MODELIZACIÓN DE PROCESOS DINÁMICOS EN LA ATMÓSFERA

Curs d’estiu UIB
“L’oceà i l’atmosfera vistos a través del models numèrics”
(Palma, Juliol 2010)

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SIMULACIÓN/PREDICCIÓN NUMÉRICA DEL TIEMPO

1) OBJETIVO: Predecir el estado futuro de la circulación atmosférica a partir de su estado presente mediante aproximaciones numéricas de las ecuaciones dinámicas

Distribución inicial 3-dimensional de *P, T, u, v, q* (*s*,*l*,*v*):
- Observaciones SYNOP, TEMP ...
- Análisis objetivo
- Inicialización

\+

Sistema cerrado de ecuaciones ∂t que las relacionan

\+

Método de integración numérica de las ecuaciones

\+ Condiciones de contorno → Distribución futura de las variables meteorológicas → + Interpretación humana → PREDICCIÓN ÚTIL

- Diagnóstico / MOS
- Modelos conceptuales
- Efectos regionales

2) HISTORIA:

a) L. F. Richardson (≈ 1920): Primer intento

Ecuaciones diferenciales → Sistema algebraico de ecuaciones de diferencias para las tendencias sobre nº finito de puntos en el espacio: Tendencias → $\varphi(t+\delta t)$

Meses de cálculo (64000 personas en la práctica) !! Resultados pobres: ΔPs >> observado

Debido a falta de sondeos ? NO Sus ecuaciones contenían ondas sonoras y gravitatorias

b) Tras 2ª Guerra Mundial:

Auténtica red de observación meteorológica → Estado inicial

Desarrollo de computadoras digitales

Ondas lentas (interés meteorológico)	*vs*	~~Ondas sonoras/gravitatorias (sin relevancia meteorológica)~~

↓ Inestabilidad numérica

Amplificación espúrea (ruido)

c) J. G. Charney (1948): Aprox. geostrófica/hidrostática QG → Modelos filtrados

"Modelo barotrópico equivalente" → 1ª predicción con éxito (1950)
Daba ϕ a ≈500 hPa (relación sfc)

Versiones multinivel del modelo QG → Psfc, Tsfc

Calidad de la predicción limitada debido a las aproximaciones del modelo QG

d) Últimas décadas:

Supercomputadoras
+
Técnicas sofisticadas de modelización → Modelos de ecuaciones primitivas (mucho más precisos y adecuados para la mesoescala: 2-2000 km)

MODELO BAROTRÓPICO

$$\frac{d(\zeta + f)}{dt} = 0$$

Ecuación de vorticidad barotrópica (conservación de la vorticidad absoluta)

En forma euleriana: $\frac{\partial \zeta}{\partial t} = -\vec{V} \cdot \vec{\nabla}(\zeta + f)$

Plano β

$f = f_0 + \beta y \qquad \beta \equiv \left.\frac{df}{dy}\right|_{\phi_0} = 2\Omega \cos\phi_0 / R_T$

$\vec{V}$ es no divergente

$\vec{V} \equiv \vec{V}_\psi = \hat{k} \times \vec{\nabla}\psi \qquad \zeta = \nabla^2 \psi$

$$\nabla^2\left(\frac{\partial \psi}{\partial t}\right) = \frac{\partial \psi}{\partial y}\frac{\partial}{\partial x}\left(\nabla^2 \psi\right) - \frac{\partial \psi}{\partial x}\frac{\partial}{\partial y}\left(\nabla^2 \psi\right) - \beta \frac{\partial \psi}{\partial x} \qquad (1)$$

A partir de la ecuación de divergencia para movimientos de escala sinóptica a latitudes medias:

$$\psi = \frac{\phi}{f_0} \qquad (2)$$

donde $\phi = gz$ (geopotencial) y por lo tanto $\vec{V}_\psi = \vec{V}_g$ (viento geostrófico)

La resolución de (1) y (2) nos dará la evolución de la onda de geopotencial de los sistemas sinópticos, aunque las aproximaciones utilizadas implican que los sistemas únicamente se podrán trasladar, pero no desarrollarse (no aparece el término de divergencia en (1))

EJERCICIO PRÁCTICO

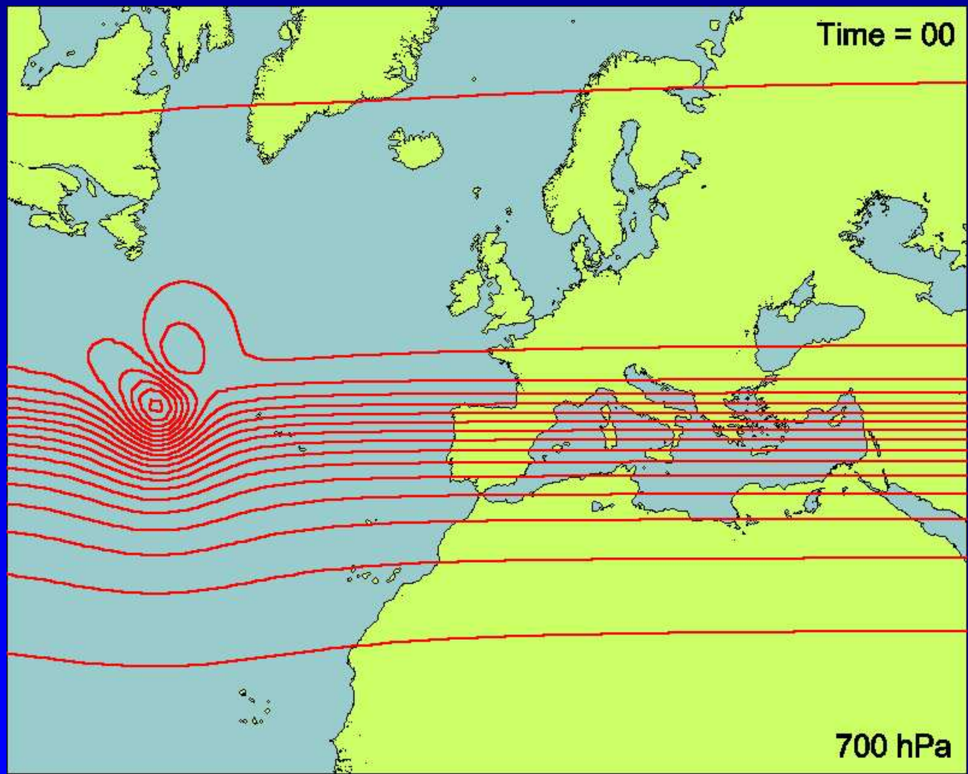
Programar el modelo barotrópico y predecir la evolución de estos estados atmosféricos:

I. Caso analítico (funciones de Lai, 1988):

$$z(x,y,500) = 5430 - 143\tan^{-1}\left[\left(\frac{y - y_c \pm y_1}{2000}\right)\right] - 160\left[\left(\frac{x - x_c + x_1}{400}\right)^2 + \left(\frac{y - y_c + y_1}{500}\right)^2 + 1\right]^{-1}$$

$$z(x,y,p) = z(x,y,500) + \ldots \left(\frac{p - 500}{200}\right), \quad 300 \le p \le 700$$

7200 km



9000 km

$$\begin{cases} x_c = 1500 \text{ km} \\ y_c = 3600 \text{ km} \end{cases}$$

$$\begin{cases} x_1 = 50 \text{ km} \\ y_1 = 150 \text{ km} \end{cases}$$

Predicción a 4 días

101 x 81 nodos

Δs = 90 km

Δt = 1800 s

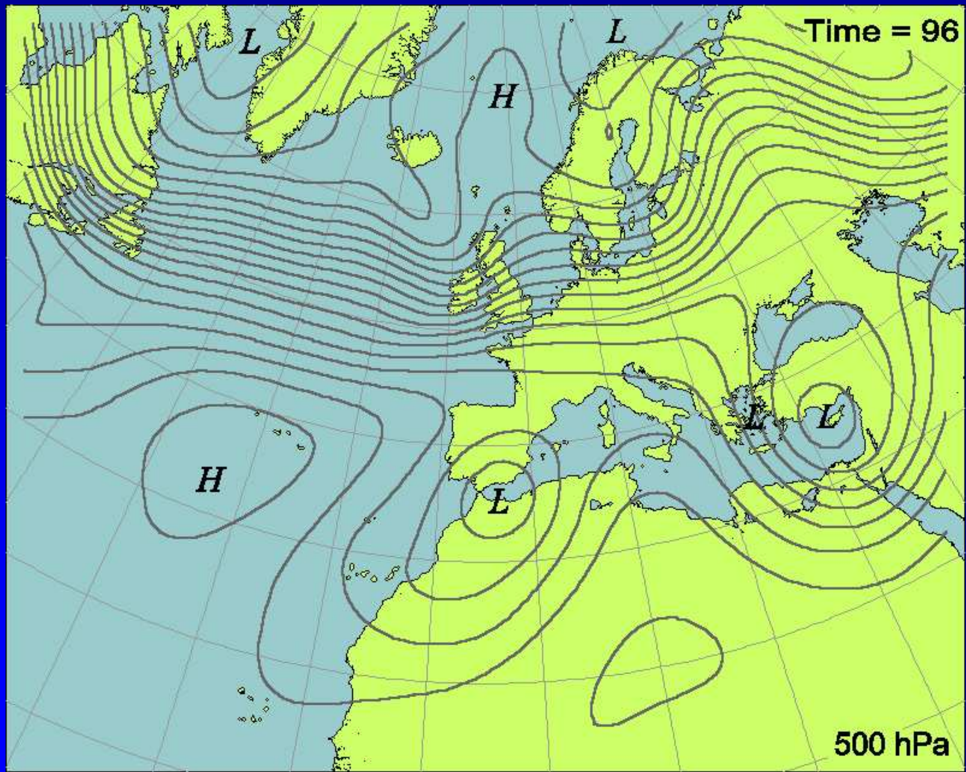
EJERCICIO PRÁCTICO

Programar el modelo barotrópico y predecir la evolución de estos estados atmosféricos:

II. Caso real (21 de Octubre de 2000, 00 UTC):

- Formación de una "gota fría" al sur de la Península Ibérica que dura varios días
- Lluvias intensas sobre el este peninsular que provocan inundaciones y graves daños

7200 km



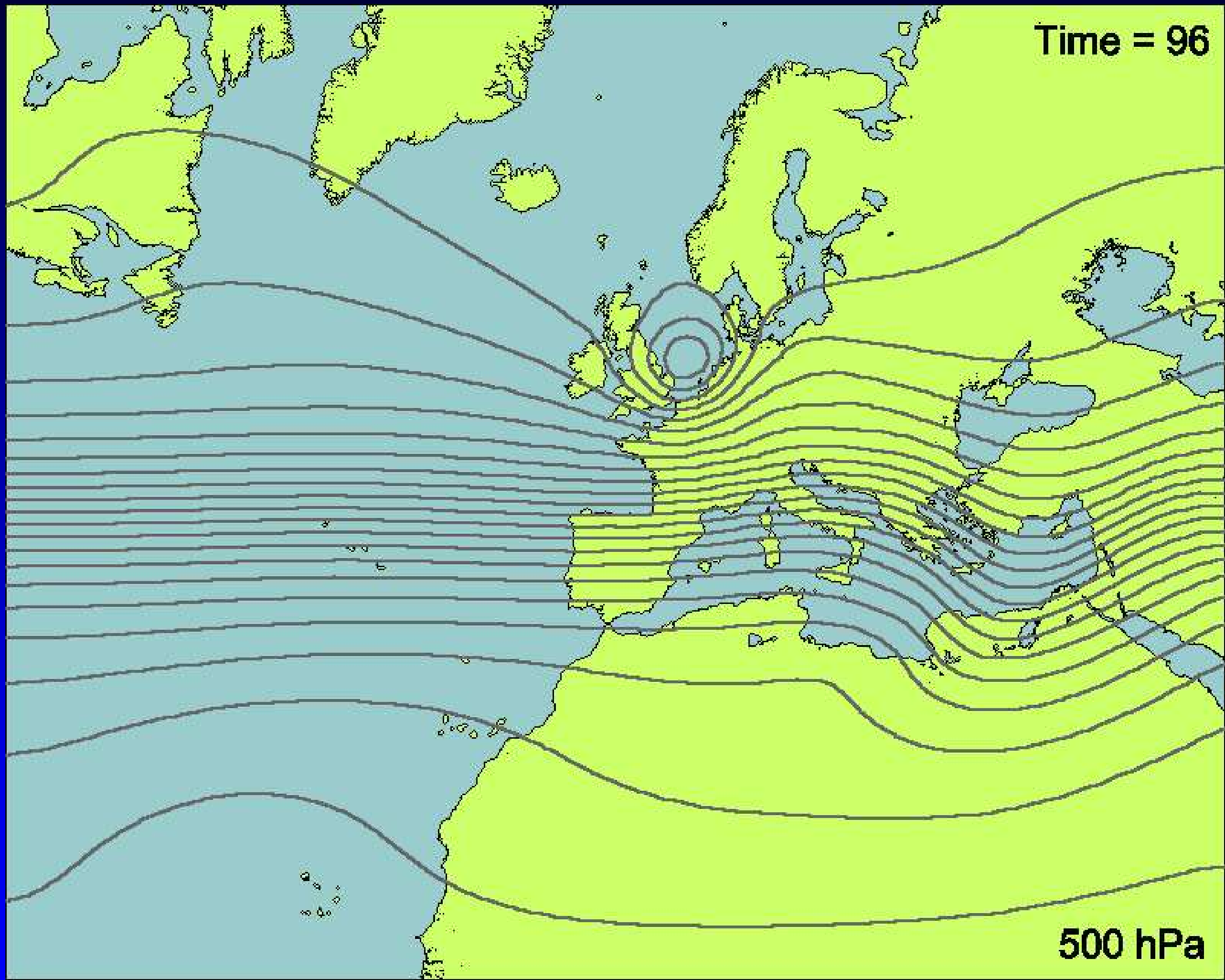
9000 km

Predicción a 4 días

101 x 81 nodos
Δs = 90 km
Δt = 900 s

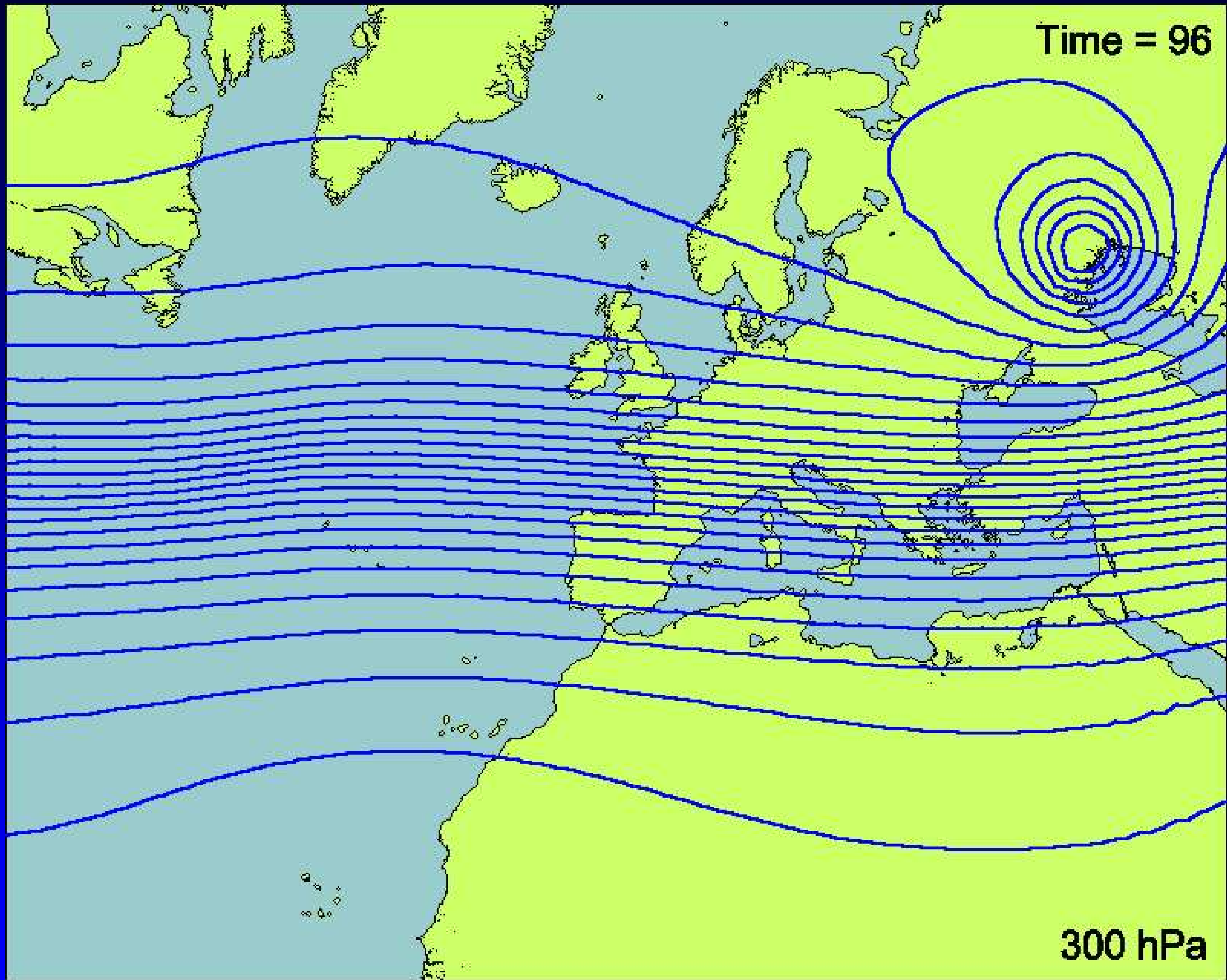
f real / c.c. variables

MODELO BAROTRÓPICO: I. Caso analítico / 500 hPa



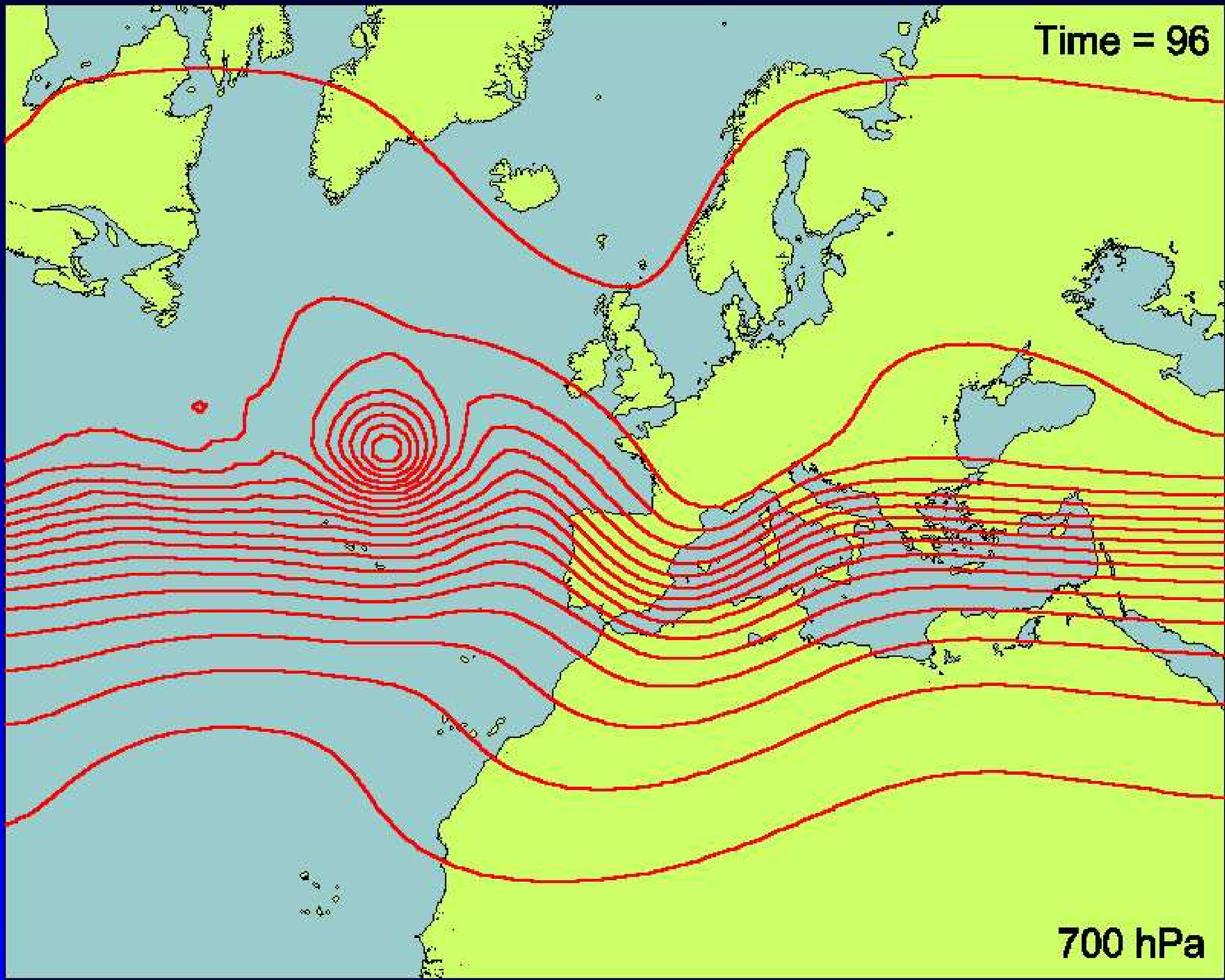
- Las ondas cortas se propagan hacia el E, pero las ondas largas lo hacen hacia el W
- En su traslación hacia el N (f crece), disminuye la vorticidad relativa de la perturbación

MODELO BAROTRÓPICO: I. Caso analítico / 300 hPa



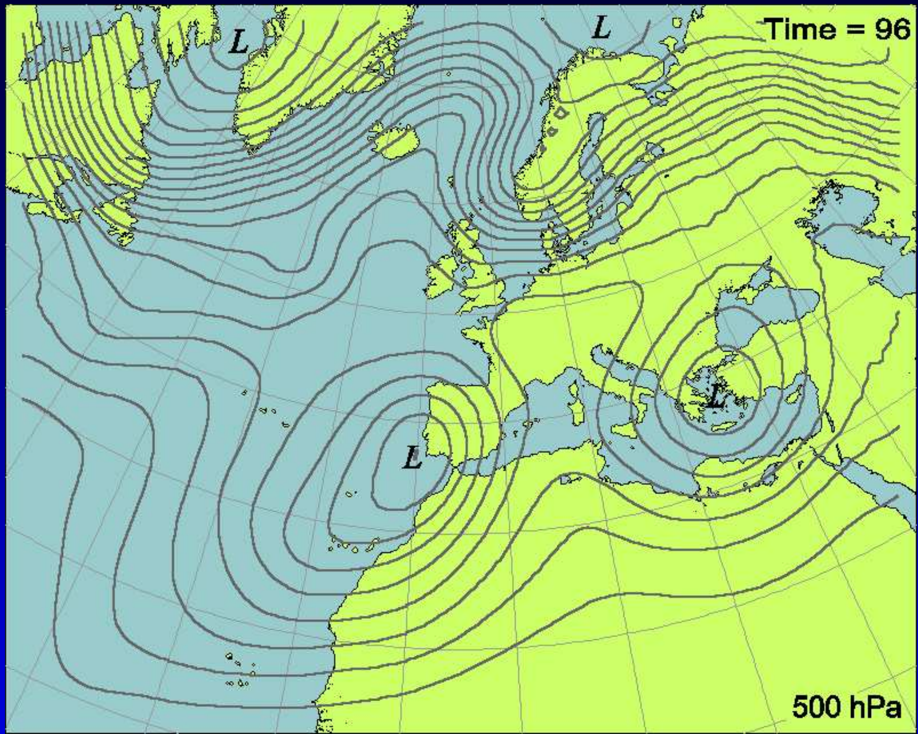
- Una evolución barotrópica a niveles altos (vientos fuertes), es demasiado rápida
- En la atmósfera real, la convergencia/divergencia se opone a los efectos advectivos

MODELO BAROTRÓPICO: I. Caso analítico / 700 hPa

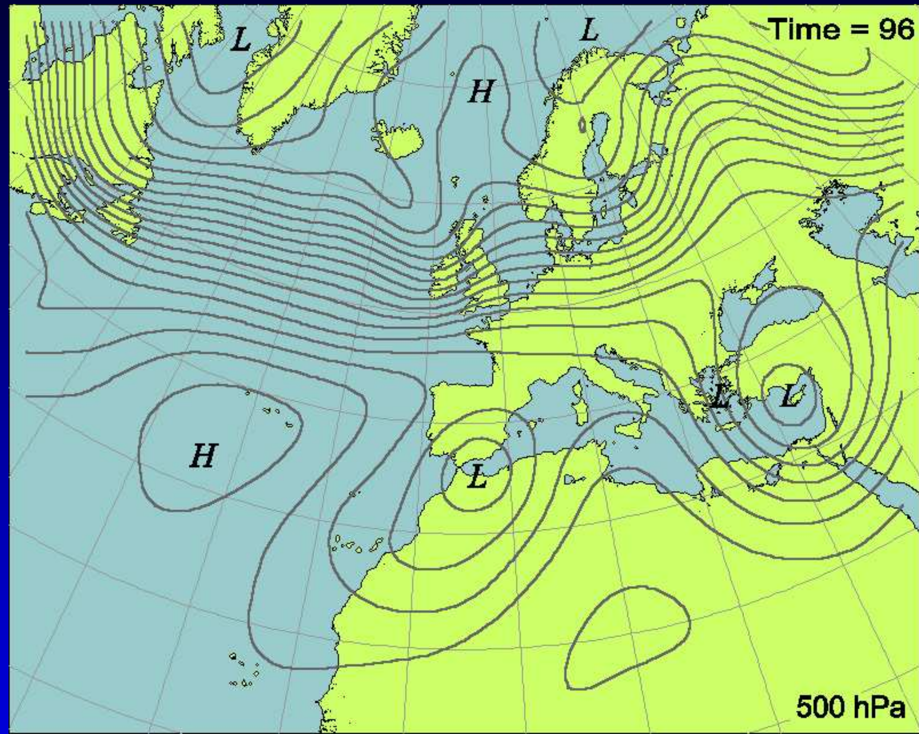


- Una evolución barotrópica a niveles bajos (vientos débiles), es demasiado lenta
- En la atmósfera real, la convergencia/divergencia refuerza los efectos advectivos

MODELO BAROTRÓPICO: I. Caso real / 500 hPa



PREDICCIÓN



OBSERVACIÓN

- Un simple modelo barotrópico reproduce razonablemente bien la evolución a 500 hPa
- Climatológicamente, la troposfera media comprende el nivel de divergencia nula

MODELO BAROTRÓPICO EQUIVALENTE

Ecuación de vorticidad QG: $\frac{\partial \zeta}{\partial t} + \vec{V}_\psi \cdot \nabla(\zeta + f) = f_0 \frac{\partial \omega}{\partial p} \quad [= -f_0 D]$ (1)

Ecuación de divergencia QG: $f_0 \nabla^2 \psi = \nabla^2 \phi \longrightarrow \psi = \frac{\phi}{f_0} \quad \vec{V}_\psi = \vec{V}_g$ (2)

Se asume que el viento no cambia de dirección con la altura (omitimos subíndice ψ):

$$\vec{V}(x,y,p,t) = A(p)\overline{\vec{V}}(x,y,t) \tag{3}$$

donde el valor medio en la vertical es: $\overline{\Delta} = \frac{1}{p_0}\int_0^{p_0 = 1000\,hPa} \Delta dp \longrightarrow \overline{A} = 1$

A partir de datos climatológicos de latitudes medias: $\overline{A^2} = 1.25 \longrightarrow p^* \approx 500$ hPa

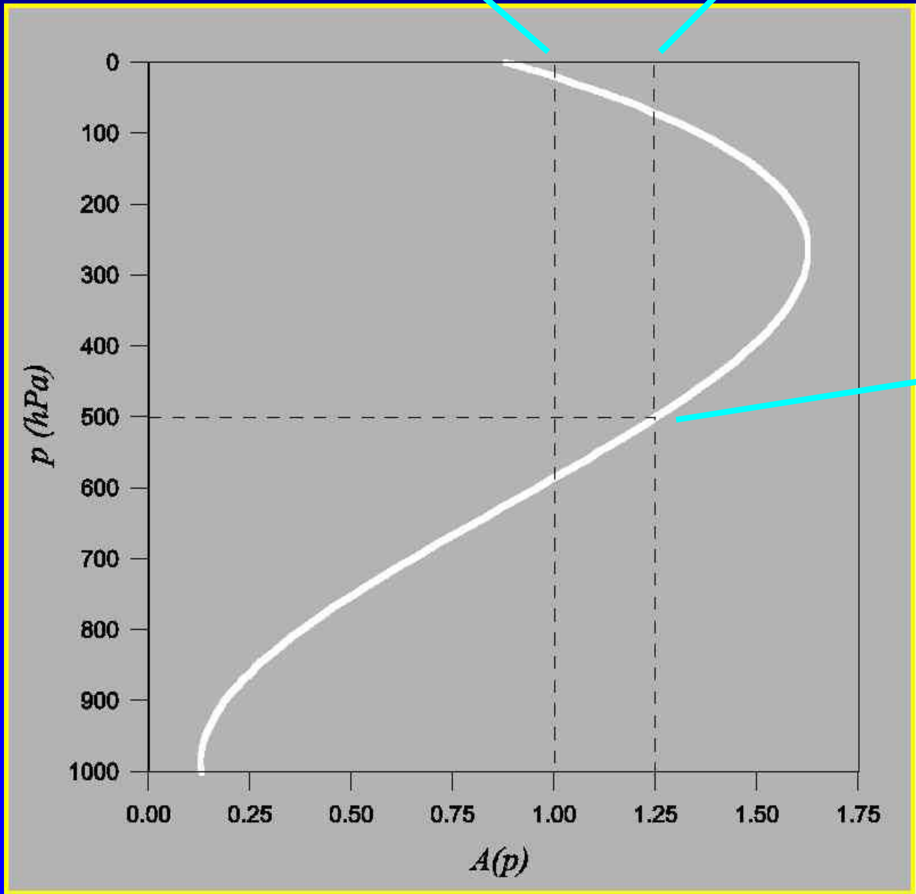
(cte sobre toda la región)

EJERCICIO PRÁCTICO

Programar el modelo barotrópico equivalente y resolverlo para los casos propuestos.

