SENSITIVITY OF CYCLONES TO BOUNDARY AND PHYSICAL FACTORS: THE FACTOR SEPARATION TECHNIQUE

Mediterranean School on Mesoscale Meteorology – 1st Edition
(Alghero, Sardinia, June 7-11, 2004)

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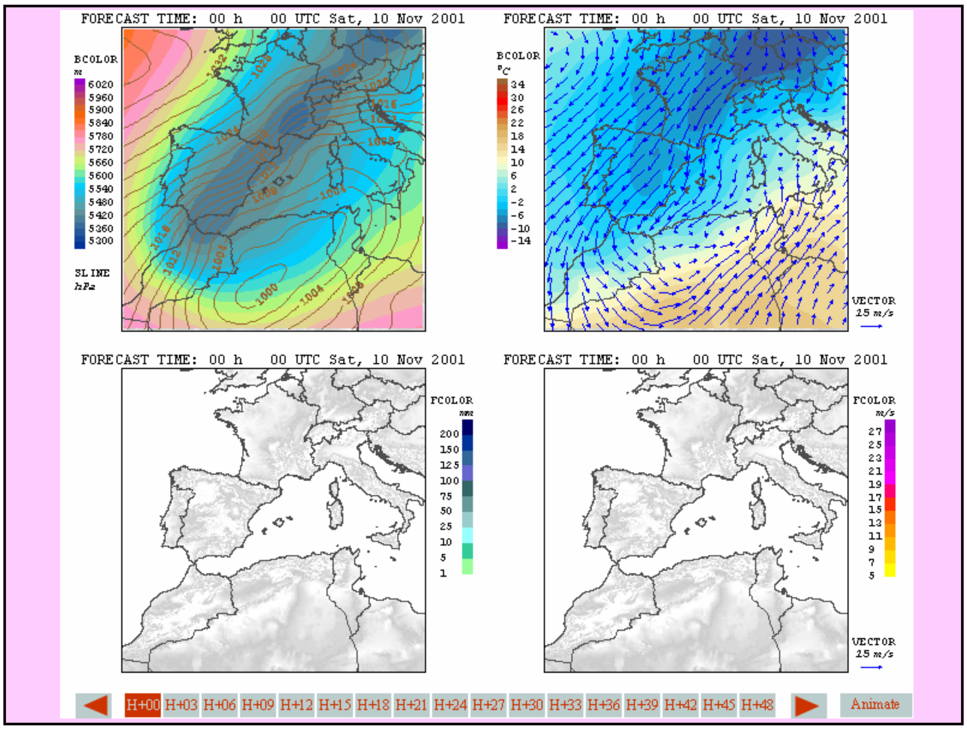
THE STUDY OF CYCLONES

