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Mesoscale atmospheric models and their use in a meteotsunami research

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Mesoscale numerical models

- Mesoscale numerical models are designed for simulation and forecasting of mesoscale processes (2-2000 km)
- Based on conservation of momentum, energy and mass + moisture
- Allow for evolution of phenomena not contained in global models (challenging terrain, convection,…)
- Mesoscale atmospheric models are used in two “modes”
  - 1. simulation mode - for analysis and documentation of the atmosheric phenomena (due to the lack of the dense observation networks)
  - 2. prediction mode (only if 1., we can hope for 2.)
- Principal questions:
  - How well does a mesoscale model simulate the required process?
  - Does the refinement in resolution increases the model accuracy?

A typical mesoscale model setup

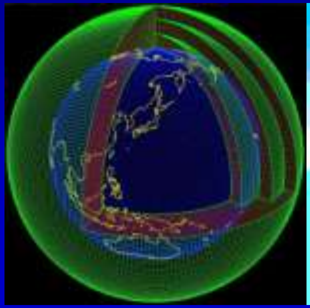
"The model chain"

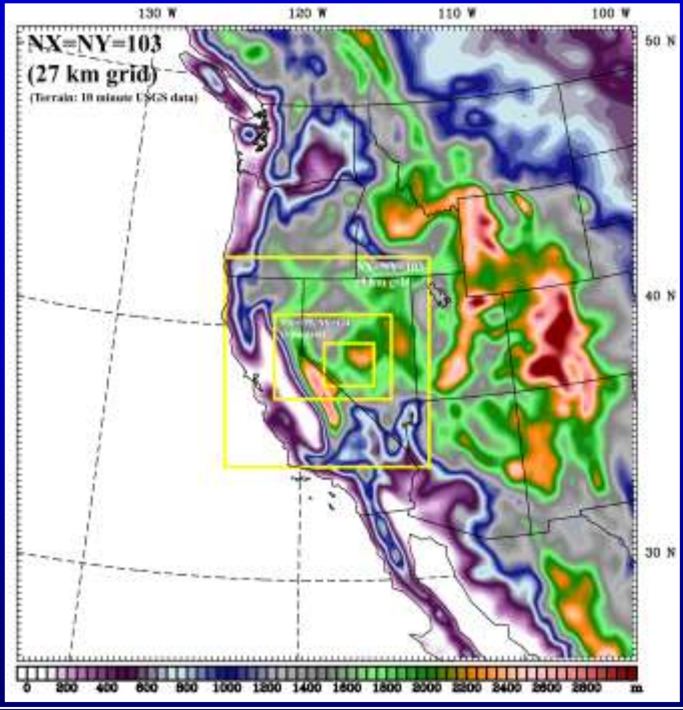
Global reanalysis/forecast
e.g., NCEP/NCAR or ECMWF
Grid increment ~20-100 km

OUTER MESOGRID (mesoDA?, DFI?)

'one-way' nesting 'two-way'

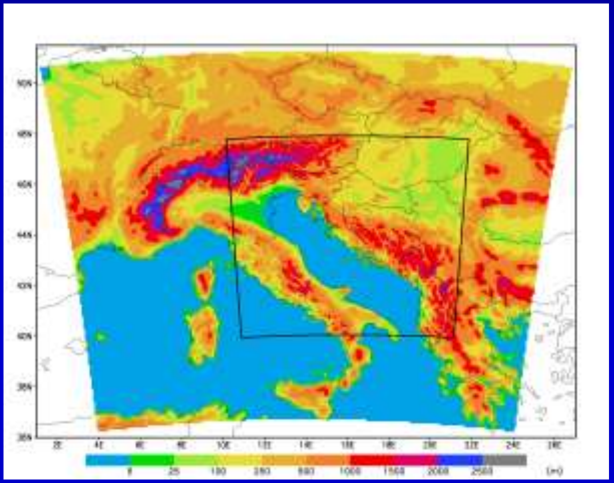
NESTED DOMAINS 1, 2,…
The final resolution is ideally chosen knowing the properties of the process





The mesoscale model accuracy

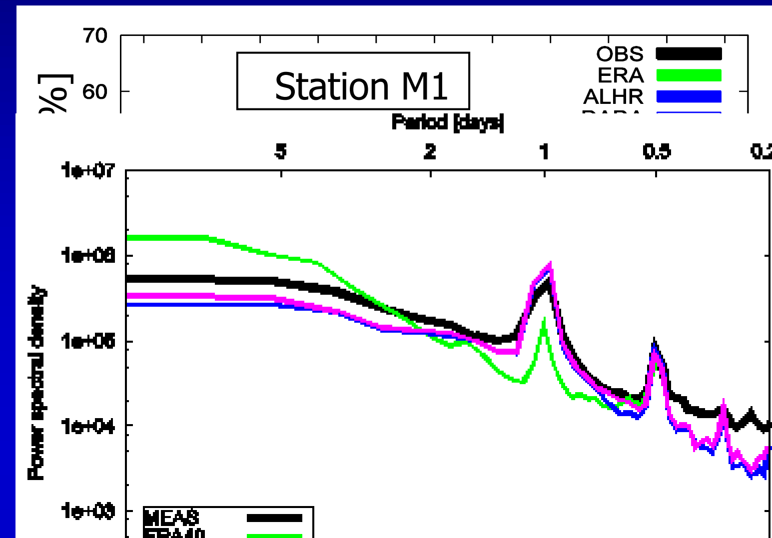
- However, constraints do exist, especially in (the 3D vicinity of) complex terrain, such as:
  - Initiation
  - Numerical instabilities
  - Mixing in SABL
  - And many others…
- → lower accuracy in complex terrain
- Eg. Dynamical downscaling
- ALADIN model, D1=8 km, D2=2 km
- 37 lev, Kuo-Geleyn CPS, Louis PBL
- 10yrs, ERA-40



