Waves to Weather

DFG Collaborative Research Center 165

Stochastic perturbations representing the mechanical effect of subgrid-scale orography

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Diurnal cycle problem

Forecasting the diurnal cycle of precipitation in synoptic situations with weak large-scale forcing shows low skill in mesoscale NWP models:

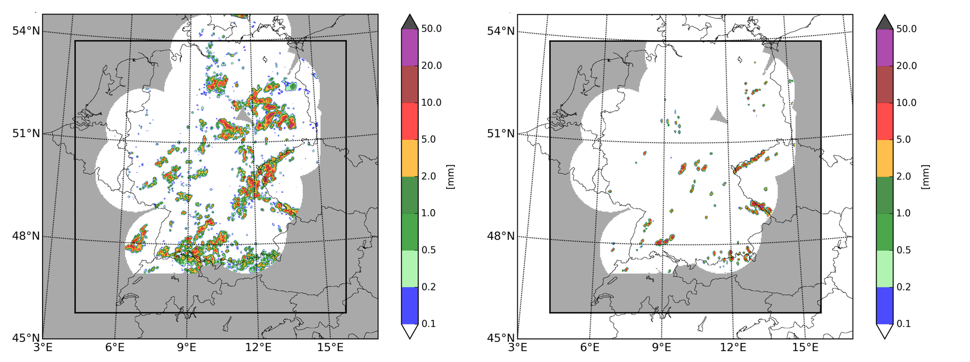


Fig. 1: Left: Observation of accumulated precipitation at 12UTC for 1 July 2009. Right: like left but for COSMO-DE forecast.

Missing small-scale variability due to boundary layer processes is one reason.

Boundary layer processes - General

Several processes contribute to the variability in a convective boundary layer, eg. surface heating (sh), flow – subgrid-scale orography interaction (sso), cold pools (cp), mesoscale circulations (mc):

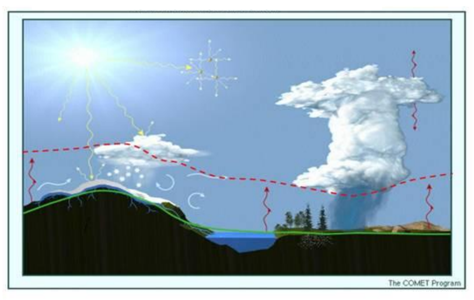


Fig. 2: Boundary layer processes creating small-scale variability.

Increasing the small-scale variability by stochastic perturbations representing boundary layer processes improves the precipitation forecast (Kober&Craig, 2016).

General equation for perturbations:

$$\left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{all} = \left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{sh} + \left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{sso} + \left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{cp} + \left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{mc}$$

An approach representing surface heating has shown improved forecast skill (see conference contribution of Stephan Rasp and Kober & Craig, 2016):

I. Basic principle

Heating of surface drives turbulence in boundary layer ⇒ relevant for initiation of convection

II. Mathematical formulation

Perturbation structure: $\left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{sh} = \frac{\partial\Phi}{\partial t} + \alpha_{sh}\cdot\eta_{sh}\cdot\langle\Phi^2\rangle^{1/2}$ ⇒ tendencies of temperature T, vertical velocity w and moisture q perturbed

Φ: resolved variable T, w, q and fluxes $\langle\Phi^2\rangle$ α_{sh}: scaling factor η_{sh}: random number field

