leading atmospheric modeling teams around the world. The main audience is researchers and graduate students using the FS method, but it is also of interest to advanced students, researchers, and professionals across the atmospheric sciences.

Cover illustration: sun setting over the Mediterranean near Cesaria, Israel coast. Low-level stratocumulus, typical for evening coastal cloudiness. Image © Tatiana Sholokhman.

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Alpert and Sholokhman **Factor Separation** in the **Atmosphere** CAMBRIDGE

Factor Separation
in the **Atmosphere**

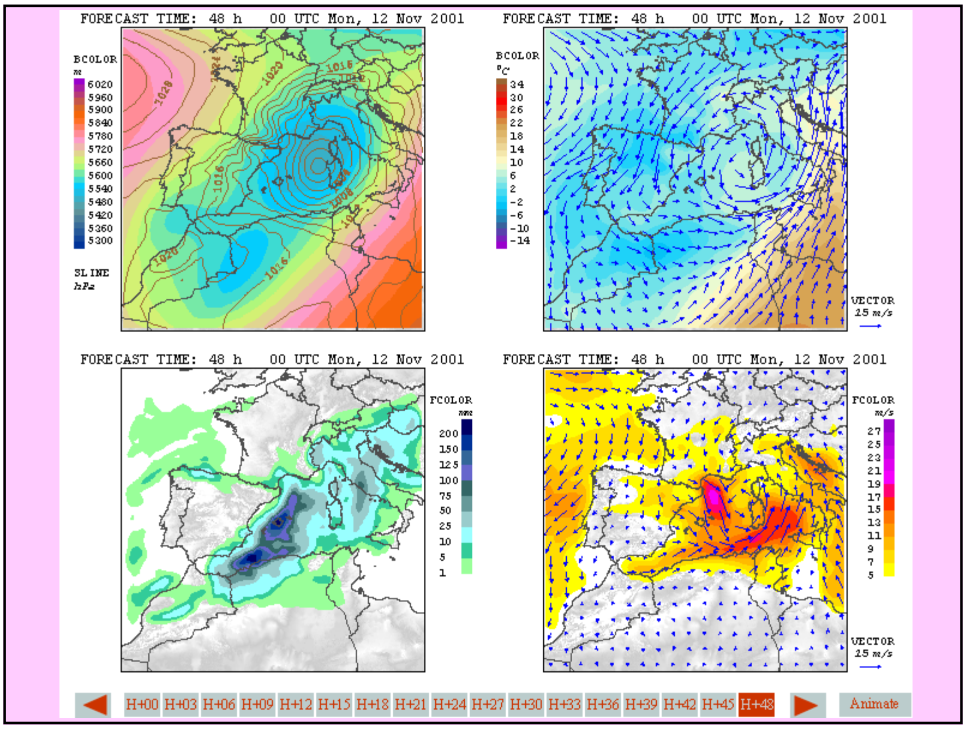
Applications and Future Prospects

Edited by **Pinhas Alpert**
and **Tatiana Sholokhman**

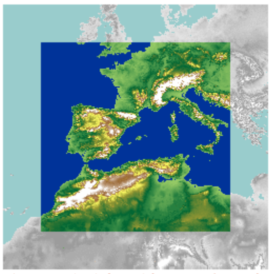
CAMBRIDGE

THE STUDY OF ATMOSPHERIC PHENOMENA

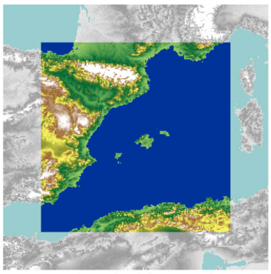
- Observations (limited in number, space and time)
- Theory (requires simplifications)
- Experimentation (*Numerical Modeling*)



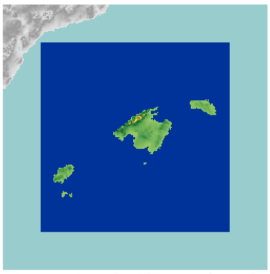
- ***Multiscale*** perspective of the problem



DOMAIN 1 (22.5 km resolution)

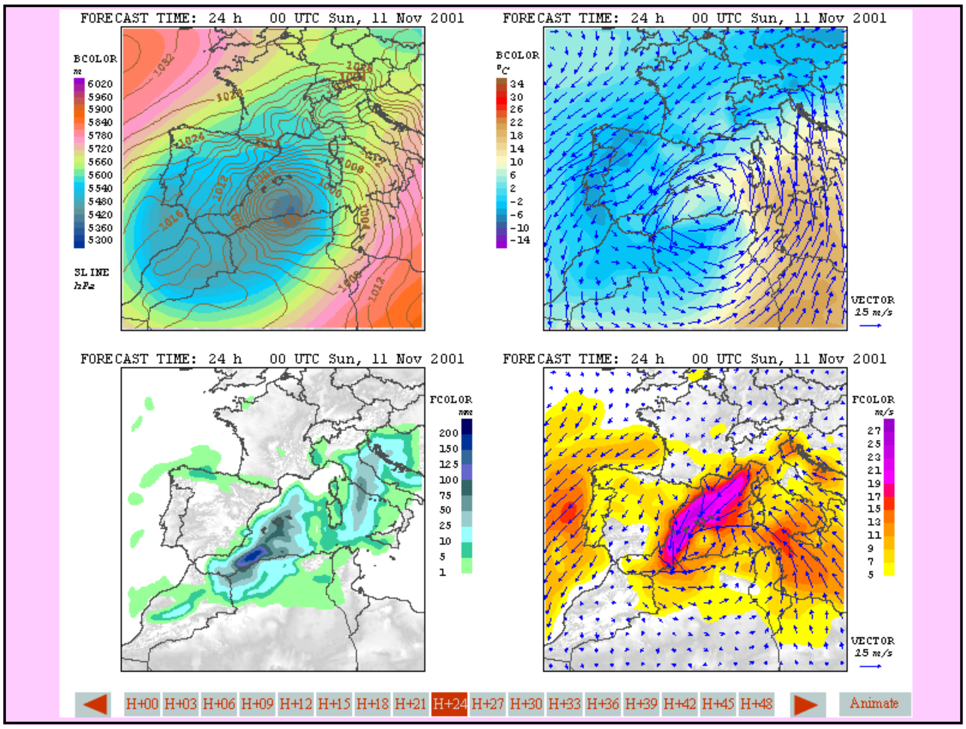


DOMAIN 2 (7.5 km resolution)



DOMAIN 3 (2.5 km resolution)

- Realistic ***physical processes*** parameterized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SLINE hPa
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FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
BCOLOR °C
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VECTOR 25 m/s
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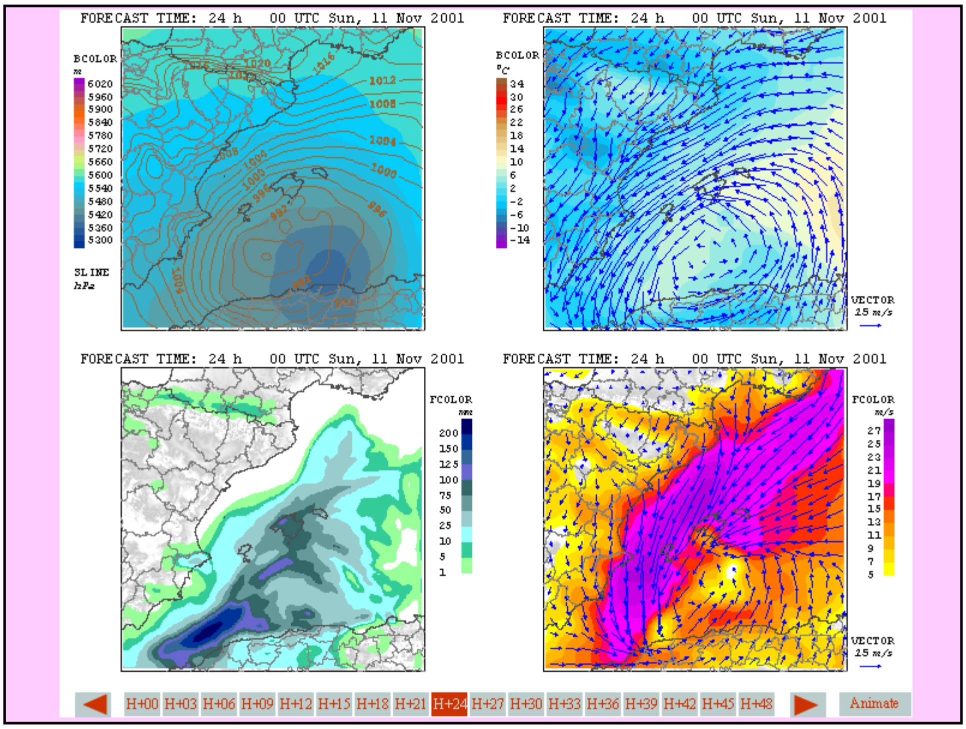
Animate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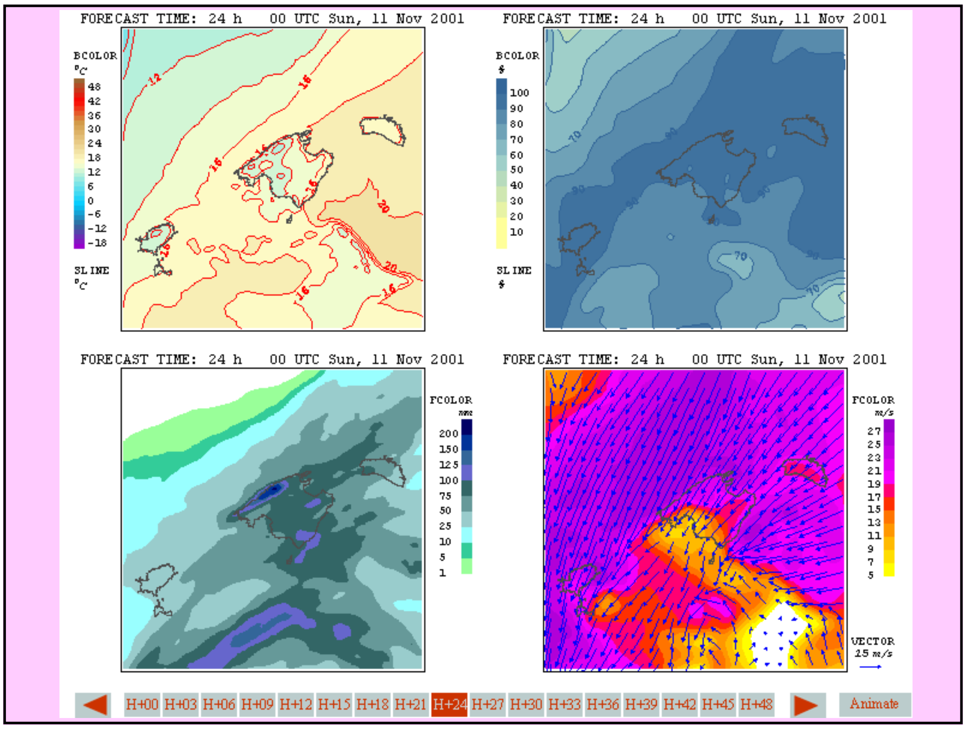
Animate