10-m wind speed	MBIAS	RMSE
Continental	1.01	0.19
Coastal	0.91	0.55

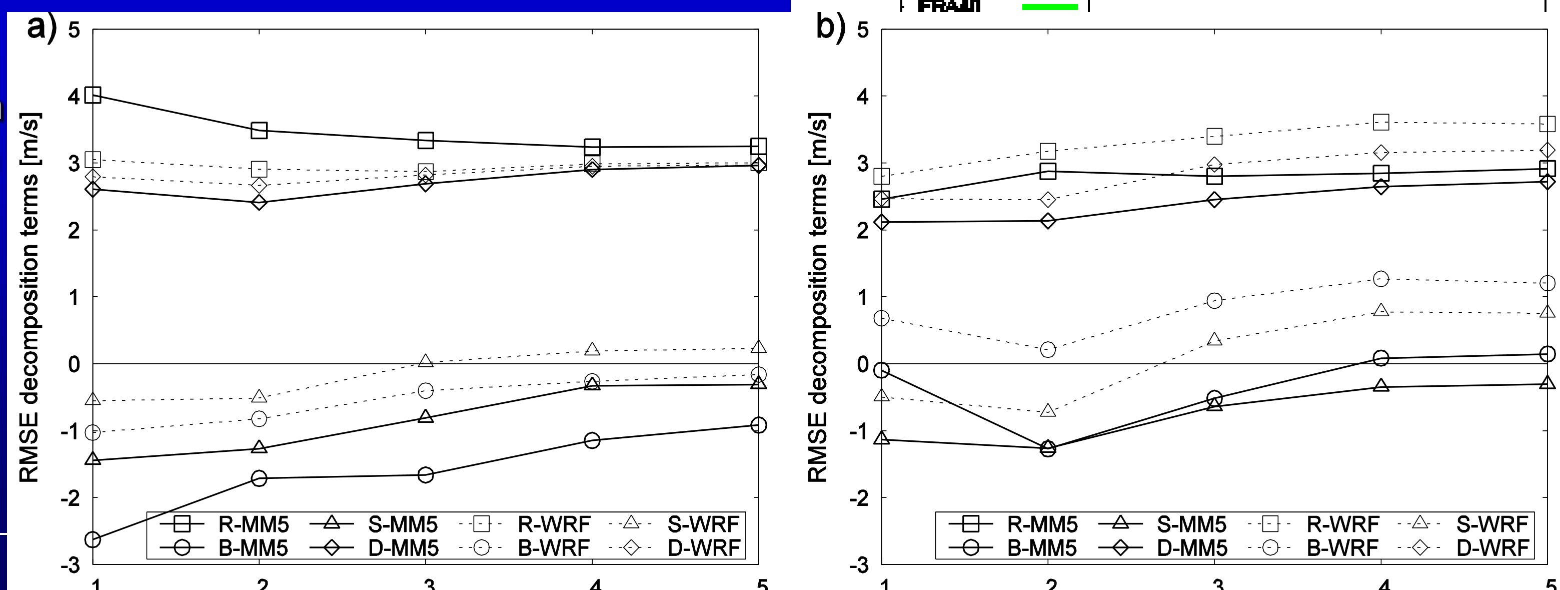
The mesoscale model accuracy

- In complex terrain, it is expected that models benefit from resolution (i.e. due to better resolved lower BCs)
- However, the benefit:
  - Is not always easy to show due to “double penalty” errors
  - Is not always found



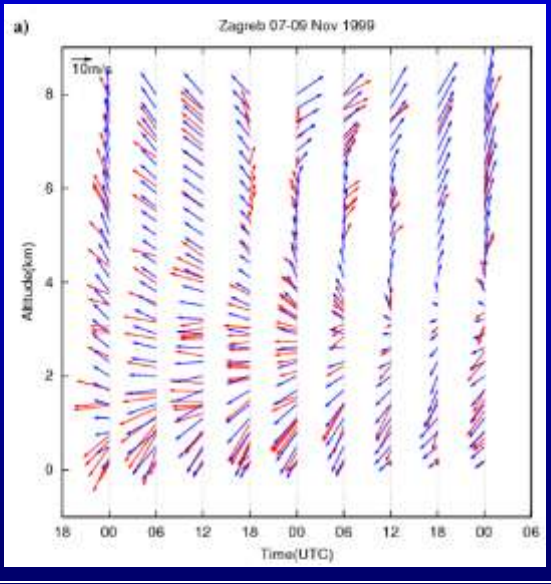
WRF&MM5
Dx=27km-0.333km
MYJ PBL, KF (d1,2)
Thompson MPS