Boundary layer processes - Subgrid-scale orography

Methods

I. Basic principle

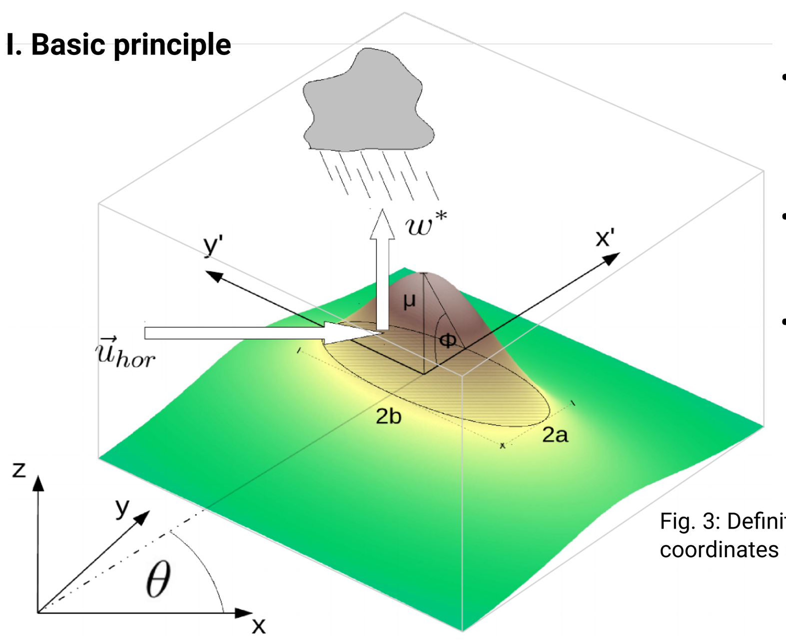


Fig. 3: Definition of the subgrid-scale orography parameters in rotated coordinates (x', y'), describing a bell-shaped mountain.

- Variability due to mechanical effect of subgrid-scale orography (SSO) on the atmospheric flow.
- Horizontal wind forces vertical motion leading to initiation of convection.
- COSMO-DE model configuration (2.8 km horizontal resolution).

II. Mathematical formulation

Perturbation structure: $\left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{sso} = \left(\frac{\partial w}{\partial t}\right)^{stoch}_{sso} = \frac{\partial w}{\partial t} + \frac{\alpha_{sso}}{dt}\cdot\eta_{sso}\cdot w^*$ ⇒ tendencies of vertical velocity w perturbed

w^*: forced vertical motion α_{sso}: scaling factor η_{sso}: random number field

Calculation of w^* based on internal gravity wave formalism for constant Brunt-Väisälä frequency N in an incompressible medium (Gill, 1982).
w^* depends on SSO parameters (orientation θ, shape γ_{sso}, slope σ_{sso}, standard deviation of height μ_{sso}), horizontal wind (u', v') in the rotated SSO coordinates and stability N (see Baines & Palmer (1990) for details about SSO parameters):

$\omega^2 \le N^2$ - vertical propagation possible:

$$w^* = w_0\cdot\cos(kx + ly + \boldsymbol{mz} - \omega t)$$

$\omega^2 > N^2$ - amplitude decays with height:

$$w^* = w_0\cdot \boldsymbol{e^{-\gamma z}}\cdot\cos(kx + ly - \omega t)$$

$$w_0 = w_0(k, l, u', v', \mu_{sso})$$
$$k = k(\sigma_{sso}, \mu_{sso})$$
$$l = l(\sigma_{sso}, \mu_{sso}, \gamma_{sso})$$
$$m = m(k, l, N^2)$$
$$\gamma^2 = -m^2$$

