Mesoscale modelling and predictability of (heavy) precipitating systems

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OVERVIEW

Aim: - provide a (quick!) overview of the state of the art
     - provide a synthesis of submitted proposals
     - contribute to initiate coordination/collaboration

Focus on heavy precipitation systems

Outline: - mesoscale modelling issues & proposal
          - deterministic forecast
          - predictability issues & proposal
          - ensemble forecast
Heavy precipitation systems

HPE are not uncommon over the Mediterranean region
- peculiar topography (steep orography surrounding the sea)
- geographical location (cyclogenesis and Atlantic influence)
- source of heat and moisture feeding convective and baroclinic systems

General factor leading to HPE
- conditionally or potentially unstable air masses
- moist LLJ impinging the orography
- steep orography
- slowly evolving synoptic pattern, maintaining the precipitation system nearly stationary or slow-moving
- interaction between the above factors

Orographic forcing ↔ HPE ↔ convection (embedded)
MESOSCALE MODELLING

Mesoscale α: 200-2000 km
Mesoscale β: 20-200 km
Mesoscale γ: 2-20 km

The interest is focused on small scales!

Many aspects of NWP models have made great advances, BUT progress in QPF has been comparatively slow

-Precipitation involves a complex chain of interacting physical processes extending on a wide range of scales (upward motions, condensation, microphysics...)
-Some important small scale processes need suitable parameterizations especially at very high-resolution (turbulence and microphysics)
-Orographic dynamical forcing needs to be adequately resolved
-Dependence on larger scale models (initial and boundary conditions)

Recent progresses → development of high-res CRM models (operational)
MAP (Mesoscale Alpine Programme) → first major European field experiments for which a quasi-operational forecasts were made with a 3-km non-hydrostatic model (MC2). MAP & subsequent research activities strongly stimulated models development.
In 2007 **MAP D-PHASE & COPS** addressed the issue of (orographically-induced) convection

**D-PHASE**: demonstration of the ability of forecasting heavy precipitation and related flooding events in the Alpine region (operational forecasting)

**COPS** (field campaign): advance the quality of forecasts of orographically-induced convective precipitation by 4D observations and modelling of its life cycle
Scientific perspective

Although the debate about the suitable resolution for representing convection is still open (e.g.: 4 km for MCS but not for isolated cells - Weisman et al. 2008) state-of-the-art high resolution models provide:

- superiority of the non-hydrostatic models over the coarse resolution models, especially in case of convection/orographic forcing
- better representation of convective system evolution
- high resolution removes the “damage” due to inaccurate parameterization

Greater realism does not necessarily means better forecasts (verification is tricky!)

- Data assimilation:
  > large sensitivity to the initial condition suggests that much attention has to be devoted to the improvement of the initial state
  > several studies demonstrated improvement due to assimilation of high resolution/non conventional observation
PROPOSALS OVERVIEW - mesoscale modelling

- Idealized simulations
  - investigate mechanisms (research)

- Hindcasting / post-event activities
  - investigate mechanisms
  - verification and development

- Real time operational forecasting
  - support to field campaign
  - verification and development

- Data assimilation
NUMERICAL SIMULATIONS OF CONDITIONALLY UNSTABLE FLOWS OVER A RIDGE

Miglietta (ISAC-CNR) and Rotunno (NCAR)

Cloud model (Bryan) at 250 m horizontal resolution
Investigate conditions favourable for convective development and stationarity

FIG. 1. Numerical setup (a) and terrain profile (b) of the experiments. In (a) Nx, Ny and Nz are, respectively, the number of grid points in x and y directions and the number of vertical levels. In (b) the terrain profile is shown in an expanded view close to the mountain top.
wind speed: evaporation (cold pool) vs advection

mountain shape: wider ridge $\rightarrow$ spreading of precipitation

FIG. 8. Explanation of the effect of the wind speed on the solution. For weak wind, the rainfall generated on the upstream side of the ridge may evaporate into midlevel, potentially cool air which can descend to the surface and subsequently produce a cold outflow. For larger wind speeds, the net cooling from evaporation is small compared to the advection of ambient potential temperature to the windward face of the ridge, so that the decrease in potential temperature is minimal. For the intermediate wind case, convection is triggered on the downstream face of the ridge, and the precipitation over a larger region is produced by the stationary cold pool