UNIQUE FEATURE
OF NUMERICAL MODELS

- Reasonably ***good*** control simulation of your case study

↓

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

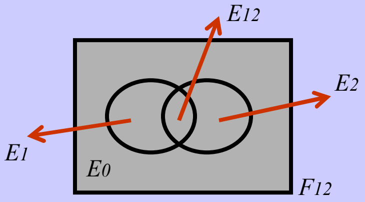
↓

- Improved physical ***understanding*** of your case study

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

2 FACTORS

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** ⟶ **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 $i_1 i_2 i_3 \ldots i_k$

PART 1.- CASE STUDIES

2 FLASH FLOOD EVENTS OVER EASTERN SPAIN

2 FACTORS

- Atlas Mountains (a **boundary** factor)
- Latent heat exchange (a **physical** factor)

THE EVENTS

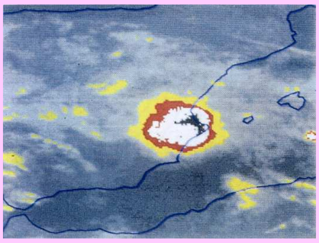
GANDIA (3-4 Nov. 1987)

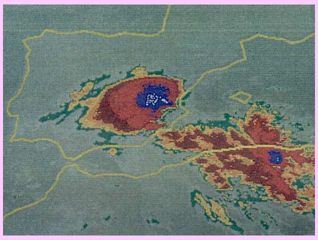
MCS (33 h)
Circular shape (~200 km diameter)
1000 mm / 36 h in **Gandia**

TOUS (20 Oct. 1982)

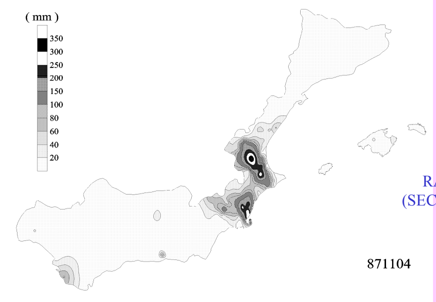
MCC (>12 h)
>400 mm
Dam breaking in **Tous**

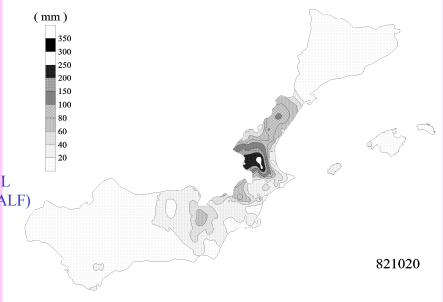
INFRARED METEOSAT





RAINFALL (SECOND HALF)

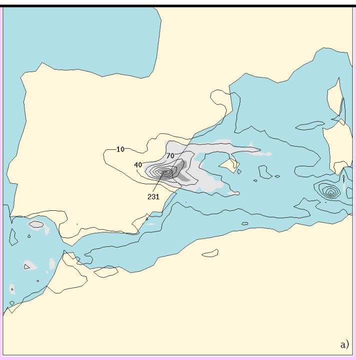


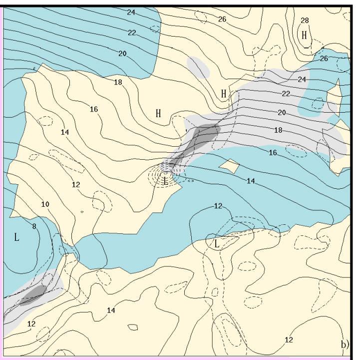


GANDIA

Location / Stationarity: well
QPF: underestimated

Algerian low / Mesolow
Convergence ahead of LLJ





FULL SIMULATION

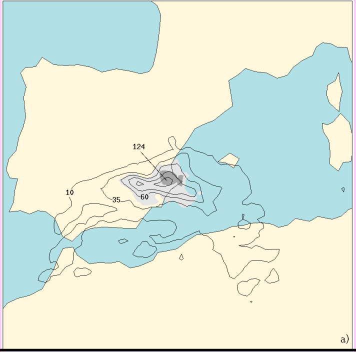
PRECIPITATION

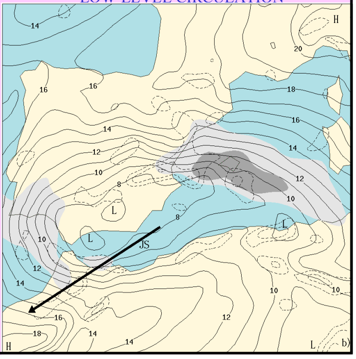
LOW-LEVEL CIRCULATION

TOUS

Location / Stationarity: well
QPF: underestimated

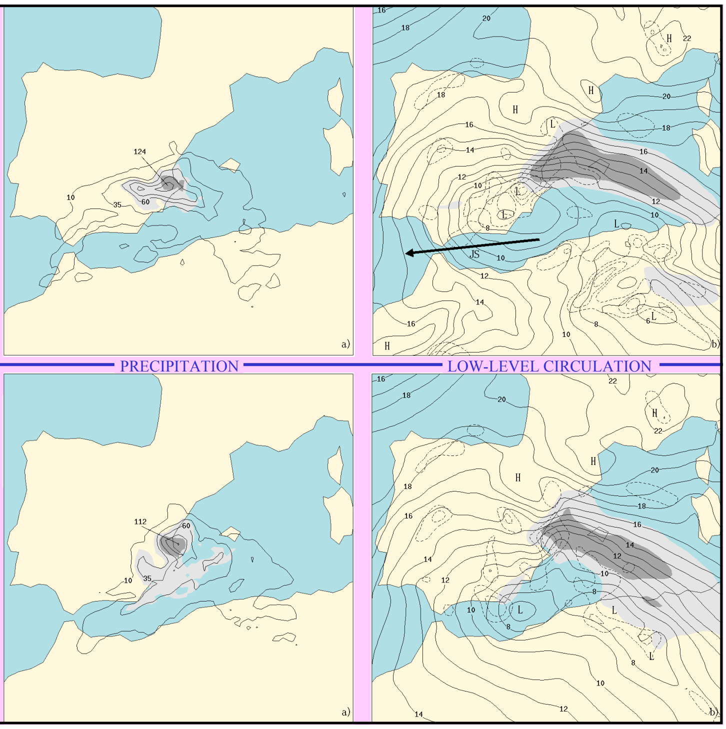
Westward-moving low / ULJ
Embedded mesolow
Convergence over SE Spain





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 factors → **2^n simulations**

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

a. Effect of the Atlas Mountains = $F_1 - F_0$

b. Effect of the Latent heat = $F_2 - F_0$

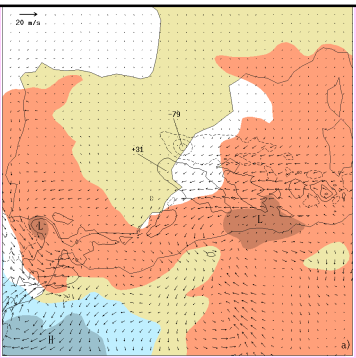
c. Effect of the interaction Atlas/Latent heat = $F_{12} - (F_1+F_2) + F_0$

GANDIA

Extensive pressure decrease over the Mediterranean

Cyclogenesis / Enhancement of easterlies and convergence

Southward shift of the rainfall activity



EFFECT
ATLAS MOUNTAINS

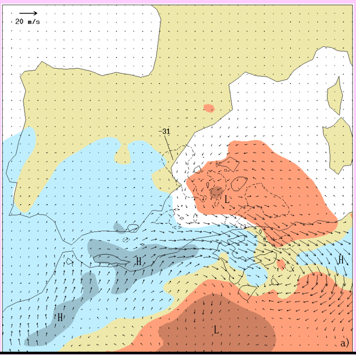
SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Pressure decrease limited to the east of the Balearics

Northerly winds and offshore outflows over eastern Spain

General rainfall suppression

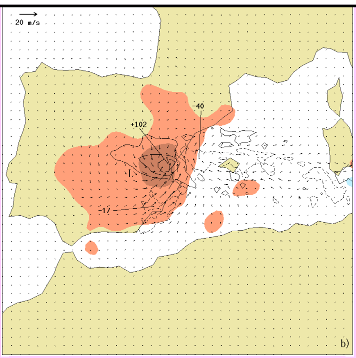


GANDIA

Mesolow over eastern Spain

Intense mesoscale cyclonic circulation / strong convergence

Focusing of rainfall over central Valencia



EFFECT
LATENT HEAT

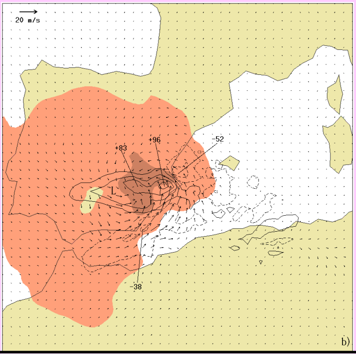
SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Mesolow over southeastern Spain