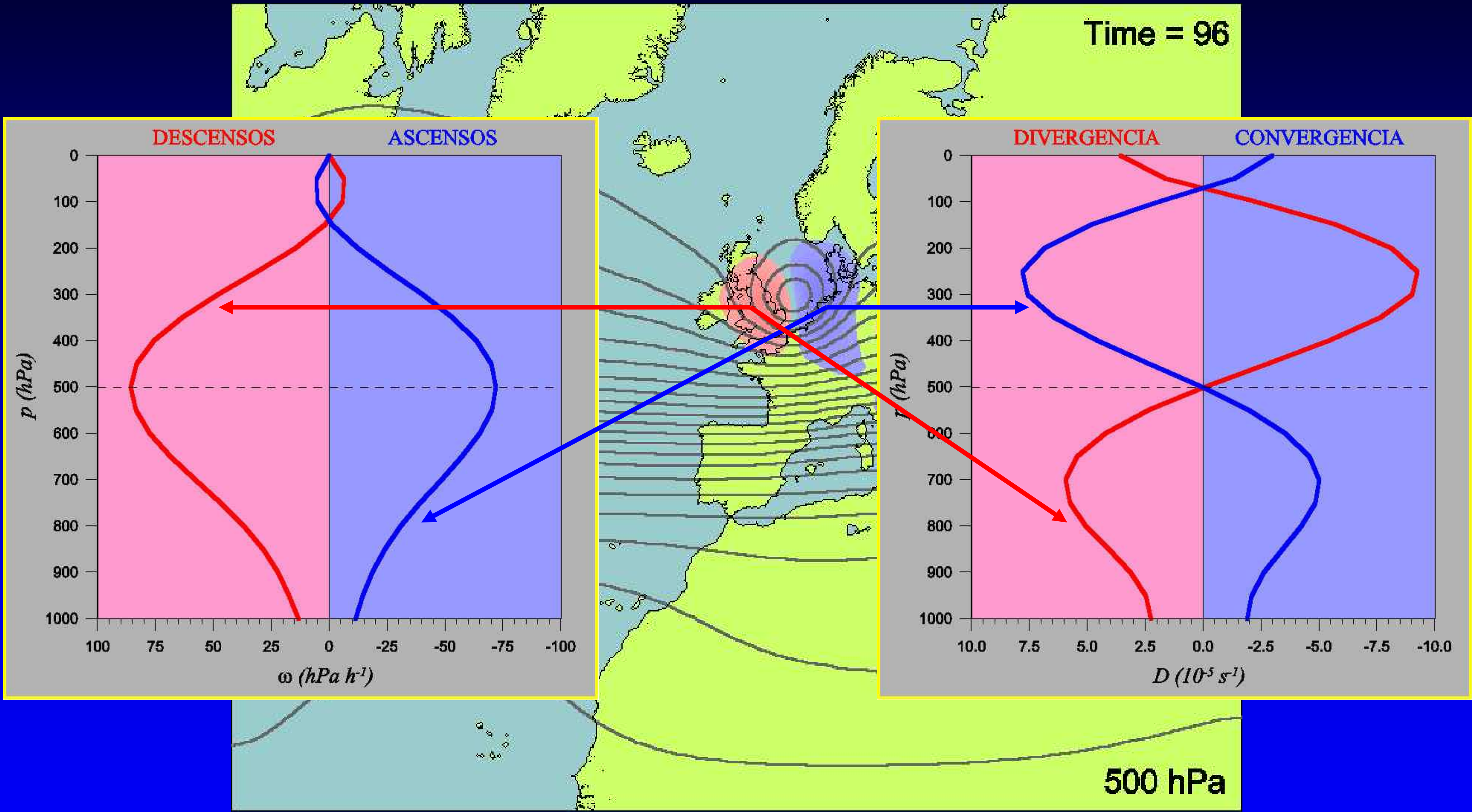
- Perfil A(p) del viento geostrófico: $A(p) = 7.94 \cdot 10^{-9} p^3 - 1.49 \cdot 10^{-5} p^2 + 6.21 \cdot 10^{-3} p + 0.88$

$\overline{A} = 1$ $\quad\quad$ $\overline{A^2} = 1.25$



$A(500\,\text{hPa}) = \overline{A^2}$

MODELO BAROTRÓPICO EQUIVALENTE: I. Caso analítico / 500 hPa



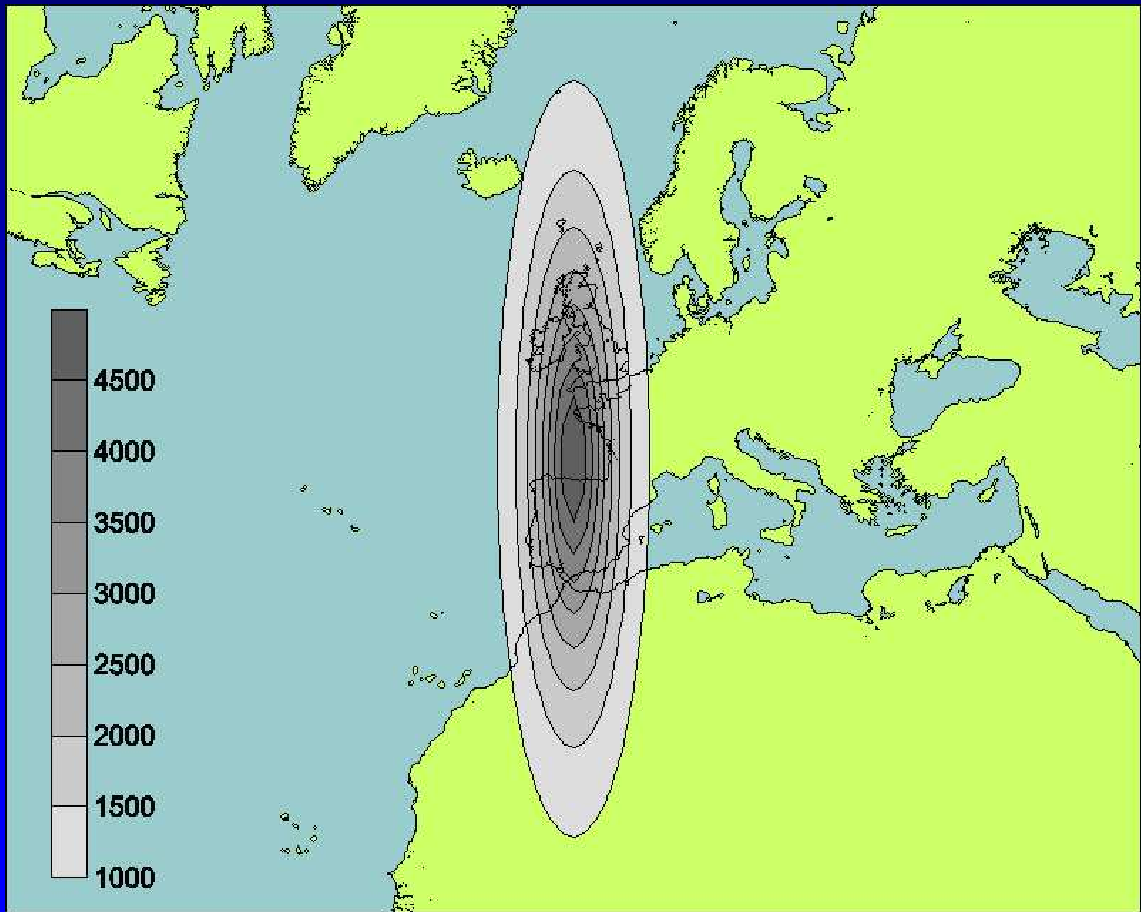
- Escala sinóptica: Ascensos delante de la vaguada / Descensos detrás de la vaguada
- Máximos a 500 hPa (≈ nivel de divergencia nula): Perfil de Convergencia/Divergencia

¿EN QUÉ MEDIDA INFLUYE LA OROGRAFÍA?

→ Repetir la predicción anterior, pero considerando orografía en lugar de superficie plana

- Orografía z_s según la función de Agnesi:

$$z_s(x,y) = h\left[1+\left(\frac{x-x_c}{a}\right)^2+\left(\frac{y-y_c}{b}\right)^2\right]^{-1}$$

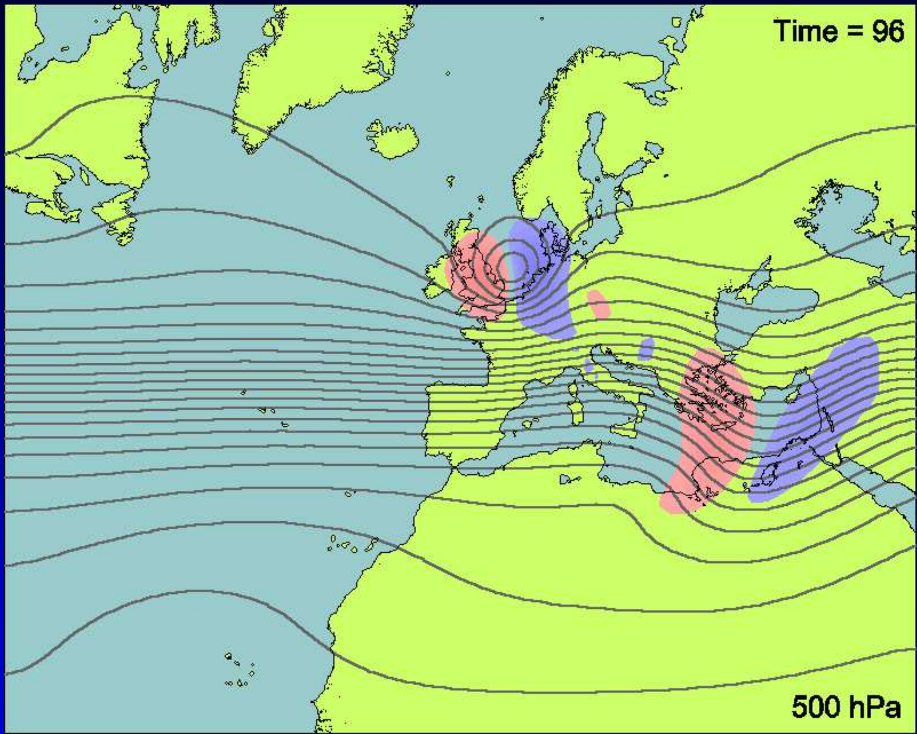


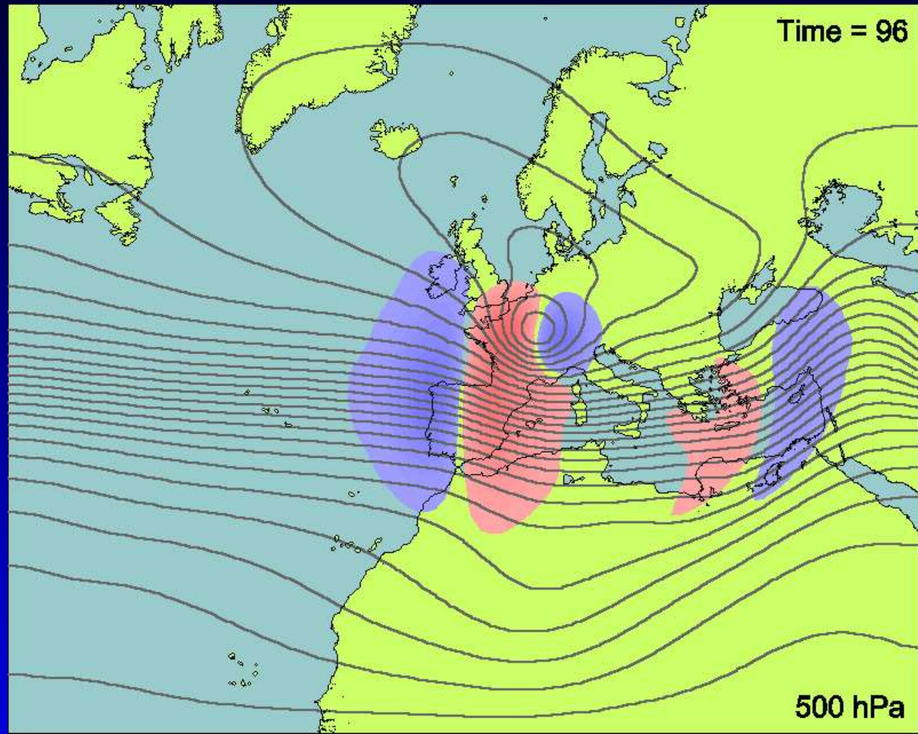
$h = 5000\ \mathrm{m}$

$$\begin{cases} x_c = 4500\ \mathrm{km} \\ y_c = 3600\ \mathrm{km} \end{cases}$$

$$\begin{cases} a = 300\ \mathrm{km} \\ b = 1500\ \mathrm{km} \end{cases}$$

MODELO BAROTRÓPICO EQUIVALENTE: I. Caso analítico / 500 hPa





SIN OROGRAFÍA

CON OROGRAFÍA

- La cadena montañosa induce ciclogénesis al E y anticiclogénesis al W
- Al superar la cordillera, la baja se desvía hacia el S, es mayor y se extiende hacia el NW

MODELO BAROCLINO MULTINIVEL

Se admite que el viento geostrófico (dirección y magnitud) pueda variar libremente en la vertical:

Ecuación de vorticidad QG: $\frac{\partial \zeta}{\partial t} + \vec{V}_\psi \cdot \nabla(\zeta + f) = f_0 \frac{\partial \omega}{\partial p}$ $[= -f_0 D]$ (1)

Ecuación de divergencia QG: $f_0 \nabla^2 \psi = \nabla^2 \phi \longrightarrow \psi = \frac{\phi}{f_0} \quad \vec{V}_\psi = \vec{V}_g$ (2)

+ 1ª Ley de la Termodinámica, tras aplicar la Ecuación hidrostática $T = -\frac{1}{pR_d} \frac{\partial \phi}{\partial p}$:

Ecuación termodinámica QG: $\frac{\partial}{\partial t} \frac{\partial \phi}{\partial p} + \vec{V}_g \cdot \nabla \frac{\partial \phi}{\partial p} + \sigma \omega = -Q$ (3)

donde el parámetro de estabilidad estática $\sigma = \frac{\partial \phi}{\partial p} \frac{\partial \ln \theta}{\partial p} \approx \sigma_s(p)$ y el calor diabático $Q \approx 0$

Las ecuaciones (1), (2) y (3) forman un sistema cerrado de predicción para el dominio 3D, donde para resolver la ecuación (1) para la tendencia χ, se requiere ω. Ésta puede calcularse de un modo diagnóstico mediante la Ecuación ω, que resulta de hacer:

$$\nabla^2(3) - f_0 \frac{\partial}{\partial p}(1) \longrightarrow \sigma_s \nabla^2 \omega + f_0^2 \frac{\partial^2 \omega}{\partial p^2} = f_0 \frac{\partial}{\partial p}\left[\vec{V}_g \cdot \nabla(\zeta + f)\right] - \nabla^2\left(\vec{V}_g \cdot \nabla \frac{\partial \phi}{\partial p}\right) \quad (4)$$

EJERCICIO PRÁCTICO

➜ Programar el modelo baroclino multinivel y resolverlo para los casos propuestos.

I. Caso analítico:

Predicción a 2 días

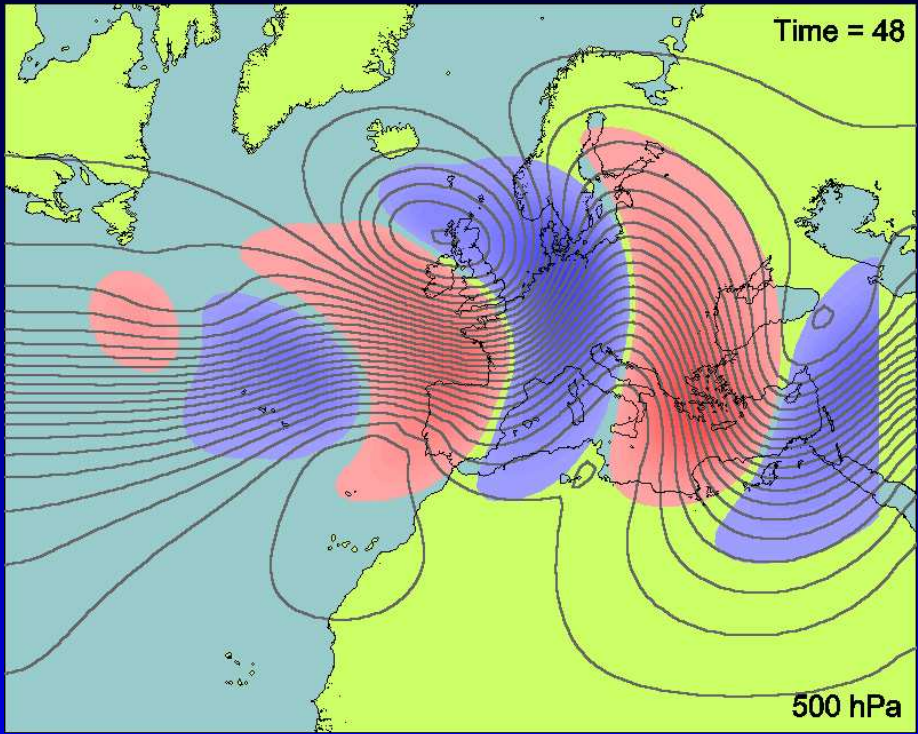
3 niveles: 300, 500 y 700 hPa

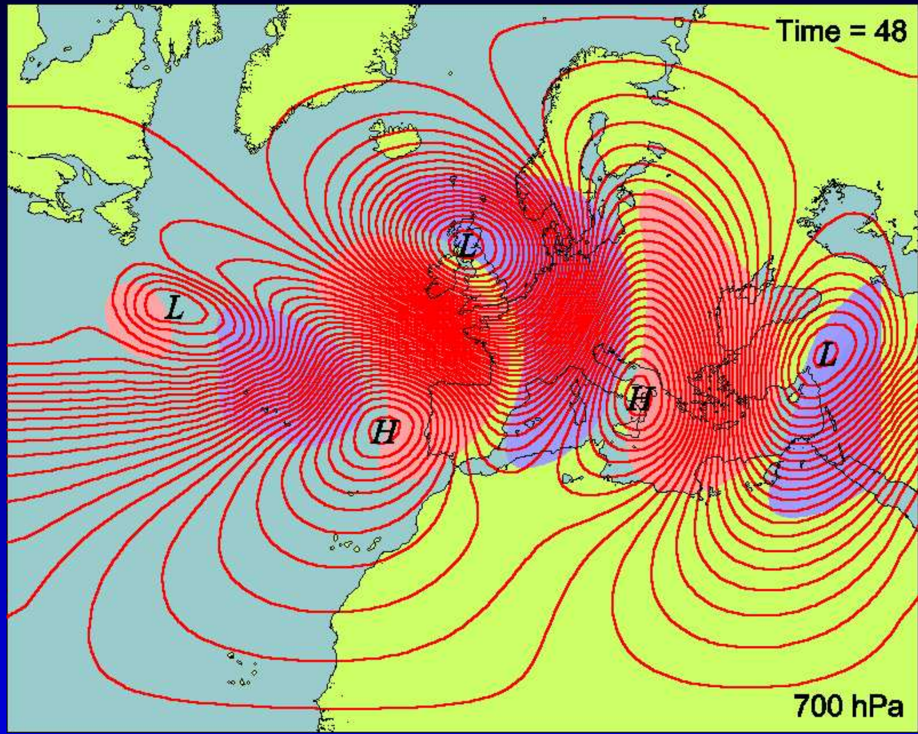
II. Caso real:

Predicción a 4 días

10 niveles: 50, 150, 250, 350, 450, 550, 650, 750, 850, 950 hPa

MODELO BAROCLINO MULTINIVEL: I. Caso analítico / 500 y 700 hPa



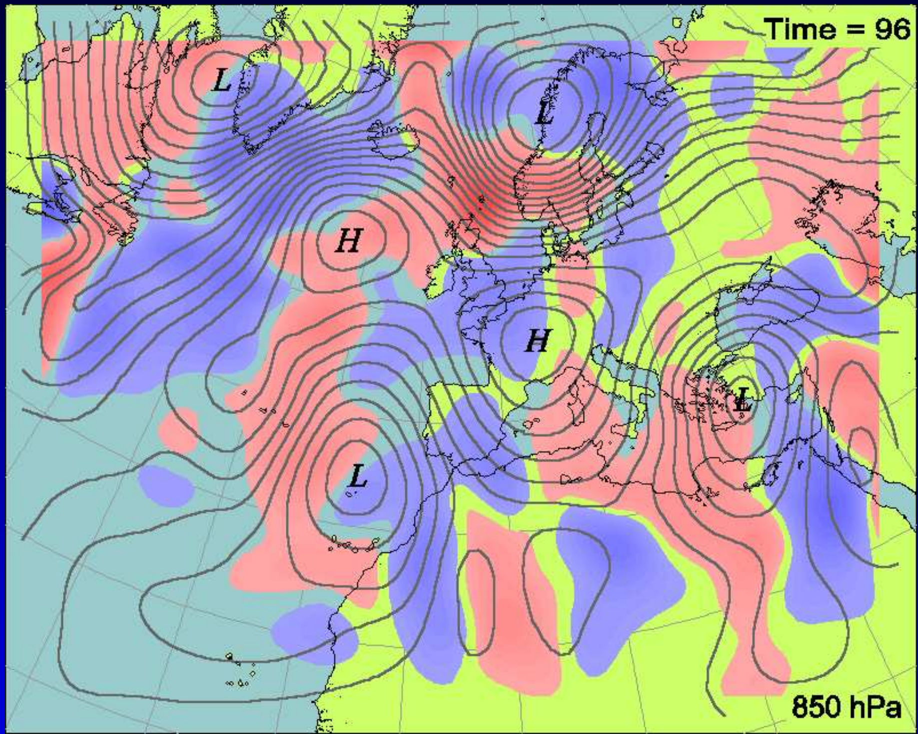


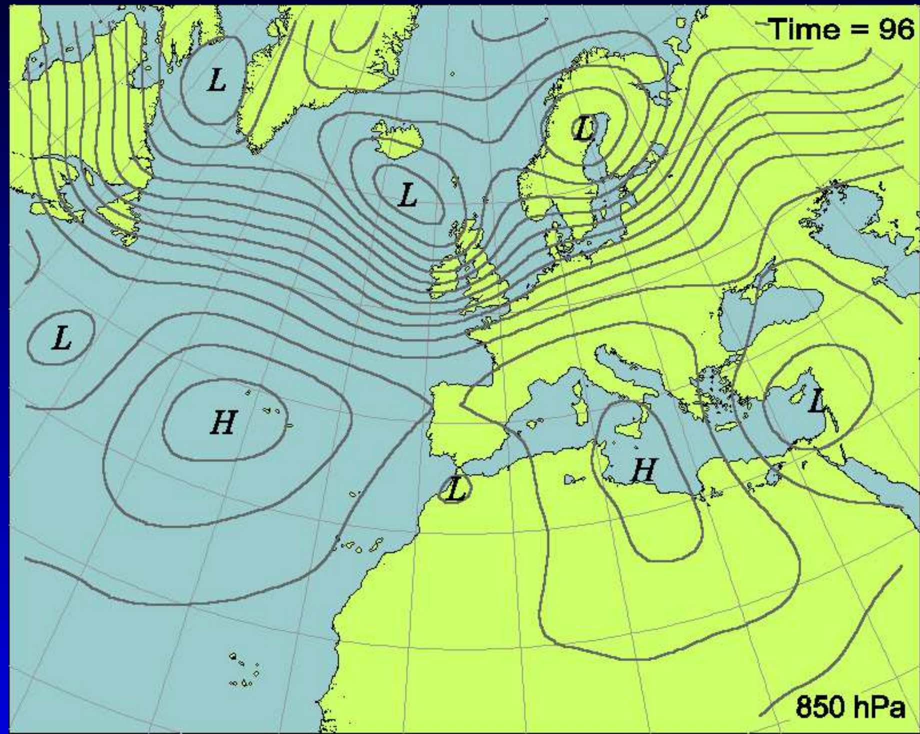
500 hPa

700 hPa

- Pequeñas perturbaciones crecen rápidamente por la inestabilidad baroclina del fluido
- La inclusión de fricción y procesos físicos en el modelo limitaría dicha amplificación

MODELO BAROCLINO MULTINIVEL: I. Caso real / 850 hPa





PREDICCIÓN

OBSERVACIÓN

- Con este modelo, la predictabilidad de la situación a partir de 48 h es bastante baja
- Como en el caso previo, las altas y bajas presiones se amplifican excesivamente

NOCIONES DE UN MODELO METEOROLÓGICO DE ECUACIONES PRIMITIVAS: EL CASO DEL MM5

1.1 Introduction to MM5 Modeling System

The Fifth-Generation NCAR / Penn State Mesoscale Model is the latest in a series that developed from a mesoscale model used by Anthes at Penn State in the early '70's that was later documented by Anthes and Warner (1978). Since that time it has undergone many changes designed to broaden its usage. These include (i) a multiple-nest capability, (ii) nonhydrostatic dynamics, and (iii) a four-dimensional data assimilation capability as well as more physics options, and portability to a wider range of computing platforms. These changes have effects on how jobs are set up using the modeling system, so the purpose of this introduction is to acquaint the user with some concepts as used in the MM5 system.

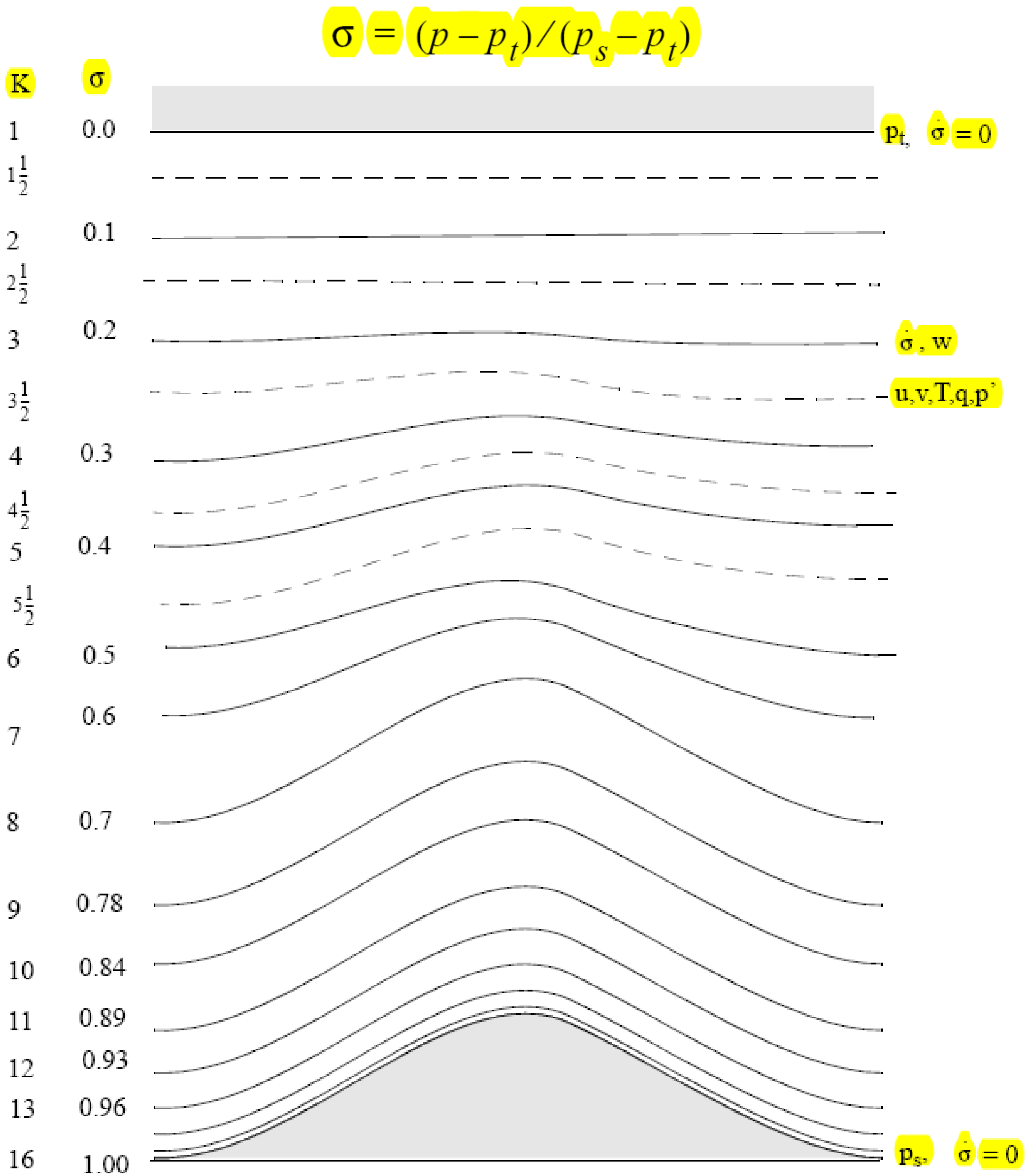


Figure 1.2 Schematic representation of the vertical structure of the model. The example is for 15 vertical layers. Dashed lines denote half-sigma levels, solid lines denote full-sigma levels.

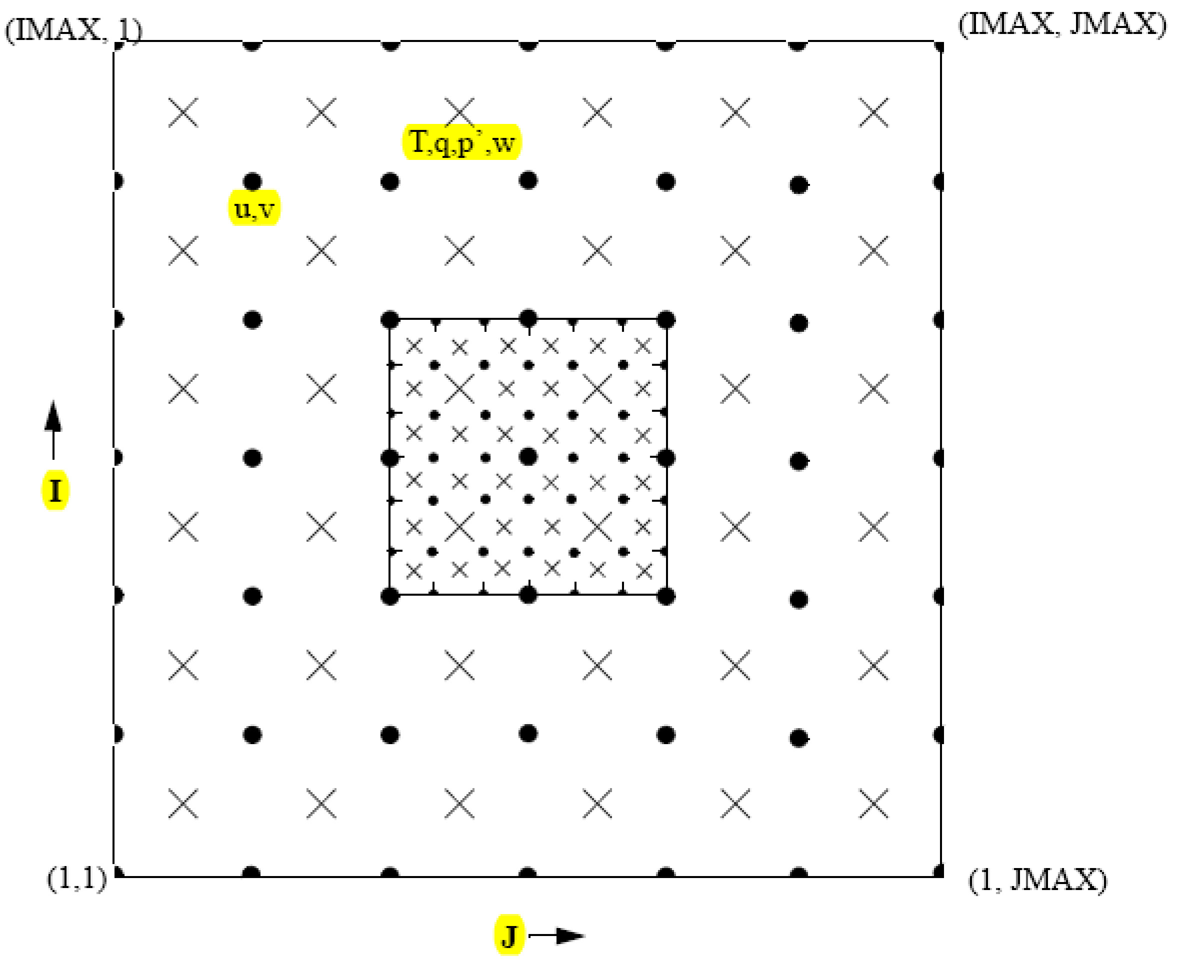


Figure 1.3 Schematic representation showing the horizontal Arakawa B-grid staggering of the dot (l) and cross (x) grid points. The smaller inner box is a representative mesh staggering for a 3:1 coarse-grid distance to fine-grid distance ratio.