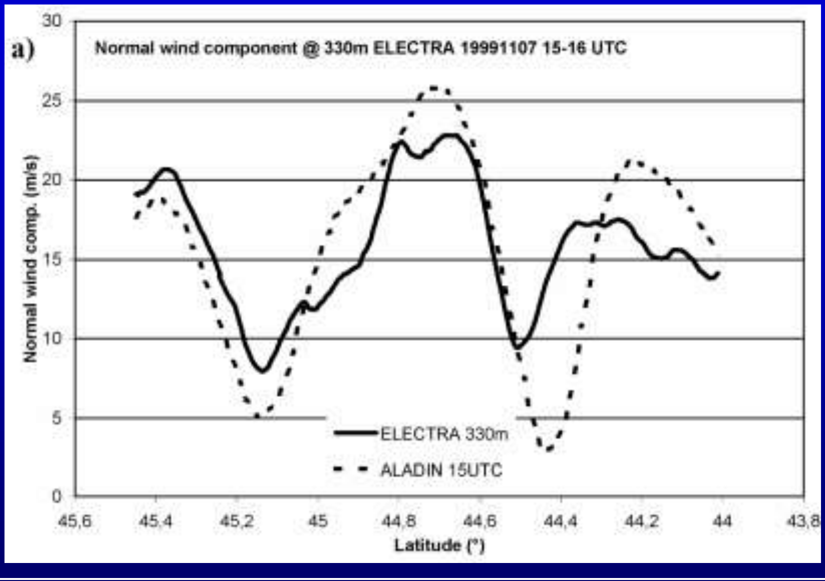
Decomp. of RMSE:
-bias of the mean
-bias of the st. dev
-dispersion error



The mesoscale model accuracy

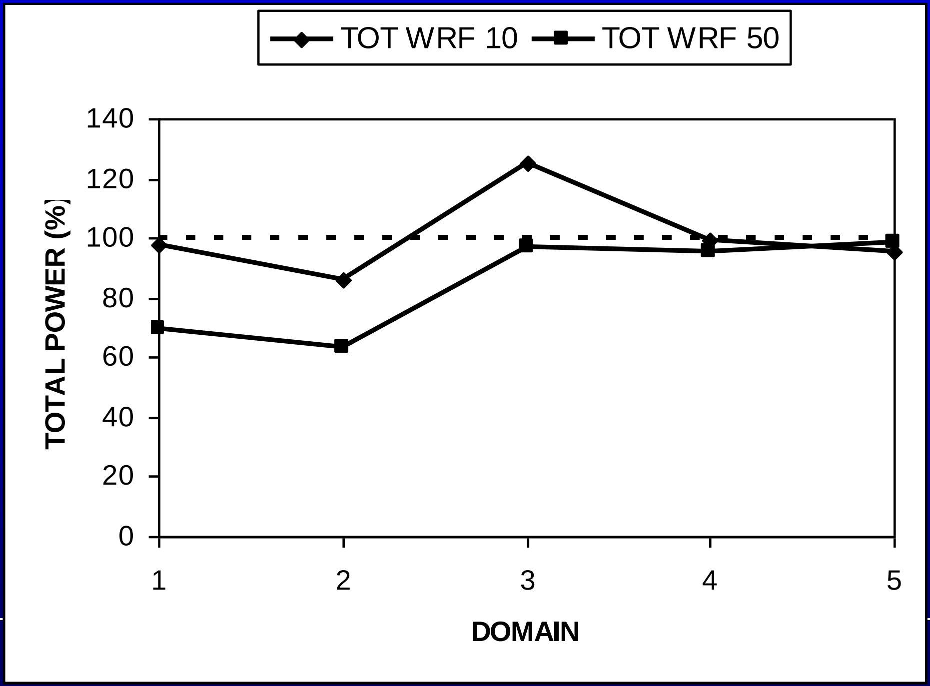
- For verification of occasional phenomena (meteotsunamis), systematic verification is typically less important
- The criteria of success is the realism of the simulated process (visual inspection)
- This is the most referenced benefit of high-resolution mesoscale modeling





The assessment of the model accuracy

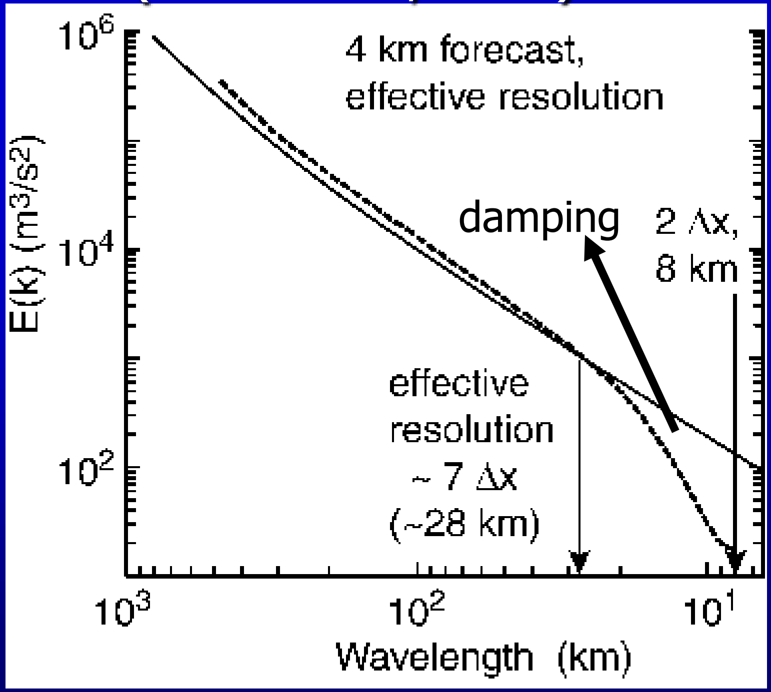
- Nevertheless, integral properties of the models reveal many useful information for designing the modeling setup for case studies:
- 1. What is the resolution required to simulate well the energy of motions in the area
  - Integrated spectral power density functions over the frequency range