Intense vortex / strong convergence line

Substantial rainfall enhancement (elongated structure)

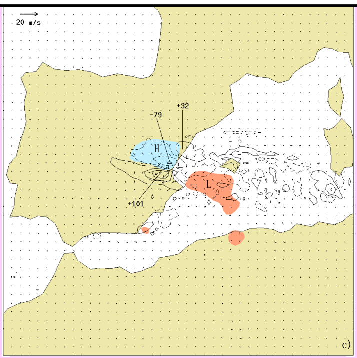


EFFECT
ATLAS MOUNTAINS / LATENT HEAT

GANDIA

Complex pattern in space and time

Southward shift of the rainfall activity

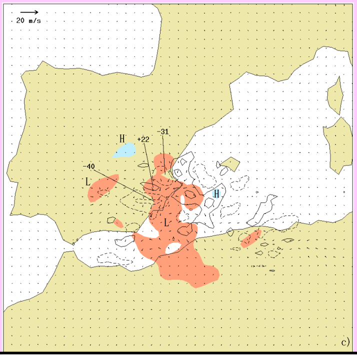


SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Complex pattern in space and time

General rainfall suppression over land



CONCLUSIONS (I) - PART 1

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** !!!

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** ⟶ **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 (**I.C**) ?

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 **???**

↓

PIECEWISE PV INVERSION

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:

$$QGPV\begin{cases}\zeta_g+f & \text{Coriolis parameter increases with latitude}\\ \dfrac{\partial}{\partial p}\left(\dfrac{f_0}{\sigma}\dfrac{\partial\phi}{\partial p}\right)=-\dfrac{\partial}{\partial p}\left(\dfrac{f_0R_d}{\sigma p}T\right)\approx-\dfrac{f_0R_d}{\sigma p}\dfrac{\partial T}{\partial p} & \begin{matrix}<0\text{ in troposphere}\\>0\text{ in stratosphere}\end{matrix}\end{cases}$$

- *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

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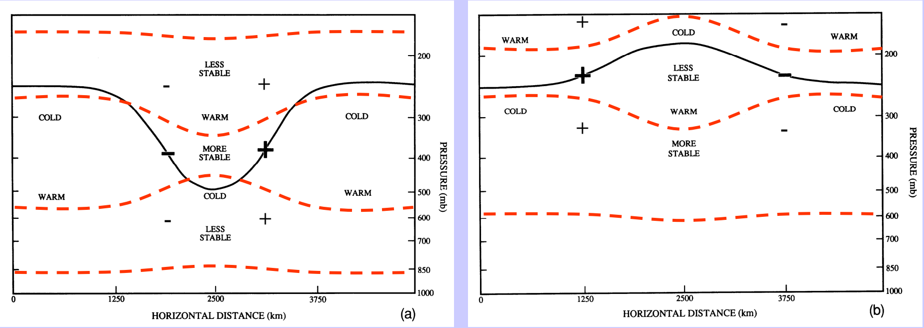
FUNDAMENTALS PV - Upper Level PV Anomalies



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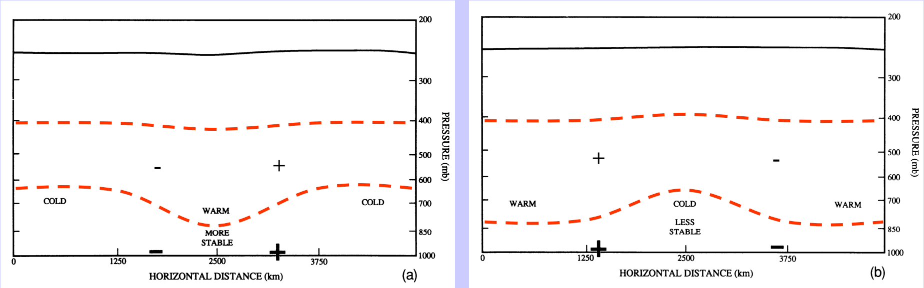
FUNDAMENTALS PV - Surface Thermal Anomalies



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COMPARISON – Ertel's Potential Vorticity

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

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

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*

Charney nonlinear balance
(very small irrot.wind)
(**Accurate for *Ro* →1**)

Under the same scale analysis

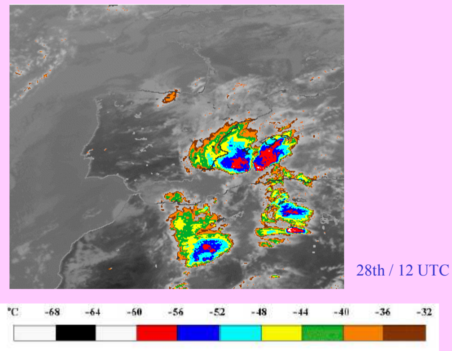
Nonlinear operator
(anomalies !!!)

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

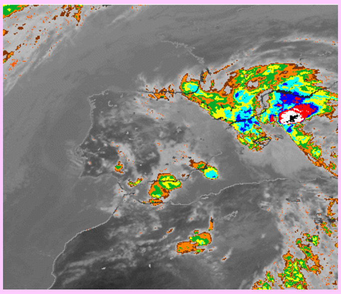
c) About the anomalies: Same qualitative picture as for the *QGPV* anomalies

THE EVENT
(28-29 Sept. 1994)

INFRARED METEOSAT

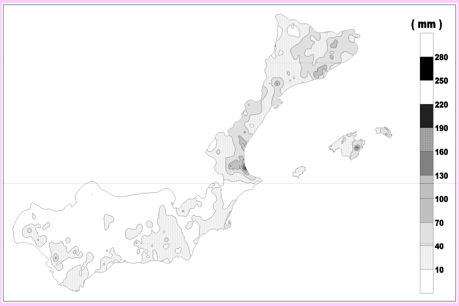


28th / 12 UTC



29th / 12 UTC

PRECIPITATION



28th / 07 UTC ⟶ 30th / 07 UTC

The cyclone progressed northwards during the episode

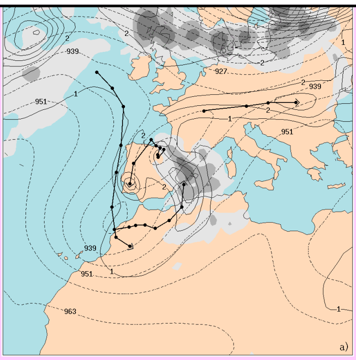
Main MCSs developed over the sea (**strong QG forcing**)

Heavy precipitation and flash floods in eastern Spain

SYNOPTIC ASPECTS

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

Strong low-tropospheric **warm advection**

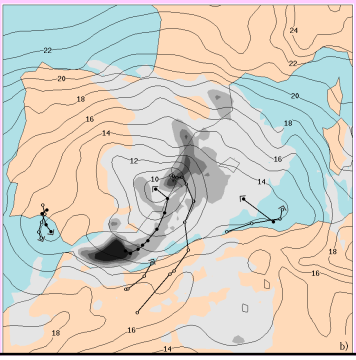


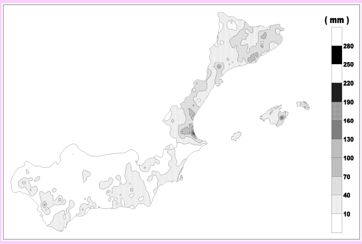
CONTROL SIMULATION

MESOSCALE FORECAST

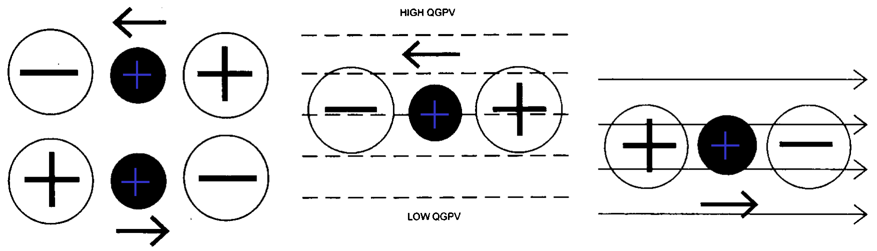
Intense, broad and **mobile surface cyclone**