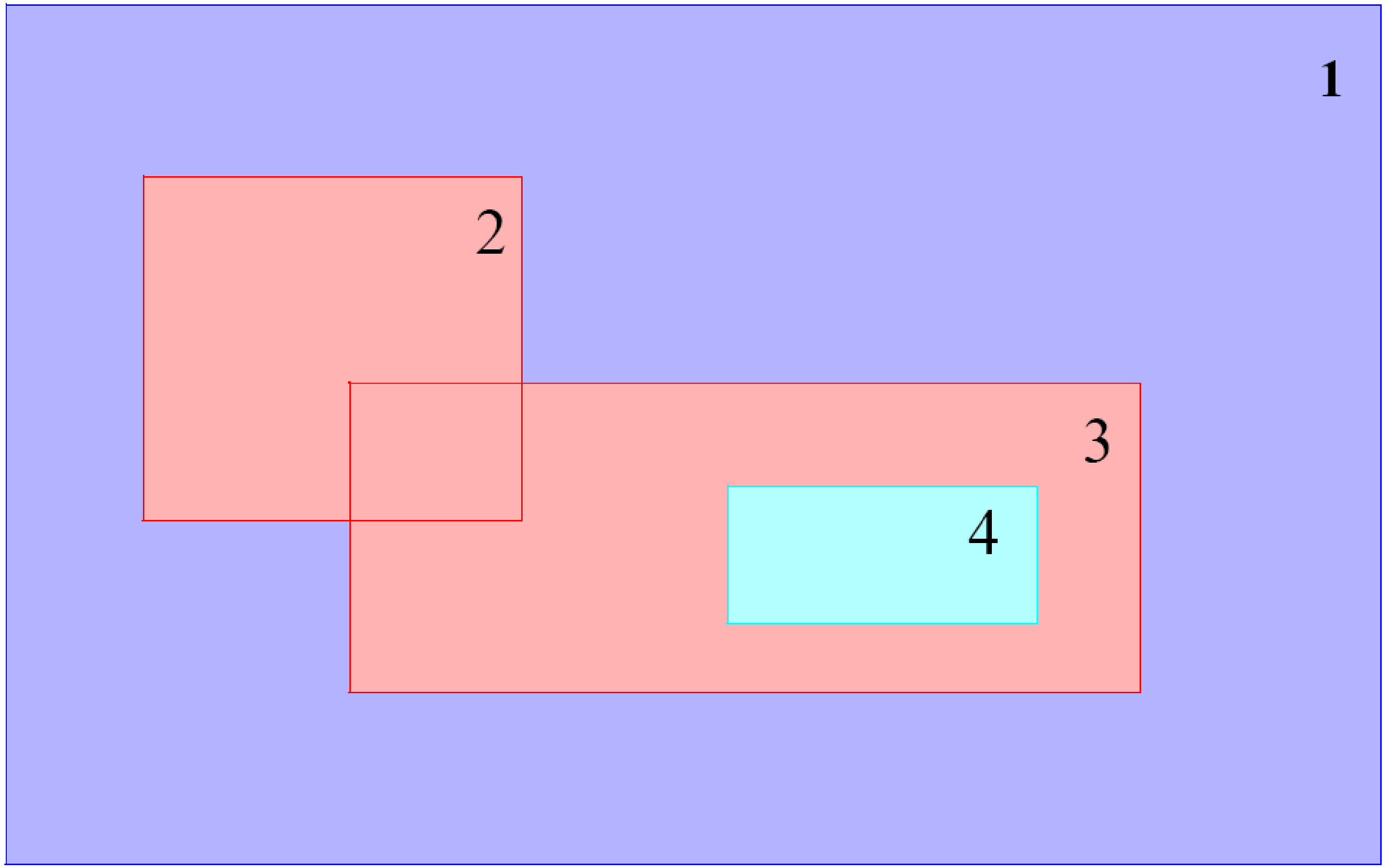
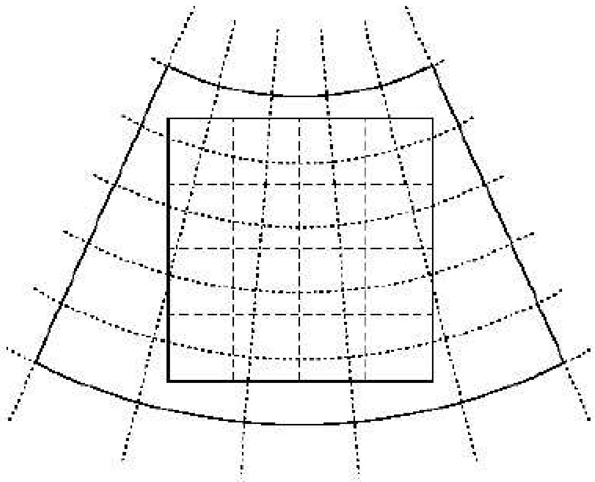
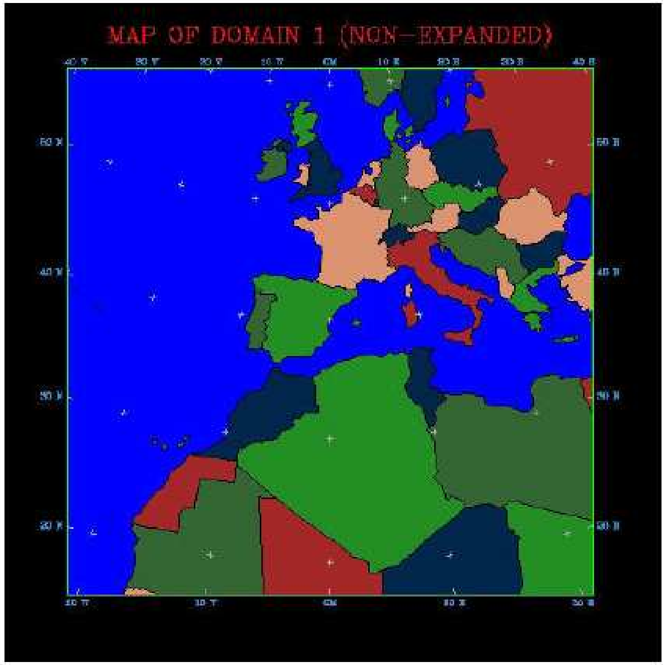
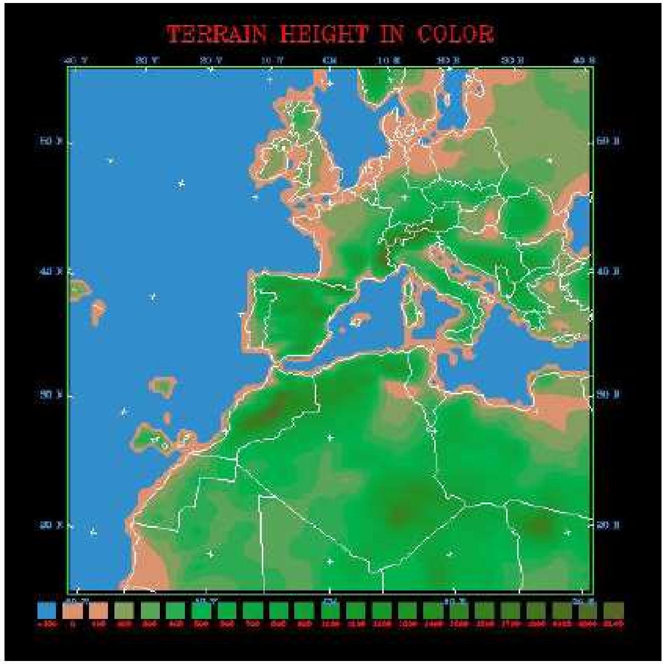
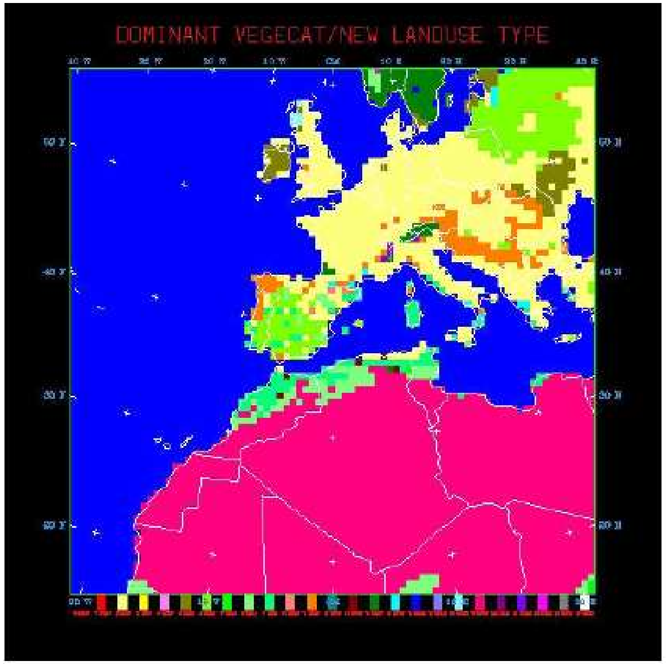


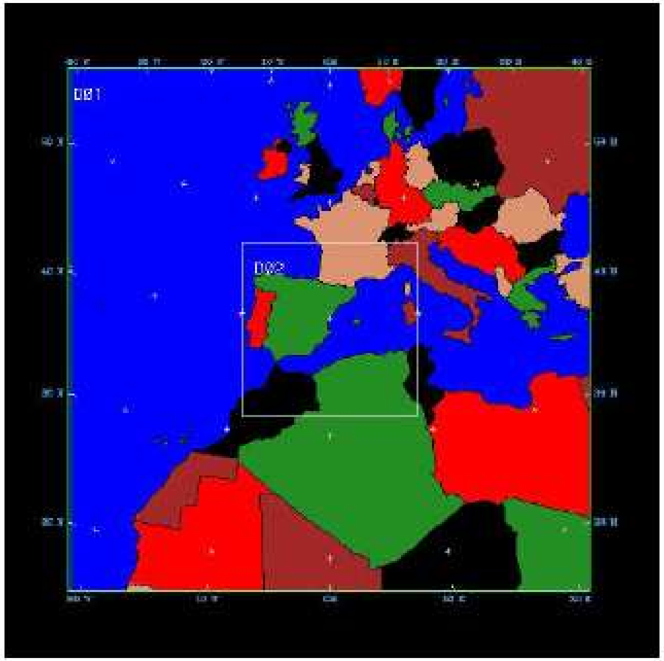
Fig 1.4 Example of a nesting configuration. The shading shows three different levels of nesting.

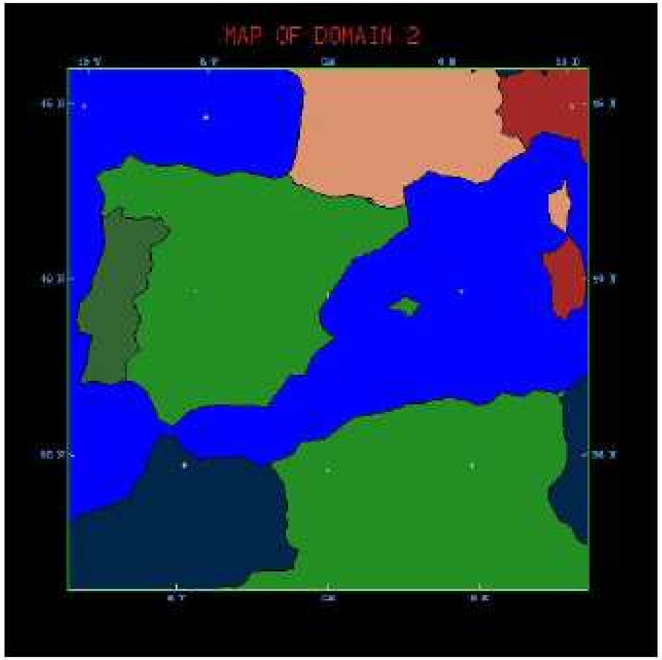


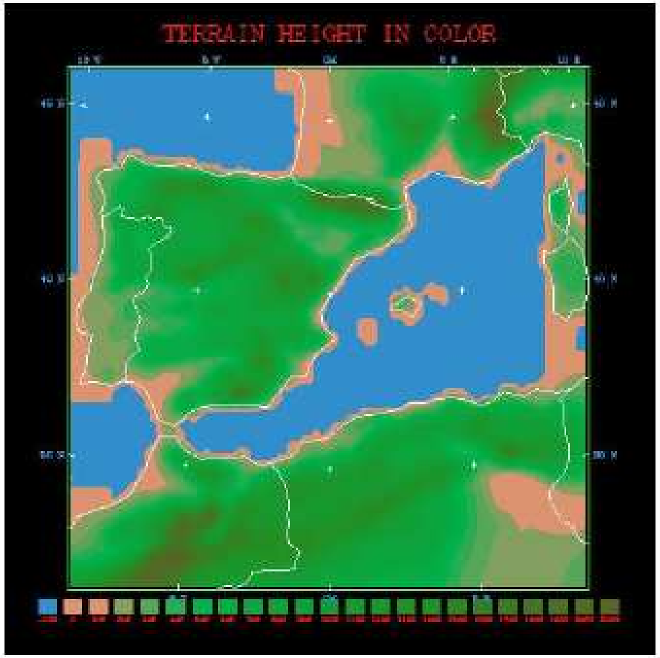

MAP OF DOMAIN 1 (NON-EXPANDED)

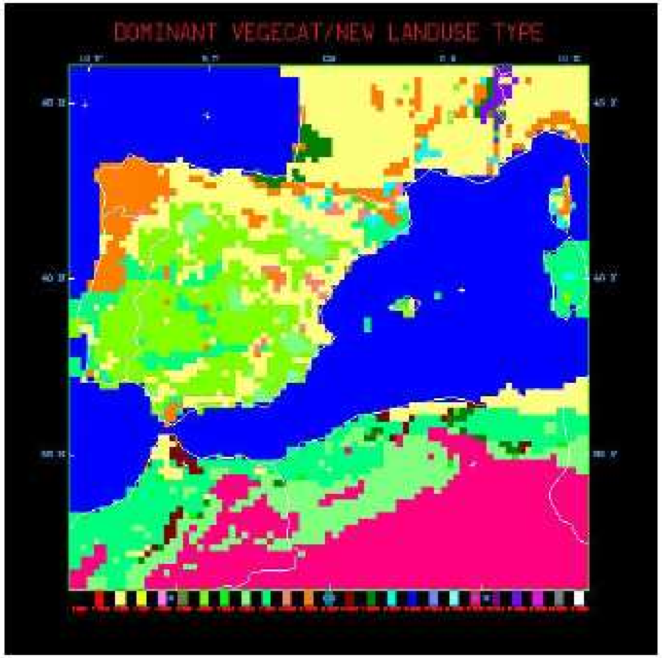

TERRAIN HEIGHT IN COLOR

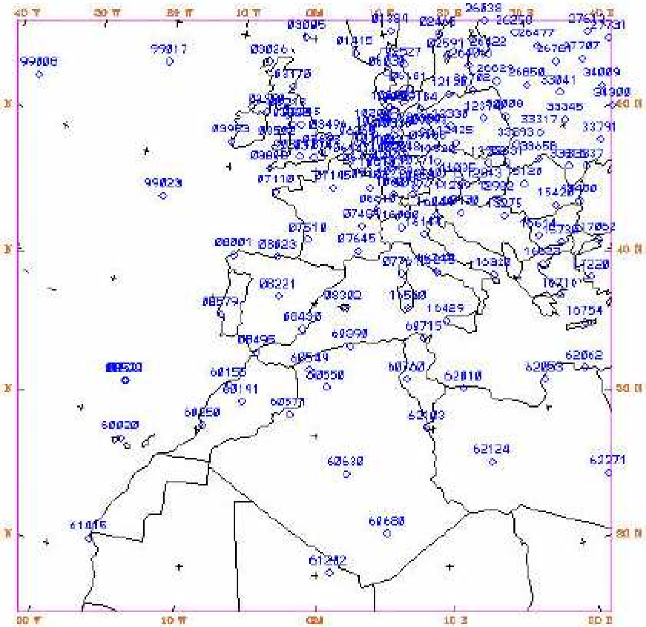

DOMINANT VEGECAT/NEW LANDUSE TYPE


D01
D02

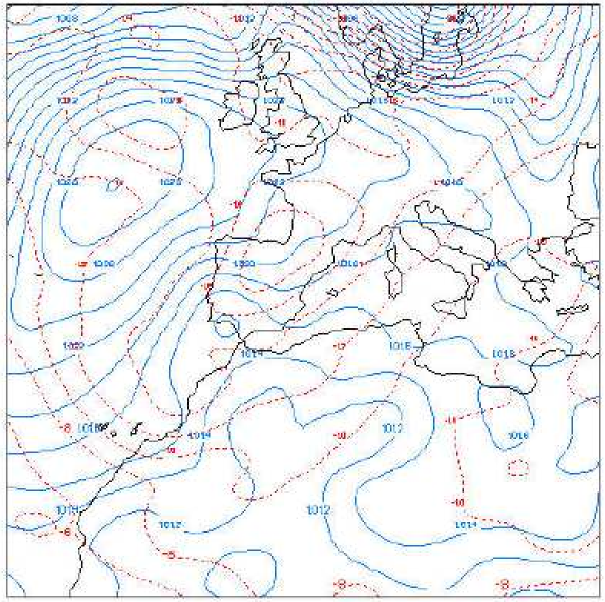

MAP OF DOMAIN 2


TERRAIN HEIGHT IN COLOR


DOMINANT VEGECAT/NEW LANDUSE TYPE

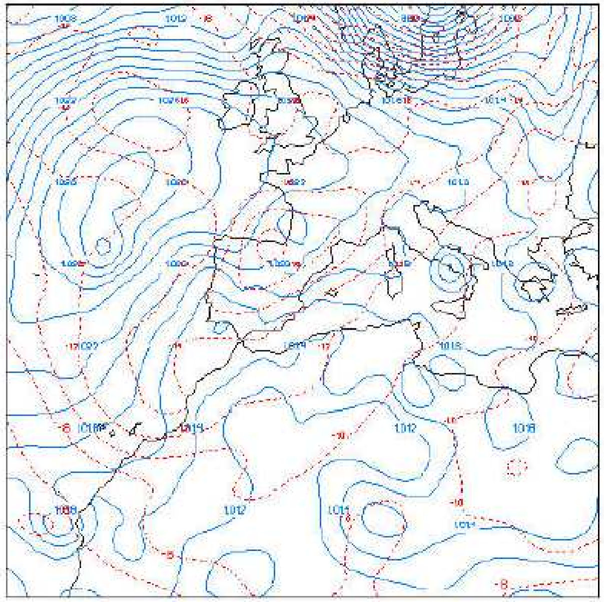


SLP and T500 28 September 1994 / 00 UTC



REGRID

SLP and T500 28 September 1994 / 00 UTC



RAWINS

8.1 Purpose

- This is the numerical weather prediction part of the modeling system.
- MM5 can be used for a broad spectrum of theoretical and real-time studies, including applications of both predictive simulation and four-dimensional data assimilation to monsoons, hurricanes, and cyclones.
- On the smaller meso-beta and meso-gamma scales (2-200 km), MM5 can be used for studies involving mesoscale convective systems, fronts, land-sea breezes, mountain-valley circulations, and urban heat islands.

8.2 Basic Equations of MM5

In terms of terrain following coordinates (x, y, σ), these are the equations for the nonhydrostatic model's basic variables excluding moisture.

Pressure

$$\frac{\partial p'}{\partial t} - \rho_0 g w + \gamma p \nabla \cdot \mathbf{v} = -\mathbf{v} \cdot \nabla p' + \frac{\gamma p}{T}\left(\frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta\right) \quad (8.1)$$

Momentum (x-component)

$$\frac{\partial u}{\partial t} + \frac{m}{\rho}\left(\frac{\partial p'}{\partial x} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial p'}{\partial \sigma}\right) = -\mathbf{v}\cdot\nabla u + v\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) - ew\cos\alpha - \frac{uw}{r_{earth}} + D_u \qquad (8.2)$$

Momentum (y-component)

$$\frac{\partial v}{\partial t} + \frac{m}{\rho}\left(\frac{\partial p'}{\partial y} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial p'}{\partial \sigma}\right) = -\mathbf{v}\cdot\nabla v - u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) + ew\sin\alpha - \frac{vw}{r_{earth}} + D_v \qquad (8.3)$$

Momentum (z-component)

$$\frac{\partial w}{\partial t} - \frac{\rho_0}{\rho}\frac{g}{p^*}\frac{\partial p'}{\partial \sigma} + \frac{gp'}{\gamma p} = -\mathbf{v}\cdot\nabla w + g\frac{p_0}{p}\frac{T'}{T_0} - \frac{gR_d}{c_p}\frac{p'}{p} + e(u\cos\alpha - v\sin\alpha) + \frac{u^2+v^2}{r_{earth}} + D_w \qquad (8.4)$$

Thermodynamics

$$\frac{\partial T}{\partial t} = -\mathbf{v} \cdot \nabla T + \frac{1}{\rho c_p}\left(\frac{\partial p'}{\partial t} + \mathbf{v} \cdot \nabla p' - \rho_0 g w\right) + \frac{Q}{c_p} + \frac{T_0}{\theta_0} D_\theta \qquad (8.5)$$

Advection terms can be expanded as

$$\mathbf{v} \cdot \nabla A \equiv m u \frac{\partial A}{\partial x} + m v \frac{\partial A}{\partial y} + \dot{\sigma}\frac{\partial A}{\partial \sigma} \qquad (8.6)$$

where

$$\dot{\sigma} = -\frac{\rho_0 g}{p^*} w - \frac{m\sigma}{p^*}\frac{\partial p^*}{\partial x} u - \frac{m\sigma}{p^*}\frac{\partial p^*}{\partial y} v \qquad (8.7)$$

Divergence term can be expanded as

$$\nabla \cdot \mathbf{v} = m^2 \frac{\partial}{\partial x}\left(\frac{u}{m}\right) - \frac{m\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial u}{\partial \sigma} + m^2 \frac{\partial}{\partial y}\left(\frac{v}{m}\right) - \frac{m\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial v}{\partial \sigma} - \frac{\rho_0 g}{p^*}\frac{\partial w}{\partial \sigma} \qquad (8.8)$$