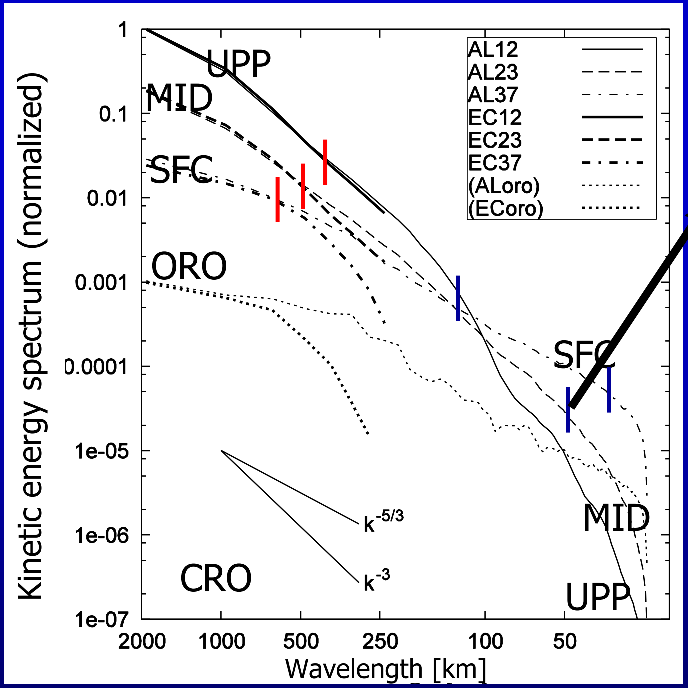
The assessment of the model accuracy

- 2 . What is the effective model resolution?
  - Kinetic energy spectrum – deviation from the expected values→ reveals which modes (wavelenghts) in the model are dynamically suspect

WRF (Skamarock, 2004)