Heavy precipitation in agreement with observations





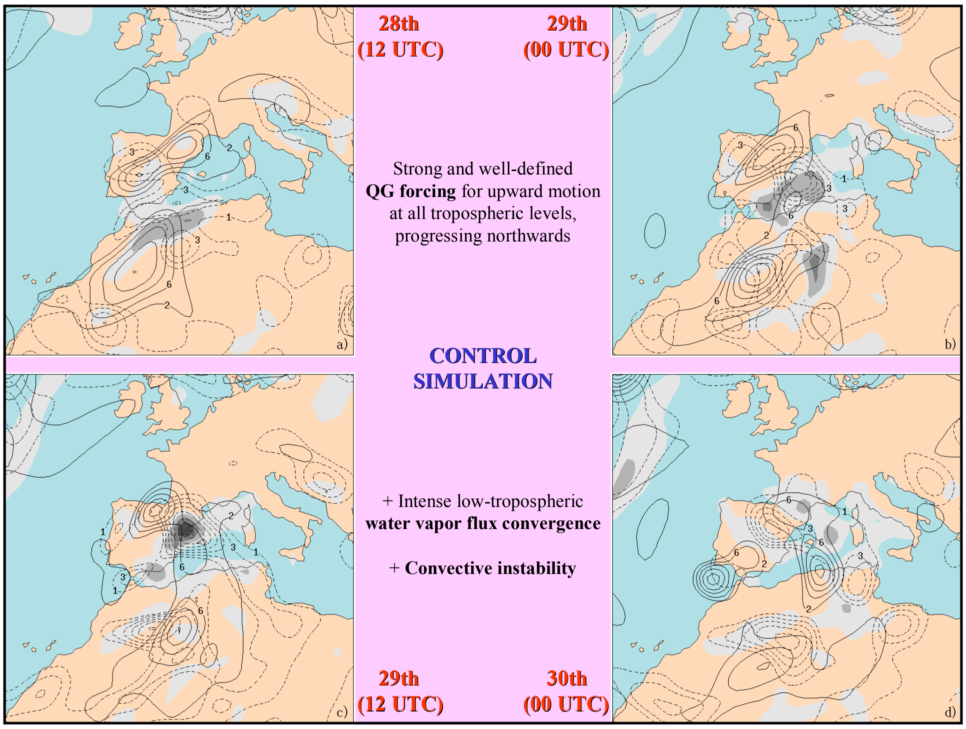
PV THINKING - Lateral Interactions



Vortex-vortex interactions

Vortex retrogression

Background-flow advection of vortex



28th (12 UTC)

29th (00 UTC)

Strong and well-defined **QG forcing** for upward motion at all tropospheric levels, progressing northwards

CONTROL SIMULATION

+ Intense low-tropospheric **water vapor flux convergence**

+ **Convective instability**

29th (12 UTC)

30th (00 UTC)

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:

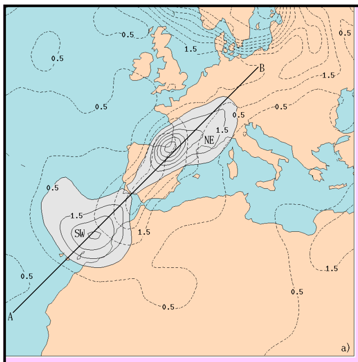
$$\nabla^2\phi_n = \boldsymbol{\nabla}\cdot f\boldsymbol{\nabla}\psi_n + 2m^2\left(\frac{\partial^2\psi^*}{\partial x^2}\frac{\partial^2\psi_n}{\partial y^2} + \frac{\partial^2\psi^*}{\partial y^2}\frac{\partial^2\psi_n}{\partial x^2} - 2\frac{\partial^2\psi^*}{\partial x\partial y}\frac{\partial^2\psi_n}{\partial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

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

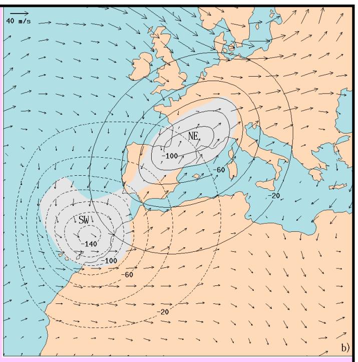
where $()^* = \overline{()} + \frac{1}{2}()'$ **Boundary conditions:** Lateral (homogeneous) / Top and bottom (using θ_n)

* **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

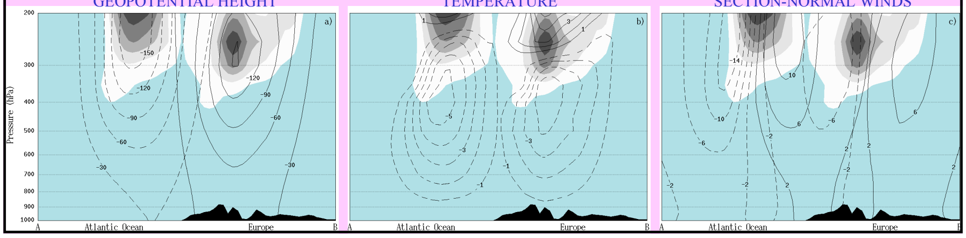
Mutual **interactions** among background flow and anomalies

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

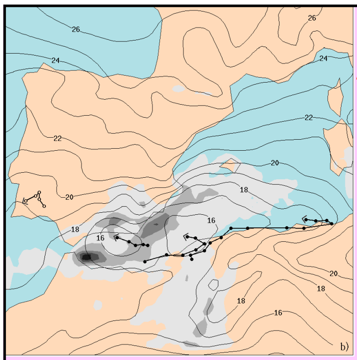
(One or both PV anomalies removed or doubled)

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

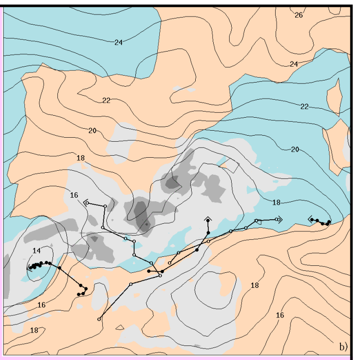
(One or both PV anomalies shifted 425 km along A-B)

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

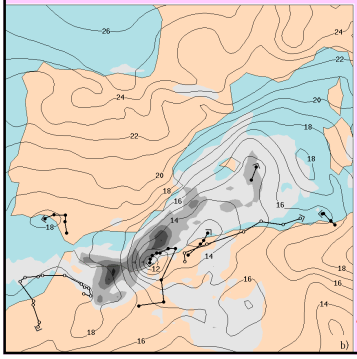


PV anomalies **removed or moved away** from each other

FIRST GROUP
(Mesoscale forecast)

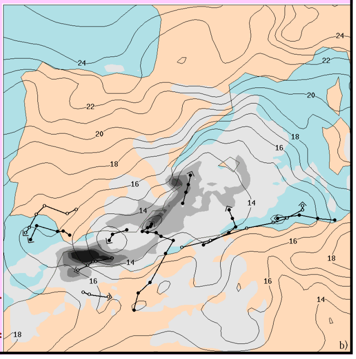
Stationary surface lows along the **lee of the Atlas**

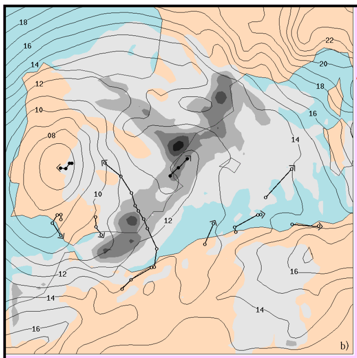
Rainfall restricted to the **southern Mediterranean** areas



S_+^+

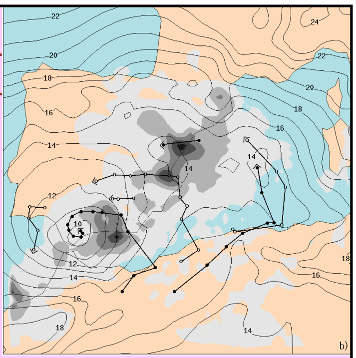
$S_=^+$





S_2^2

S_{--}^{--}

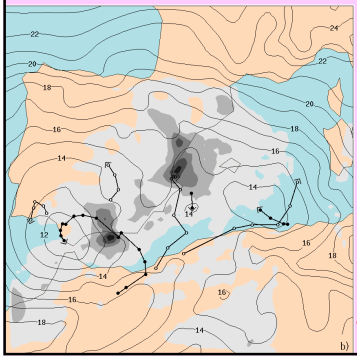


Enhanced PV structures aloft

SECOND GROUP
(Mesoscale forecast)

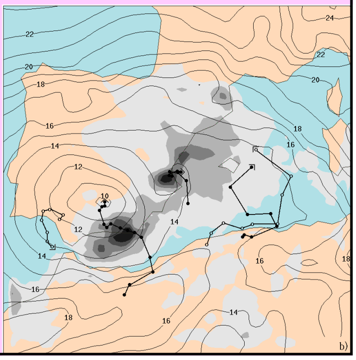
Extensive and **very mobile** surface disturbances

Heavy rain in both the **southern and northern Mediterranean** zones

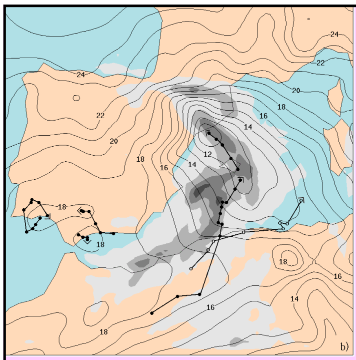


$S_=^{--}$

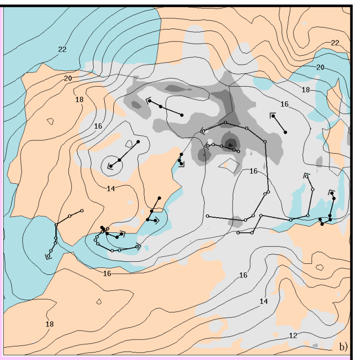
$S_{--}^=$



S_0^1



S_0^2



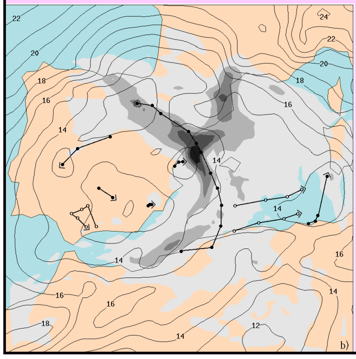
Relative weight of the **NE** anomaly **enhanced**

THIRD GROUP (Mesoscale forecast)

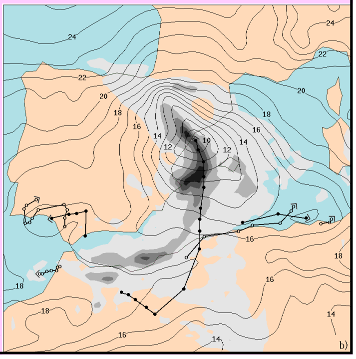
The cyclone evolves further **east and north** of southeastern Spain