Illustration of Microphysics Processes

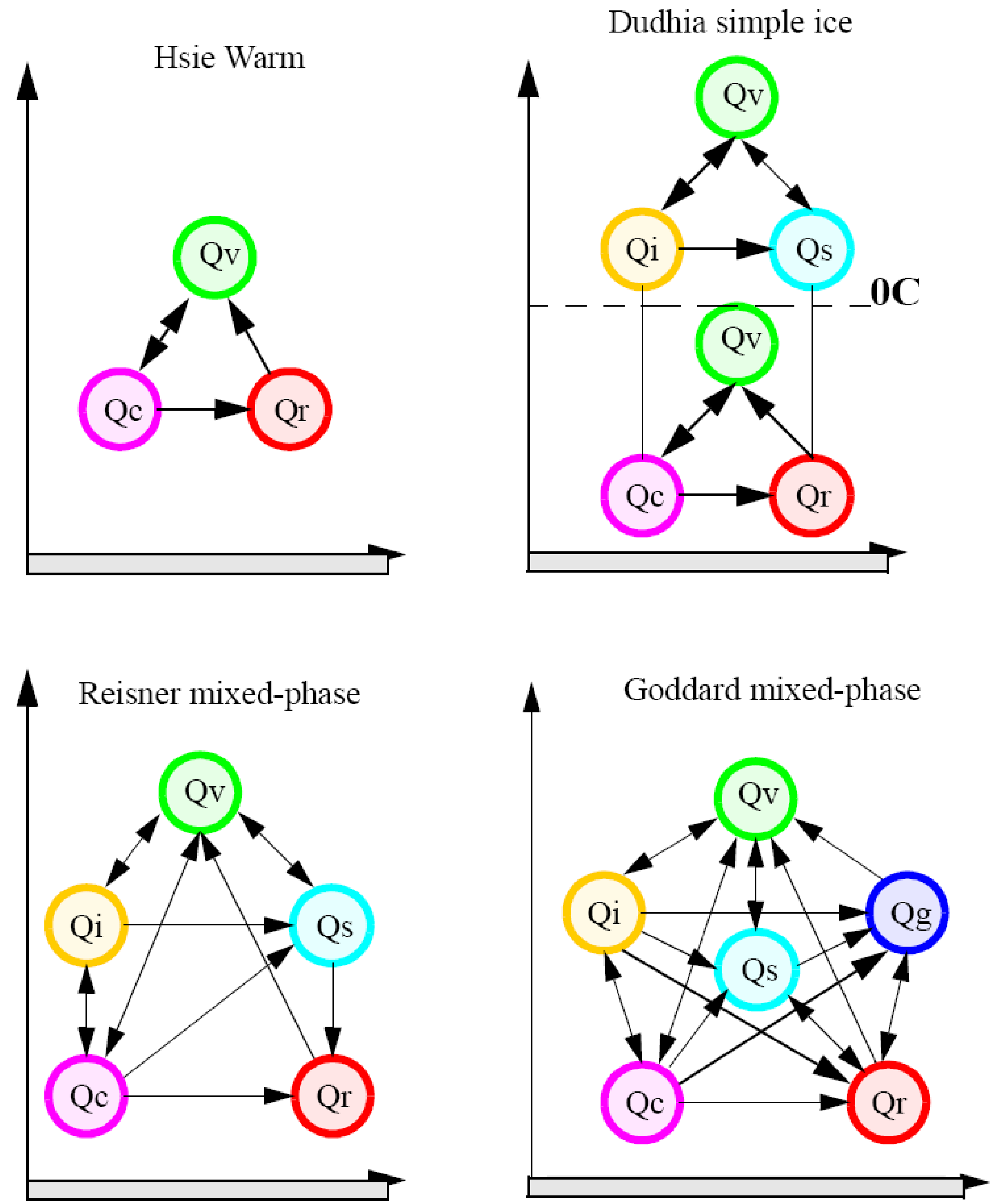


Illustration of Cumulus Processes

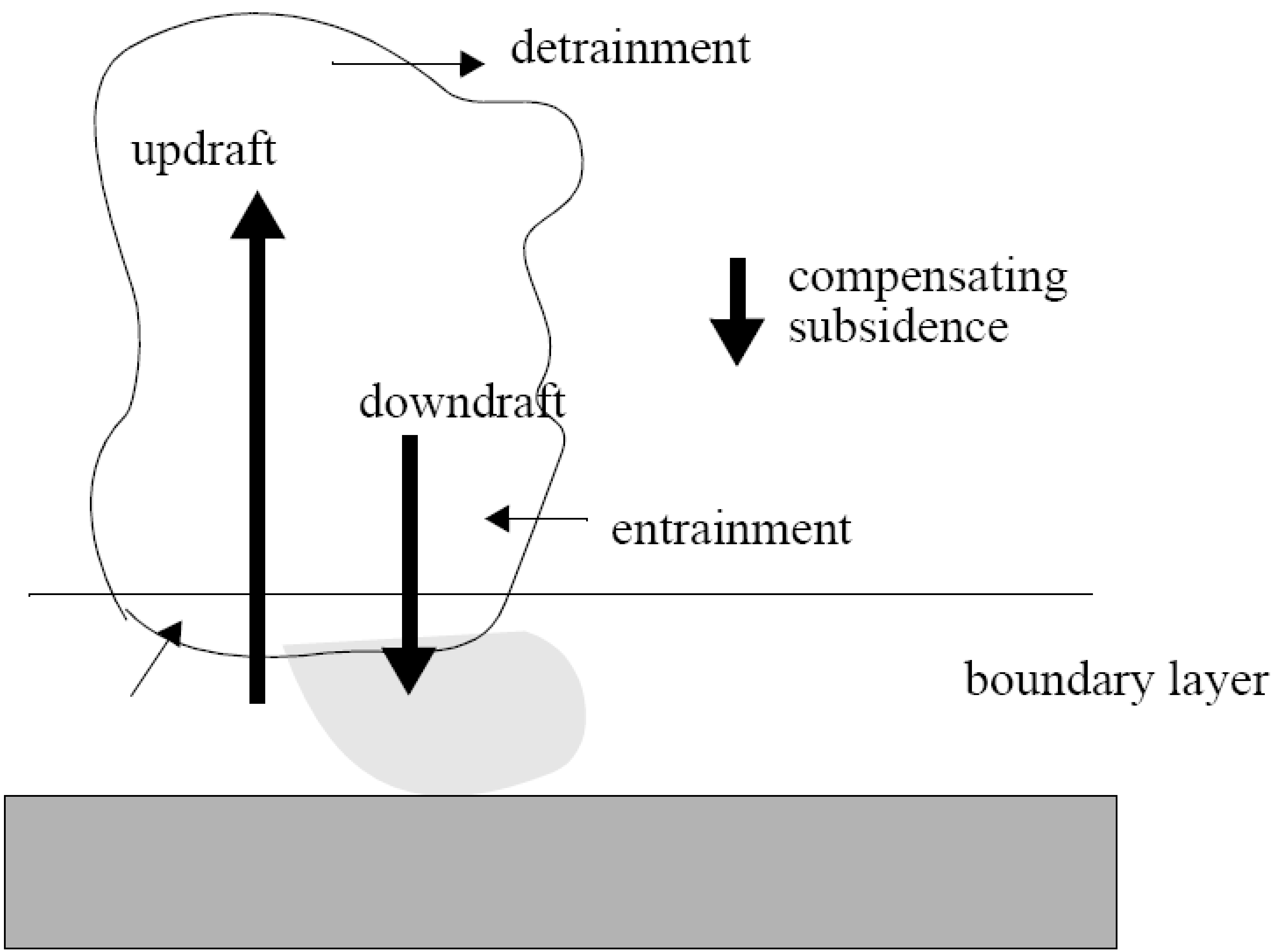


Illustration of PBL Processes

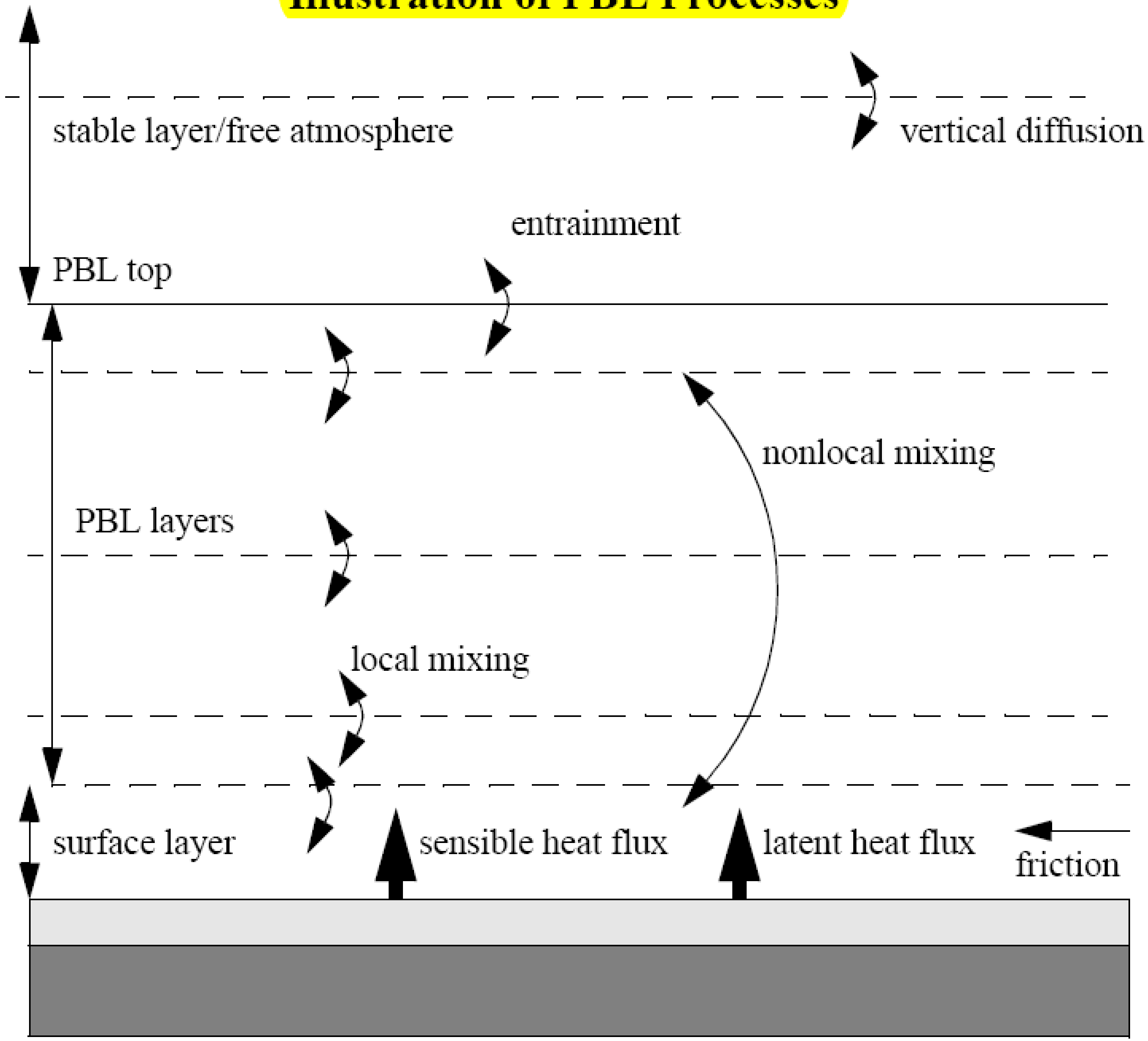


Illustration of Free Atmosphere Radiation Processes

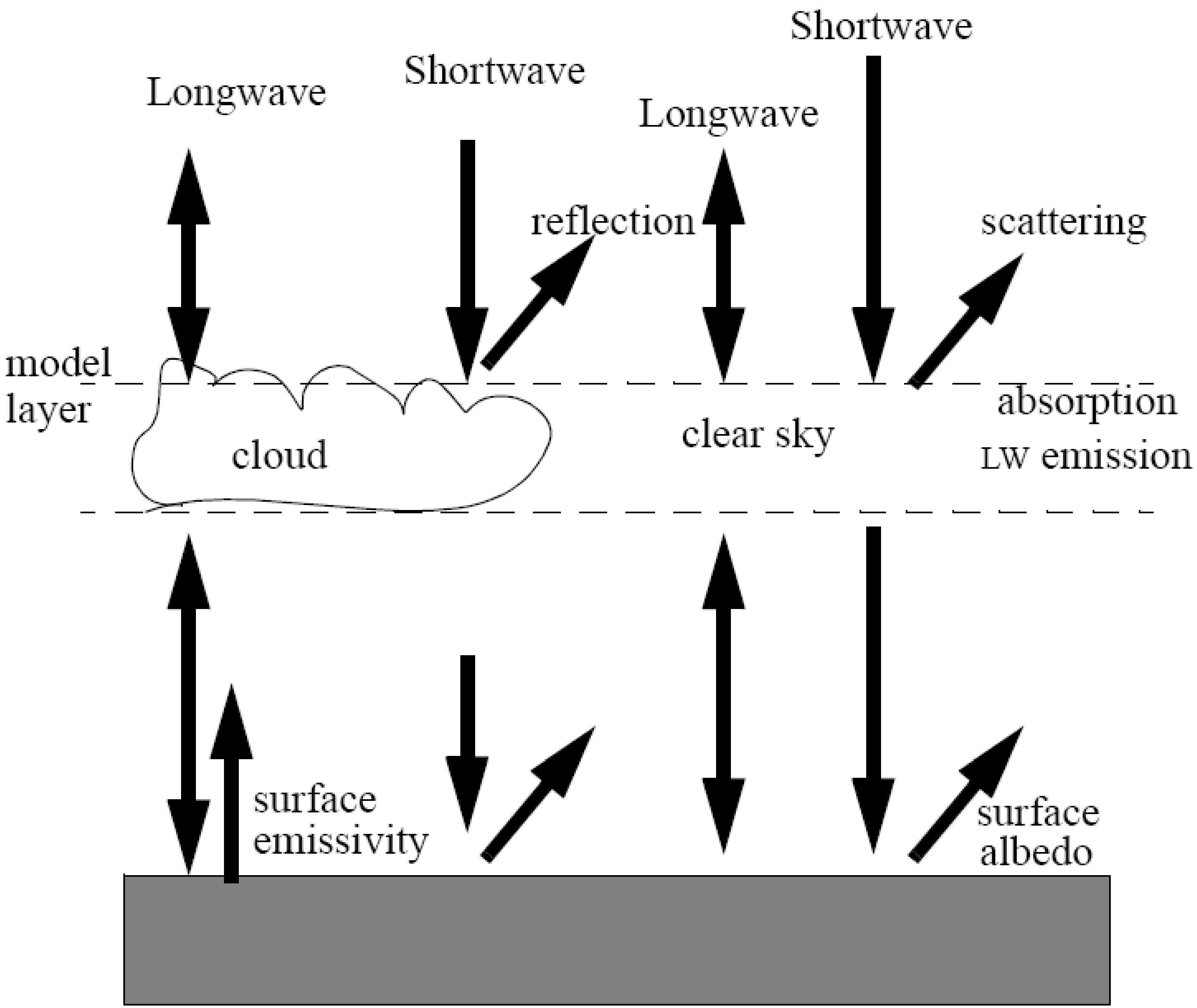
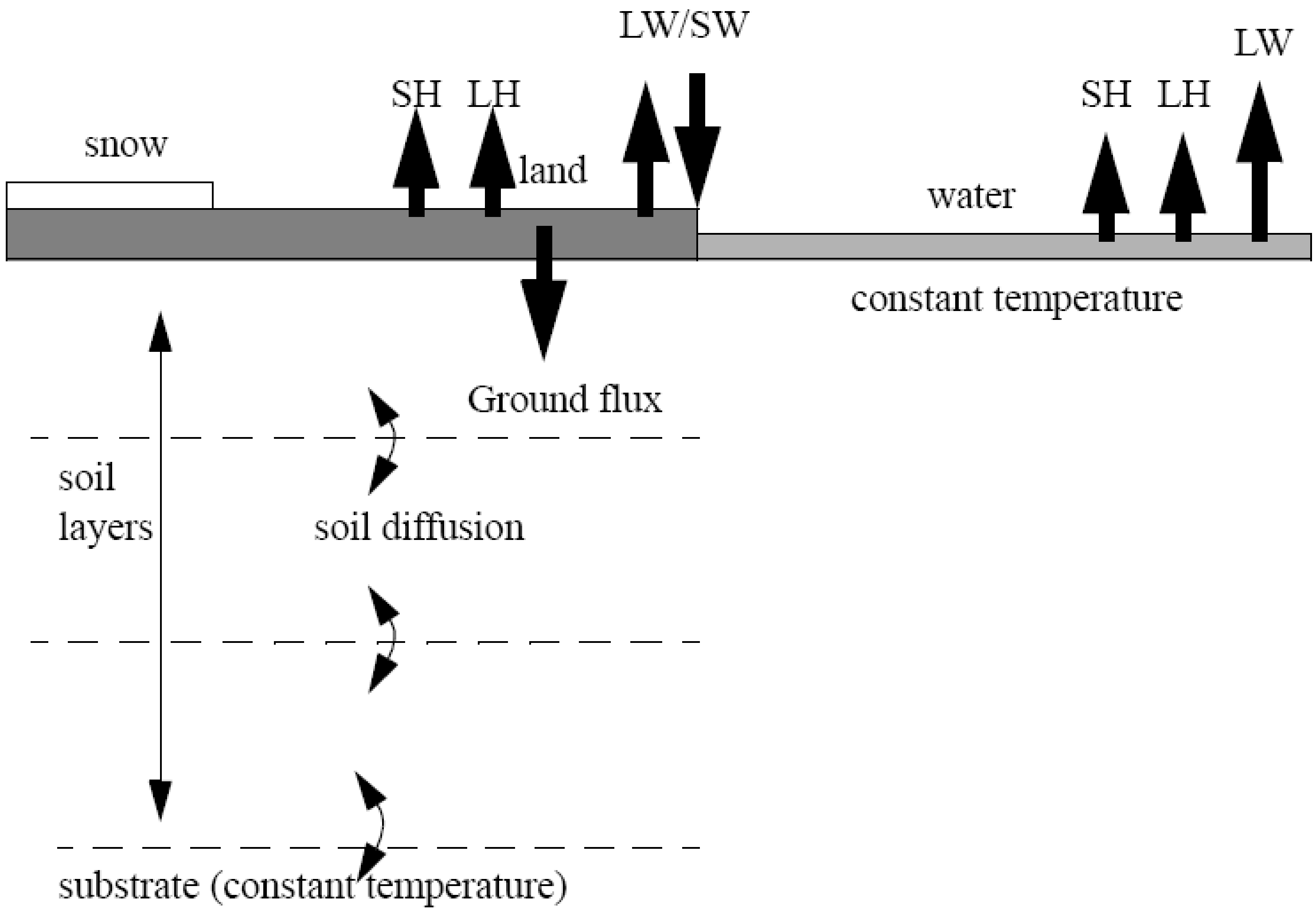
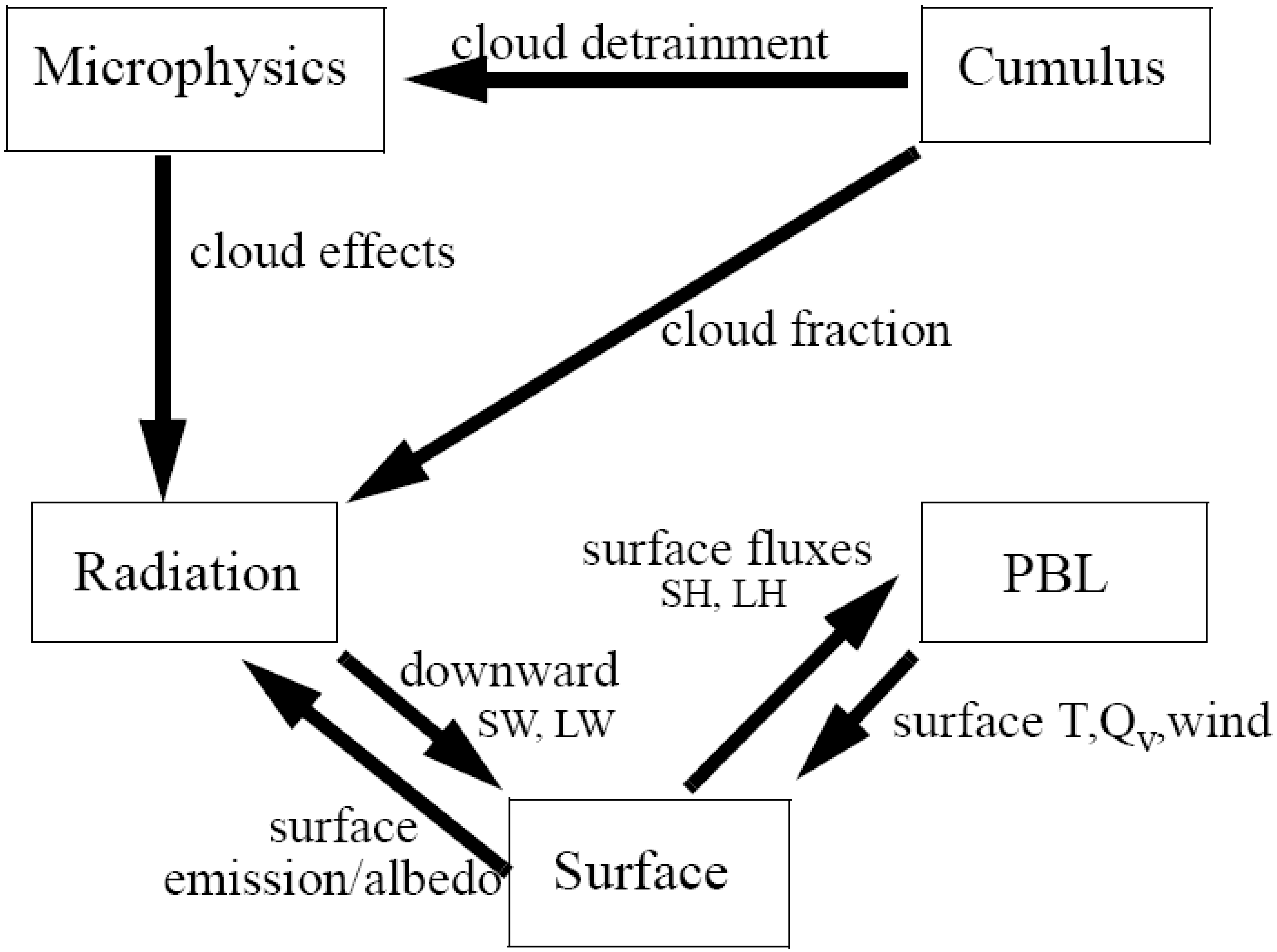


Illustration of Surface Processes



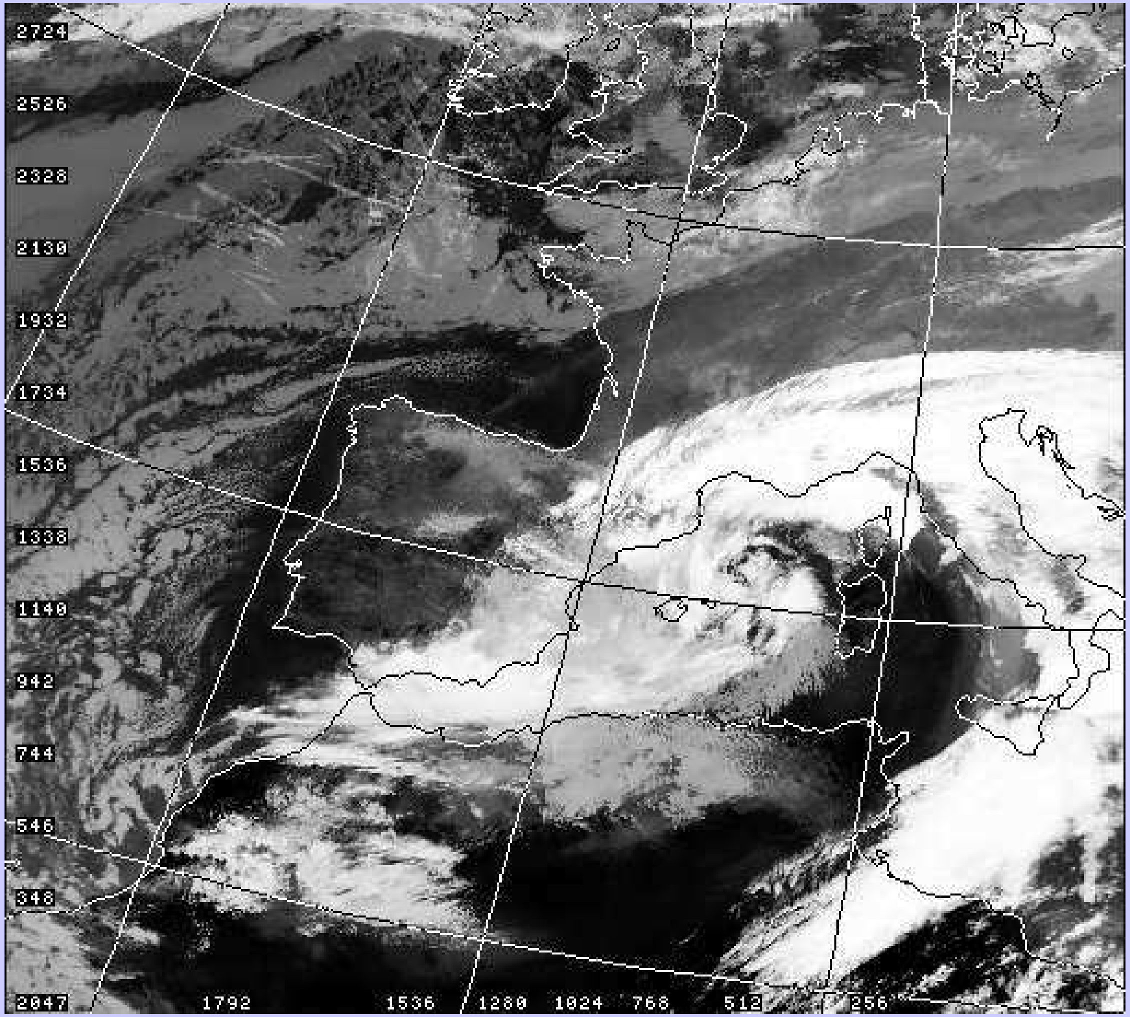
Direct Interactions of Parameterizations



THE STUDY OF CYCLONES

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

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

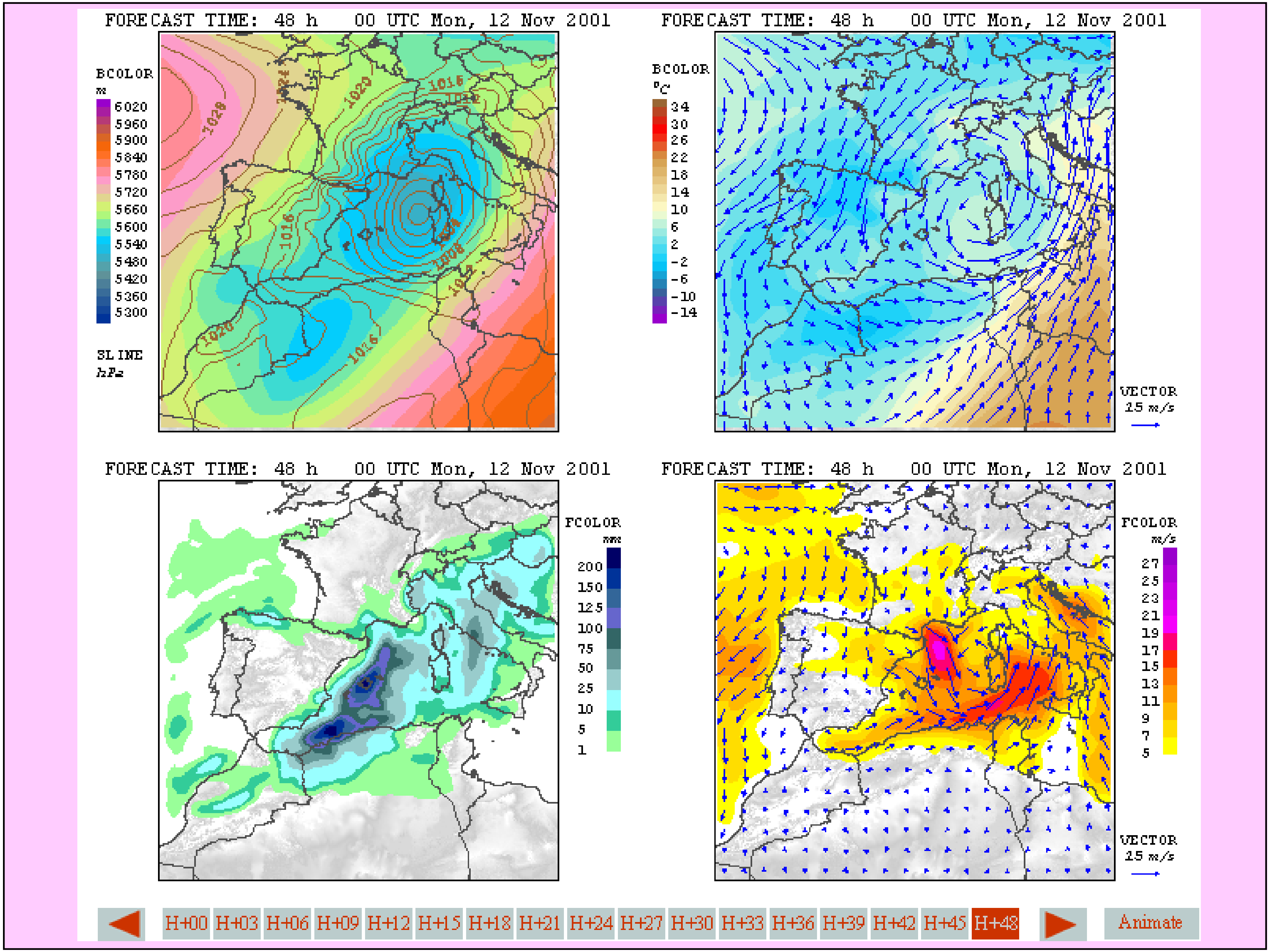


Some effects of the cyclone in the Balearics

Some effects of the cyclone in the Balearics

Some effects of the cyclone in the Balearics

Some effects of the cyclone in the Balearics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5840
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SLINE
hPa
1028
1024
1020
1016
1012
1008
1004
FORECAST TIME: 48 h 00 UTC Mon, 12 Nov 2001
BCOLOR
°C
34
30
26
22
18
14
10
6
2
-2
-6
-10
-14
VECTOR
15 m/s
FORECAST TIME: 48 h 00 UTC Mon, 12 Nov 2001
FCOLOR
mm
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FORECAST TIME: 48 h 00 UTC Mon, 12 Nov 2001
FCOLOR
m/s
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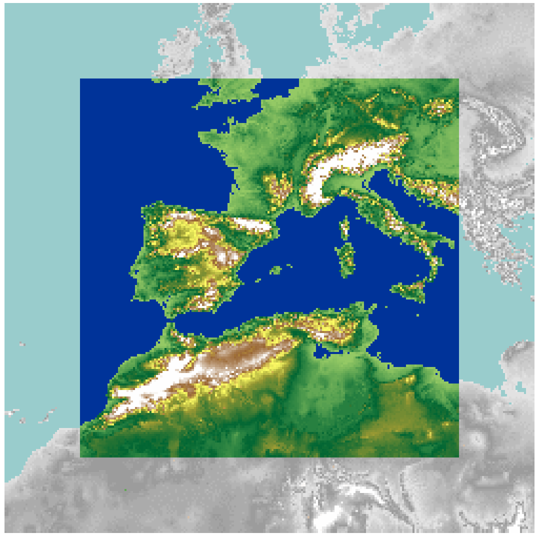
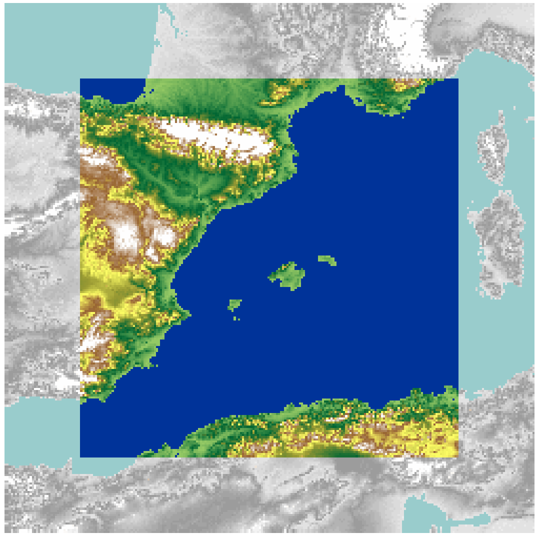
VECTOR
15 m/s
H+00 H+03 H+06 H+09 H+12 H+15 H+18 H+21 H+24 H+27 H+30 H+33 H+36 H+39 H+42 H+45 H+48
Animate

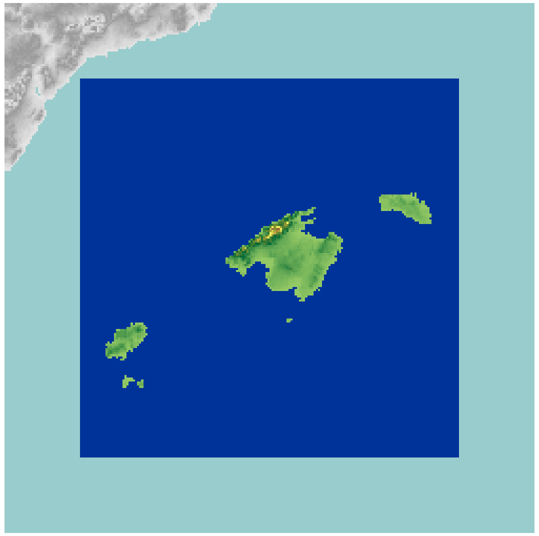
- ***Multiscale*** perspective of cyclone structure



DOMAIN 1 (22.5 km resolution)

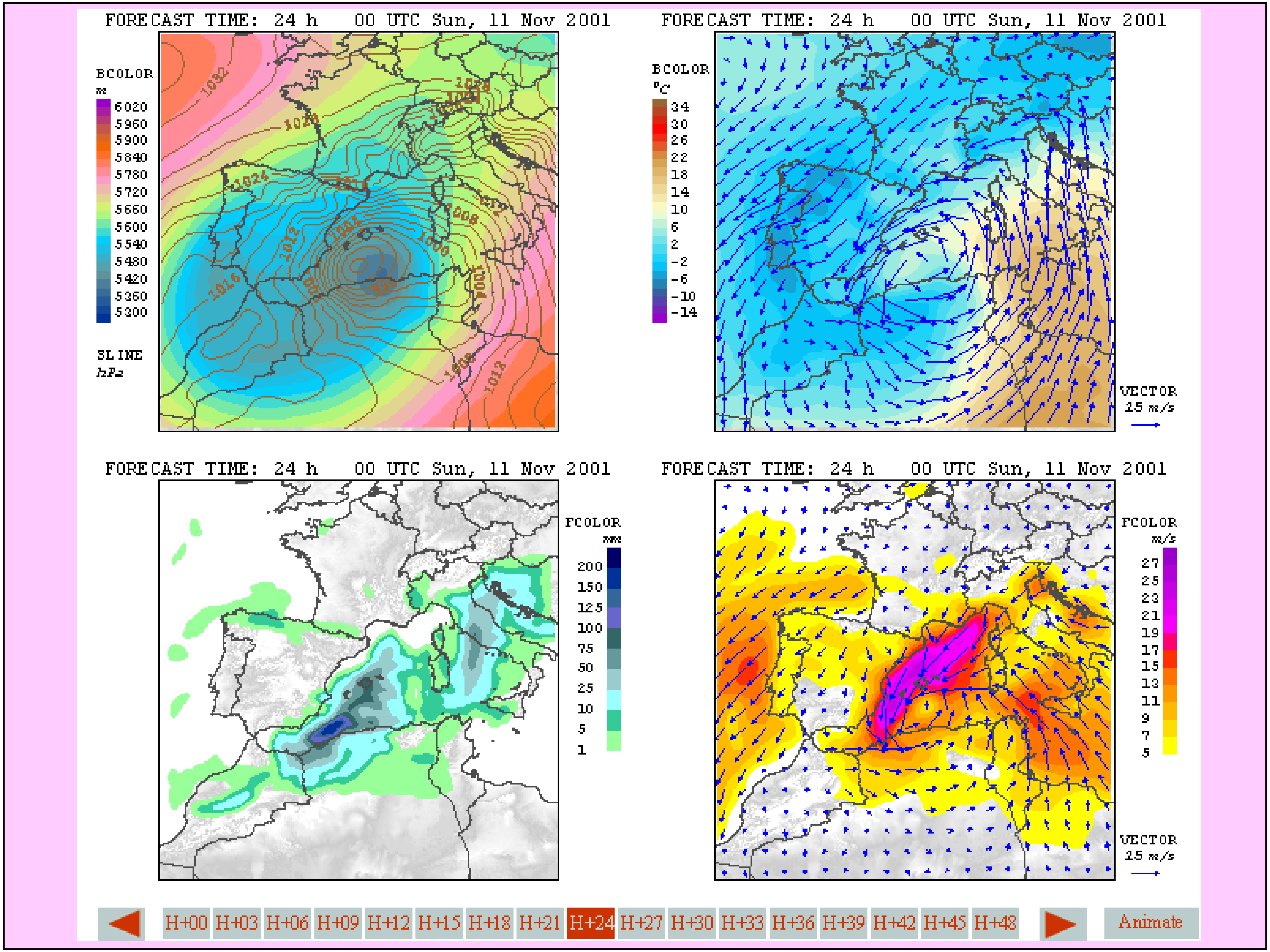


DOMAIN 2 (7.5 km resolution)



DOMAIN 3 (2.5 km resolution)

- Realistic ***physical processes*** parameterized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SLINE
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FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
BCOLOR
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VECTOR
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FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
FCOLOR
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FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
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VECTOR
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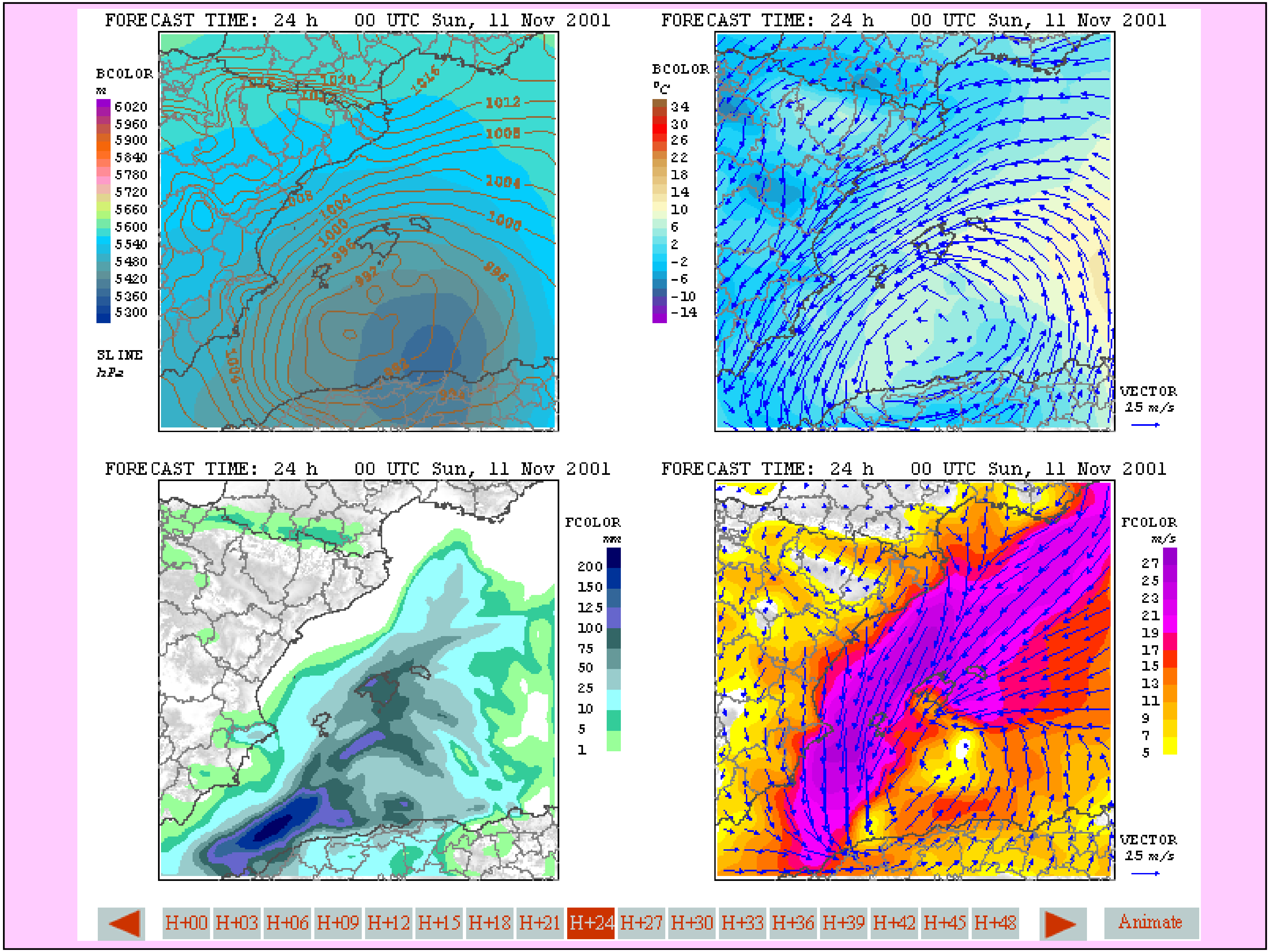
H+00 H+03 H+06 H+09 H+12 H+15 H+18 H+21 H+24 H+27 H+30 H+33 H+36 H+39 H+42 H+45 H+48
Animate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SLINE
hPa
FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
BCOLOR
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VECTOR
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FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
FCOLOR
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FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
FCOLOR
m/s
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21
19
17
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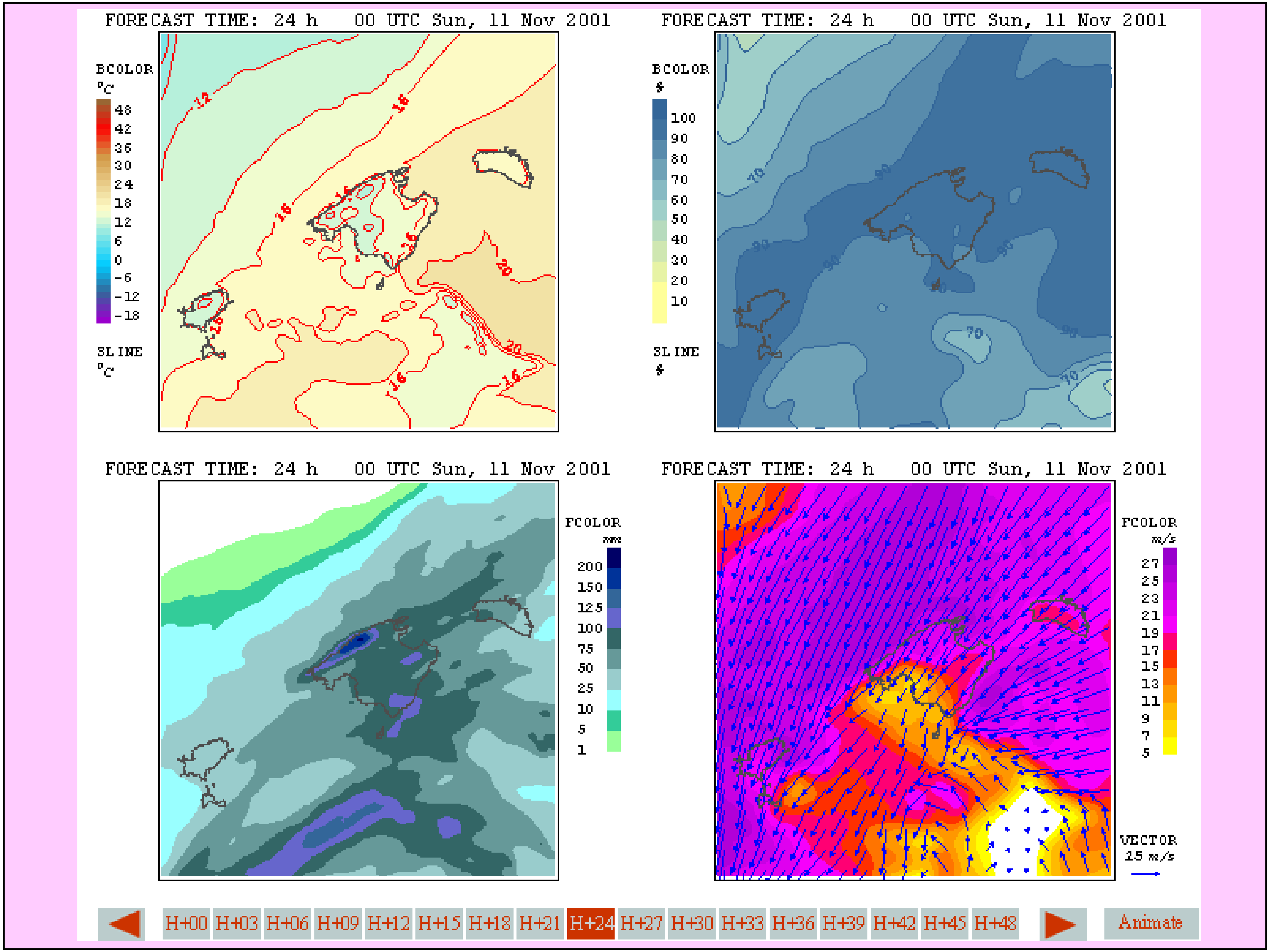
13
11
9
7
5
VECTOR
15 m/s
H+00 H+03 H+06 H+09 H+12 H+15 H+18 H+21 H+24 H+27 H+30 H+33 H+36 H+39 H+42 H+45 H+48
Animate


FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
BCOLOR
°C
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42
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SLINE
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16
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20
16
16
FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
BCOLOR
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90
80
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%
70
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70
90
70
FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
FCOLOR
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FORECAST TIME: 24 h 00 UTC Sun, 11 Nov 2001
FCOLOR
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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

UNIQUE FEATURE OF NUMERICAL MODELS

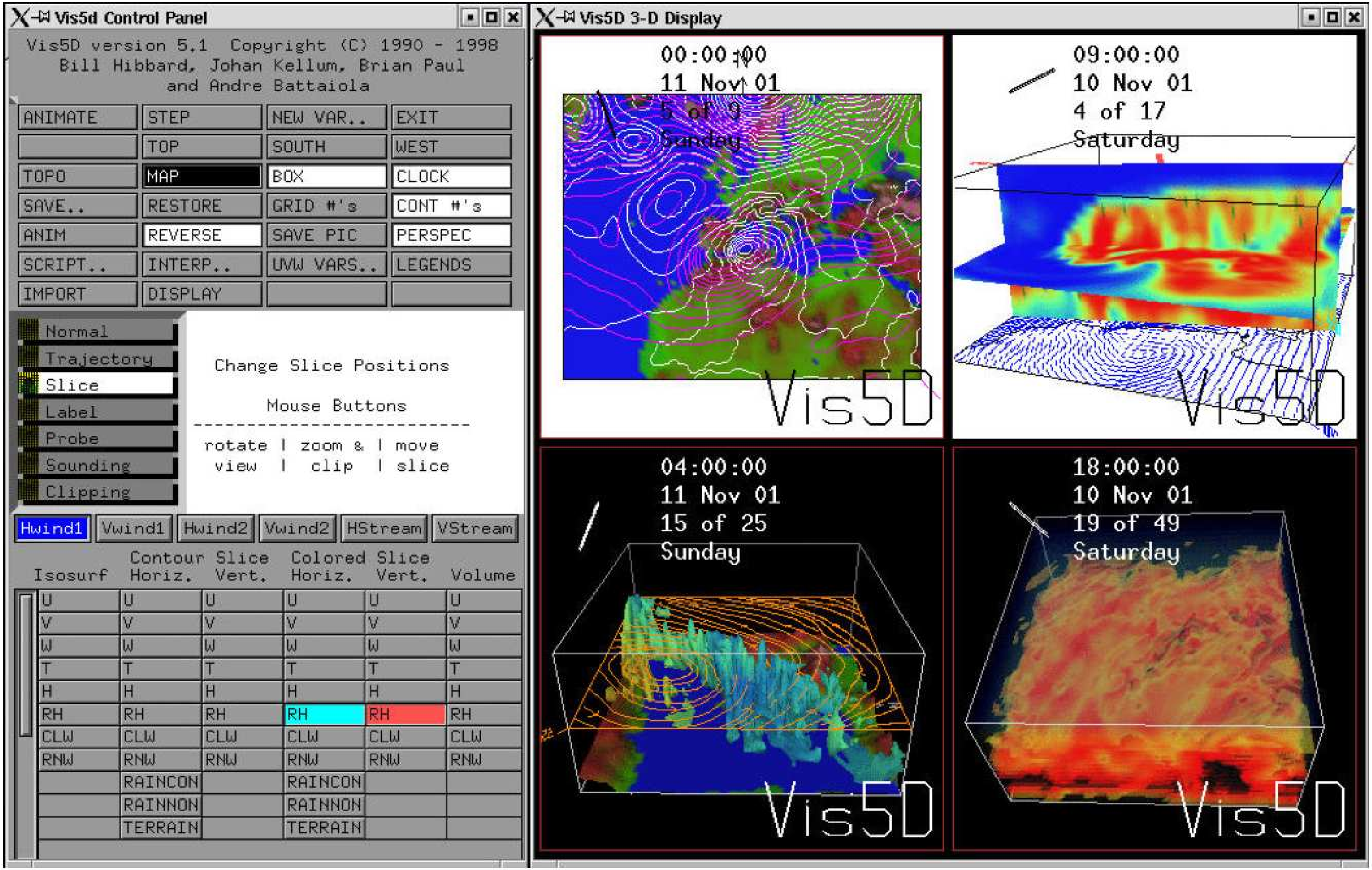
- Reasonably ***good*** control simulation of your case study

↓

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

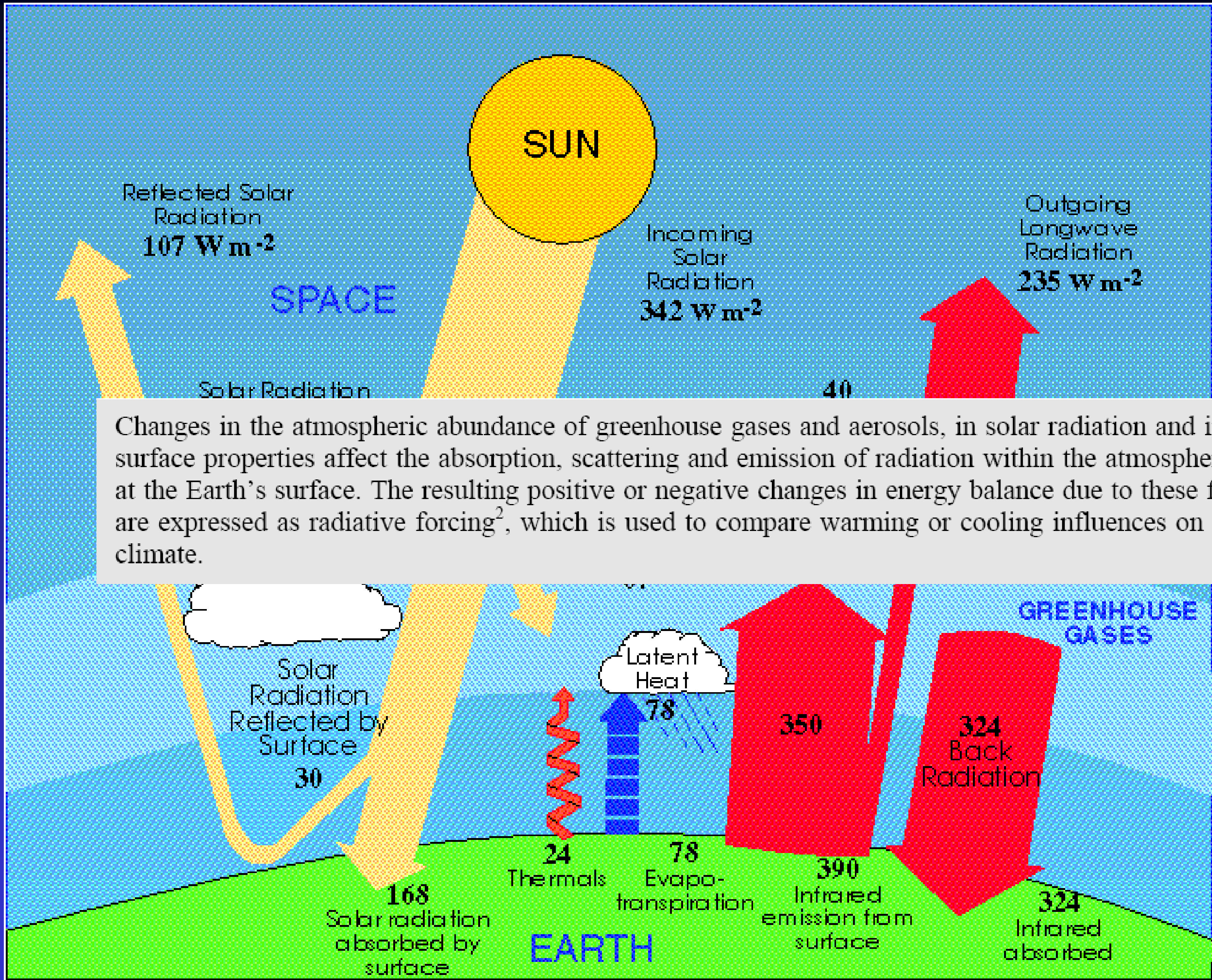
↓

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



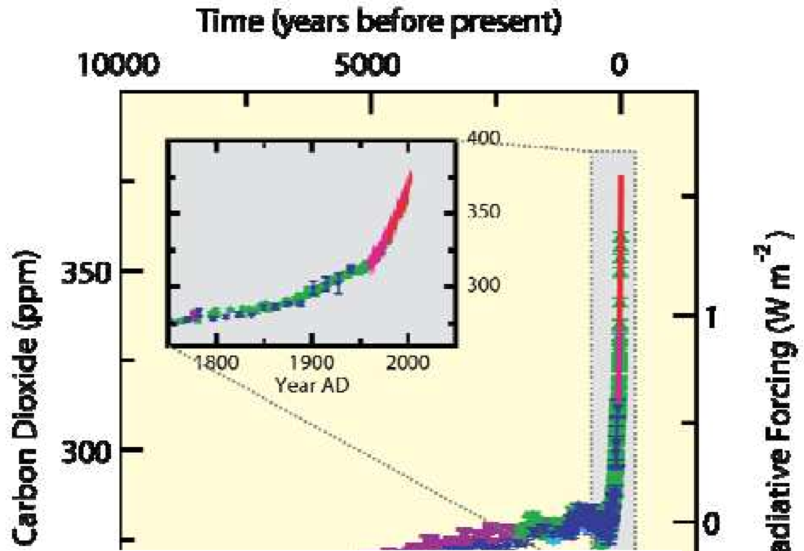
Más en el TEMA 5.2 !!!!

MODELS DE SIMULACIÓ CLIMÀTICA. APLICACIÓ A L'ESTUDI DEL CANVI CLIMÀTIC

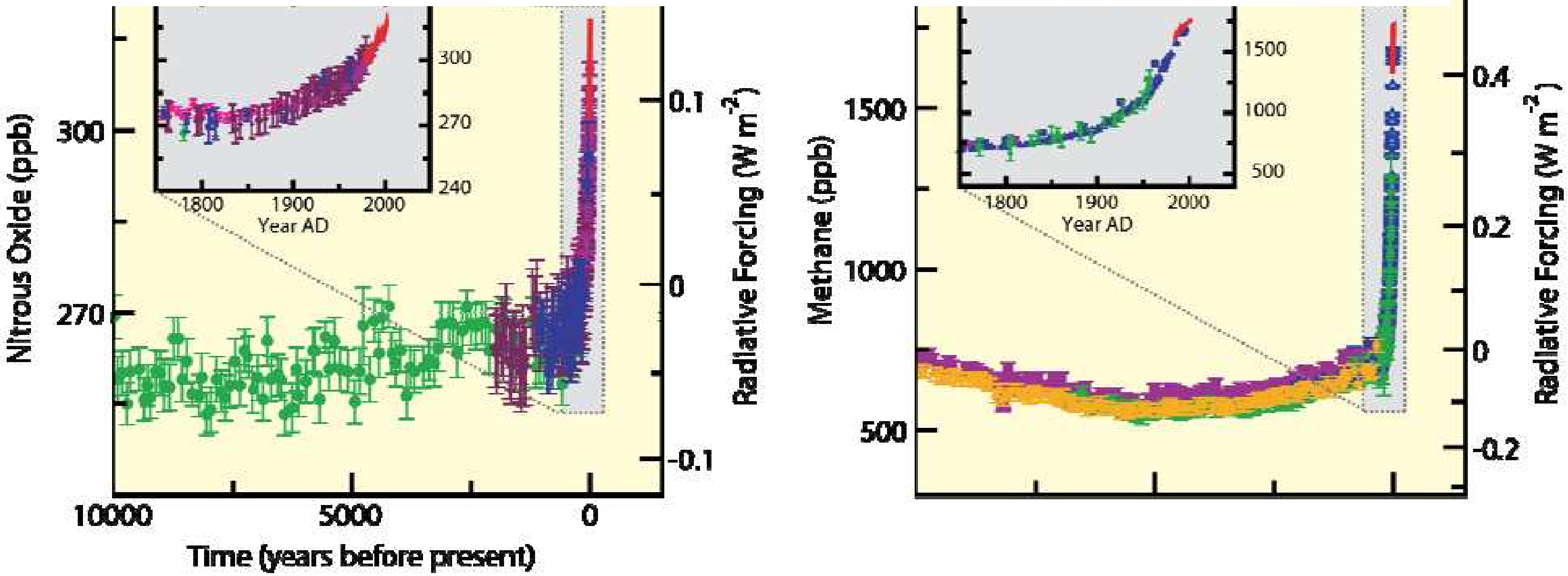


Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties affect the absorption, scattering and emission of radiation within the atmosphere and at the Earth's surface. The resulting positive or negative changes in energy balance due to these factors are expressed as radiative forcing[2], which is used to compare warming or cooling influences on global climate.

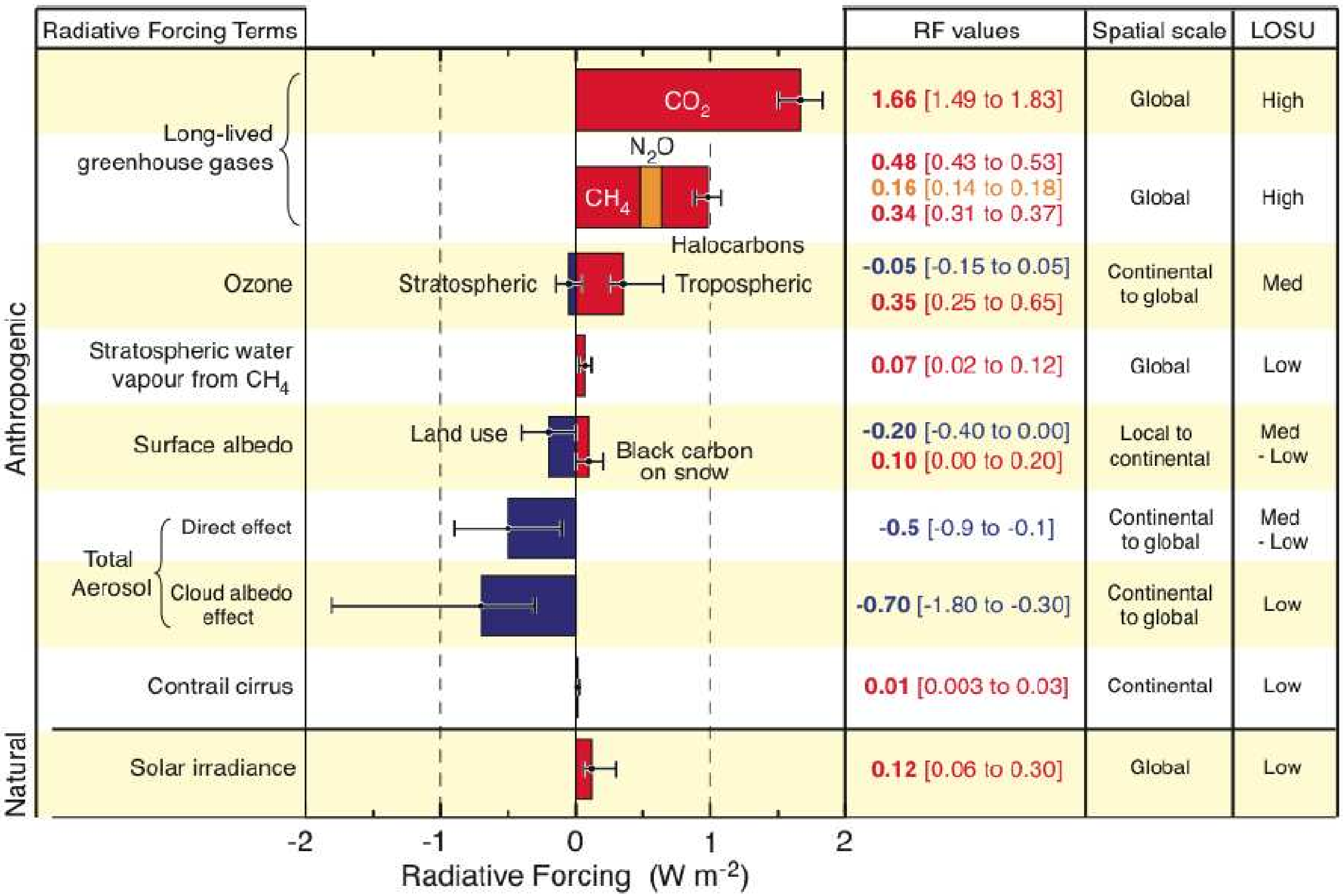
FIGURE SPM-1.
Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (lines). The corresponding radiative forcings are shown on the right hand axes of the large panels. {Figure 6.4}



Current atmospheric concentrations of carbon dioxide and methane far exceed pre-industrial values determined from ice cores spanning the last 650,000 years. The increases in these greenhouse gases since 1750 (see Figure SPM-1) are due primarily to emissions from fossil fuel use, agriculture, and land-use changes. {2.3, 6.4, 7.3}



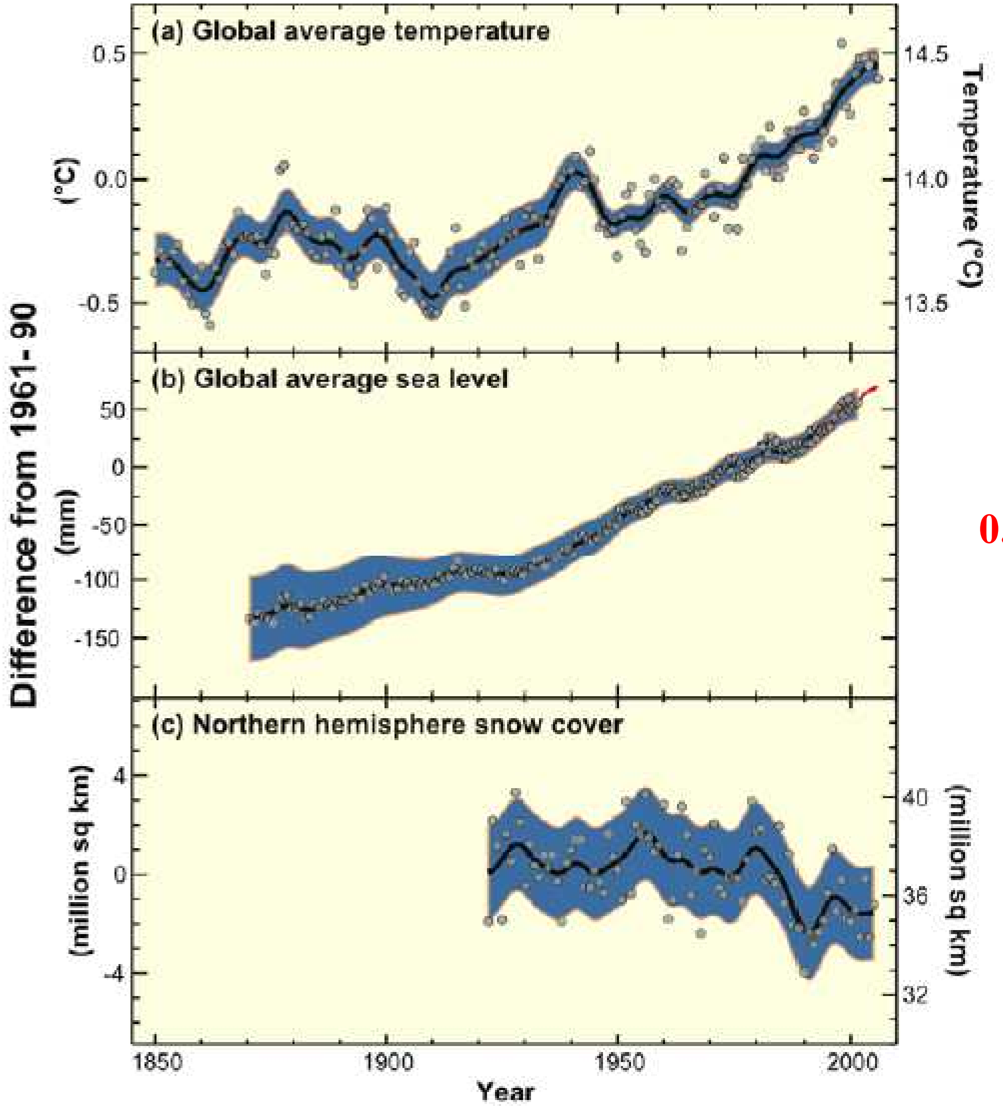
RADIATIVE FORCING COMPONENTS



Globally averaged warming effect of human activities since 1750 (1.6 Wm^{-2}), at least 5 times larger than that of solar output changes

FIGURE SPM- … for carbon dioxide (CO_2), methane … , together with the typical geograph… …tific understanding (LOSU). Volcan… …n this figure due to their episodic nature. {2.9, Figure 2.20}

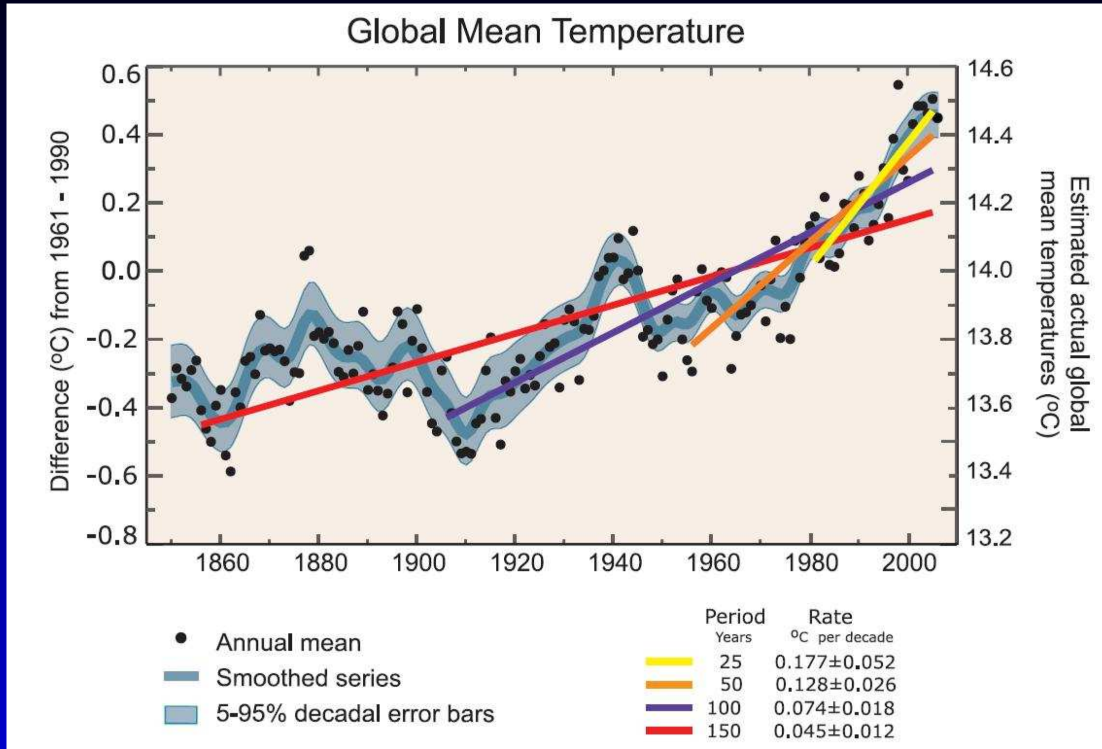
CHANGES IN TEMPERATURE, SEA LEVEL AND NORTHERN HEMISPHERE SNOW COVER



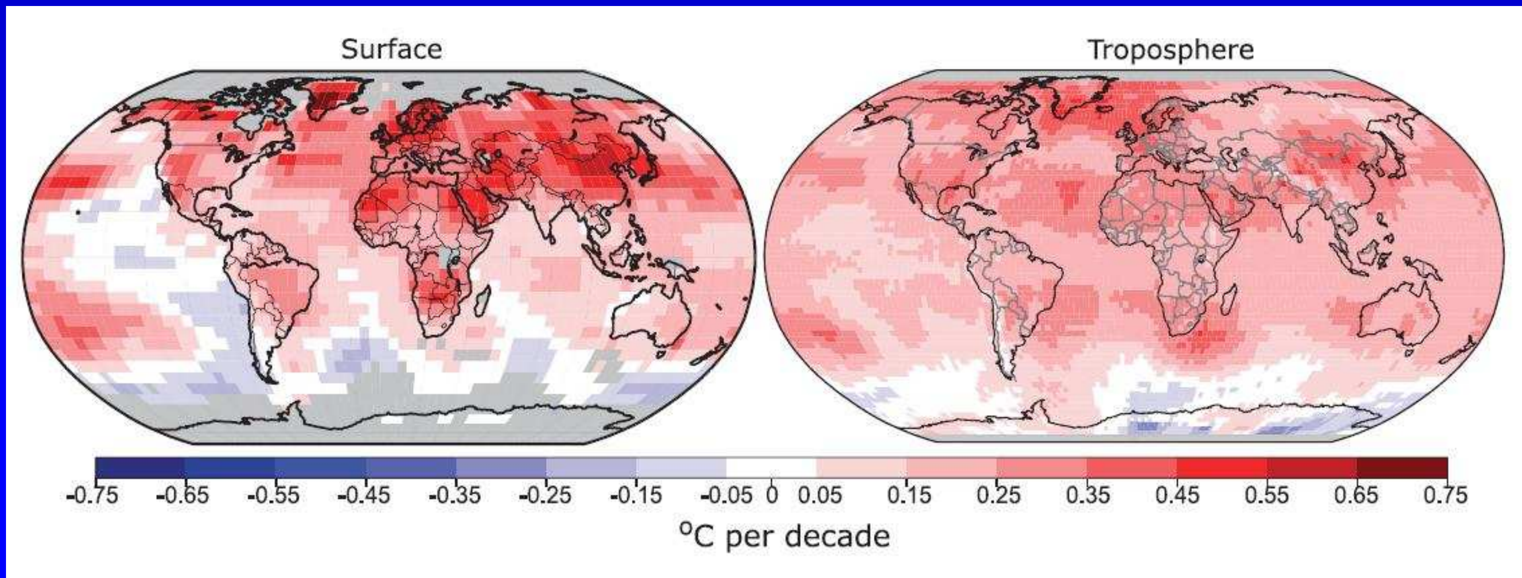
0.74 °C during 1906-2005

0.17 m during 20th century

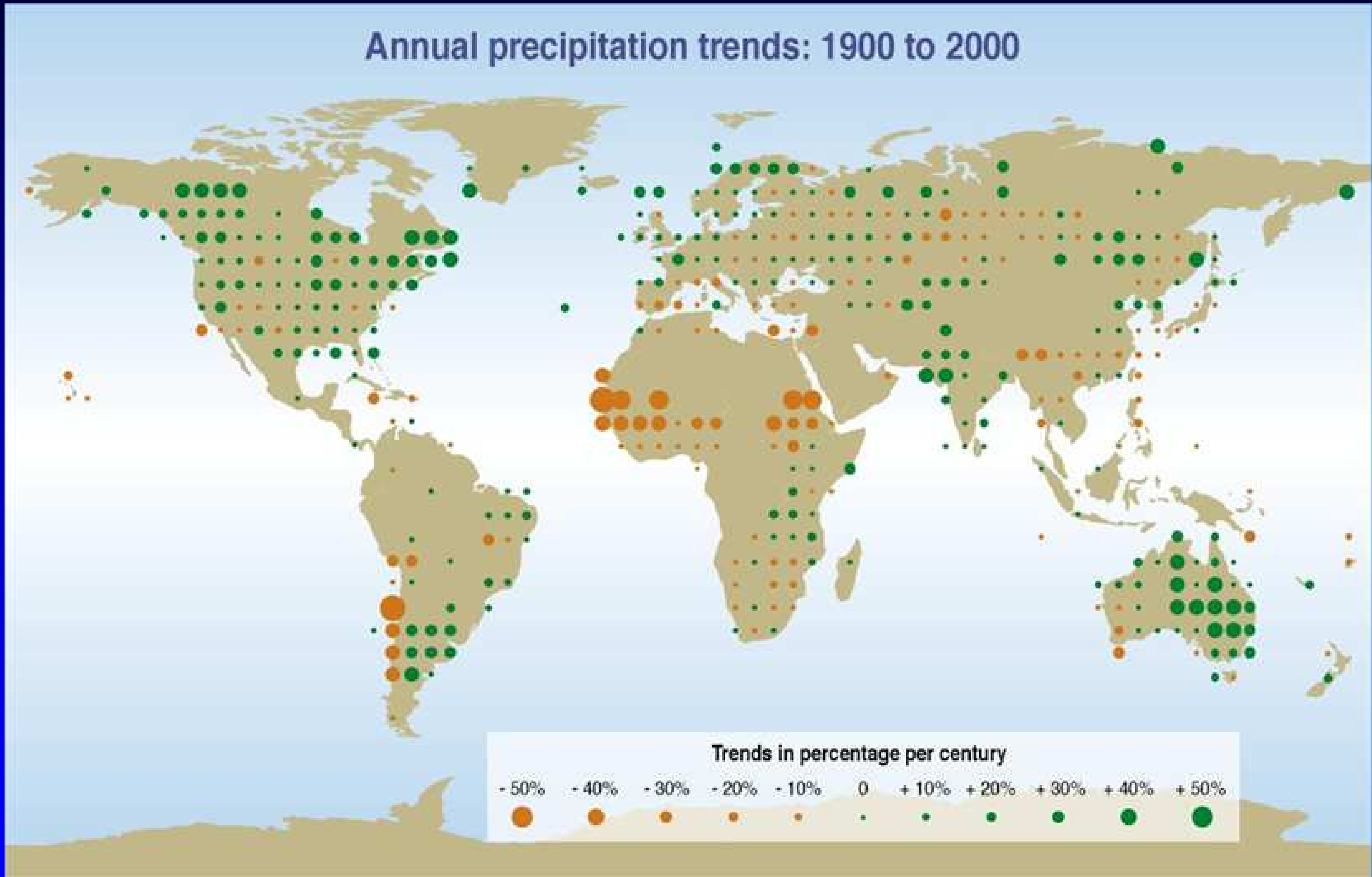
FIGURE SPM-3. Observed changes in (a) global average surface temperature; (b) global average sea level rise from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961-1990. Smoothed curves and shaded areas represent decadal averaged values and their assessed uncertainty intervals, while circles show yearly values. {Question 3.1, Figure 1, Figure 4.2 and Figure 5.13}



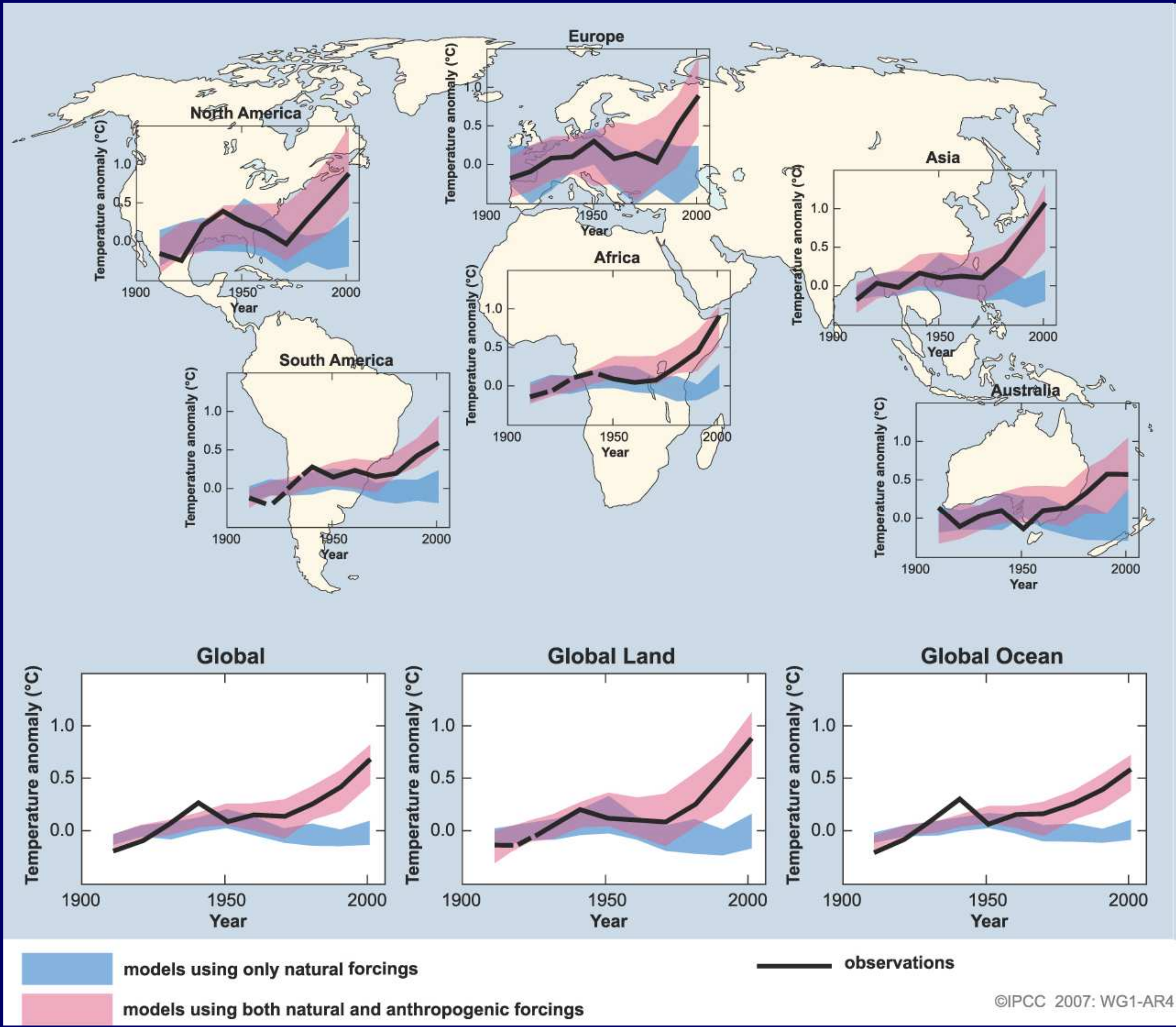
Global Mean Temperature
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Difference (ºC) from 1961 - 1990
14.6
14.4
14.2
14.0
13.8
13.6
13.4
13.2
Estimated actual global mean temperatures (ºC)
1860
1880
1900
1920
1940
1960
1980
2000
Annual mean
Smoothed series
5-95% decadal error bars
Period Years
Rate ºC per decade
25 0.177±0.052
50 0.128±0.026
100 0.074±0.018
150 0.045±0.012