ALADIN&ECMWF



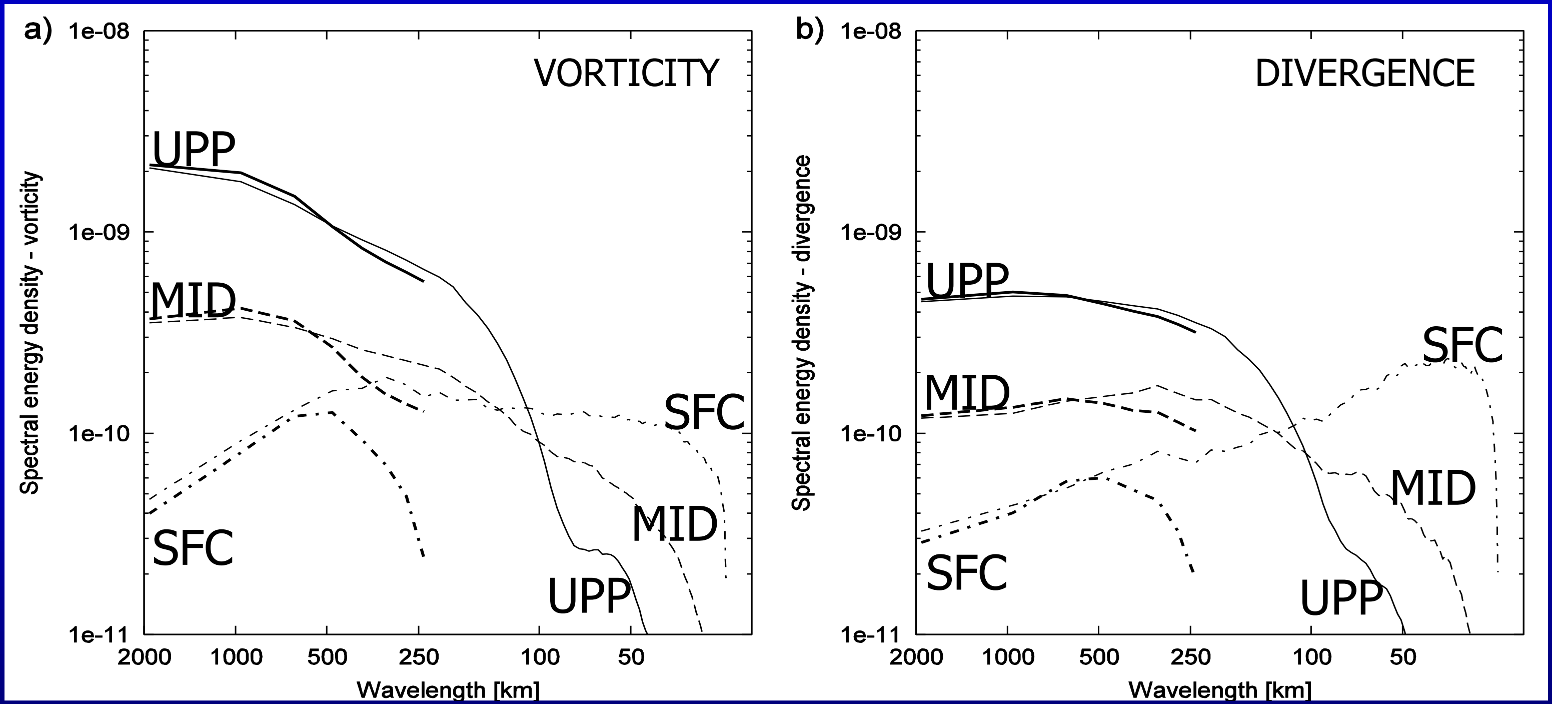
6dx in mid-levels

Similar to WRF

Large variation with altitude

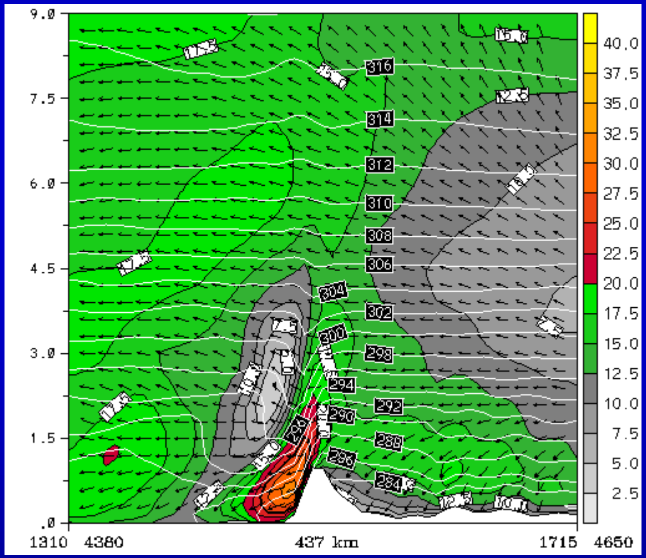
The assessment of the model accuracy

- Spectral energy densities of vorticity and divergence
  - Highly-variable vertical structure (varB, instabilities&div. damping)



Mesoscale models, mesoscale gravity waves & convection

- The most common atmospheric components of meteotsunamis are internal mesoscale gravity waves (IMGW) and convection
- IMGW (linear) are analytically well described and are also of the trademarks of mesoscale models
- IMGW originate from:
  - Orography (studied the most)
  - Moist convection
  - Mesoscale instabilities
  - Geostrophic adjustment
  - Surface heating or cooling
  - Density currents, and other



- They transfer E between scales, transport E and M in space, trigger instabilities → severe weather & Cbs and organize them into larger-scale convective storms…

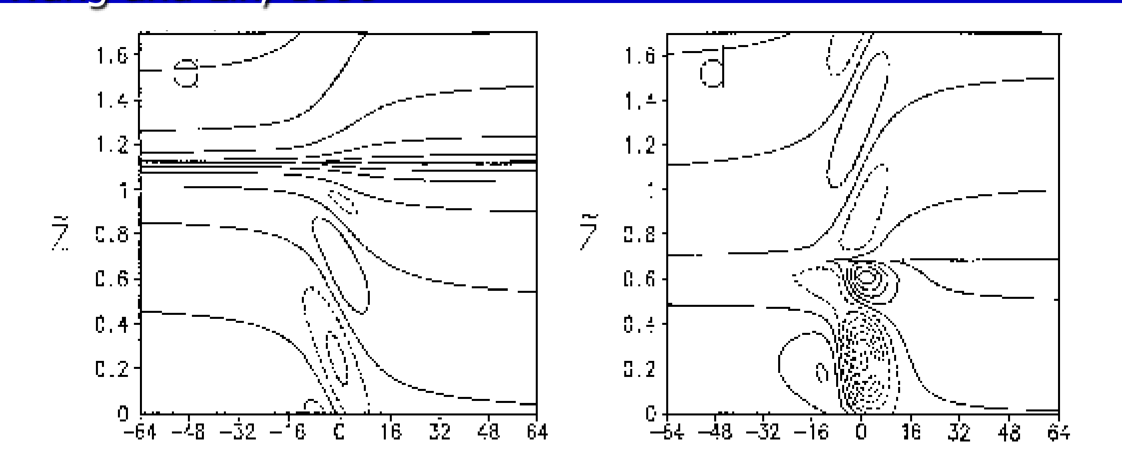
Mesoscale models, mesoscale gravity waves & convection

- IMGWs are generally dispersive and quickly lose their energy
- However, IMGWs associated with meteotsunamis have commonly traveled far away from the source of origin
- The maintenance mechanisms of IMGWs away from the area of origin:
- 1. Wave ducting mechanism
  - The IMGW energy is trapped in the lower layer
- 2. Wave-CISK mechanism
  - The IMGW is externally re-inforced
- 3. Solitary wave mechanism
  - A mechanism such that the IMGW dissipation is balanced
- These mechanisms generally apply to long-lived large-amplitude IMGWs (isolated waves or wave packets):
  - Periods 1-4 h, horizontal wavelengths of 50-500 km, surface pressure perturbation amplitudes of 0.2 – 7 hPa

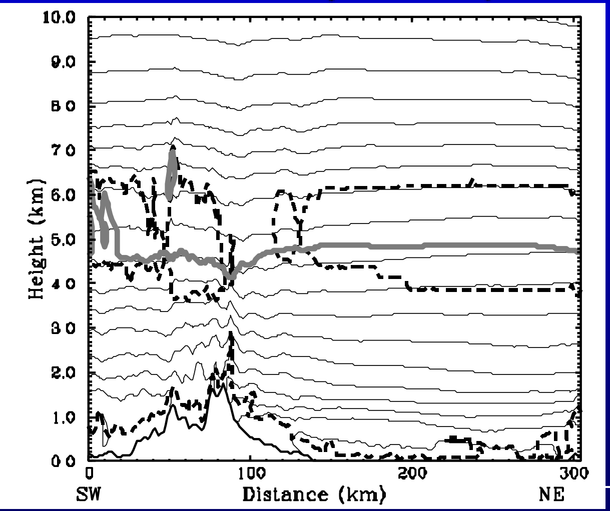
Wave duct

- The most common conditions for a duct (Lindzen and Tung, 1976):
  - The lower layer must be statically stable and sufficiently thick to accommodate ¼ of the vertical wave-length
  - A reflective layer must be present above the duct (shear, Ri<0.25) and a critical level must be inexistent within the stable layer
- LT is a subset of possible ducted modes (Wang and Lin, 1999)
- Mesomodels are able to simulate basic duct conditions