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

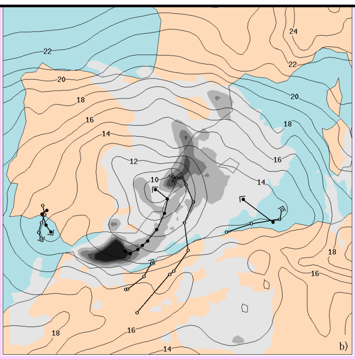
S_1^2

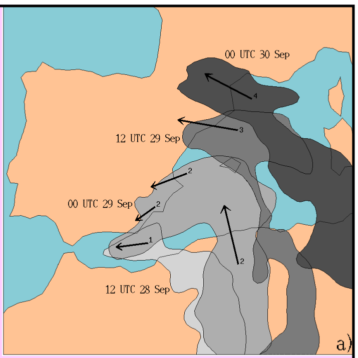


$S_+^=$



CONTROL SIMULATION





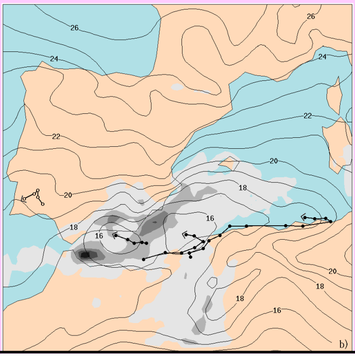
DYNAMICAL CONTROL of PRECIP

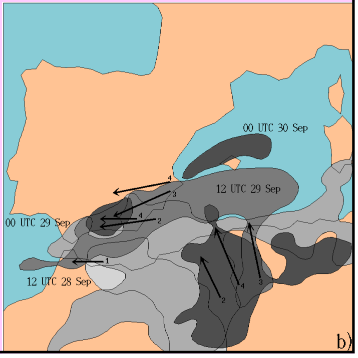
MESOSCALE FORECAST

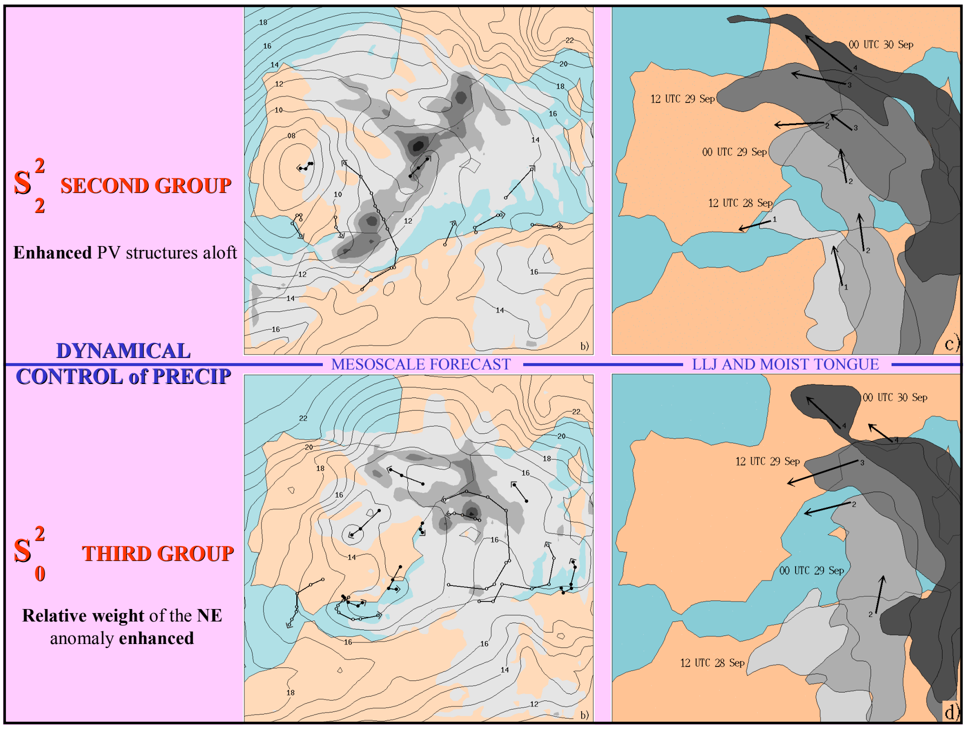
LLJ AND MOIST TONGUE

S_0^0 **FIRST GROUP**

PV anomalies **removed or moved away** from each other







S_2^2 **SECOND GROUP**

Enhanced PV structures aloft

DYNAMICAL CONTROL of PRECIP

MESOSCALE FORECAST

LLJ AND MOIST TONGUE

S_0^2 **THIRD GROUP**

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

INTRODUCTION - PART 3

* The previous example shows that the two embedded **upper-level PV centres** played 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 the precursor **upper-level trough** would affect a **mesoscale forecast ?**

↓

* Such uncertainties can be accounted for by means of an **ensemble prediction system** defined by a collection of simulations with perturbed initial conditions (using the PV inversion method)

* **How much** to perturb**?** A **PV-error climatology** has been derived

* **Where** to perturb**?** Sensitivity areas according to **MM5-adjoint** run / **human-based** criteria

PV error climatology

Comparing the PV fields of

ECMWF analysis ⟷ ECMWF 24 h forecast,

of a large collection of MEDEX cyclones,
one can define:

- The displacement error (DE): the minimum displacement of the 24 h forecast PV field showing local maximum correlation with the analysis PV field
- The intensity error (IE): the difference between the displaced 24 h forecast PV field and analysis PV field relative to the analysis PV average

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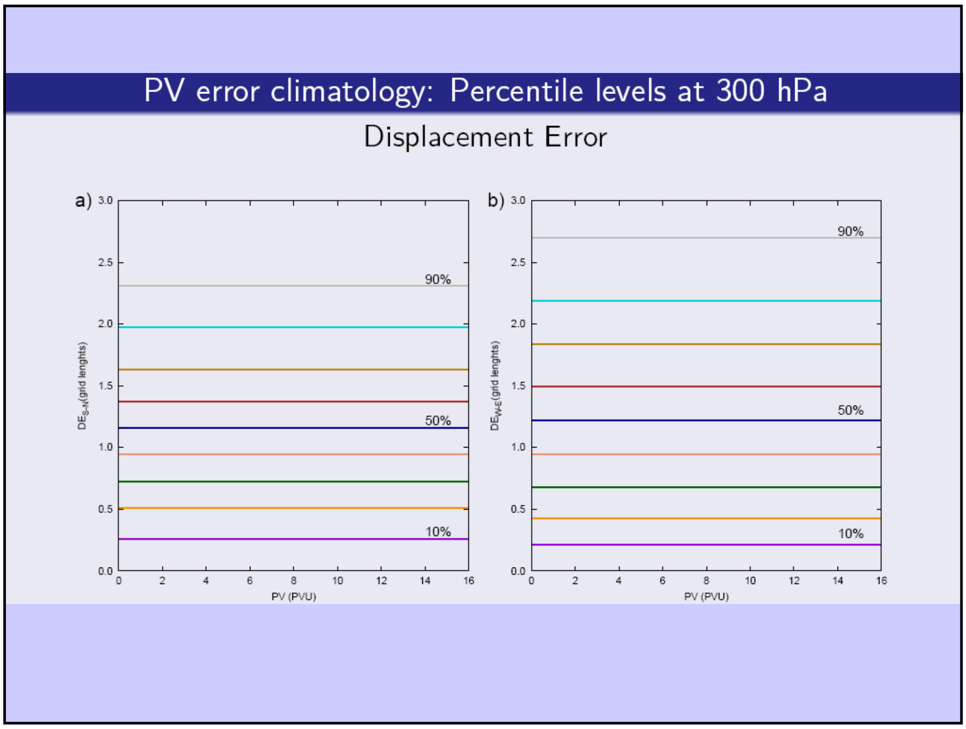
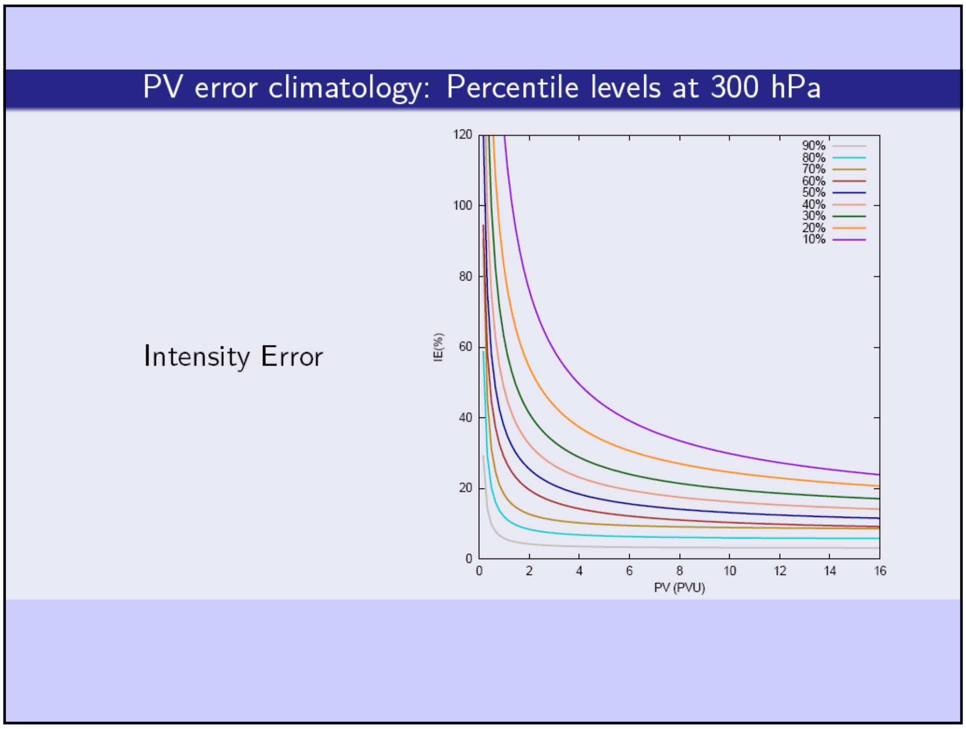