- Observations (limited in number, space and time)
- Theory (requires simplifications)
- Experimentation (*Numerical Modeling*)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BCOLOR m
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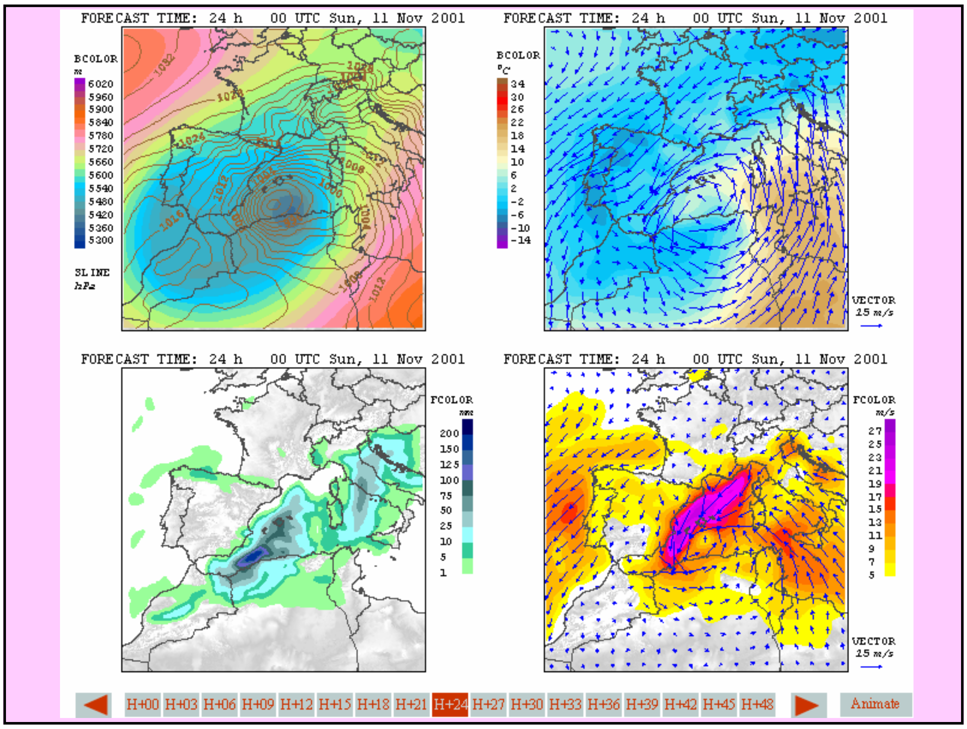
SLINE hPa
FORECAST TIME: 00 h 00 UTC Sat, 10 Nov 2001
BCOLOR °C
34 30 26 22 18 14 10 6 2 -2 -6 -10 -14
VECTOR 15 m/s
FORECAST TIME: 00 h 00 UTC Sat, 10 Nov 2001
FCOLOR mm
200 150 125 100 75 50 25 10 5 1
FORECAST TIME: 00 h 00 UTC Sat, 10 Nov 2001
FCOLOR m/s
27 25 23 21 19 17 15 13 11 9 7 5
VECTOR 15 m/s
H+00 H+03 H+06 H+09 H+12 H+15 H+18 H+21 H+24 H+27 H+30 H+33 H+36 H+39 H+42 H+45 H+48
Animate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FCOLOR mm
200 150 125 100 75 50 25 10 5 1
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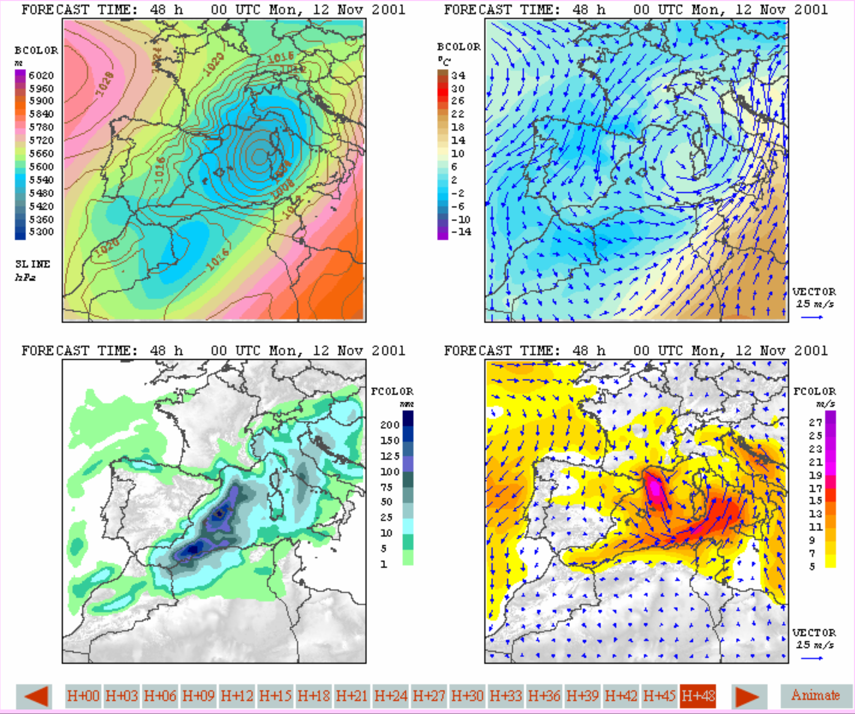
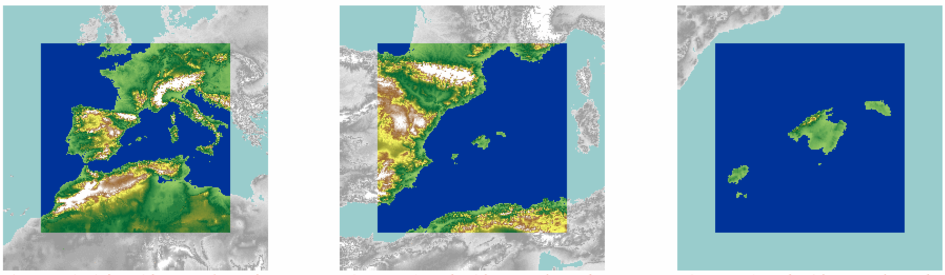
Animate