Surface
Troposphere
-0.75
-0.65
-0.55
-0.45
-0.35
-0.25
-0.15
-0.05
0
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
ºC per decade



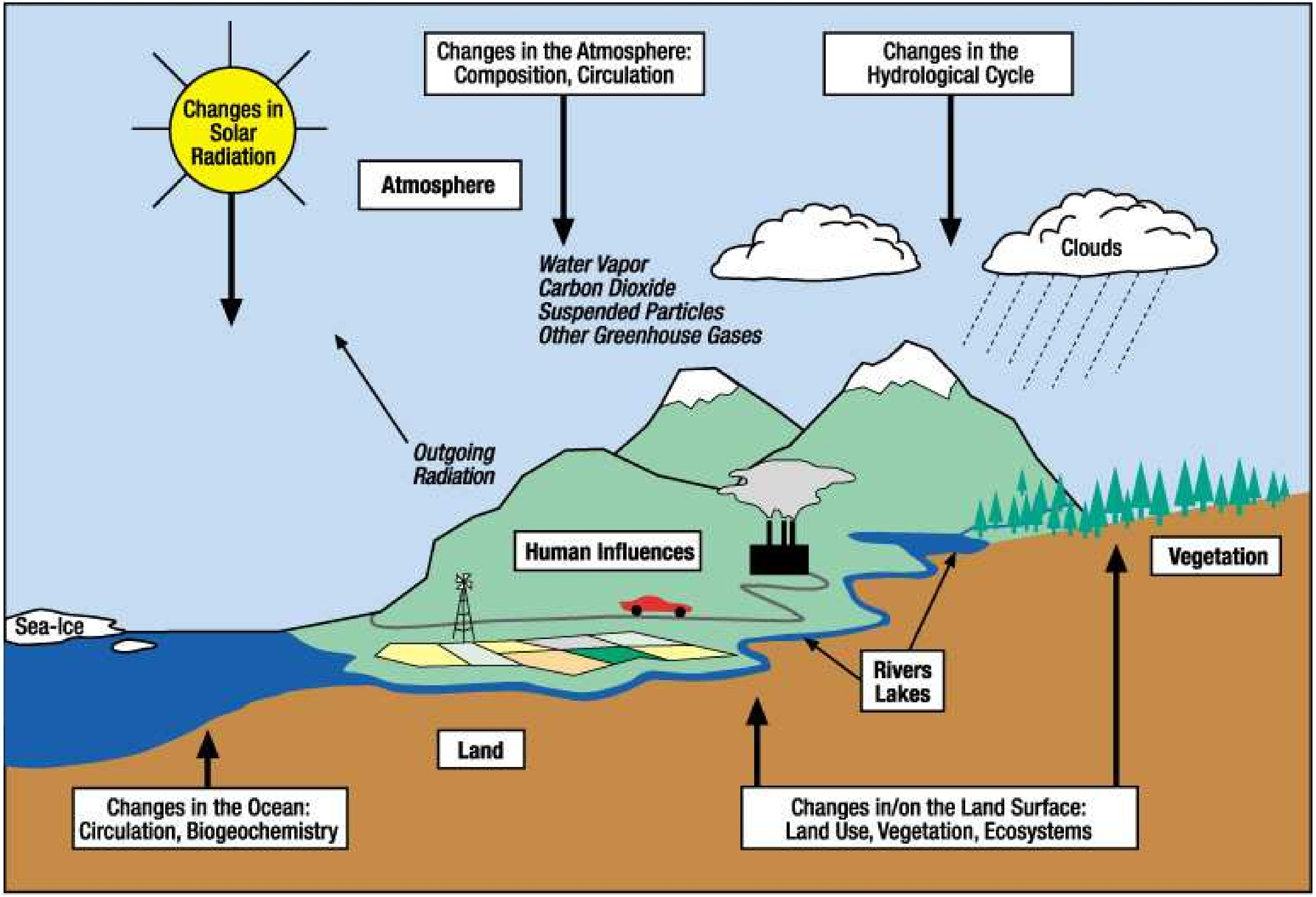
Annual precipitation trends: 1900 to 2000
Trends in percentage per century
- 50%
- 40%
- 30%
- 20%
- 10%
0
+ 10%
+ 20%
+ 30%
+ 40%
+ 50%

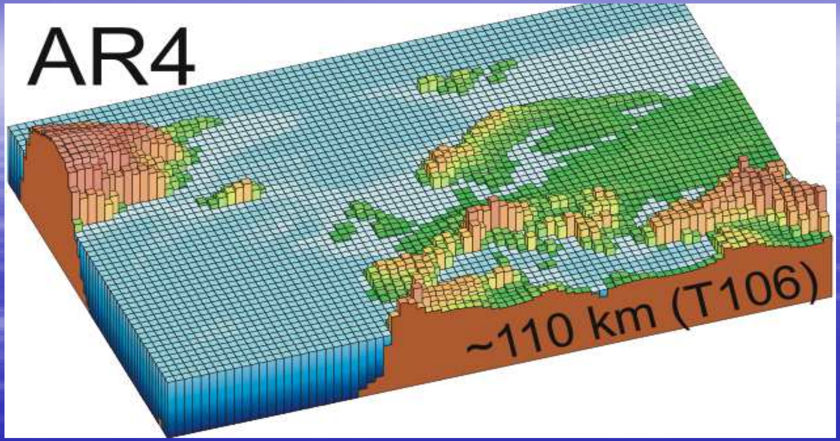


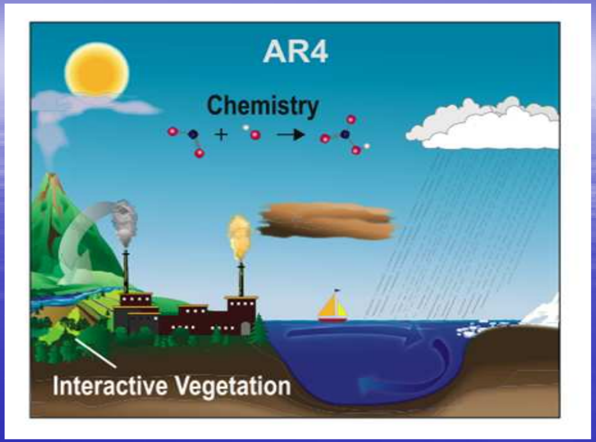
Europe
North America
Asia
Africa
South America
Australia
Temperature anomaly (°C)
1.0
0.5
0.0
1900
1950
2000
Year
Global
Global Land
Global Ocean
models using only natural forcings
models using both natural and anthropogenic forcings
observations

Models globals de simulació del clima (GCM)

The Climate System and Influences





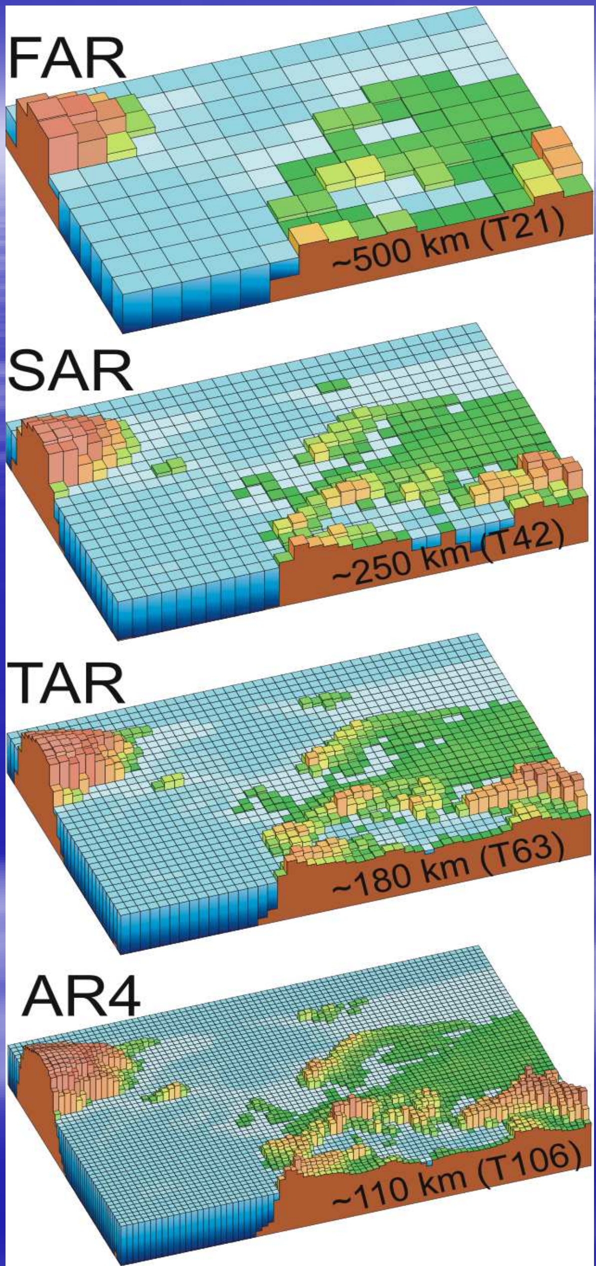


- Són la millor eina disponible per a l'estudi del canvi climàtic (p.e. Quart Informe AR4 de l'IPCC, 2007)

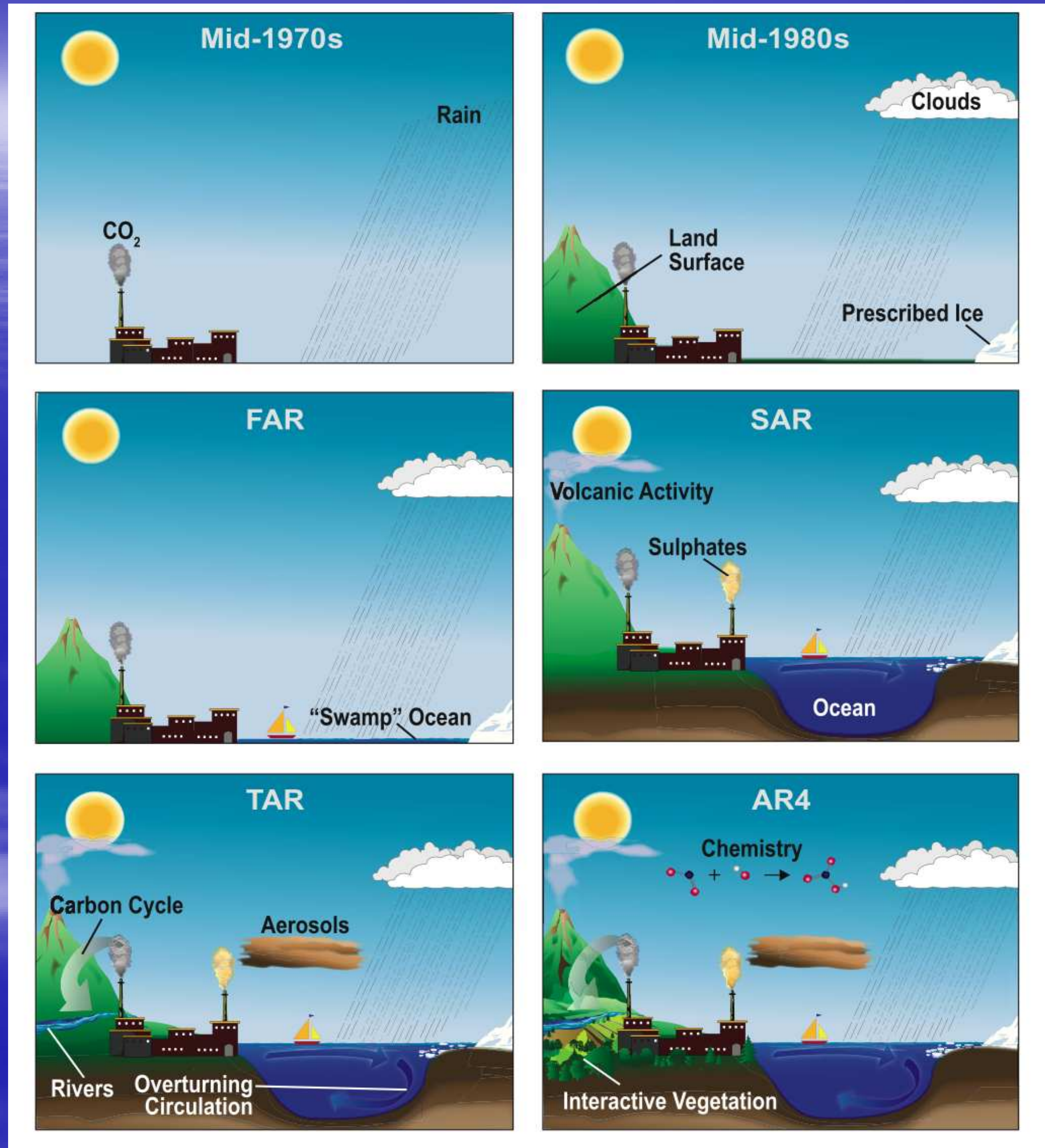
- Contenen una representació dels processos físics, químics i biològics influents així com de les seves complexes interaccions

- Realitzen simulacions de "control" del segle XX, i simulacions "futures" del segle XXI sota un ventall d'escenaris d'emissions de gasos d'efecte hivernacle i aerosols

- Tenen el problema de no capturar completament els efectes locals i regionals degut a la seva baixa resolució de càlcul (100 – 400 km) ⟶ Downscaling



FAR
~500 km (T21)
SAR
~250 km (T42)
TAR
~180 km (T63)
AR4
~110 km (T106)



Mid-1970s
Rain
CO2
Mid-1980s
Clouds
Land Surface
Prescribed Ice
FAR
"Swamp" Ocean
SAR
Volcanic Activity
Sulphates
Ocean
TAR
Carbon Cycle
Aerosols
Rivers
Overturning Circulation
AR4
Chemistry
Interactive Vegetation

Table 10.4. *Summary of climate change model experiments produced with AOGCMs. Numbers in each scenario column indicate how many ensemble members were produced for each model. Coloured fields indicate that some but not necessarily all variables of the specific data type (separated by climate system component and time interval) were available for download at the PCMDI to be used in this report; ISCCP is the International Satellite Cloud Climatology Project. Additional data has been submitted for some models and may subsequently become available. Where different colour shadings are given in the legend, the colour indicates whether data from a single or from multiple ensemble members is available. Details on the scenarios, variables and models can be found at the PCMDI webpage (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). Model IDs are the same as in Table 8.1, which provides details of the models.*

time-independent land surface
>1 1 monthly-mean atmosphere
daily-mean atmosphere
3-hourly atmosphere
time-independent ocean
>1 1 monthly-mean ocean
>1 1 Extreme Indices
Forcing
ISCCP Simulator

Model ID	Model, Country	Pre industr. control	Present day control	20th century	Commit-ment	SRES A2	SRES A1B	SRES B1	1% to $2xCO_2$	1% to $4xCO_2$	Slab ocean control	$2XCO_2$	AMIP
1	BCC-CM1, China		2	4		2		2	1	1			4
2	BCCR-BCM2.0, Norway	1		1	1	1	1	1	1				
3	CCSM3, USA *	2	1	9	5	5	7	8	1	1	1	1	1
4	CGCM3.1(T47), Canada	1		5	5	5	5	4	1	1	1	1	
5	CGCM3.1(T63), Canada	1		1			1	1	1		1	1	
6	CNRM-CM3, France	1		1	1	1	1	1	1	1			1
7	CSIRO-MK3.0, Australia	2		3	1	1	1	1	1		1	1	
8	ECHAM5/MPI-OM, Germany	1		4	3	3	4	3	3	1	1	1	3
9	ECHO-G, Germany/Korea	1	1	5	4	3	3	3	1	1			
10	FGOALS-g1.0, China	3		3	3		3	3	3				3
11	GFDL-CM2.0, USA	1		3	1	1	1	1	1	1			
12	GFDL-CM2.1, USA	1		3	1	1	1	1	1	1			
13	GISS-AOM, USA	2		2			2	2					
14	GISS-EH, USA	1		5			4		1				
15	GISS-ER, USA	1		9	1	1	5	1	1	1	1	1	4
16	INM-CM3.0, Russia	1		1	1	1	1	1	1	1	1	1	1
17	IPSL-CM4, France	1	1	2	1	1	1	1	1	1			6
18	MIROC3.2(hires), Japan	1		1			1	1	1		1	1	1
19	MIROC3.2(medres), Japan	1		3	1	3	3	3	3	3	1	1	3
20	MRI-CGCM2.3.2, Japan	1	1	5	1	5	5	5	1	1	1	1	1
21	PCM, USA	1	1	4	3	4	4	4	5	1			1
22	UKMO-HadCM3, UK	2		2	1	1	1	1	1				
23	UKMO-HadGEM1, UK	1		1		1	1		1		1	1	1

** Some of the ensemble members using the CCSM3 were run on the Earth Simulator in Japan in collaboration with the Central Research Institute of Electric Power Industry (CRIEPI).*

LA ATMÓSFERA ES UN SISTEMA CAÓTICO:

¿Cómo vamos a predecir el CLIMA a lo largo d
capaces de predecir el TIEMPO para finales de

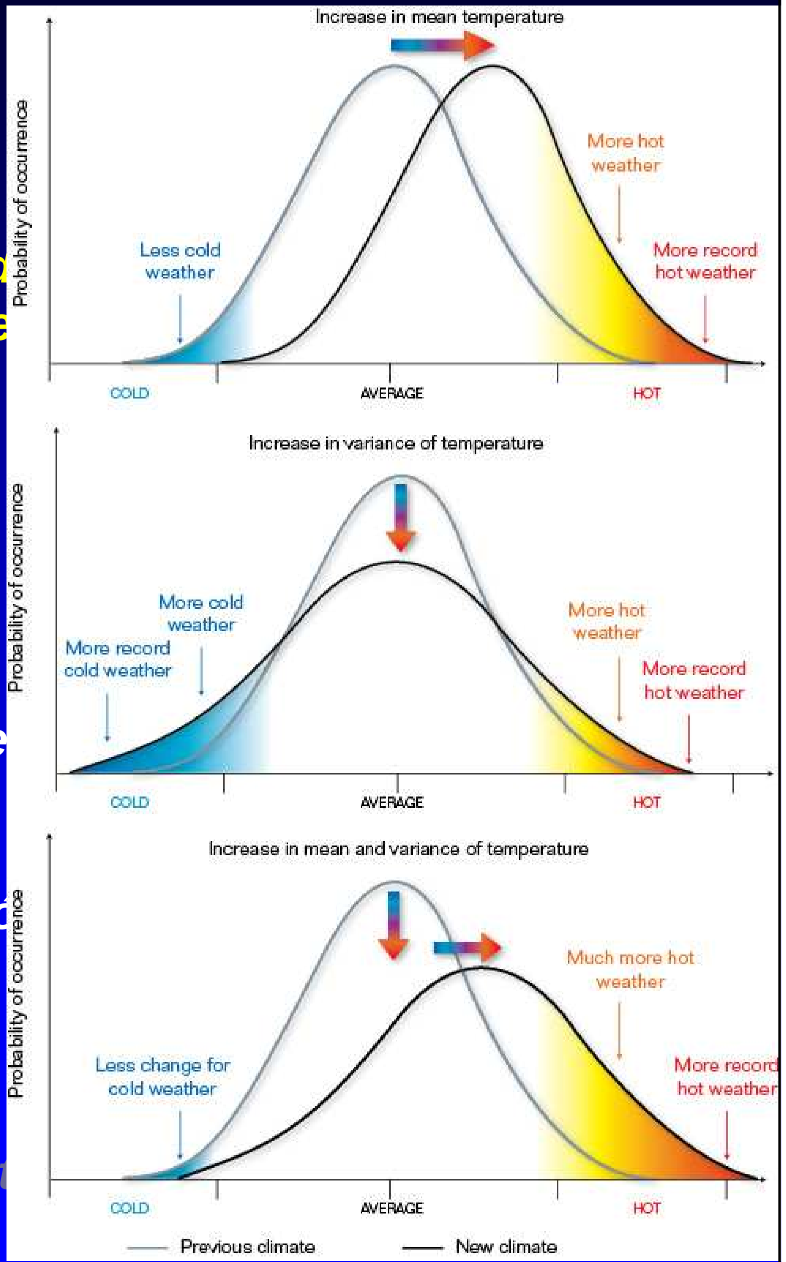
- *Tiempo y Clima son cosas diferentes:*

Estado atmosférico en un lugar y momento de

VS

Información estadística (función de distribució

- Analogía: Lanzamiento de un dado, o este int



LA ATMÓSFERA ES UN SISTEMA CAÓTICO:

¿Cómo vamos a predecir el CLIMA a lo largo del siglo XXI si ni siquiera somos capaces de predecir el TIEMPO para finales de la semana que viene?

- Tiempo y Clima son cosas diferentes:

Estado atmosférico en un lugar y momento determinados

VS

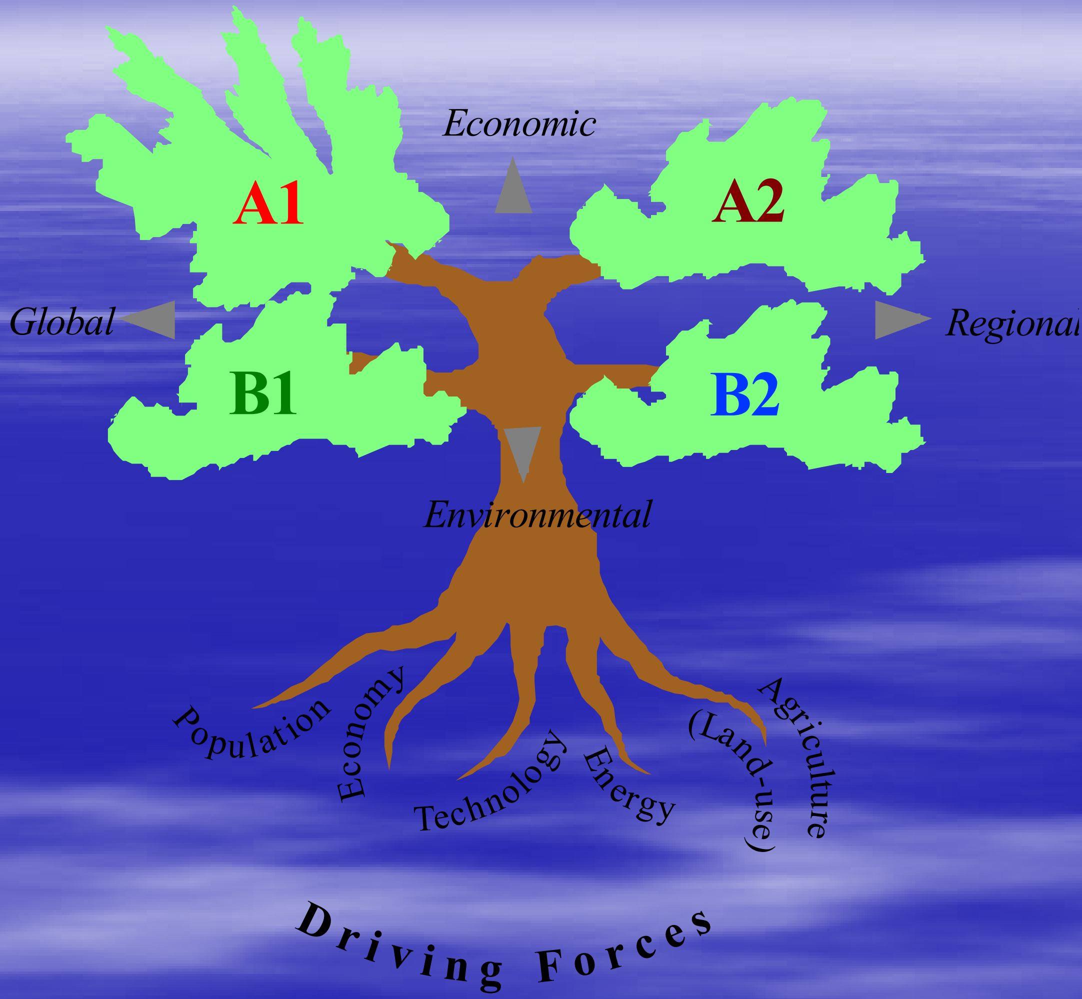
Información estadística (función de distribución de probabilidad)

- ***Analogía: Lanzamiento de un dado, o este interesante ejemplo***

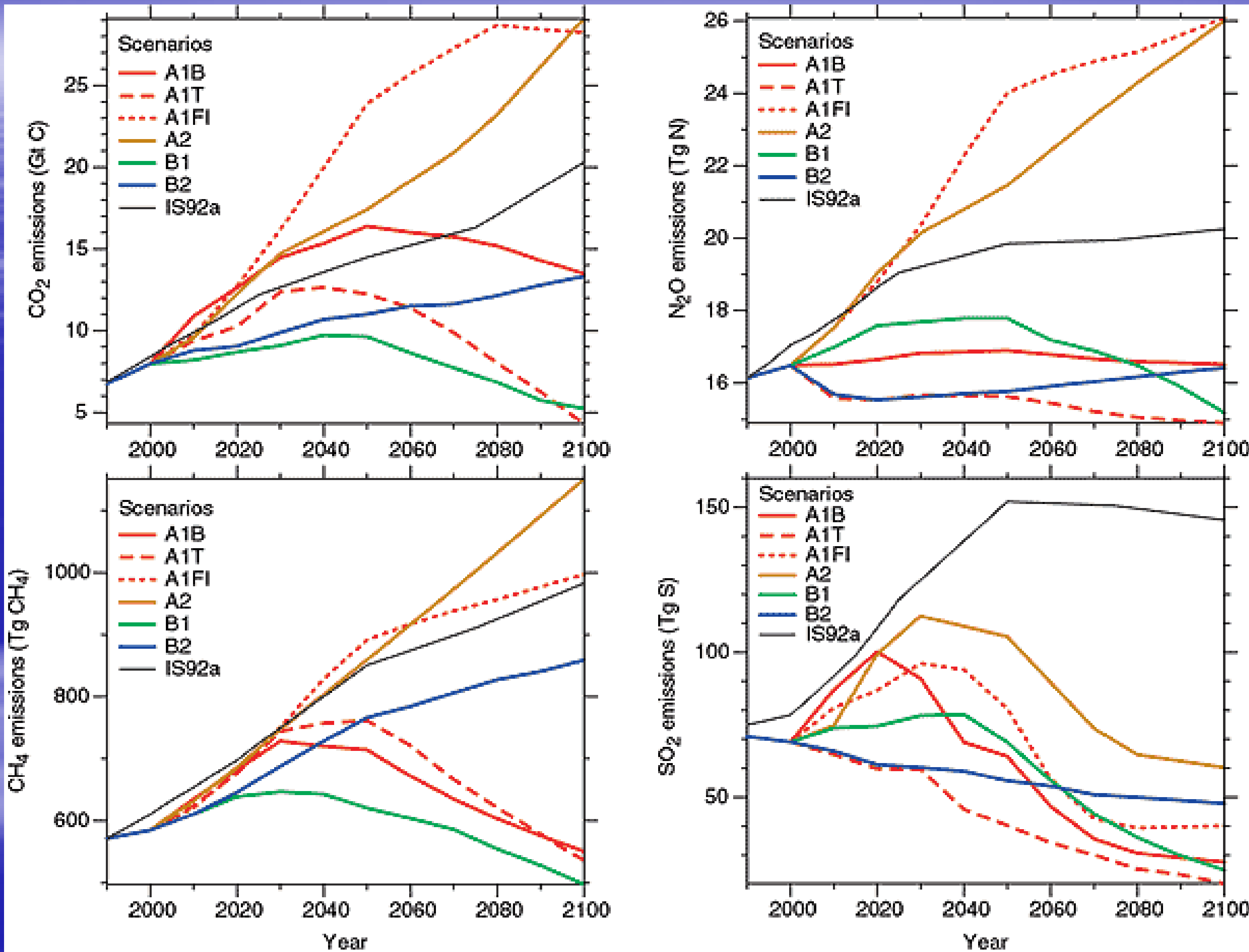
http://www.clivar.org/science/magnets.php

Escenaris d'emissions

SRES Scenarios



- Els escenaris SRES defineixen diferents evolucions de les emissions, i per tant de les concentracions, en funció dels factors socioeconòmics i els models de desenvolupament


Scenarios
A1B
A1T
A1FI
A2
B1
B2
IS92a
CO_2 emissions (Gt C)
N_2O emissions (Tg N)
CH_4 emissions (Tg CH_4)
SO_2 emissions (Tg S)
Year

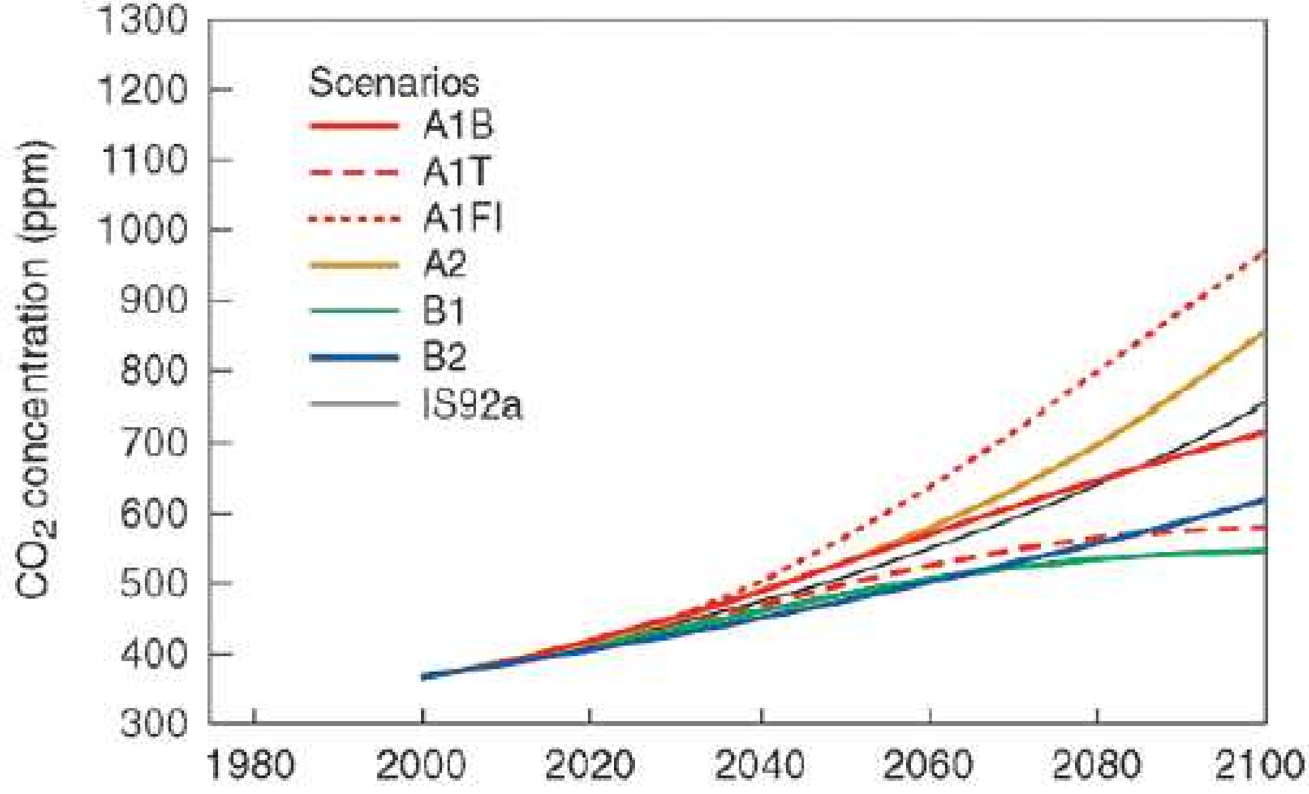


Figura 6.3. La concentració de CO2 a l'atmosfera, com a resultat de les emissions presentades en la figura anterior. Noteu que malgrat en alguns escenaris les emissions comencen a disminuir cap a mitjan de segle, la concentració segueix augmentant, atès que l'escala de temps característica per assolir un nou equilibri en la concentració de CO2 és d'uns 200 anys. [Figura extreta de Houghton *et al.*, 2001]