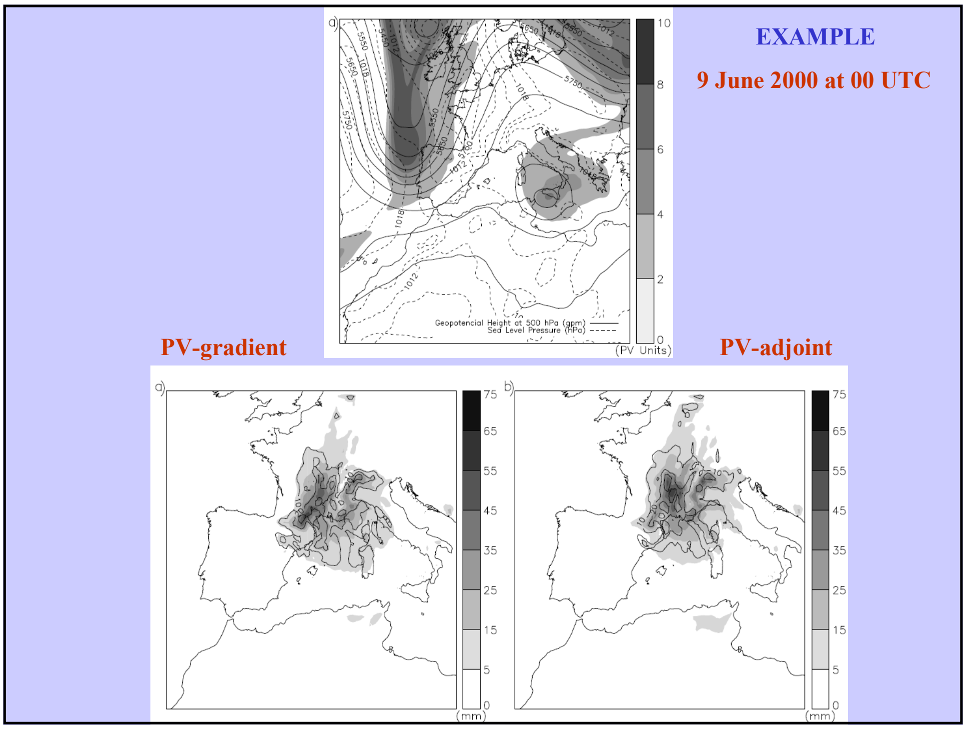
PV error climatology: Percentile levels at 300 hPa

Displacement Error



PV error climatology: Percentile levels at 300 hPa

Intensity Error



EXAMPLE

9 June 2000 at 00 UTC

PV-gradient

PV-adjoint

Results

- The two ensembles have a good performance (better than a multiphysics EPS)
- PV-gradient performes better than PV-adjoint
- PV-adjoint higher computational cost than the PV-gradient

INTRODUCTION - PART 4

LIFE CYCLE OF AN INTENSE MEDITERRANEAN CYCLONE

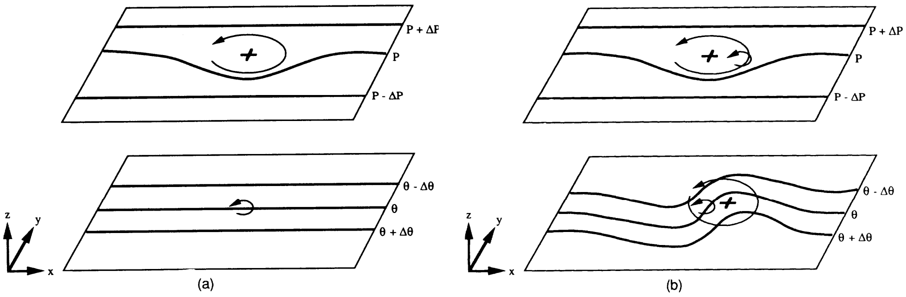
PV THINKING → An analysis of the cyclone event in terms of the **impacts** and **interactions** of dry and moist **PV anomalies** (and mean flow)

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

↓

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

PV THINKING - Vertical Interactions

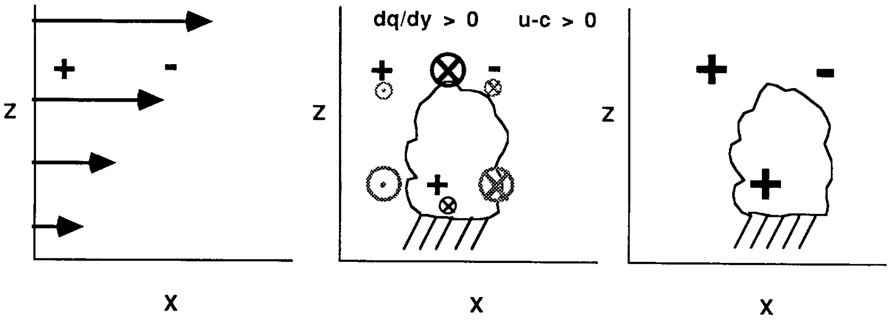


(a)

(b)

Growth of an idealized baroclinic wave-cyclone

PV THINKING - Vertical Interactions

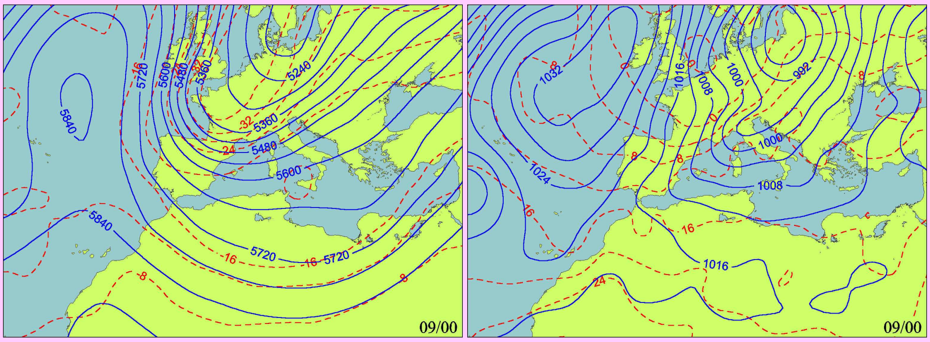


Effects of diabatic processes (condensation)

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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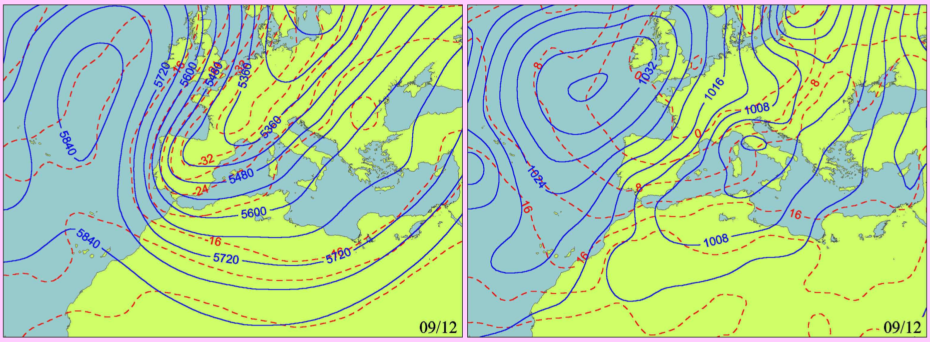

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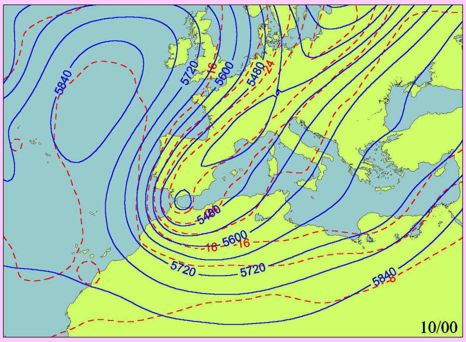
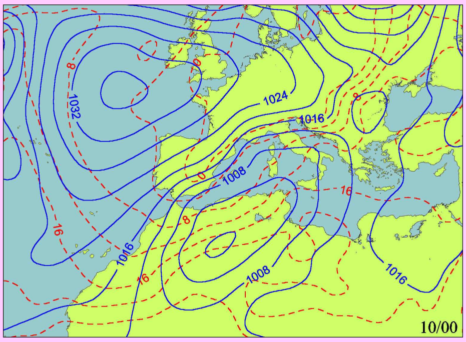


Low levels (SLP / T 925)

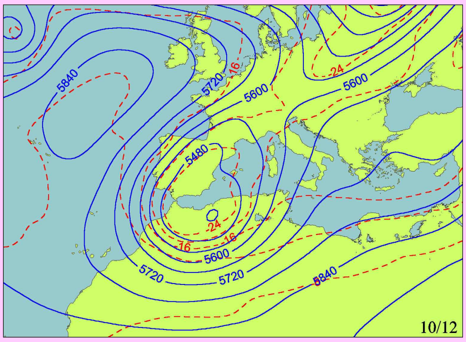


ALGERIA

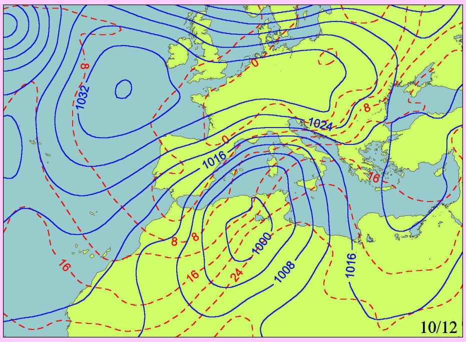
- **Over 100 mm/6 h that led to catastrophic flooding**
- **737 people were killed and 23000 left homeless**