FIG. 11. Explanation of the effect of the ridge half-width $a$ on the solution. A wider ridge has the effect of spreading the precipitation over a larger region, as the LFC is reached by the low-level parcels far upstream of the ridge.
Dependence on physical parameters

Rainfall distribution: in convective situation, the Froude number is not a very important control parameter.

More relevant: triggering term \( \frac{h_m}{LFC} \), orographic forcing \( \frac{h_m}{a} \) and the advective time \( a/U \) wrt the rain cell development time \( \frac{h_t}{\sqrt{CAPE}} \).

FIG. 12. Explanation of the effect of the maximum ridge height \( h_m \) on the solution. For short ridges, the uplift required to trigger convection is reached closer to the ridge top and the rainfall pattern is shifted downstream.

FIG. 15. Plot of \( \frac{R_{\pi}}{po^{0.5}} \times 10^2 \) vs. \( \frac{h_m}{LFC} \) and \( \frac{h_m}{a} \) for \( t_a = t_c = a/U (CAPE)^{1/2} / h_t = 3.2 \), b) 12.9, c) 24.9.

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Scientific issue: As the meteorological ingredients favouring HPEs are quite well-known, understanding about how they combine and interact is still an open question.

To assess this issue:

**High-resolution idealized numerical simulations**

- **Meso-NH model** with no convective parameterization, 5 hydrometeor categories, 2.4km horizontal resolution;
- **Idealized framework**: real topography, idealized convective flow from a sounding, unidirectional SSE wind)

Representative of “Cevenol” HPE environment

**Sensitivity experiments**:

- **Flow intensity**: $U_0 = 10, 15, 30, 40 \text{ m.s}^{-1}$
- **Humidity field**: $\alpha = 85, 90, 100\%$

Mountain ranges

Remove: Alps, Pyrenees, Alps&Pyrenees, Massif Central, all mountain ranges

Results in terms of location and severity of the quasi-stationary mesoscale convective systems. (Results will be exposed during the poster session)

This study helps to identify regions and mechanisms that are important to better document during the HyMeX SOPs.
**IC and BC**: both imposed using horizontally uniform profiles of wind, T, q derived from the ECMWF analysis (Sept. 8, 2002)

The **BOLAM** hydrostatic model used to define a 3-D "basic state" flow, in quasi-equilibrium with the orography

The **MOLOCH** non-hydrostatic model used to model the convection developing in the above-defined "basic state"
TOTAL (7 hours) ACCUMULATED PRECIPITATION

Stability diagram

CONVECTION

UNSTABLE

NO CONVECTION

STABLE

CNTR

orography x1.25

orography x1.5
Factors leading to HPE

*Ducrocq et al. - CNRM-GMME*

Understanding the role of the complex orography:
role of orographic small scale features in organizing/enhancing precipitation of MCS
very high resolution model (500 m)

Impact of SST:
impact of mesoscale SST anomalies existing before convective triggering
investigate the pre-conditioning and initiation phase of convection
high resolution model and hourly high resolution SST data
Some aspects of the Croatian meteorological research toward HyMeX

Post event simulation with WRF (9-3-1 km)
Heavy rainfall associated to Bora events

3h precipitation valid for 29 June 2004, 10 UTC

10-m wind 
29 June 2004, 10 UTC

Maximum vector: 14.5 m s⁻¹
LA-PAME contribution

Chaboureau et al. - LA-PAME (Univ. Toulouse/CNRS)

Meso-NH model with dust parameterization
Role of the Saharan dust on radiation, cloud microphysics and convective initiation \(\Rightarrow\) impact of Saharan aerosols on HPE