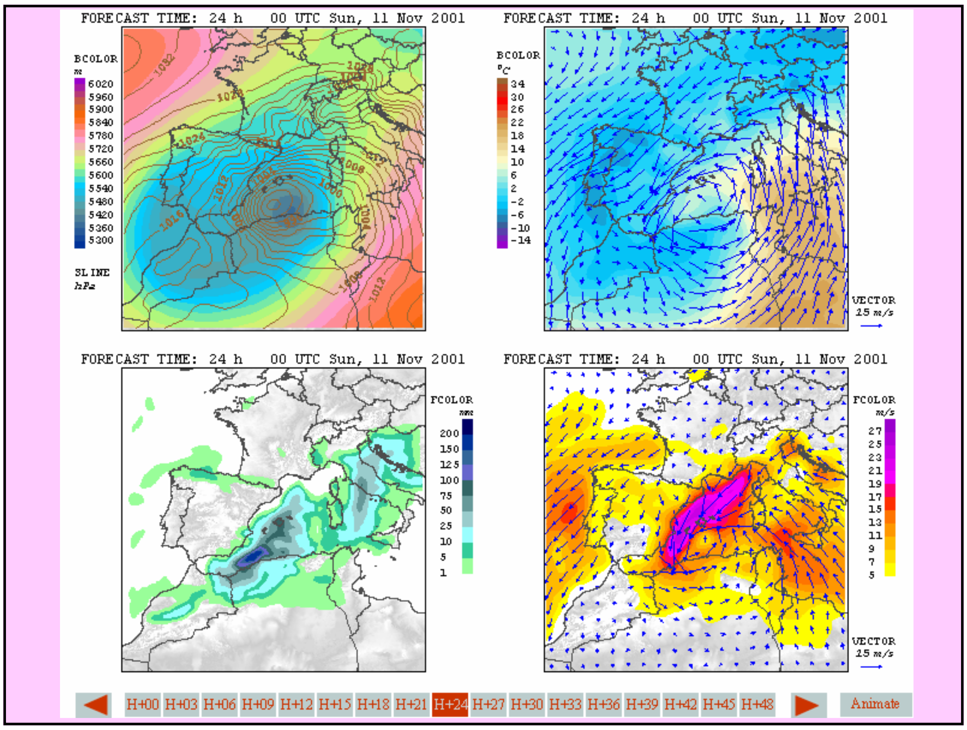


- ***Multiscale*** perspective of cyclone structure



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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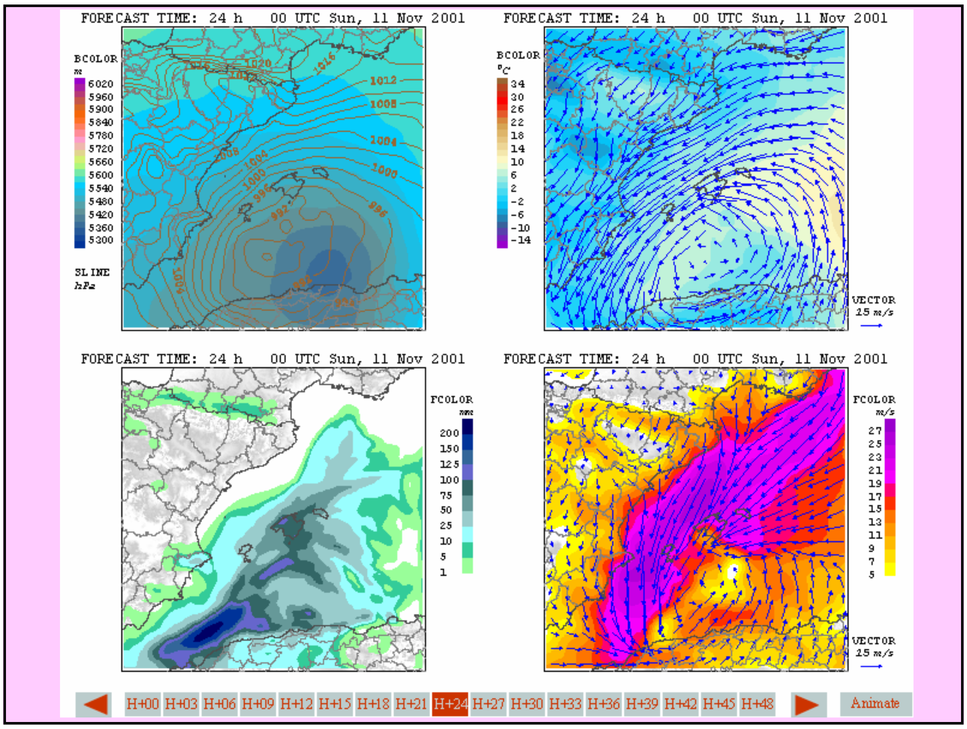
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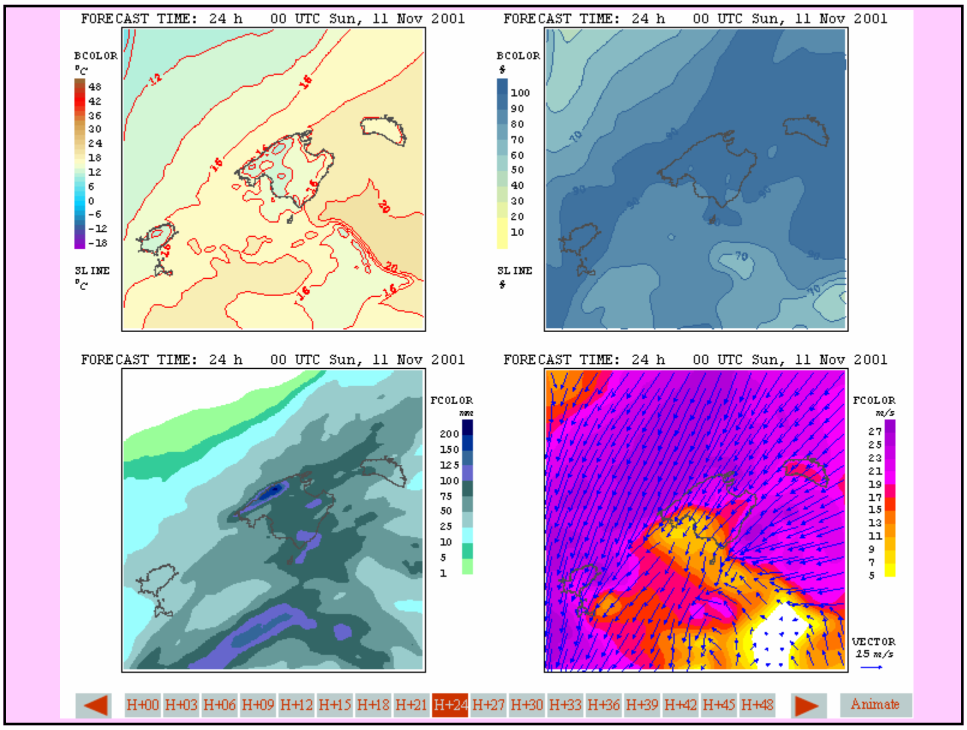
Animate



UNIQUE FEATURE OF NUMERICAL MODELS

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

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

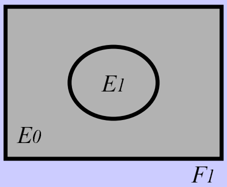
- Improved physical ***understanding*** of your case study

FACTOR SEPARATION (Traditional Approach)

1 FACTOR

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

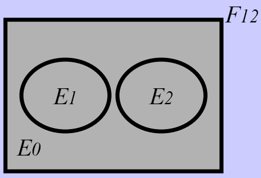
$(F_1 = E_0 + E_1)$



2 FACTORS

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

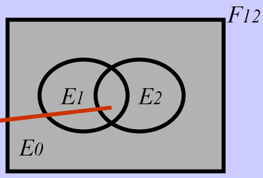
* Ideally:



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

* But in nature:

Interaction not isolated !!!