Wang and Lin, 1999

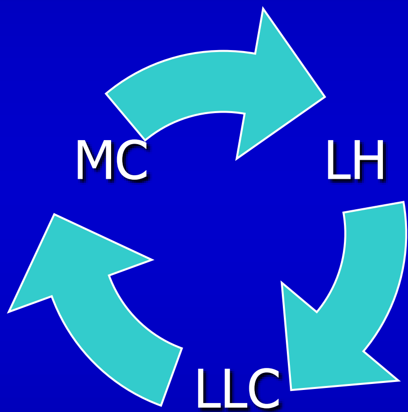


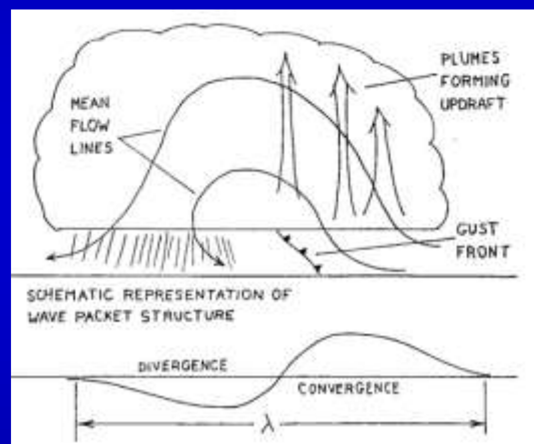
Šepić et al., 2009

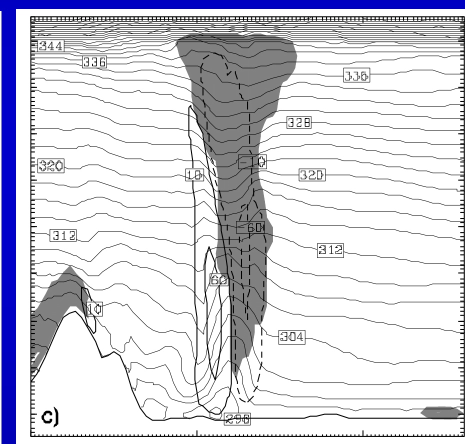


Wave-CISK

- The 2nd mechanism proposed for meteotsunami-related wave maintenance is Wave-CISK (Conditional Instability of the Second Kind)
- Moist convection - Latent heating - Low level convergence







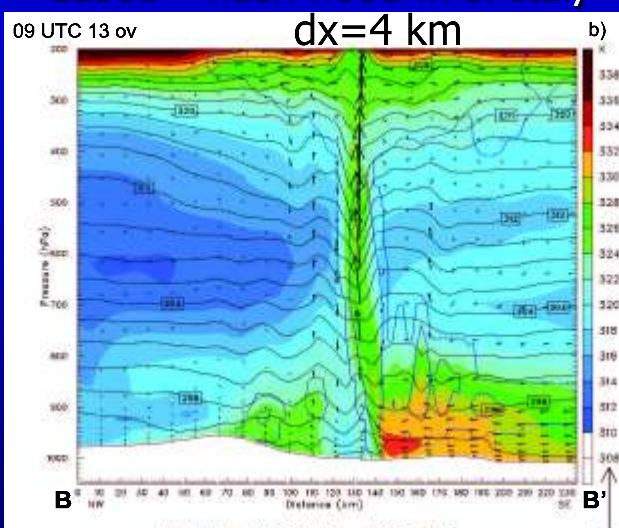
Belušić et al, 2007

- Wave-CISK may conceptually work, but some deficiencies have been raised (LH-LLC, large sensitivity)
- Convection-resolving modeling is a must
- Both duct and wave-CISK may act together (Tanaka, 2009)