Run some case studies
Mesoscale Modelling of Mediterranean Hazardous phenomena

(Romero & Homar - UIB)

- Specific attention to:
  - Heavy rain
  - Intense cyclones
  - Medicanes

Factor separation technique: investigate the effects on HPE of many factors.
Non-hydrostatic, compressible, numerical limited-area model developed by the COSMO community (http://www.cosmo-model.org)

Aims:

- Study the impact of orography on HPE and high impact weather
- Role of convection in the hydrological cycle: comparison between observed and modelled turbulent fluxes
- Investigate convection triggering mechanism and interaction with orography
- Role of aerosols (COSMO-ART)

Initialization data and boundary data interpolated from GME results
simulation start: 11 Sept. 2008, 00 UTC
simulation time: 78 h, grid spacing: 0.09° (~10 km)

Different conditions:

- reference run with unchanged model orography
- run with truncated orography (max. height approx. 600 m)
3rd HyMeX Workshop

Mean sea level pressure in hPa

Reference run with "real" model orography

Run with "eroded" orography

Accumulated precipitation in mm

Simulation time 3 d 00 h
The NWP suite AROME-WMED

Duffourg et al. - CNRM

A high-resolution data assimilation and modelling system for Mediterranean NWP

- Western Mediterranean entirely included
- 2.5 km horizontal resolution – deep convection explicitly resolved
- Non-hydrostatic dynamics
- Physics: six water species contents, 1D-TKE
- Two-way coupling with the externalised surface model SURFEX
- 3-h cycled 3D-Var data assimilation system
- Realistic simulations of two HPE cases.
- The inflow of unstable Mediterranean air is well captured. Fine description of this key ingredient for the HPE development.

Cape (J) at 00 UTC, 02 Nov. 2008 – 18 h AROME-WMED forecast

24h cum. rain (mm) at 09 UTC, 02 Nov. – 27 h AROME-WMED forecast

Not only operational activities: e.g. study the role of mid-level dry air
High resolution operational forecasting with BOLAM-MOLOCH

Davolio et al. - ISAC-CNR

BOLAM (14 km)

MOLOCH (2.3 km)

www.isac.cnr.it/dinamica/projects/forecasts
POSEIDON system
5-km operational weather forecasts for the Mediterranean region
Papadopoulos et al., HCMR

The POSEIDON-I weather forecasting system

COARSE Atmospheric Model
- Horizontal resolution: 0.25° x 0.25°
- Vertical resolution: 32 eta levels
- IC and BC from the NCEP model
  1.25° x 1.25°, 10 s.p.l, 6h
- 6 soil layers
- 72-h weather forecasts

FINE Atmospheric Model
- One-way nested in the COARSE model
- Horizontal resolution: 0.10° x 0.10°
- IC and BC from the COARSE model
  0.25° x 0.25°, 24 s.p.l, 1h
- 6 soil layers
- 72-h weather forecasts
The POSEIDON-II weather forecasting system

GFS Analysis & Forecast

0.5 x 0.5

GFS Analysis Background

Local Analysis Prediction System

LAPS setup

Analysis Products

BC

Forecast Products +120 hrs

Forecast Products

- improved parameterization
- assimilation (LAPS)

During HyMex:
- assimilation of radar/satellite/remote sensing obs.
- support marine and hydrological application

METARS + SYNOPS + RAOBS

IC
Aims:

- test, implement, and assess the impact of the assimilation of new observation types on forecasts of HPEs at a lead time of several hours.

- perform simulations to better understand the physical processes leading to HPEs (e.g.: role of moisture, etc.).

- assimilation/model intercomparisons if other groups interested.