Results

I. Perturbations

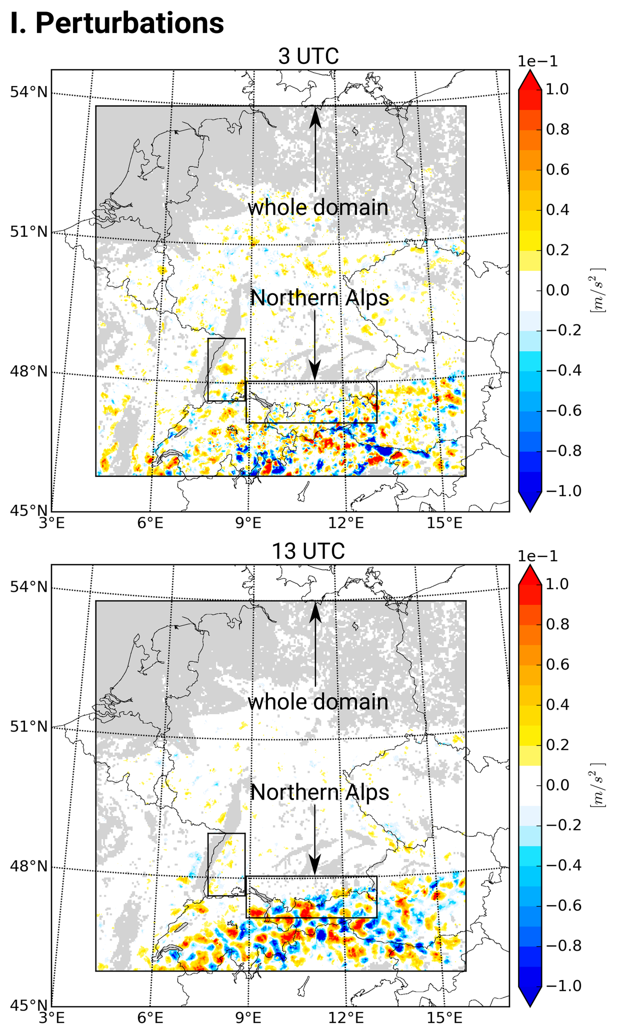


Fig. 4: Horizontal structure of perturbations $\frac{\alpha_{sso}}{dt}\cdot\eta_{sso}\cdot w^*$ for $\alpha = 1$ at model level 45 (≈300m AGL) for 1 July 2009 (top: 3UTC, bottom: 13UTC). Grey shading marks areas where orographic variations are negligible.

→Perturbations larger over increased orographic variations due to scaling with slope parameter σ_{sso}.

→Diurnal variations small due to scaling with horizontal wind velocities u', v'.

II. Vertical velocity

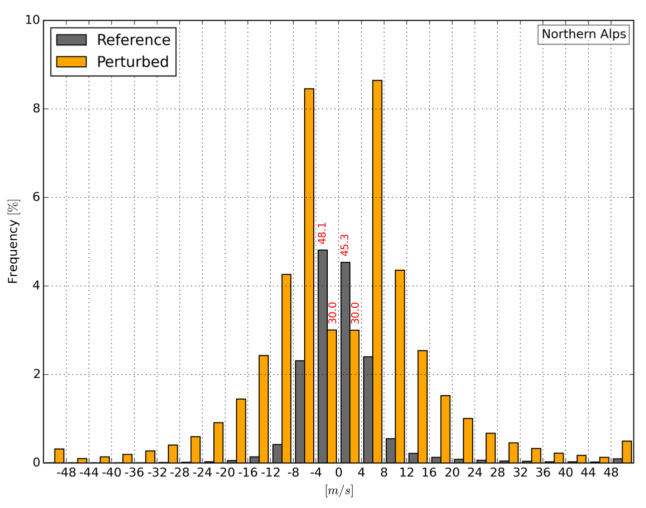


Fig. 5: Frequencies of vertically integrated vertical velocity w for 1 July 2009 between 01-23 UTC (Northern Alps). For better visualization the ranges around 0 m/s are divided by 10 and red numbers indicate the real frequencies.

→Perturbations lead to increased variability of integrated vertical velocity with larger impact over mountainous areas