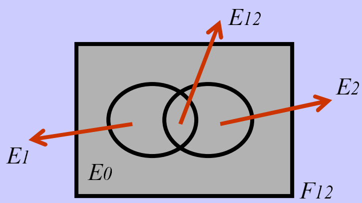


$(F_{12} \neq E_0 + E_1 + E_2)$

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

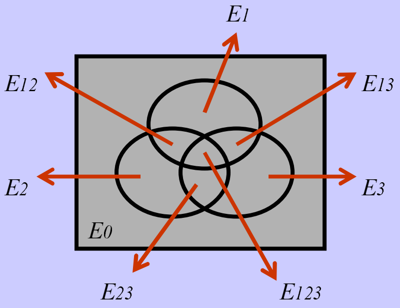
* Generalization: **n FACTORS** ⟶ **2^n SIMULATIONS**

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

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

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

3 FACTORS



$E_0 = F_0$

$E_1 = F_1 - F_0$

$E_2 = F_2 - F_0$

$E_3 = F_3 - F_0$

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

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

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

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

(8 simulations necessary)

CASE STUDIES

2 FLASH FLOOD EVENTS OVER EASTERN SPAIN

2 FACTORS

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

THE EVENTS

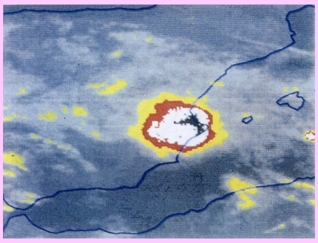
GANDIA (3-4 Nov. 1987)

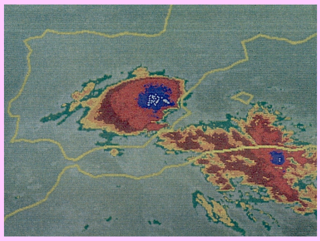
MCS (33 h)
Circular shape (~200 km diameter)
1000 mm / 36 h in **Gandia**

TOUS (20 Oct. 1982)

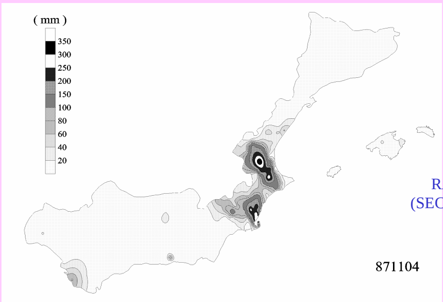
MCC (>12 h)
>400 mm
Dam breaking in **Tous**

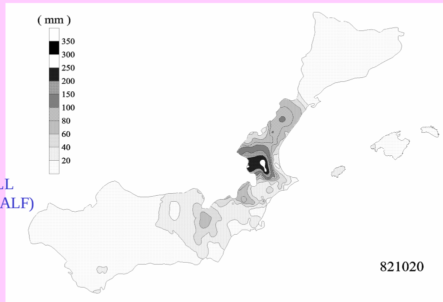
INFRARED METEOSAT





RAINFALL (SECOND HALF)