Precipitation radars:
- reflectivity
- Doppler velocity
- dual-polarization measurements
- refractivity

UHF/VHF radars:
- wind

Assimilation into high-resolution atmospheric model (AROME-WMED) over the Mediterranean region.
Mesoscale data assimilation: application to high resolution modelling

Miglietta, Davolio - ISAC-CNR

- Application of **LAPS** (NOAA’s Local Analysis and Prediction System) in combination with WRF model
- Assimilation of precipitation estimates (satellite, radar) into mesoscale models (BOLAM-MOLOCH) through a **nudging** procedure (humidity or latent heating)
PREDICTABILITY

- ERRORS
  - Initial condition
  - Model

Baroclinic & convective instabilities

forecast errors

For LAMs
Lateral boundary conditions:
- sweeps in low-res information
- introduce model errors
- inconsistent physical parameterization produces spurious gradients
- transient gravity modes

Lorenz:
- forecast error would grow more rapidly as the initial state estimate was improved and successively smaller scales were resolved
- an increase in horizontal resolution yields a corresponding decrease in error-doubling times

Increasingly rapid error growth \(\rightarrow\) inherent finite limit to the predictability
Zhang, Rotunno, Snyder et al

- small errors grow faster (non-linear behaviour)
- errors amplify faster in high-resolution convection-resolving simulations
- errors spread upscale from their origin at convective scale, contaminating the mesoscale
- transition from convective-scale unbalanced motion to large-scale balanced motion
- moist convection is the primary mechanism for forecast error growth at small scale

...if analysis continue to improve (resolution to increase) we will eventually reach the point that reducing the initial error by half (!!!) extends our forecast, at a given skill level, by only 1 hour.

**HOPELESS CONCLUSION**
BUT!!!

There is substantial room for improving existing forecasts at both synoptic and meso scale through:
- data assimilation of non-conventional observations
- new and more sophisticated data assimilation techniques
- improving forecast models (physical parameterization)

MOREOVER

Convective instability does not necessarily preclude predictability when it is connected and organized by more predictable larger-scale features which establish the mesoscale environment favourable for the convection and serve as primary triggering agents.

Cope & deal with uncertainty through probabilistic and ensemble forecasting.

Ensemble techniques well established at synoptic scale (baroclinic instability)
Suitable for convection-resolving scales?
- initial perturbation generation?
- role of non-linearity?

research needed!!!
PROPOSALS OVERVIEW - predictability
Convective-scale predictability of Mediterranean Heavy Precipitation Events within HyMeX: scientific issues

Nuissier et al. - CNRM

⇒ Development of Ensemble forecasting systems at high-resolution (AROME) for HyMeX SOPs

Uncertainties on synoptic-scale initial conditions and lateral boundary conditions

Uncertainties on meso-scale initial conditions

Model errors

Fine-scale predictability (limited-area model)

convective-scale ensemble atmospheric forecasts

Hydrometeorological ensemble forecasting (ISBA-TOPMODEL)
Convective-scale predictability of HPEs with AROME model: toward a high-resolution ensemble forecasting system

Uncertainty on synoptic-scale initial and lateral boundary conditions

(i) Selection of PEARP members

Large-scale PEARP ensemble (11 members)

Mesoscale data assimilation + AROME forecasts

SELECT (CTRL) SELECT (1) SELECT (2) SELECT (3)

AROME IC (CTRL) AROME IC (1) AROME IC (2) AROME IC (3)

FC (CTRL) FC (1) FC (2) FC (3)

(ii) Uncertainty on mesoscale initial conditions

Deterministic synoptic-scale conditions

Rapid Update Cycle (RUC) with perturbed observations

AROME forecasts

AROME IC

AROME GUESS

AROME IC
Predictability at the convective scale

*Chaboureau et al. - LA-PAME*

In order to take into account model errors and their impact on diabatic processes

- Use different sets of parameterization schemes
- Generate stochastic perturbations in the parameterization schemes

Predictability on the medium range

- In coordination with T-NAWDEX, diabatic exchanges in precursor predictability over the Atlantic ocean?
- Run a cloud-resolving model over a domain covering the upstream region and the Mediterranean using massively parallel superscalar computers
A Medicane downstream a tropical cyclone a few days later