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

Mid-Upper levels (H 500 / T 500)



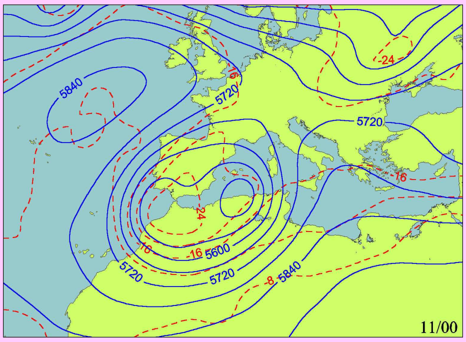
Low levels (SLP / T 925)

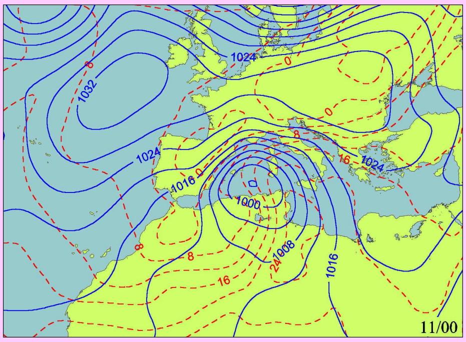


LIFE CYCLE OF THE CYCLONE (9-12 November 2001)

Mid-Upper levels (H 500 / T 500)

Low levels (SLP / T 925)





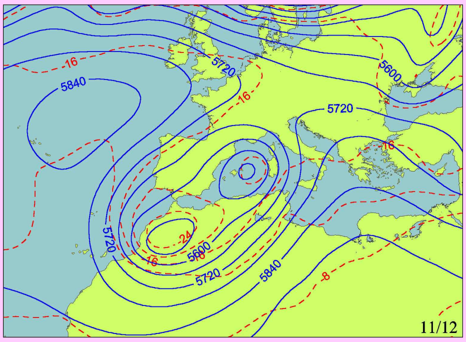
BALEARIC ISLANDS

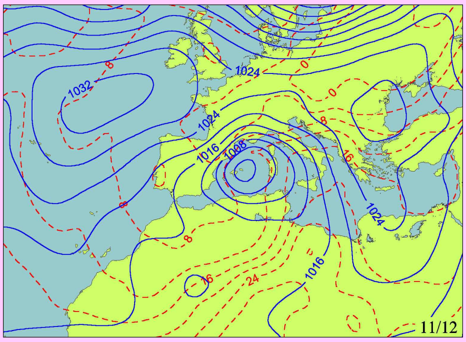
- **Up to 400 mm/24 h, 150 km/h winds and 12 m sea waves**
- **4 casualties, 500000 trees uprooted, floods and severe damages on coasts**

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

Mid-Upper levels (H 500 / T 500)

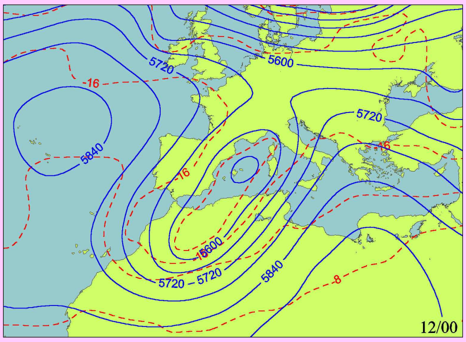
Low levels (SLP / T 925)



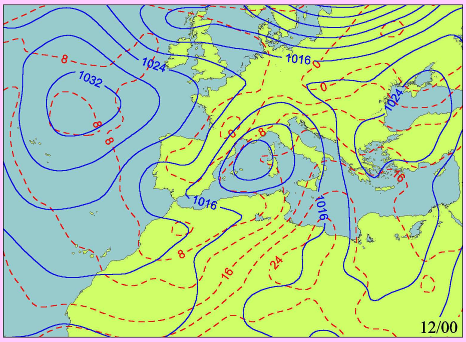


LIFE CYCLE OF THE CYCLONE (9-12 November 2001)

Mid-Upper levels (H 500 / T 500)



Low levels (SLP / T 925)



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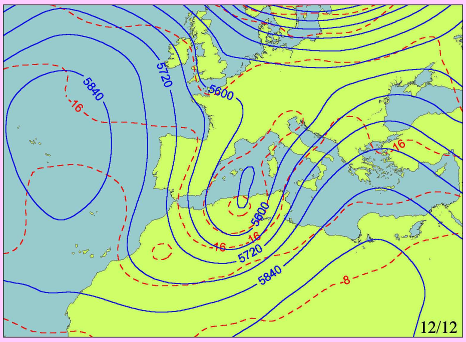

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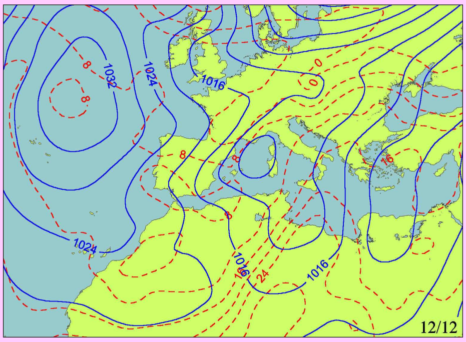
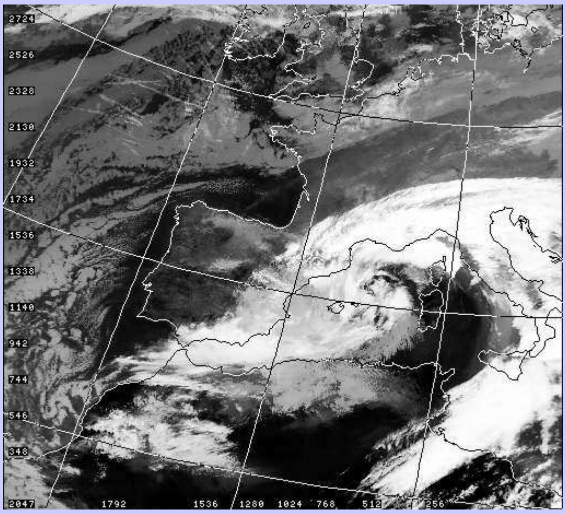


Strong baroclinic development

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

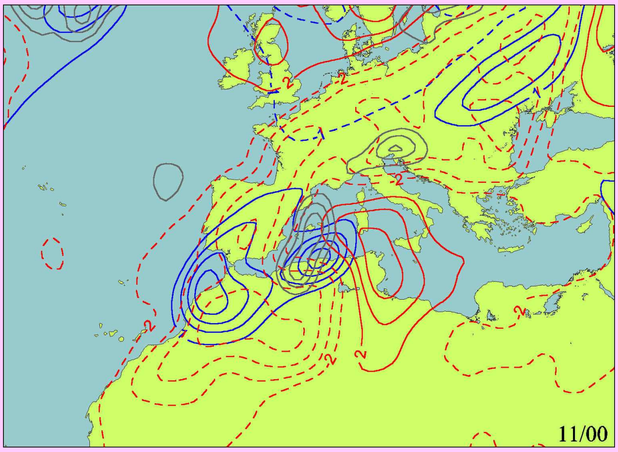
↓



Diabatic contribution ?

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%**



PV-based DIAGNOSIS

ULev	**PV perturbation above 700 hPa**
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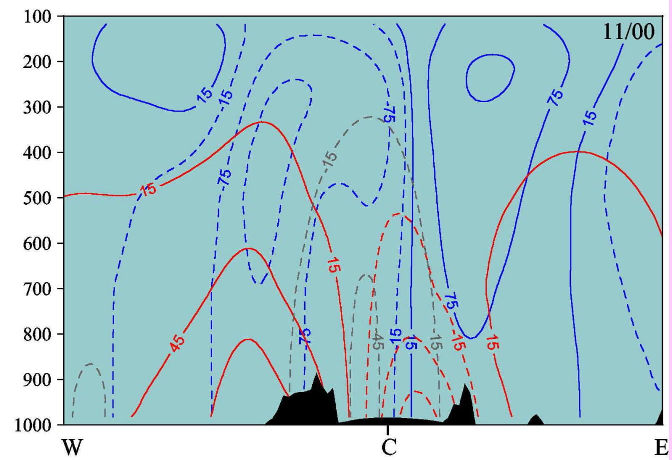
DIAB	**Positive PV perturbation below 500 hPa in areas with RH > 70%**

Geopotential height perturbation



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:

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

$\longrightarrow (\phi^t, \psi^t)$

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

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

Horizontal wind Vertical velocity $\longrightarrow q^t$

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

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

PV-BASED PROGNOSTIC SYSTEM

4) Omega equation:

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

5) Continuity equation:

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

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

Lateral B.C (Homogeneous)

$\phi^t=\psi^t=q^t=\omega^*=\chi=0$

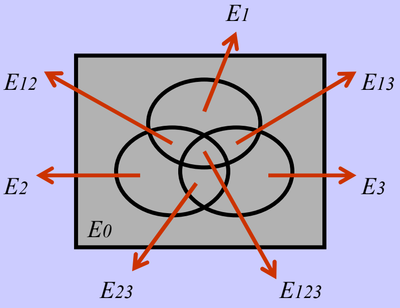
Top-Bottom B.C (Neumann)