SYNOPTIC ENVIRONMENT

GANDIA

Stationary / Weak pattern

Cold-core cut-off low

Algerian low / moist LLJ

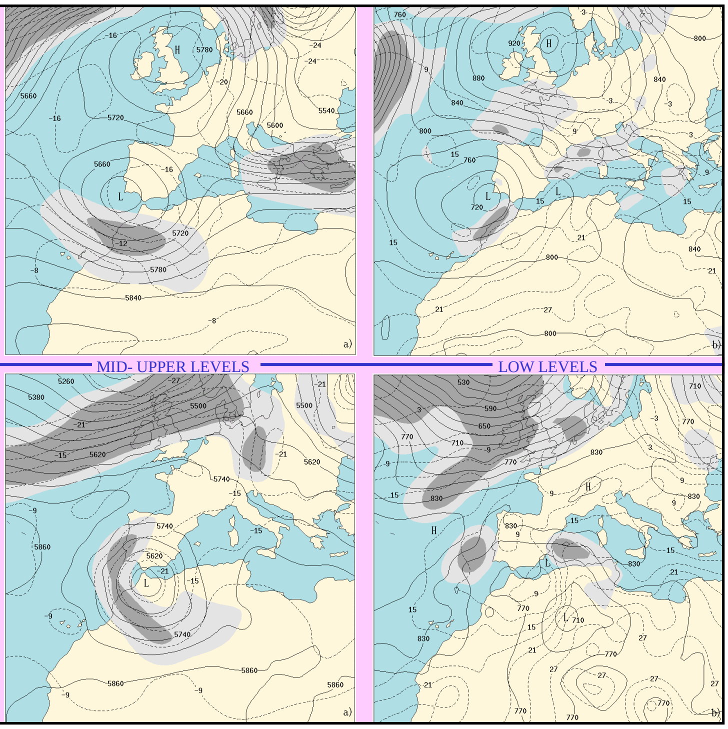
TOUS

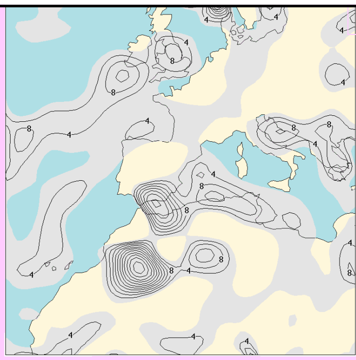
Evolving / Strong pattern

Cold-core cut-off low / ULJ

Baroclinicity / moist LLJ

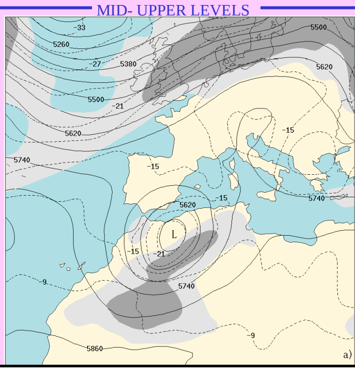
MID- UPPER LEVELS — LOW LEVELS



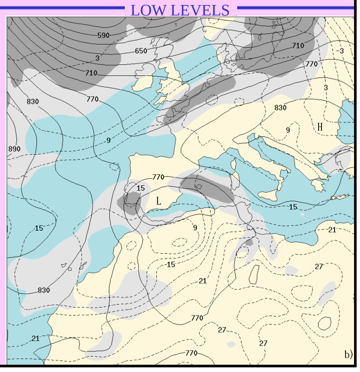


UPWARD QUASIGEOSTROPHIC FORCING 500 hPa

MID- UPPER LEVELS



LOW LEVELS



TOUS

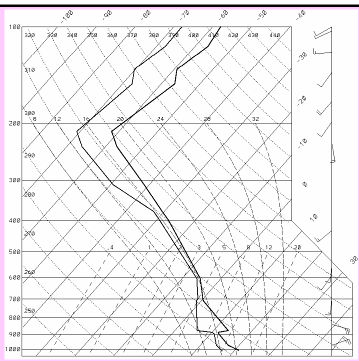
Evolving / Strong pattern

Cold-core cut-off low / ULJ

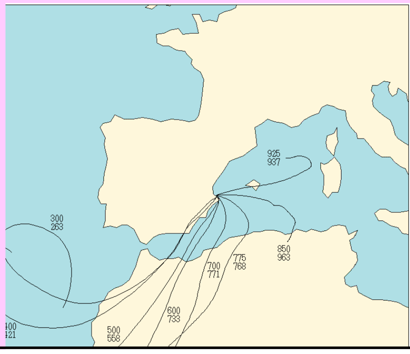
Baroclinicity / moist LLJ

GANDIA

CAPE	909 J / kg
CIN	12 J / kg
TT	47
K	31
LI	0
PW	35 mm



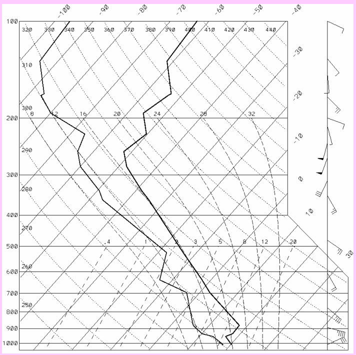
PRECONVECTIVE SOUNDING



2-DAYS BACK TRAJECTORIES

TOUS

CAPE	1243 J / kg
CIN	192 J / kg
TT	52
K	30
LI	-1
PW	32 mm



MESOSCALE NUMERICAL SIMULATIONS

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

*** Simulations:**

- **2 domains**: 82x82x31 (60 and 20 km)
- **Interaction**: two-way
- **I.C and B.C**: NCEP global analysis + Surface and Upper air obs.
- **GANDIA**: 36 h, from 00 UTC 3 Nov. 1987
- **TOUS**: 24 h, from 00 UTC 20 Oct. 1982

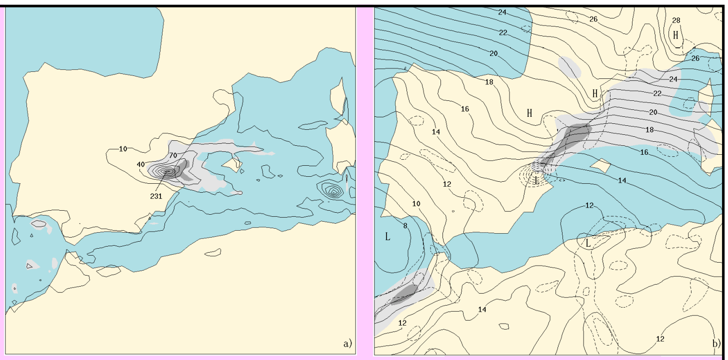
*** Physical parameterizations:**

- **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)
- **Explicit convection**: Cloud water, rainwater, cloud ice and snow (Zhang 1989)
- **Parameterized convection**: Coarse: Betts-Miller (1986) / Fine: Kain-Fritsch (1990)