- role of a trough on the intensification of the Medicane?
- role of diabatic exchanges in precursor predictability during the extratropical transition of the cyclone over the Atlantic?
LEPS technique is employed:

- ECMWF EPS
  - 51 members

- RAMS EPS
  - 51 members

**Clustering**
- Height of dynamical tropopause
  - $PV=1.5$

**Rams EPS**
- 5 members
- High resolution

**Five representative members**

**Comparison WV image**
- MSG vs members

**Rams high resolution**
Short Range Ensemble Generation Strategies

Romero & Homar - UIB

- Multiphysics
- Multimodel
- Initial Condition Perturbations: PV-driven, Adjoint-driven, Customized Bred-Vectors
- Stochastic Physics
Design a multi-scale ensemble forecasting system aimed at examining predictability issues and improving forecast quality.
- Coupling global and regional models for accounting different scales contributing to forecast uncertainty
- Development of stochastic perturbations for accounting the influence of unresolved structures

COSMO-DE-EPS: high resolution ensemble prediction system generated by combining initial and boundary conditions of four global models with five variation of physical parameterization of the COSMO-DE (2.8 km) model.

- High resolution data assimilation experiments within cloudy/precipitating systems (radar & lidar)
- Development of verification metric in order to properly assess ensemble performance
Advanced data assimilation methods

ISAC-CNR (Bologna)

- Methods of data assimilation which take into account the flow-dependent instabilities to estimate the background error
- Applied to hydrostatic models for large scale dynamics (up to now)
- The unstable directions are estimated by breeding on the data assimilation system (BDAS) and the assimilation is performed in the unstable subspace (AUS)
- To what extent these new methodologies can be successfully applied to smaller scales, such as meso-gamma and convective scale??

- Investigate first the instabilities that grow in a convection-resolving model (breeding) → strictly connected to predictability and generation of ensemble perturbation at convective scales
Precipitation is strongly influenced by the presence of orography, which acts as a forcing at the lower boundary. Even if weather forecasts and particularly ensemble forecasts could exactly simulate the large-scale flow fields, there is still much remaining uncertainty owing to the intrinsically chaotic behavior of the moisture and cloud fields themselves. It is this second source of uncertainty that we are trying to quantify.

Aim: to develop a general framework in which to study the fundamental predictability of severe convective events in the presence of orography, in order to quantify the internally generated variability of the convective field.
**Deliverables:** find a suitable statistical distribution of the variance of the convective rainfall field in space and time as a possible tool for evaluating model forecasts and associated uncertainties.

- Model is run long enough for the domain-averaged precip. to come into **statistical equilibrium**
- Statistically equilibrated atmosphere: shallow/deep clouds form, grow and die continuously
- Study the statistical oscillation of convective activity for an ensemble of clouds at statistical eq

Normalized Variance of the convective rainfall field = variance of precipitation / its mean value (for different sized domains and time scale) = measure of the natural variability of the convective rain

\[ \sqrt{2\sigma_{mn}^2} \]

\[ \sigma_{mn} = \left[ \frac{1}{N_x N_y N_t} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \sum_{t=1}^{N_t} \left\{ C_{ijt}^{mn}(t) - \overline{C} \right\}^2 \right]^{1/2} \]
Related activities:

- Moisture monitoring (limited area models & reanalyses)
- Link between HPE occurrence and large scale patterns/weather regimes
- Connection between HPE and intense cyclogenesis (factor leading to ...)
- Validation (modelling & observation)
- Hydro-meteorological prediction
## Mesoscale modelling and predictability

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Thanks!

1) Your attention

2) All those colleagues that contributed to this presentation

Missing contributions ???
References (general)

• Ducrocq V. et al., 2002: Storm-scale numerical rainfall prediction for five precipitating events over France: on the importance of the initial humidity field. Wea. Forec.
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