$\partial\phi^t/\partial\pi=f\partial\psi^t/\partial\pi=-\theta^t$

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

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

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



E0 = *F0*

E1 = *F1* - *F0*

E2 = *F2* - *F0*

E3 = *F3* - *F0*

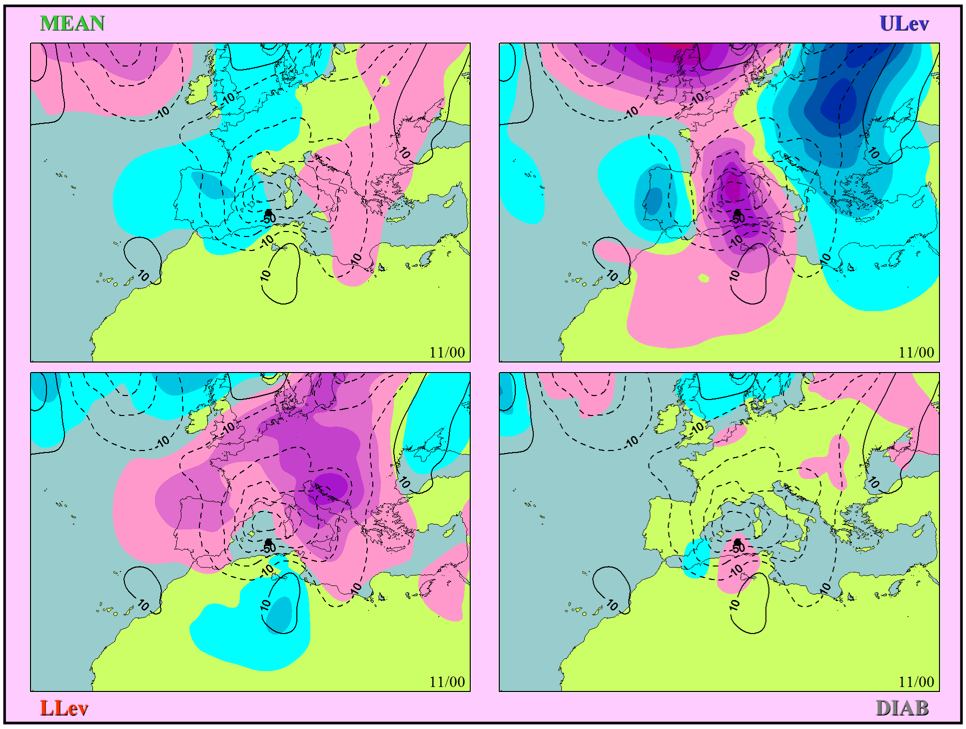
E12 = *F12* - (*F1* + *F2*) + *F0*

E13 = *F13* - (*F1* + *F3*) + *F0*

E23 = *F23* - (*F2* + *F3*) + *F0*

E123 = *F123* - (*F12* + *F13* + *F23*) + (*F1* + *F2* + *F3*) - *F0*

(8 flow configurations necessary)


MEAN
ULev
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DIAB
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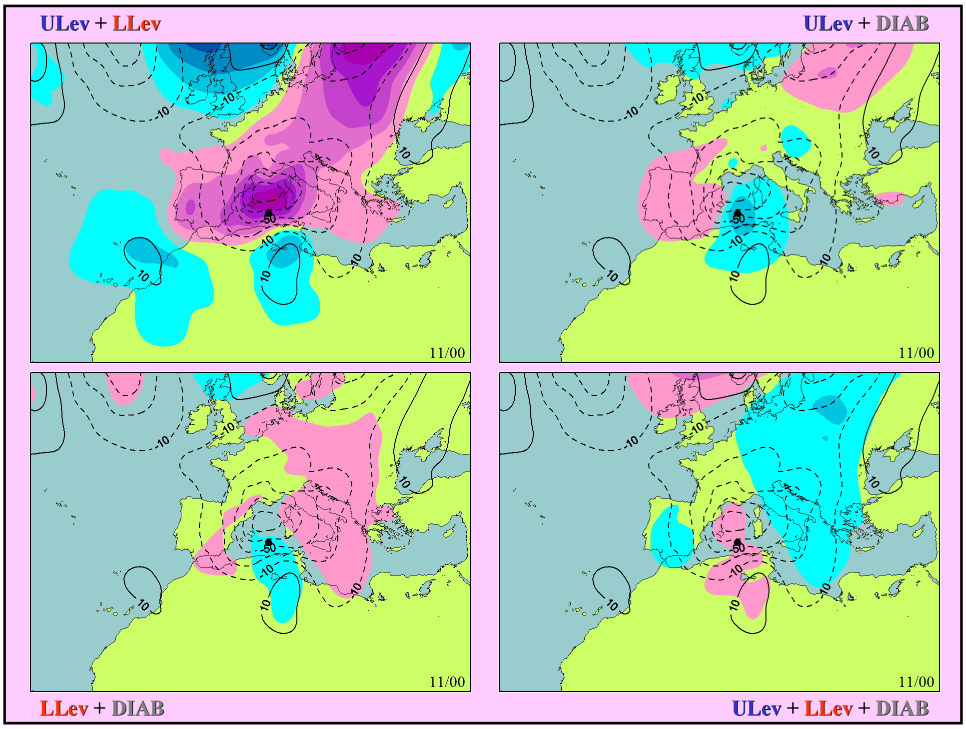
ULev + LLev
ULev + DIAB
LLev + DIAB
ULev + LLev + DIAB
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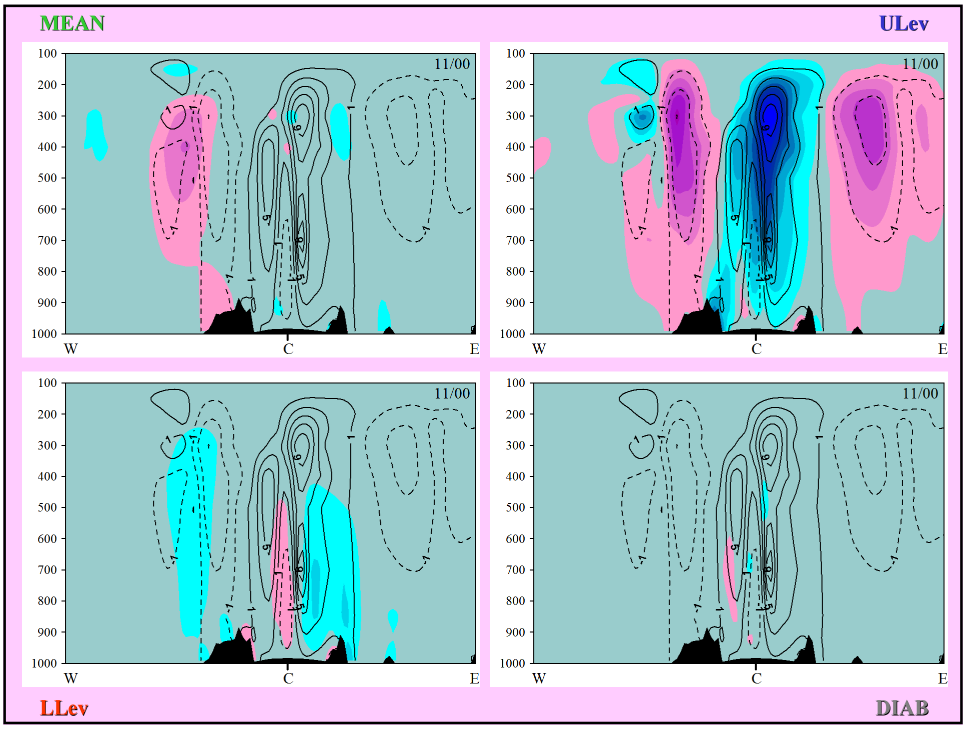
MEAN
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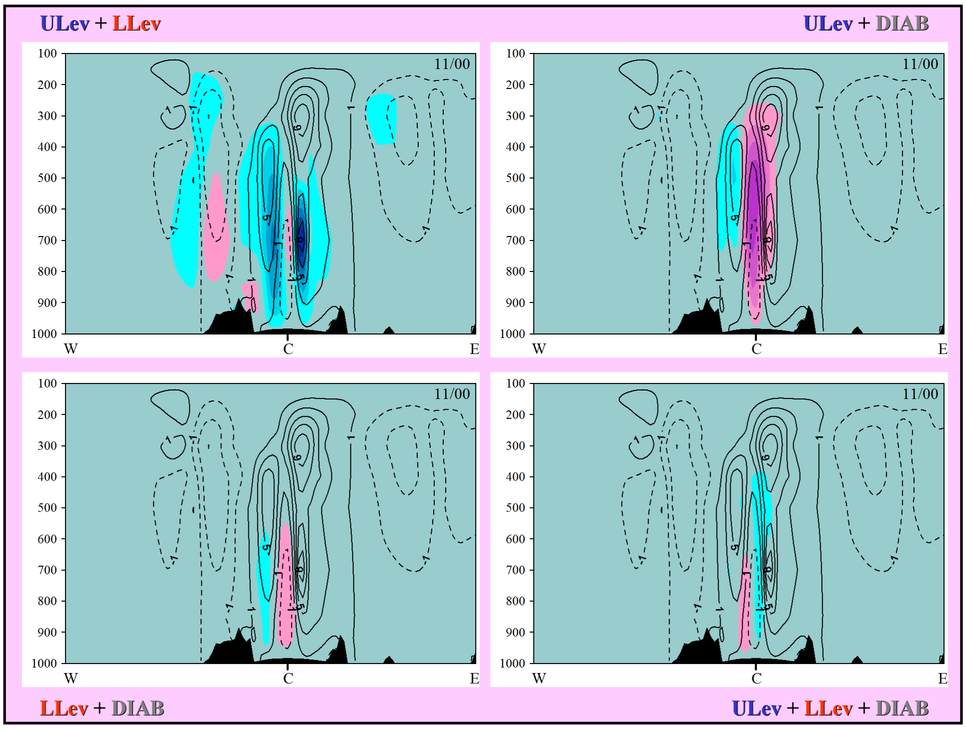
ULev + LLev
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THE END !!!