GANDIA

Location / Stationarity: well
QPF: underestimated

Algerian low / Mesolow
Convergence ahead of LLJ



FULL SIMULATION

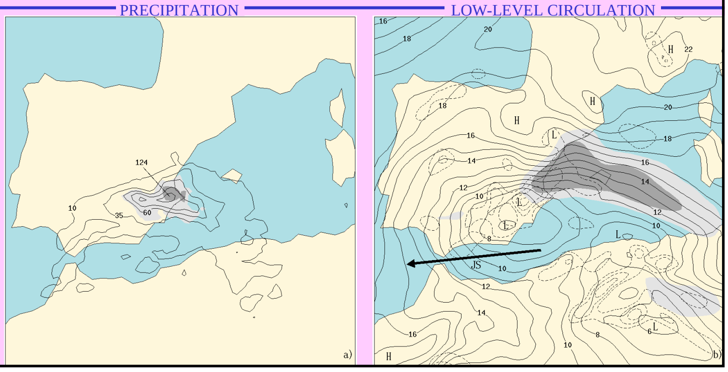
PRECIPITATION

LOW-LEVEL CIRCULATION

TOUS

Location / Stationarity: well
QPF: underestimated

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



PRECIPITATION

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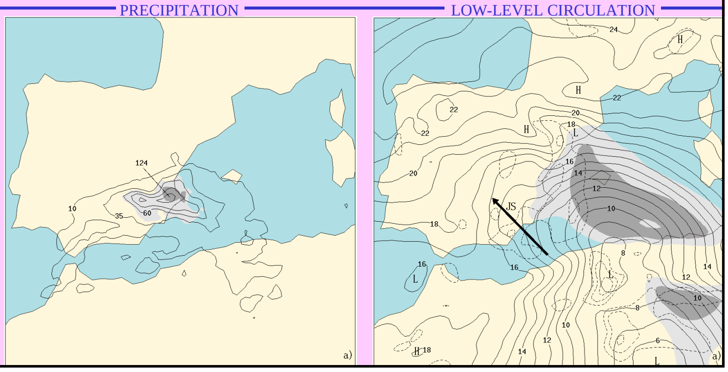

TOUS

Location / Stationarity: well
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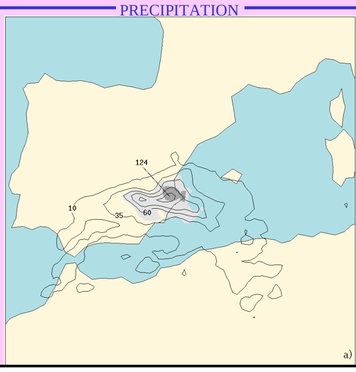
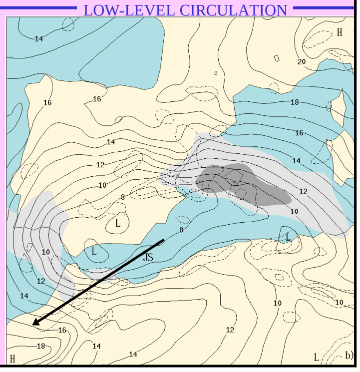
Westward-moving low / ULJ
Embedded mesolow
Convergence over SE Spain

PRECIPITATION

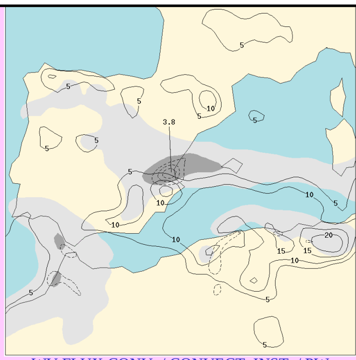


LOW-LEVEL CIRCULATION



GANDIA

Strong WV flux convergence
Boundary of instability
E-W elongated moist tongue



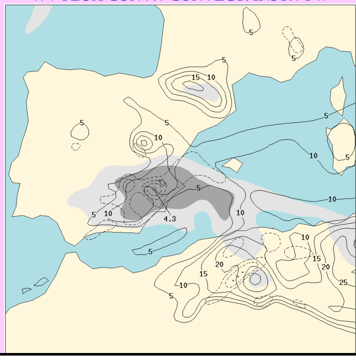
FULL SIMULATION

TOUS

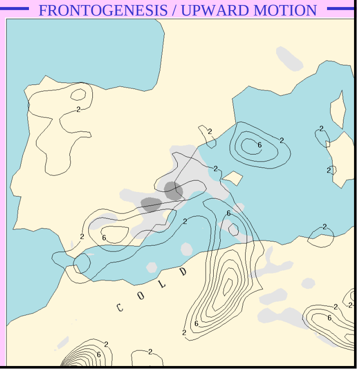
Strong WV flux convergence
Convective instability
High values of PW