III. Specific humidity

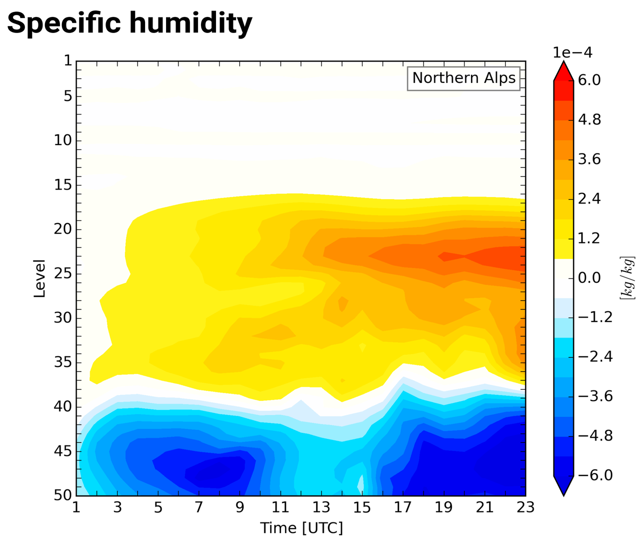
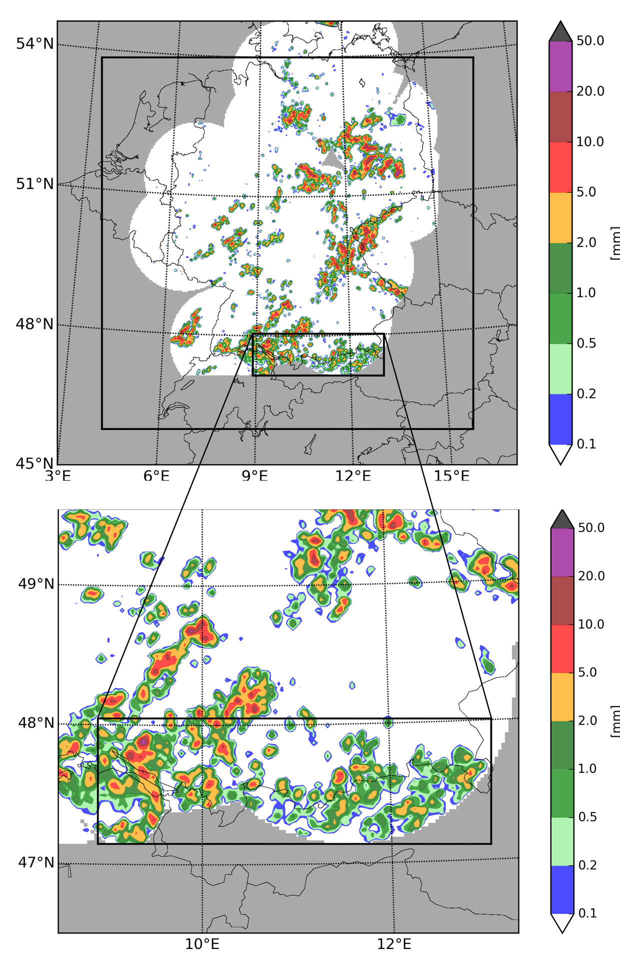


Fig. 6: Differences between a perturbed and reference simulation (perturbed - reference) of domain averaged specific humidity for 1 July 2009 (Northern Alps).

→Increased variability of vertical velocity enhances vertical transport of specific humidity.

→Drier boundary layer might suppress further initiation of convection.

IV. Precipitation



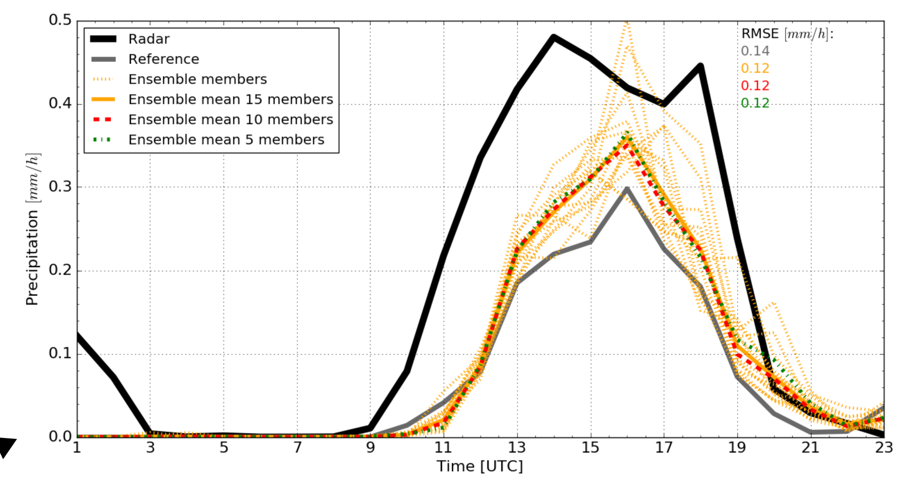


Fig. 7: Left top and bottom: Observation of accumulated precipitation at 12UTC for 1 July 2009. Right top: Timeseries of domain average hourly precipitation rates for parts of the Northern Alps for 1 July 2009. Perturbations calculated with $\alpha = 1$.

Weak synoptic forcing on 1 July 2009:

→Larger impact of scheme over increased orographic variations.