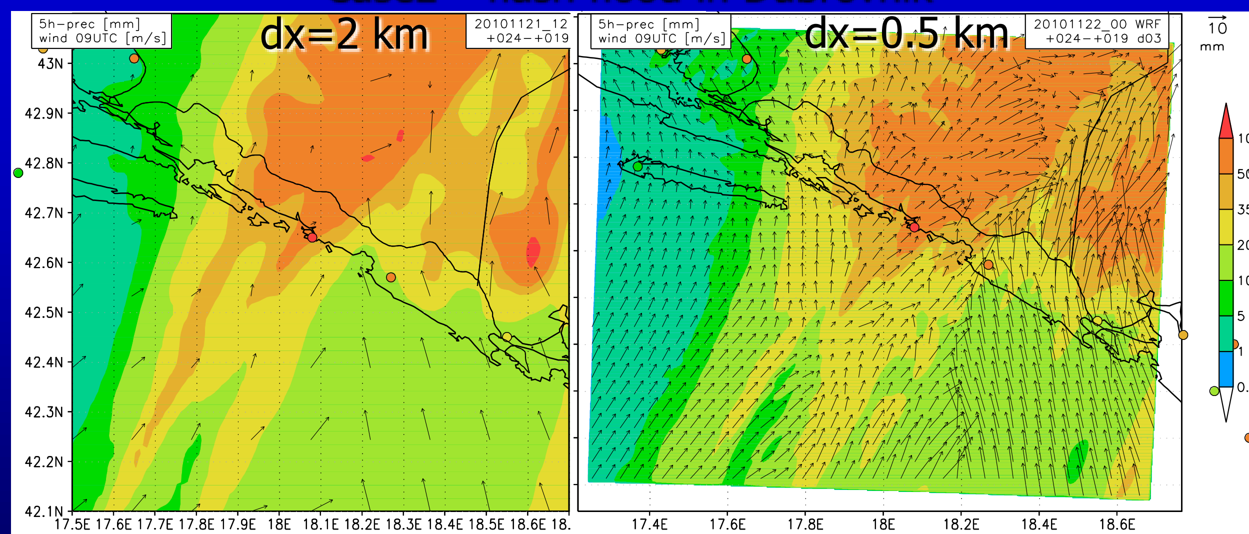
Convection

- What's the resolution required for an explicit simulation of convection?
- Depends on the individual case, but generally references suggest 100m (individual cells) < dx < 4 km (large convective systems)
- Higher-resolution may not necessarily bring the improved performance
- Mesomodels were used to simulate conv. jumps (Renault et al., 2011)

Case1 – flash flood in s. Italy

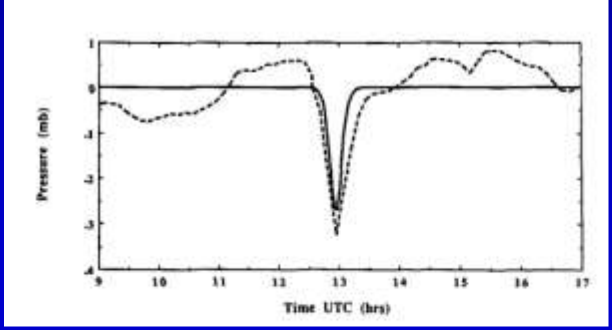


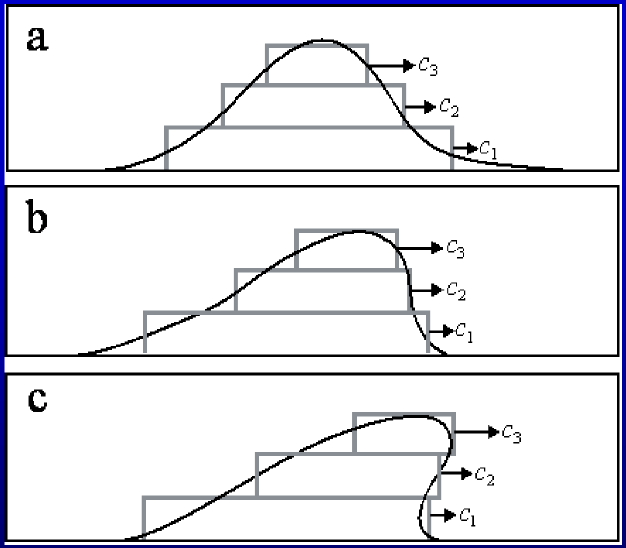
Case2 – flash flood in Dubrovnik

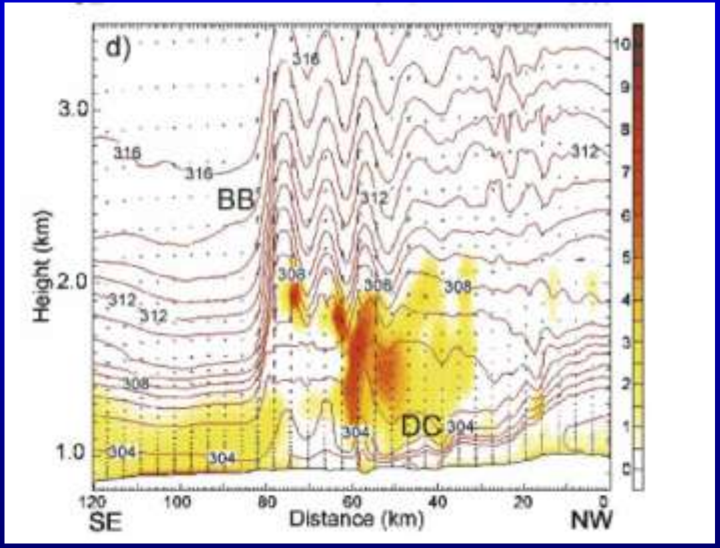


Solitary waves

- Have been observed in the atmosphere
- SW propagate without the change of form
- Balance between non-linearity and dispersion
- Can result in isolated or multiple pressure waves of elevation or depression





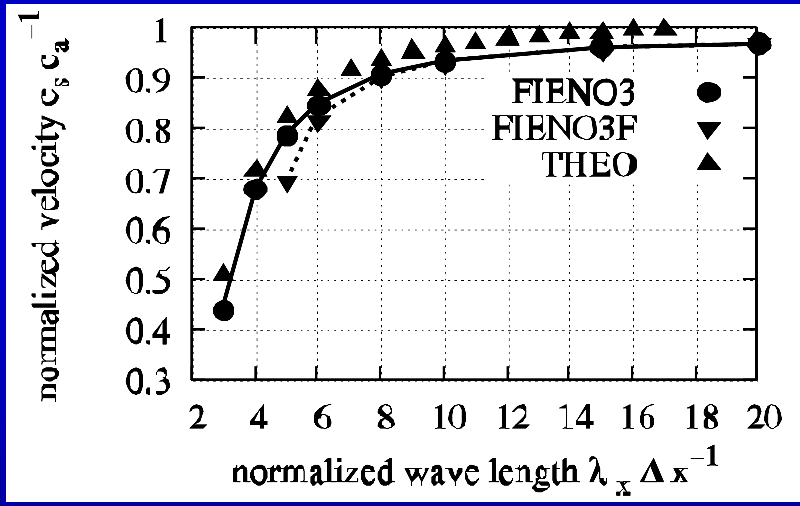


Koch et al., 2008

Modeling of IMGW

- Simulations of IMGW may be challenging
- In numerical models, IMGWs are not only dispersive due to physical but also for numerical reasons
- Whereas the physical dispersion is mostly influenced by static stability, in models IMGW properties also depend on:
  - numerical schemes
  - grid spacing
- Mes.&Ara., 1976 – C-grid
- If the resolution is inadequate, group velocity decreases