Frontogenetic action
Upward motion in response

WV FLUX CONV. / CONVECT. INST. / PW



FRONTOGENESIS / UPWARD MOTION

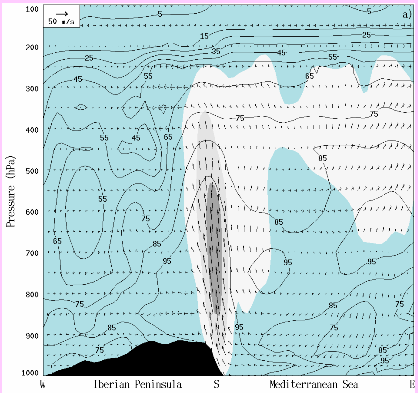


FULL SIMULATION

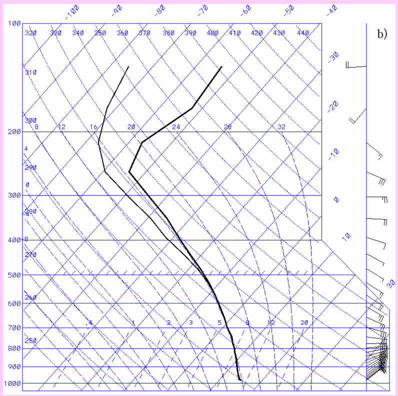
GANDIA

Coastal plume of moist, ascending air
Precipitation efficiency / Mesolow
Explicit convection

Local orography ⟶ 60% precipitation



MODEL SOUNDING AT S



W-E CROSS SECTION
(CIRCULATION / RELATIVE HUMIDITY)

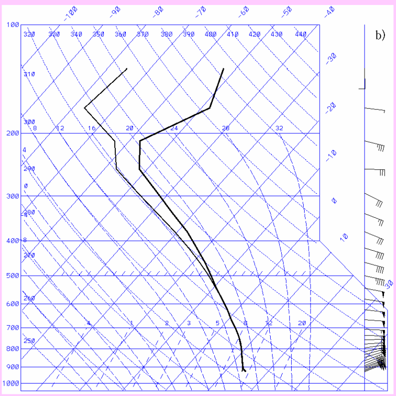
FULL SIMULATION

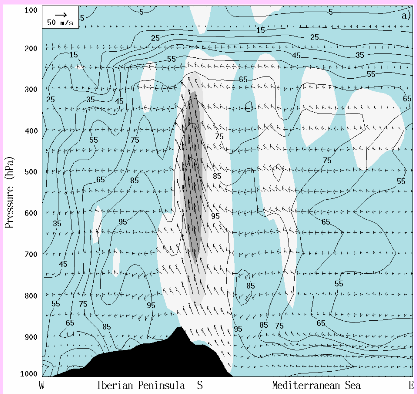
TOUS

Deep plume of moist, ascending air / Dynamic forcing
Precipitation efficiency / Mesolow
Explicit convection

Local orography ⟶ 30% precipitation

MODEL SOUNDING AT S





W-E CROSS SECTION
(CIRCULATION / RELATIVE HUMIDITY)