→Ensemble with 10 members seems to be sufficient to capture mean precipitaton rates.

→Root mean squared error (RMSE) slightly improved.

→Overall small impact on average precipitation rates compared to perturbation of other variables like temperature and moisture (see conference contribution Stephan Rasp and Kober & Craig, 2016) for 1 July 2009.

Weak synoptic forcing on 1 June 2014:

→Larger impact on precipitation compared to impact of scheme on 1 July 2009.

→Large variability among ensemble members.

→Root mean squared error (RMSE) slightly improved.

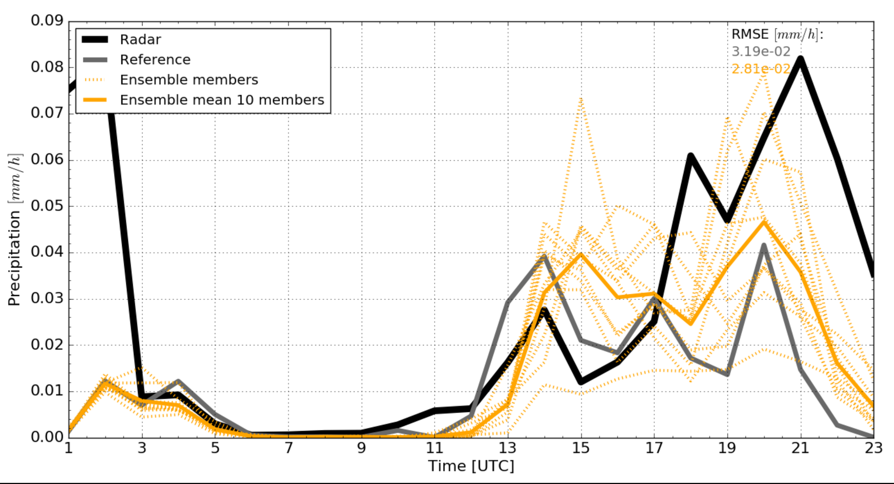


Fig. 8: Timeseries of domain average hourly precipitation rates for parts of the Northern Alps for 1 June 2014. Perturbations calculated with $\alpha = 1$.

Outlook

Develop and implement stochastic perturbation schemes, representing small-scale variability due to cold pools and mesoscale circulations:

Cold pools

I. Basic principle

Precipitating deep convective cells cool the air via evaporation which can lead to density currents at surface ⇒ alters the stability of the boundary layer and can trigger secondary cells

II. Mathematical formulation

Perturbation structure: $\left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{cp} = \left(\frac{\partial q}{\partial t}\right)^{stoch}_{cp} = \frac{\partial q}{\partial t} + \alpha_{cp}\cdot\eta_{cp}\cdot f(vel, lt)$ ⇒ tendencies of moisture q perturbed

α_{cp} : scaling factor η_{cp} : random number field vel : propagation velocity of cold pool lt: lifetime of cold pool

Mesoscale circulations

I. Basic principle

Mountain circulations due to differential heating and other processes can lead to convergence of air ⇒ relevant for initiation of convection

II. Mathematical formulation

Perturbation structure: $\left(\frac{\partial\Phi}{\partial t}\right)^{stoch}_{mc} = \frac{\partial\Phi}{\partial t} + \alpha_{mc}\cdot\eta_{mc}\cdot f(h, sso)\cdot f(\langle\phi^2\rangle)$ ⇒ tendencies of temperature T, vertical velocity w and moisture q perturbed

Φ: resolved variable T, w, q and fluxes $\langle\Phi^2\rangle$ α_{mc}: scaling factor η_{mc}: random number field h: resolved orography sso: subgrid-scale orography

References:

- Kober, K. and Craig, G. C. (2016). *Stochastic boundary layer perturbations to represent uncertainty in convective initiation.* Journ. of the Atm. Sci. In revision.
- Baines, P. G. and Palmer, T. (1990). *Rationale for a new physically-based parametrization of subgrid-scale orographic effects.* ECMWF.
- Gill, A. E. (1982). *Atmosphere-Ocean Dynamics.* Academic Press.