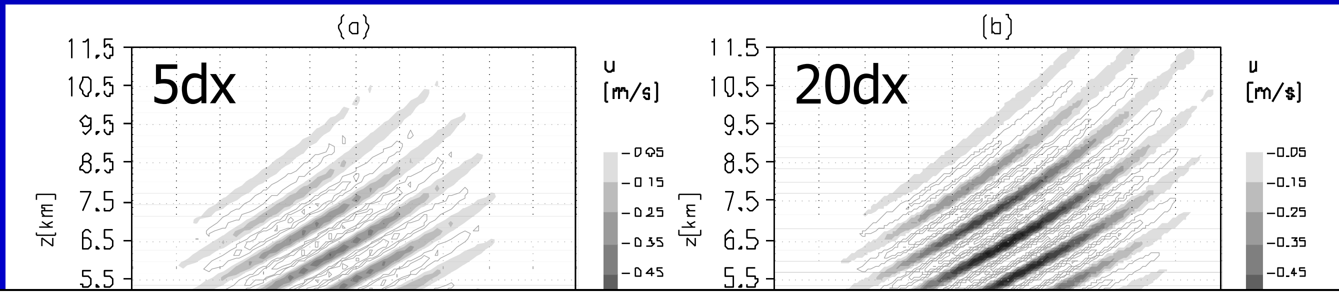
Schroeder&Schlunzen, 2009



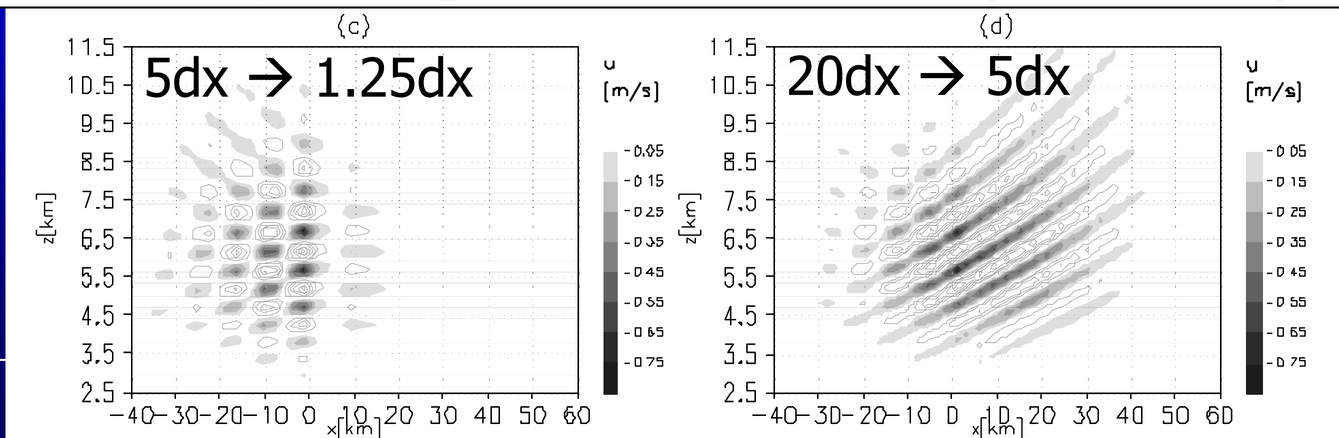
Coarse grid Fine

Modeling of IMGW

- If the grid spacing is non-uniform (two-way nesting, adaptive grids), waves from the fine grid might not be resolved in the coarse grid → reflection (trapping) in the fine grid



Therefore, if IMGW are of short wavelenths (~10-20dx), two-way nesting ratio has to be small (maximum 3) !



Other modeling issues

- 1. Some numerical diffusion is required to keep the mesoscale models stable (Takemi and Rotunno, 2003)
- E.g., types of diffusion in WRF:
  - Implicit diffusion (odd-number advection operator, RK3 time integration schemes)
  - Explicit diffusion on coordinate surfaces or in physical space
  - 6th-order diffusion (filter on scales of several grid points)
  - Vertical mixing within the PBL scheme
- 2. In models, IMGW can be generated by dynamic or thermodynamic imbalances (caused by numerical noise or unbalanced initial conditions)
  - Is spin-off a solution for already initially ducted environment?
- 3. If dx ~1 km, considerate computing resources required for both (sensitivity) simulations and forecasting

Conclusions

- Convection-resolving modeling is essential
- Modelling of IMGWs with wavelengths comparable to or less than ~15dx is numerically delicate
- Additional source of uncertainty is a proper simulation of their maintenance mechanism and the required environment
- The ability of mesomodels to simulate convection depends on the type of the convective system
- Once the phenomenon (IMGW, convection) is simulated, time-space errors are likely
- The larger the scales of IMGW/convection, the larger are chances for the accurate mesoscale simulation

THANKS FOR YOUR ATTENTION !