Temperatura

MULTI-MODEL AVERAGES AND ASSESSED RANGES FOR SURFACE WARMING

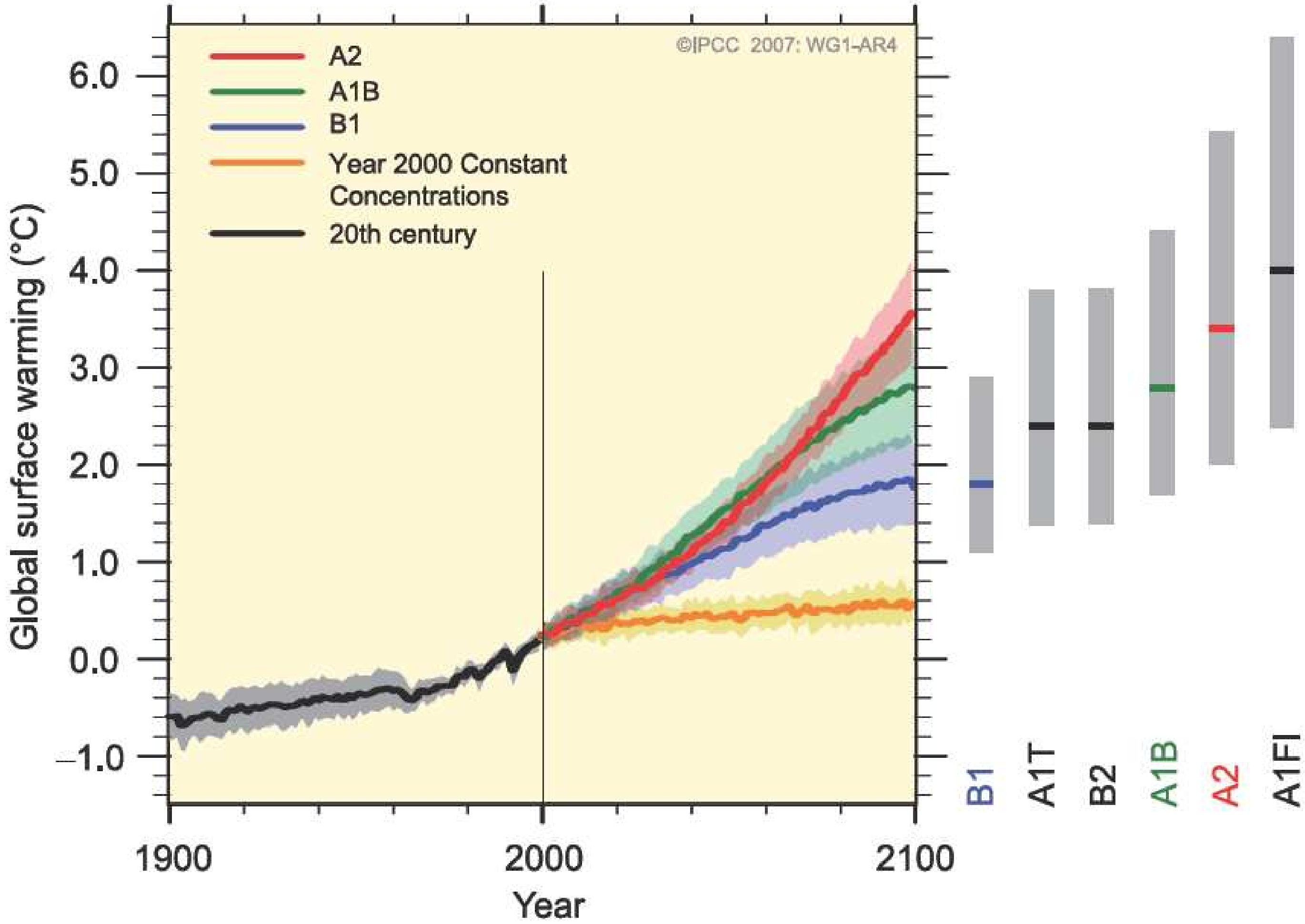
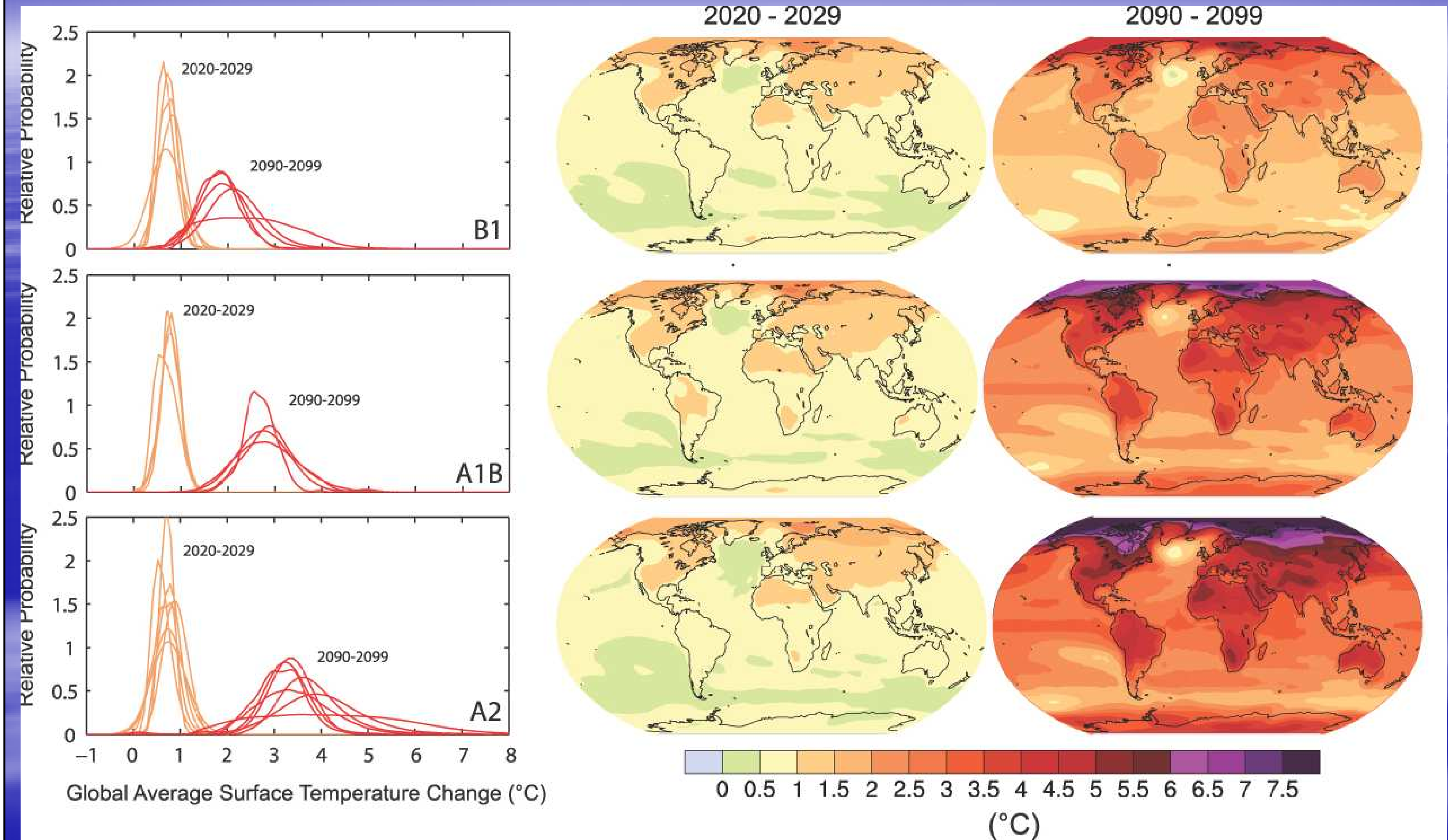
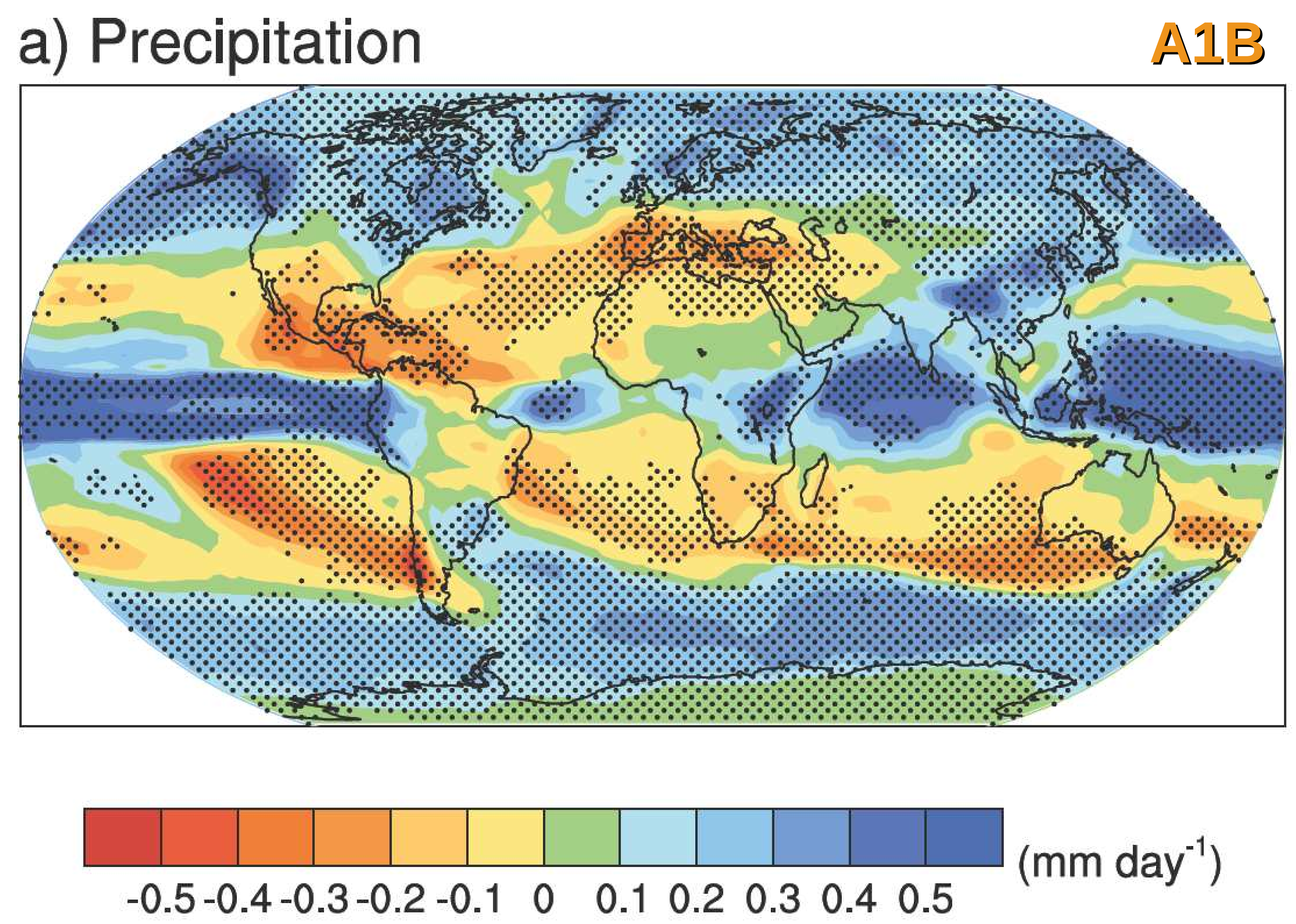


Figure SPM.5. *Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the* ***likely*** *range assessed for the six SRES marker scenarios. The assessment of the best estimate and* ***likely*** *ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29}*



2020 - 2029
2090 - 2099
Relative Probability
2020-2029
2090-2099
B1
A1B
A2
Global Average Surface Temperature Change (°C)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5
(°C)

Precipitació


a) Precipitation
A1B
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5
(mm day-1)

Projected Patterns of Precipitation Changes

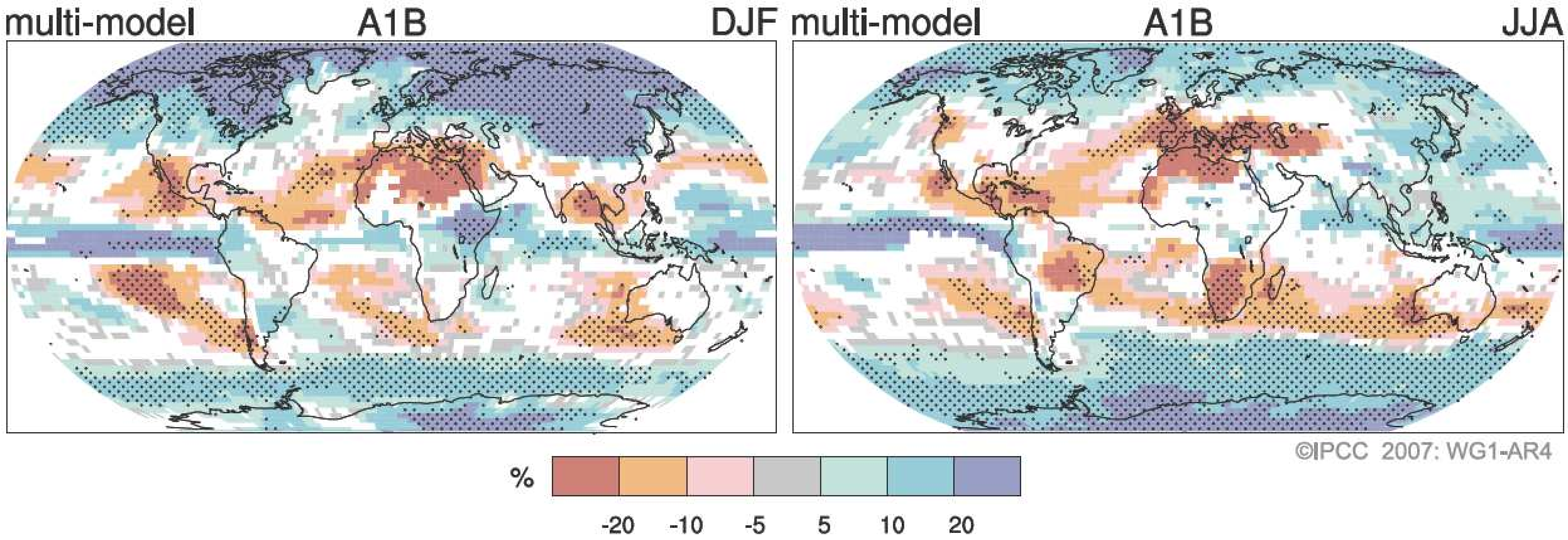


Figure SPM.7. *Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {Figure 10.9}*

Climate Change Impacts are Local

Regional Nature of Climate Change

Impacts

- **Water Resources**
- **Ecosystem Vulnerability**
- **Agriculture**
- **Coastal Systems**
- **Human Health**
- **Energy**

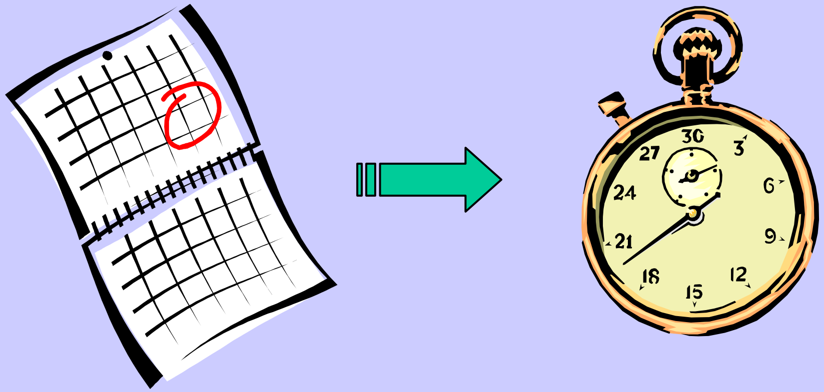
Primary Drivers

Precipitation, Winds, and Temperature

The Problem of Scale

- ***Spatial Scales of Importance***
  - Global
  - Regional
  - State/Province
  - Watershed
  - Municipality/Metropolitan

- ***Temporal Scales of Importance***
  - Long-term climate
  - Annual
  - Seasonal
  - Monthly
  - Daily

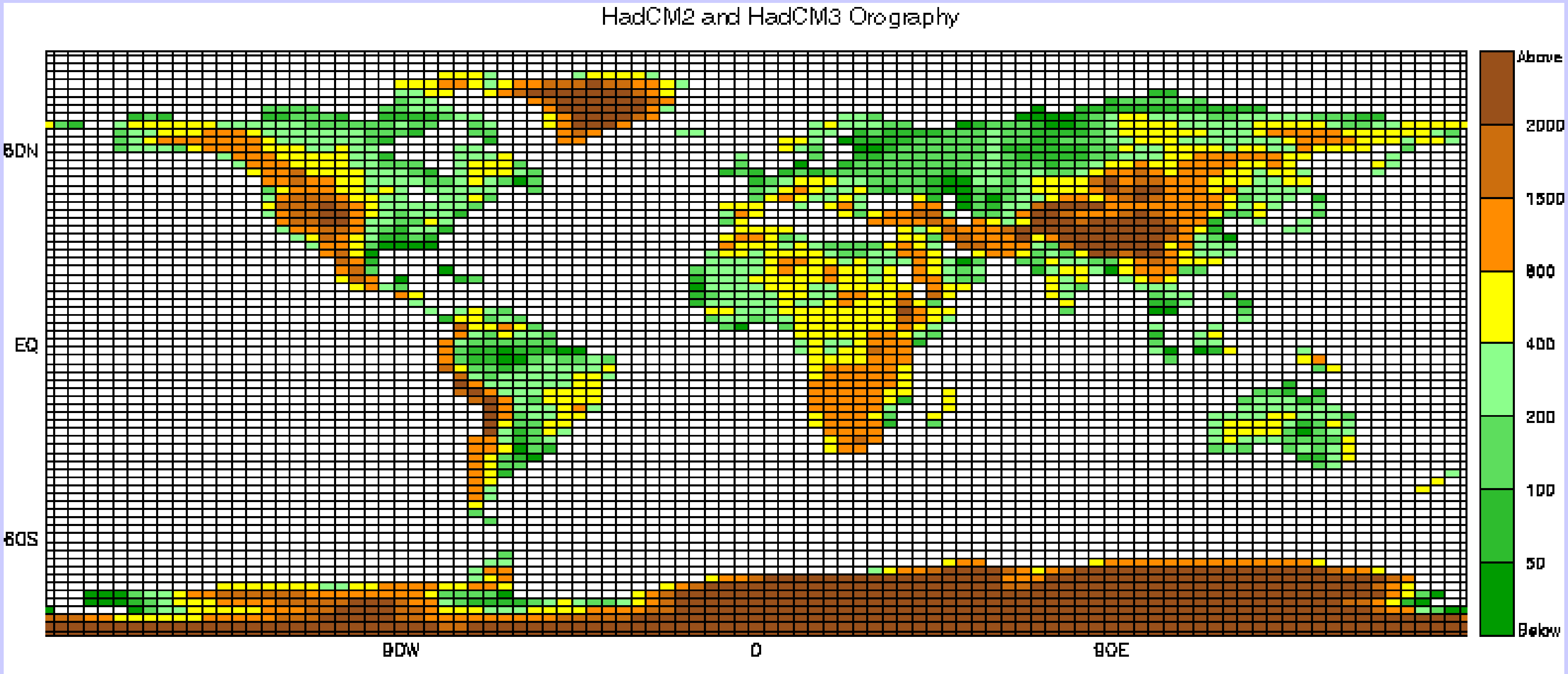


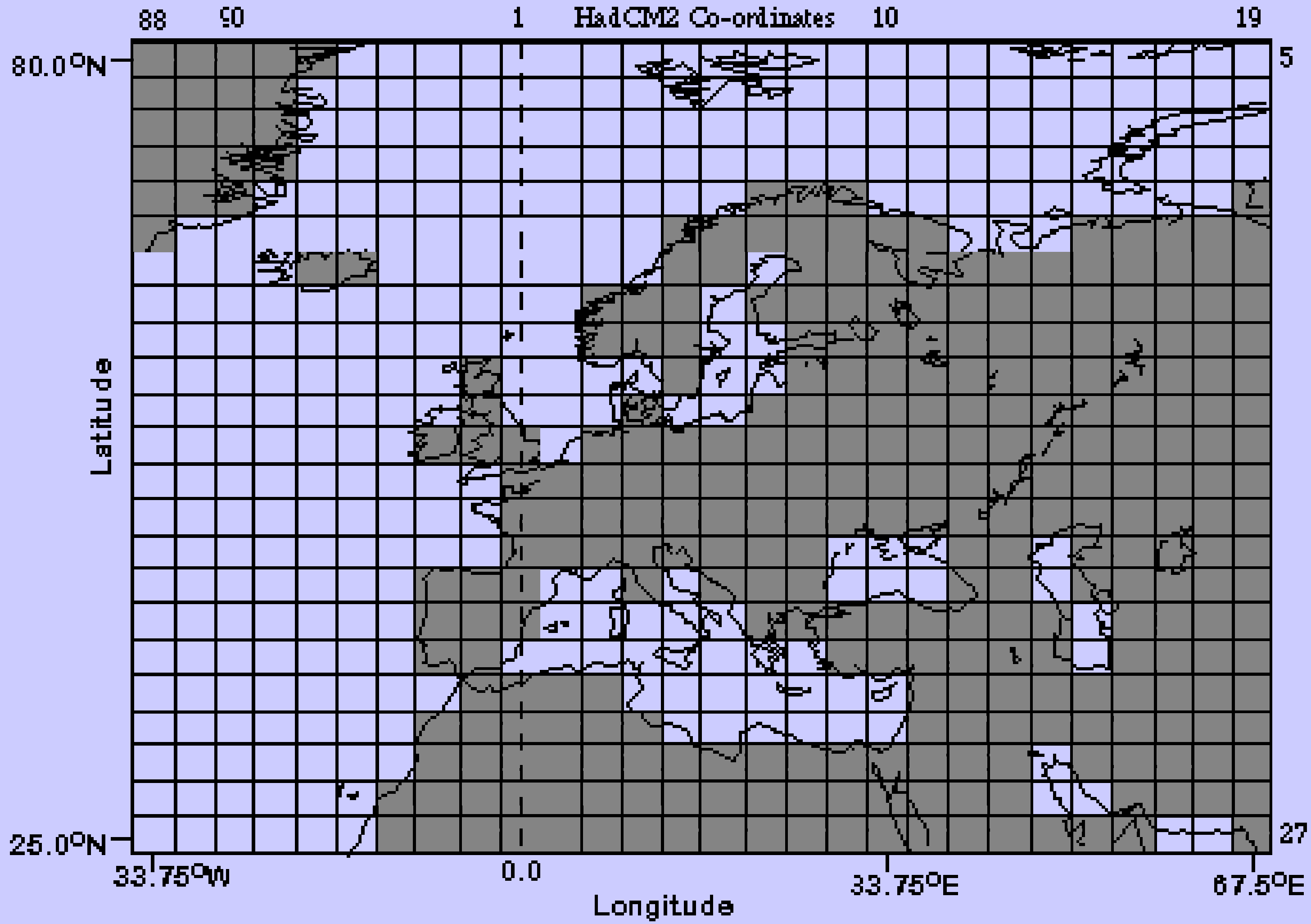
However …

Local climate is strongly influenced by local features such as mountains, sea-land transition and surface characteristics, which are not well represented in global models because of their coarse resolution.

An example: HadCM3 model

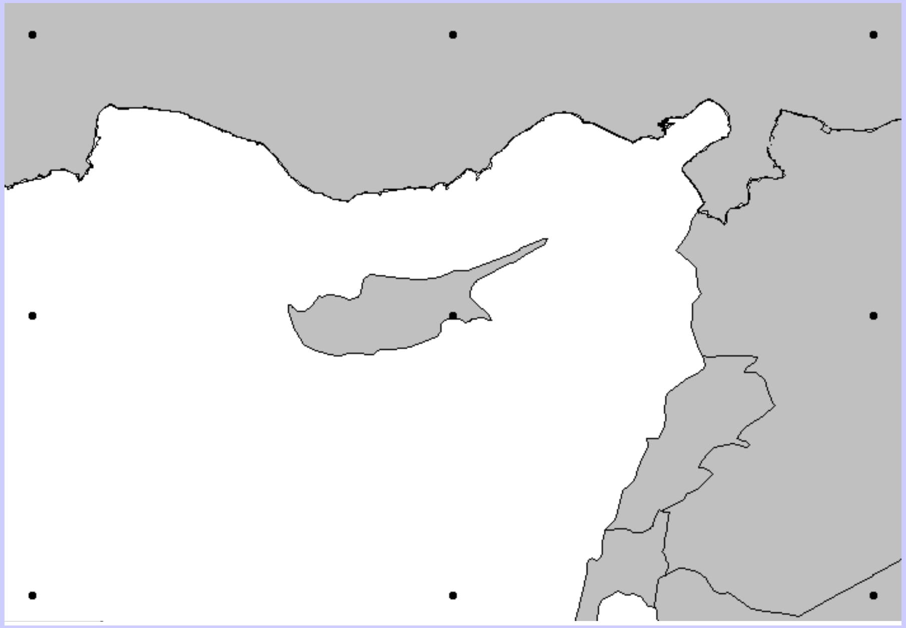
HadCM3 model is the last Hadley centre's coupled ocean-atmosphere GCM with a horizontal resolution of 2.5 x 3.75 degrees and 19 vertical levels, equivalent to a spatial resolution of 278 x 417 km in the equator, and a 278 km x 295 km in the mid latitudes (~ 45º).





Land-sea HadCM3 mask for Europe

Mediterranean islands in the HadCM3 model



Dynamical Downscaling Assumptions/Methods

- **GCM** output at large aggregate scales is useful for providing boundary conditions for nested models. These nested, higher-resolution models are called **RCM**, and include complex physical parameterizations
- Nesting is usually one-way with no feedback from mesoscale to GCM scale
- Transient run simulations can be accomplished, but are cumbersome

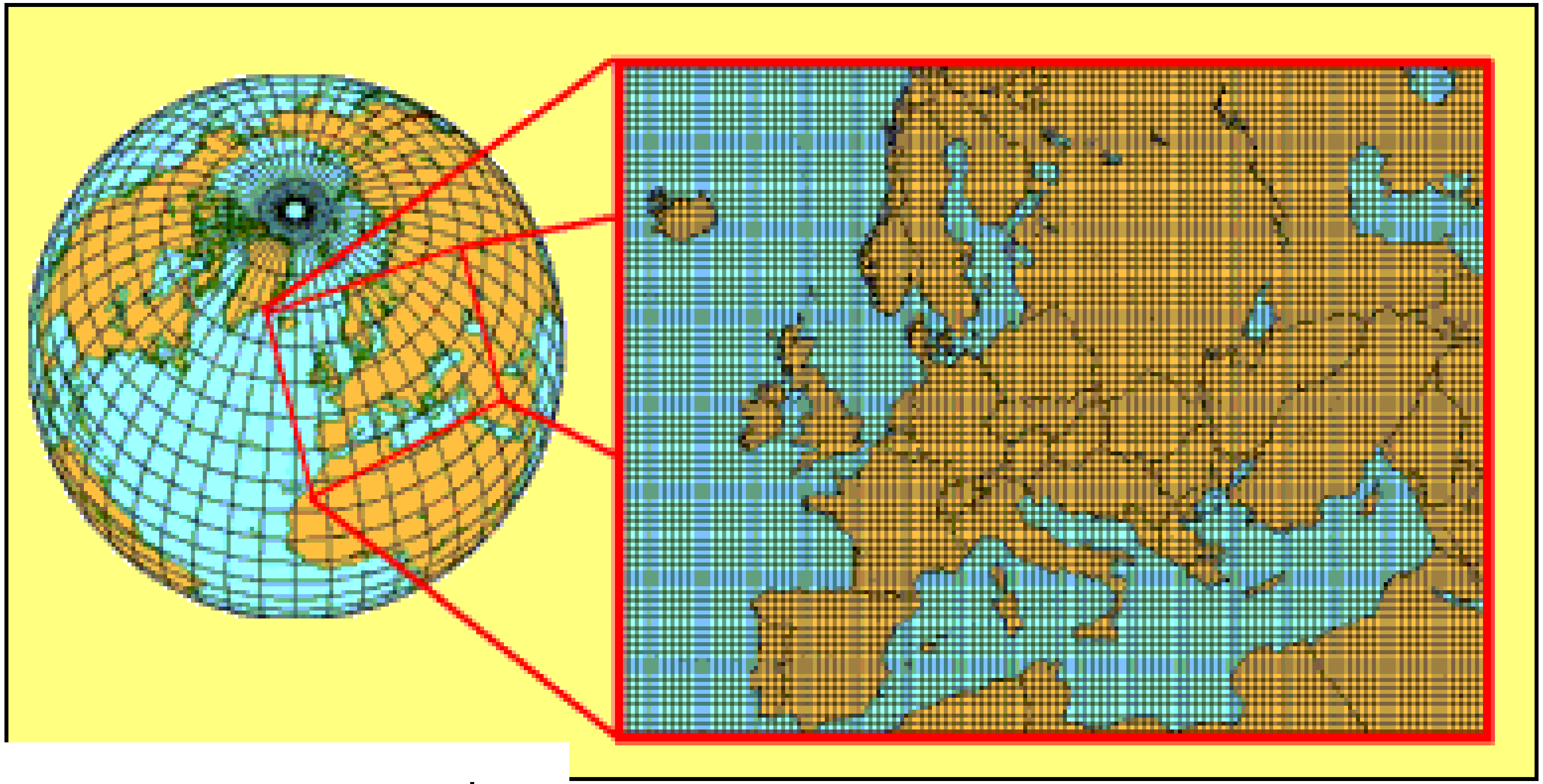
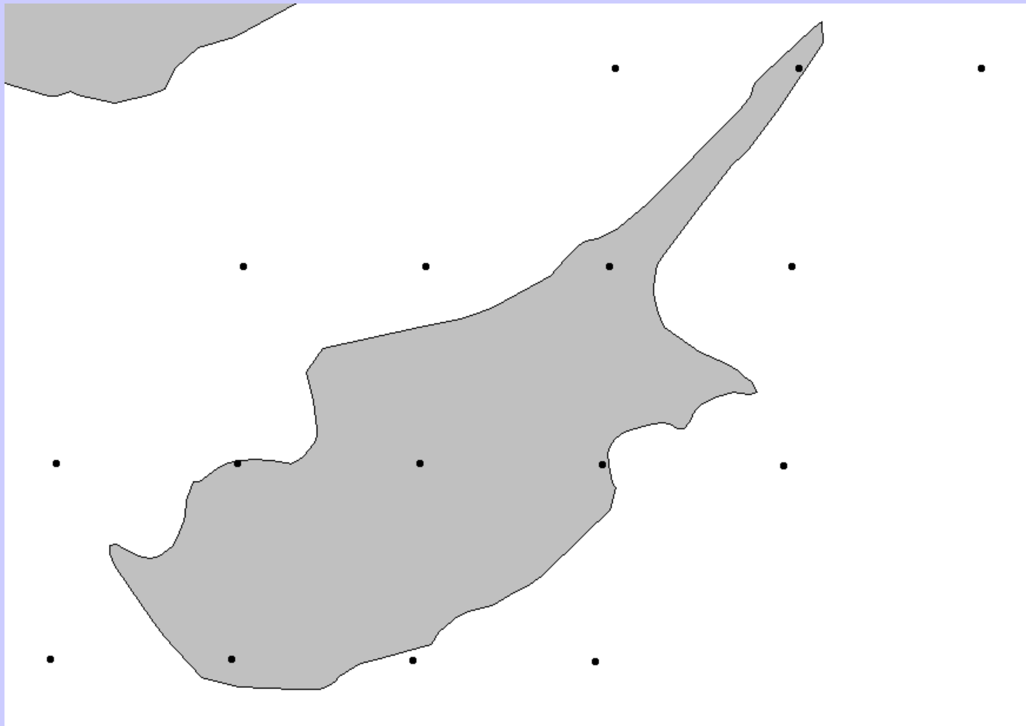


Figura 9. Ejemplo del dominio de aplicación de un RCM sobre Europa con una rejilla de 50 km. La técnica de anidamiento ("nesting") consiste en proporcionar al RCM información de la evolución de las variables atmosféricas en los puntos del contorno del dominio. Dicha información se obtiene previamente de la simulación con un AOGCM que utiliza una rejilla con resolución más baja (celdillas con mayor tamaño)

Mediterranean islands in the HadRM3 (~ 50 km) model



Modelos regionales	Anidamiento en HadAM3H			Anidamiento en ECHAM4		
	Control	A2	B2	Control	A2	B2
CNRM	x	x	x			
DMI	x	x	x	x	x	x
ETH	x	x				
GKSS	x	x				
HC	x	x				
ICTP	x	x	x			
KNMI	x	x				
MPI	x	x				
SMHI	x	x	x	x	x	x
UCM	x	x	x			

Tabla II.- Proyecciones regionalizadas basadas en modelos regionales del clima procedentes del proyecto PRUDENCE. Las simulaciones realizadas por cada modelo regional se identifican por el centro o instituto donde se ha desarrollado.