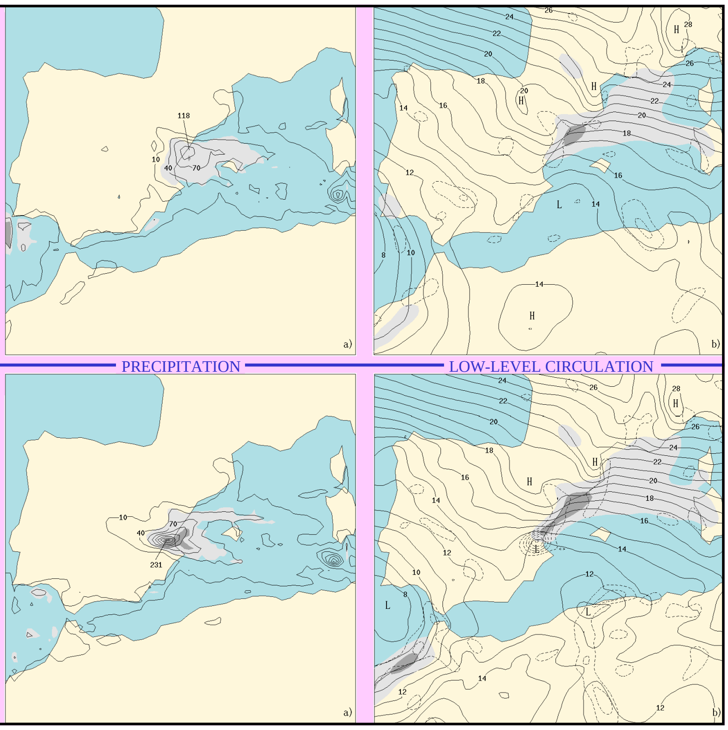
GANDIA

Rainfall suppression
No inland peak

SLP appreciably modified
Less convergence / Shift LLJ

NO ATLAS
NO LATENT HEAT

FULL SIMULATION

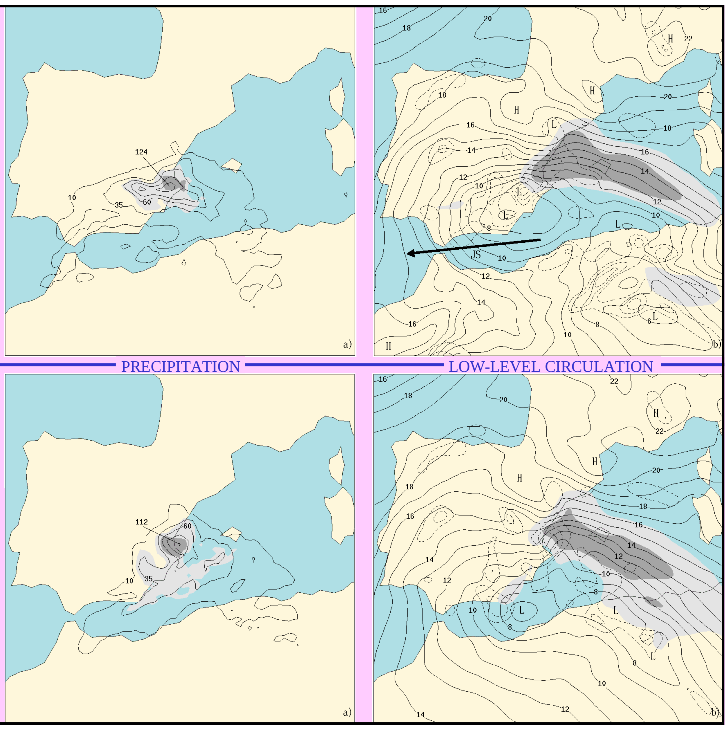


FULL SIMULATION

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 = $F_2 - F_0$

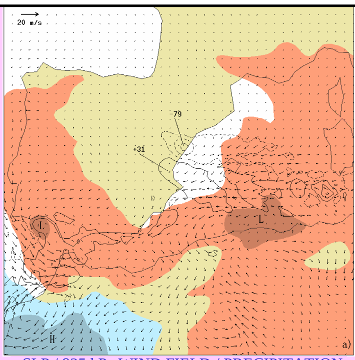
c. Effect of the interaction Atlas/Latent heat = $F_{12} - (F_1+F_2) + F_0$

GANDIA

Extensive pressure decrease over the Mediterranean

Cyclogenesis / Enhancement of easterlies and convergence

Southward shift of the rainfall activity



EFFECT ATLAS MOUNTAINS

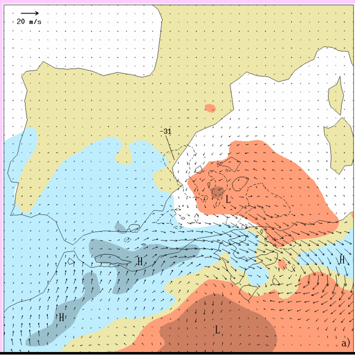
SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Pressure decrease limited to the east of the Balearics

Northerly winds and offshore outflows over eastern Spain

General rainfall suppression

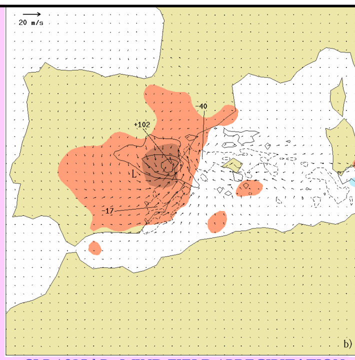


GANDIA

Mesolow over eastern Spain

Intense mesoscale cyclonic circulation / strong convergence

Focusing of rainfall over central Valencia



EFFECT
LATENT HEAT

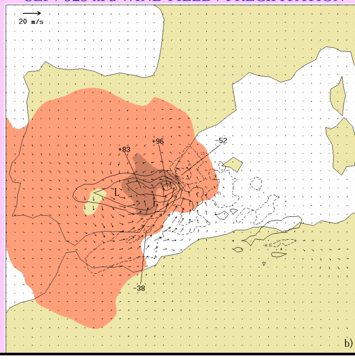
SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Mesolow over southeastern Spain

Intense vortex / strong convergence line

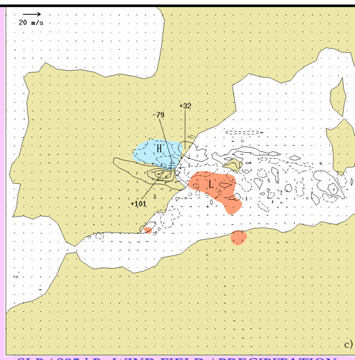
Substantial rainfall enhancement (elongated structure)



GANDIA

Complex pattern in space and time

Southward shift of the rainfall activity



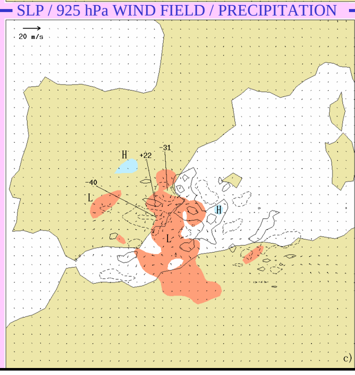
EFFECT
ATLAS MOUNTAINS / LATENT HEAT

SLP / 925 hPa WIND FIELD / PRECIPITATION

TOUS

Complex pattern in space and time

General rainfall suppression over land



CONCLUSIONS- Case Studies

*** Synoptic-scale similarities, but also unique characteristics:**
- **Gandia**: Long-lasting and dynamically weak context
- **Tous**: Relatively strong dynamic forcing and baroclinicity

*** Stationary character of the MCSs linked to:**
- **Gandia**: Stagnancy of the large-scale pattern
- **Tous**: Westward-moving disturbance

*** Mesoscale models represent a valuable forecasting tool:**
- **Location and Stationarity**: Good guidance (Topography !!!)
- **QPF**: Understimates (Deep convection !!!)

*** Atlas mountains:**
- **Gandia**: Modulation by lee cyclogenesis (fits conceptual model)
- **Tous**: Irrelevant or even negative (exception ’’ ’’)

*** Latent heat:**
- **Gandia**: Strongly positive interaction
- **Tous**: ’’ ’’ ’’

CONCLUSIONS (I)- Lecture 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**

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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)- Lecture 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- 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 **???**

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PIECEWISE PV INVERSION