Métodos empíricos	Modelos globales ECHAM4	HadCM3	HadAM3H	CGCM2	HadCM2SUL
Analog(FIC)	A2, B2		A2,B2	A2,B2	
Analog(INM)	A2, B2		A2	A2,B2	IS92a
SDSM		A2,B2			

Tabla I.- Proyecciones regionalizadas con métodos estadísticos disponibles. Los datos diarios de las proyecciones se refieren al periodo 2011-2100 y el periodo de control al periodo 1961-1990 y a las variables: precipitación, temperatura máxima y temperatura mínima. Los métodos Analog(FIC) y SDSM presentan los resultados en las estaciones, mientras que el método Analog(INM) presenta los resultados en una rejilla regular de 50 km.

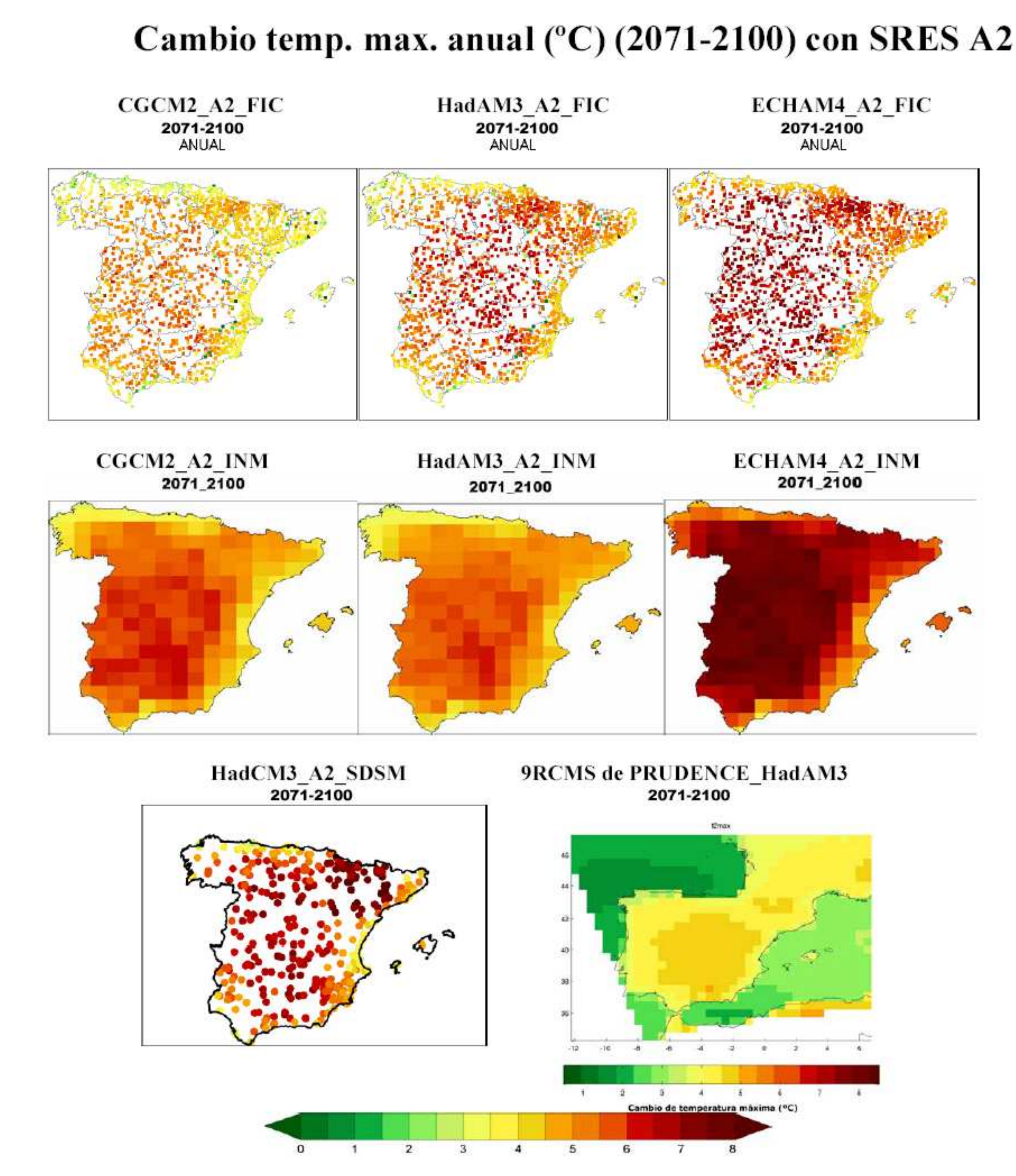


Fig. 1.- Comparación del cambio de temperatura máxima anual para el período (2070-2100) respecto al periodo de control (1961-90) proporcionado por las proyecciones regionalizadas utilizando diferentes modelos globales (HadCM3, HadAM3H, HadCM2SUL, CGCM2, ECHAM4-OPYC), el escenario de emisión A2 del SRES-IPCC y diferentes técnicas de regionalización estadísticas (Anal_FIC, Anal_INM, SDSM) y dinámicas (promedio de los 9 RCMs de PRUDENCE).

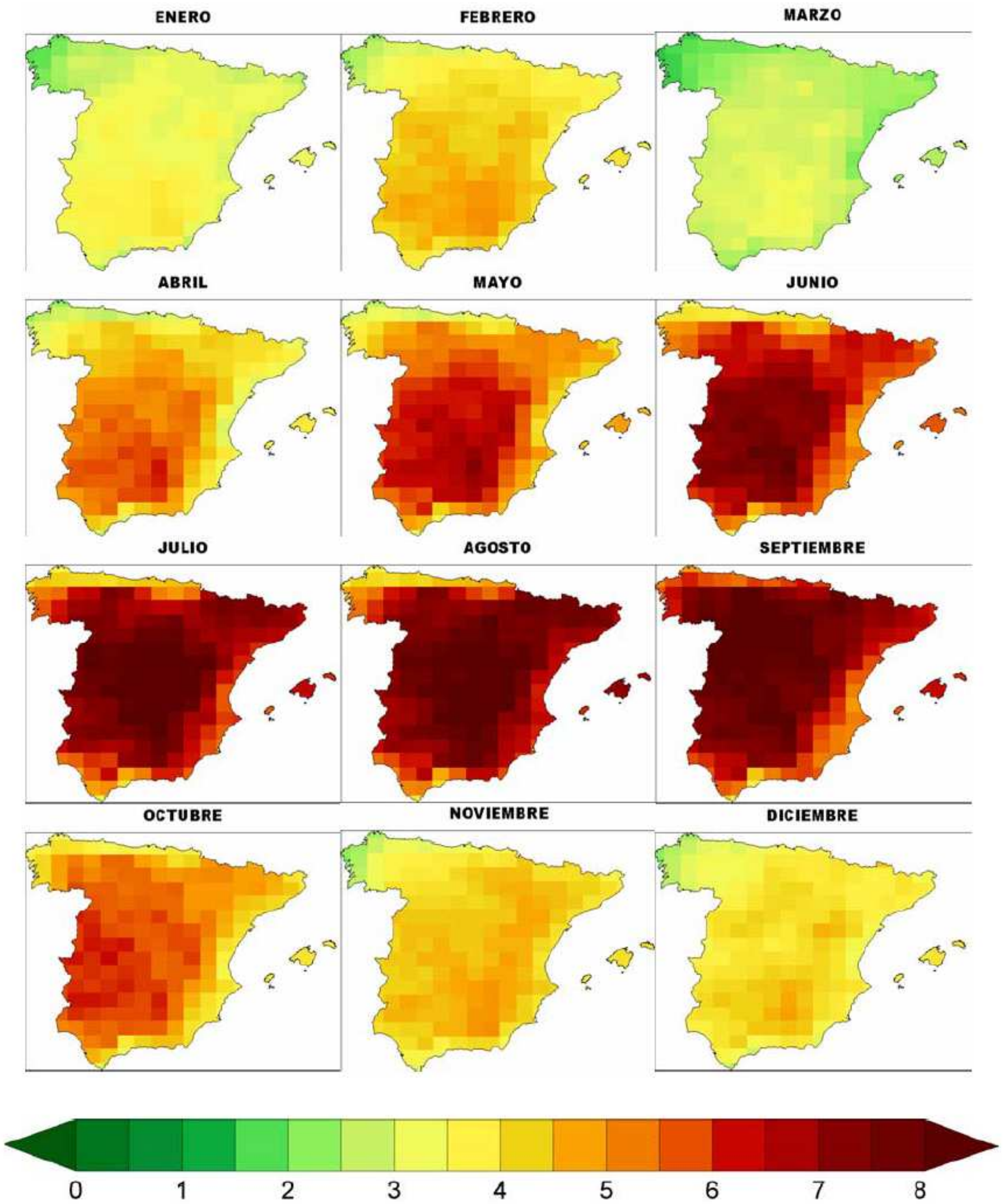


Fig.2.- Cambio medio mensual proyectado para el periodo (2071-2100) respecto al clima actual (1961-1990) por el modelo global HadAM3H y regionalizado con el método de análogos (INM) para la temperatura máxima y el escenario de emisión A2.

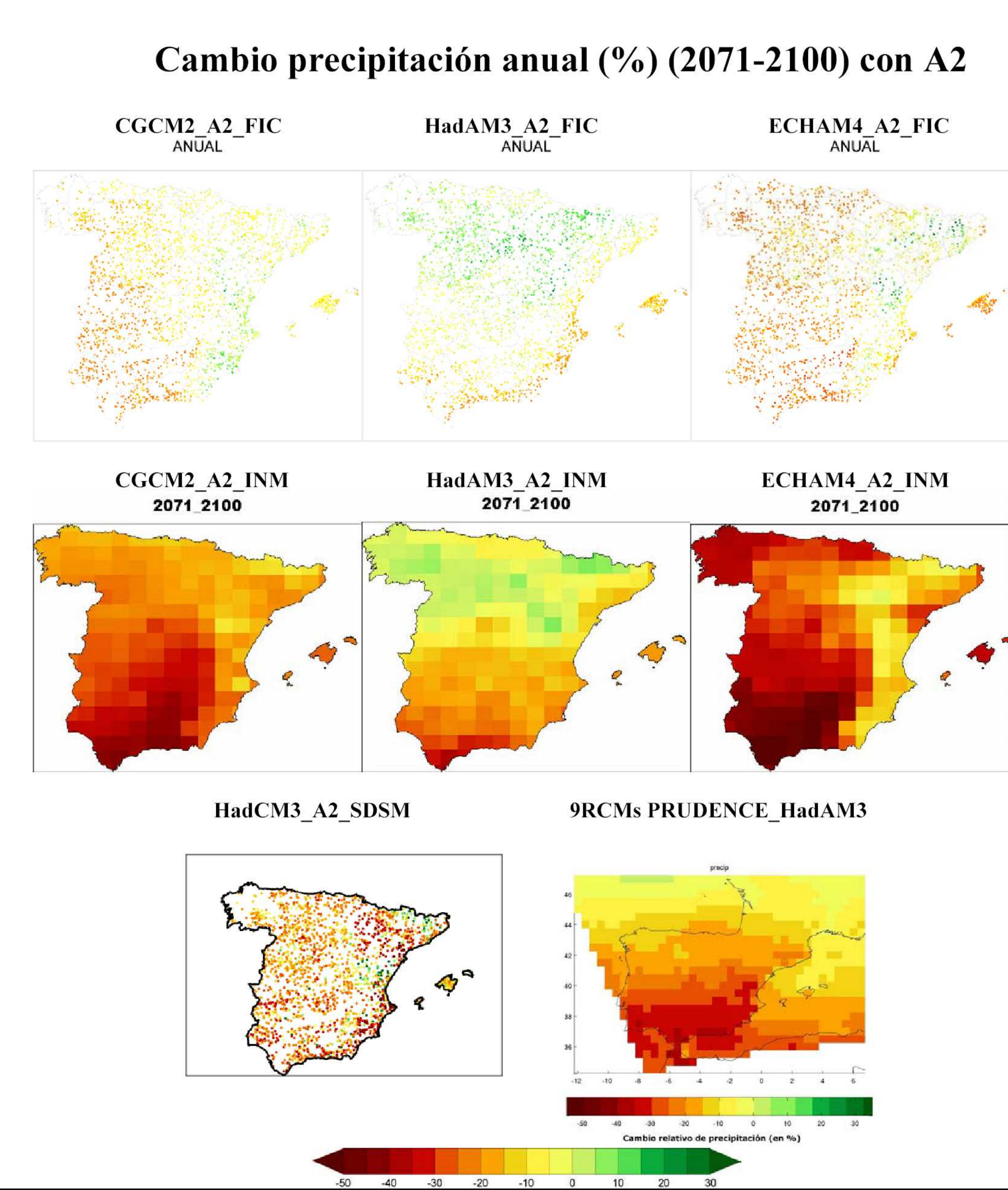


Fig. 3.- Comparación del cambio de precipitación anual para el período (2070-2100) respecto al periodo de control (1961-90) proporcionado por las proyecciones regionalizadas utilizando diferentes modelos globales (HadCM3, HadAM3H, CGCM2, ECHAM4-OPYC), para el escenario de emisión A2 del SRES-IPCC y diferentes técnicas de regionalización estadísticas (Anal_FIC, Anal_INM, SDSM) y dinámicas (promedio de los 9 RCMs de PRUDENCE).

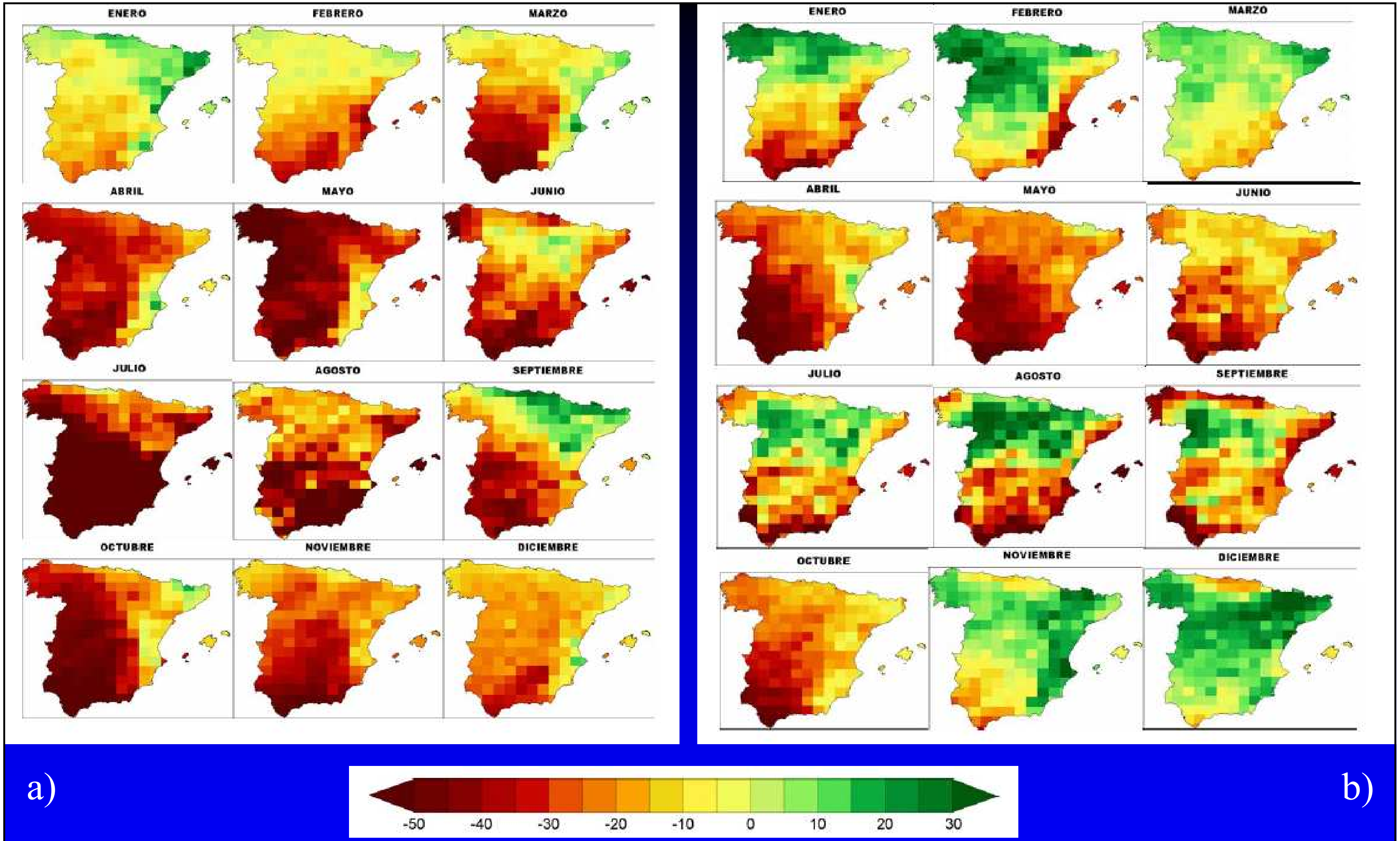
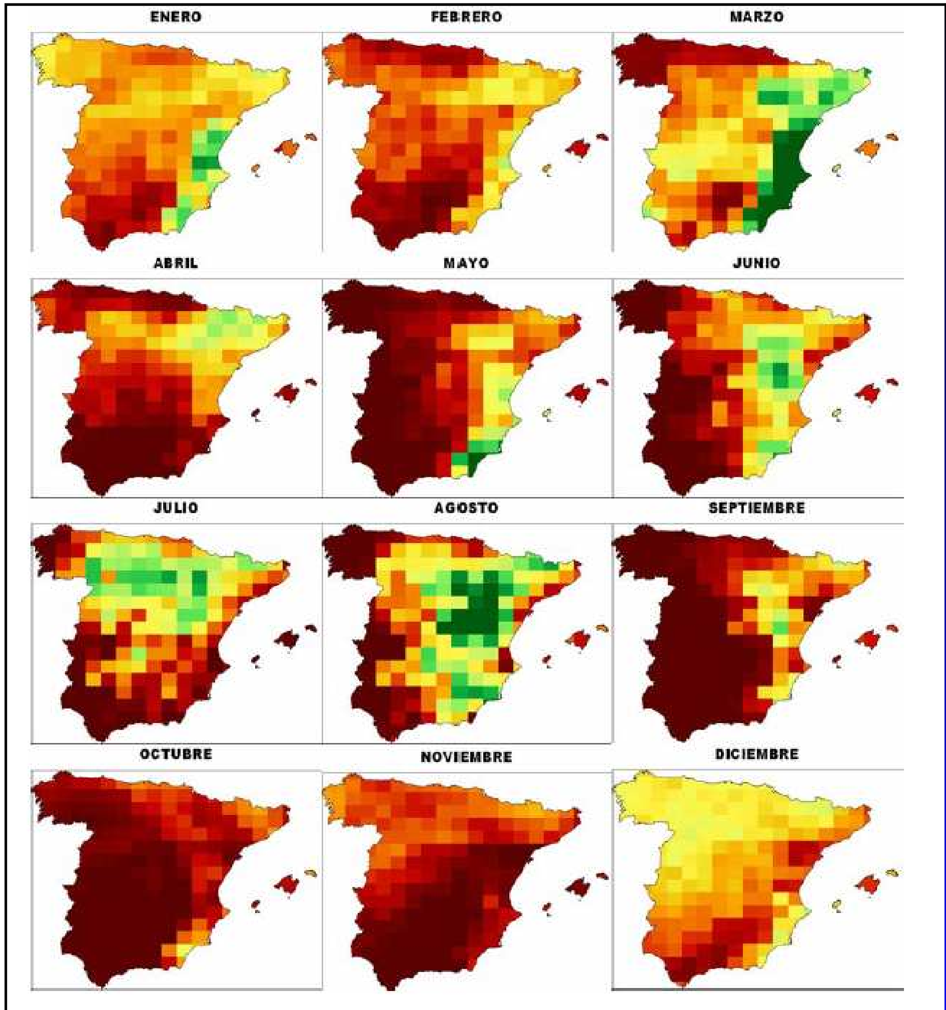
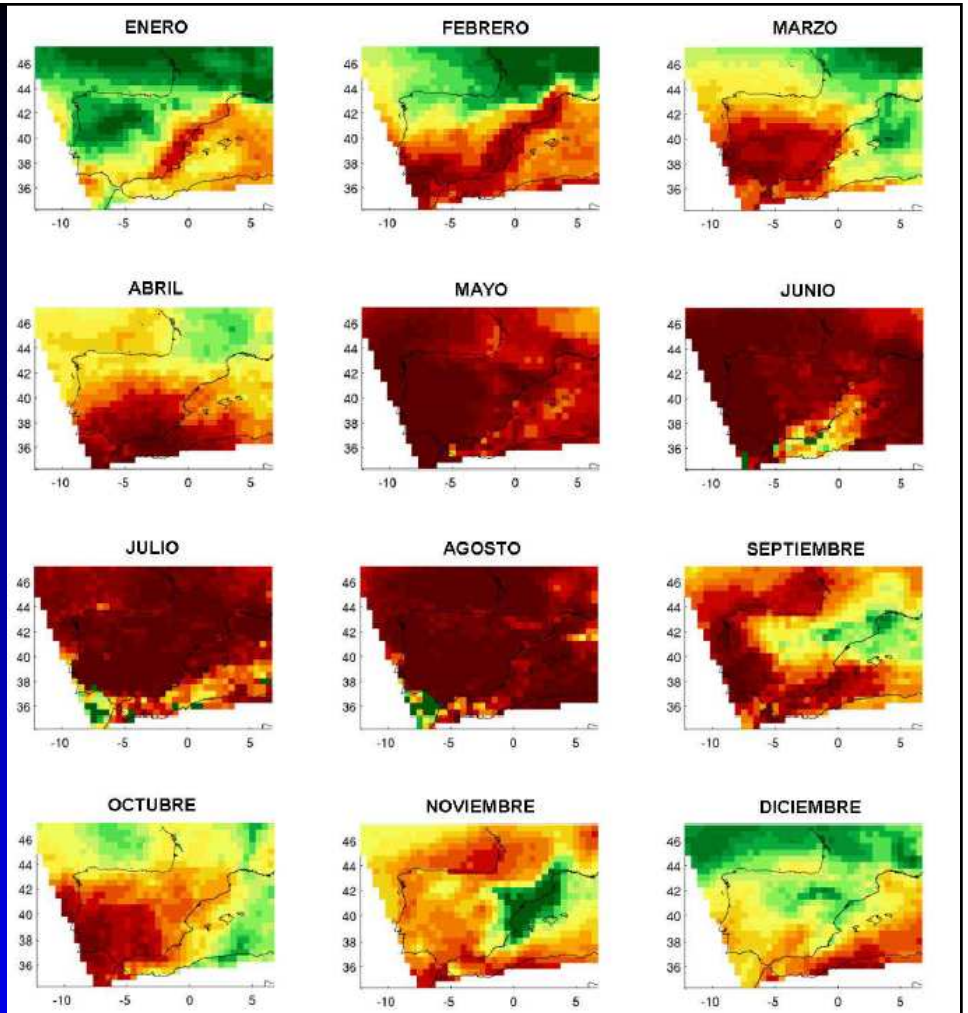


Fig.4.- Cambio de distribución mensual de precipitación (%) para el periodo (2071-2100) respecto al periodo de referencia (1961-1990) para los modelo globales CGCM2 (a) y HadAM3H (b), regionalizados ambos con el método de análogos (INM) con el escenario de emisión A2.





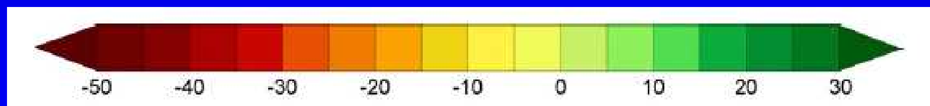


Fig.5.- Igual que fig.4, pero para el modelo ECHAM4-OPYC.

Fig.6.- Igual que fig. 4, pero para el promedio de los 10 modelos regionales de clima de PRUDENCE (incluido el modelo ARPEGE de resolución variable del CNRM).

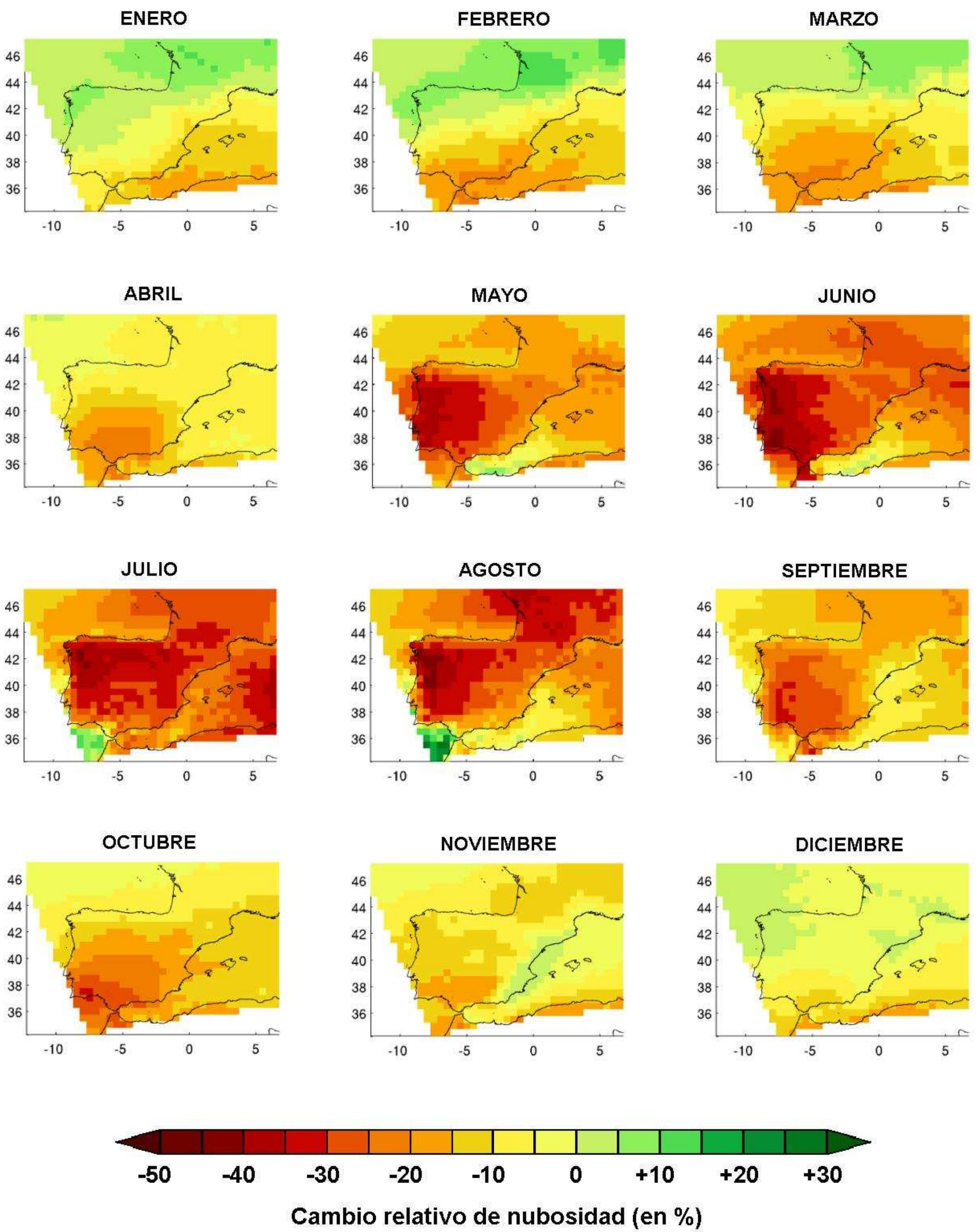


Fig.7.- Distribución mensual del cambio medio porcentual de nubosidad proyectado por los diez modelos regionales PRUDENCE en el escenario A2 (2071-2100) respecto al clima actual (1961-1990).

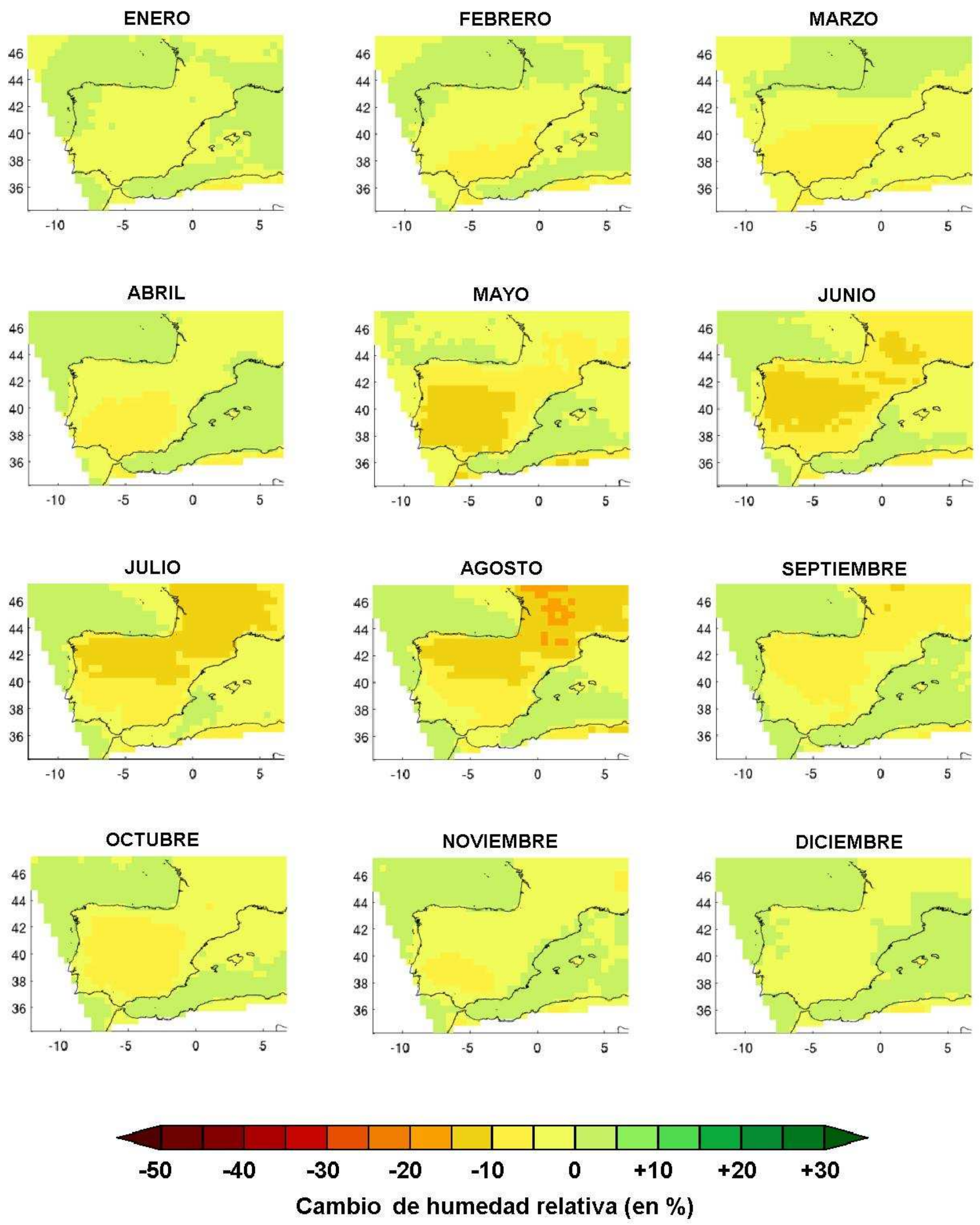


Fig.8.- Distribuciones mensuales del cambio medio de humedad relativa proyectado por los diez modelos regionales PRUDENCE en el escenario A2 (2071-2100) respecto al clima actual (1961-1990).