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CHARACTERISTICS OF OROGRAPHIC PRECIPITATING SYSTEMS -TESTS WITH TWO MODELS

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1. INTRODUCTION

Rising attention of fresh water supply and flash-flood management demands greater understanding of the orographic precipitation (OP) problem. Atmospheric problems such as OP are often buried in a complex airflow picture, challenging to fully explore with sparse traditional observational network. Numerical model simulations provide a virtual laboratory in which thorough analysis can be carried out. In real case studies, they may also bridge data gaps.

Studies (e.g. Smith et al. 2002) have shown that models reproduce OP events very differently, despite similar upstream conditions. What mechanisms in the models are responsible? How can we address this issue?

We aim at doing a water analysis of an OP-system, and identify its controlling parameters. Moreover, the OP-system is simulated in a numerical model that conserves water, and the result is compared with a linear model. Linearization simplifies a problem and makes the analysis transparent. However, crucial non-linear growth mechanism may be lost.

2. MODELS

In order to undertake a thorough analysis of an OP-system, we utilize the warm rain system proposed by Grabowski and Smolarkiewicz (2002):

$$\frac{\partial(\rho q_v)}{\partial t} + \nabla\cdot(V\rho q_v) = -\rho C_d + \rho E_p \qquad (1a)$$

$$\frac{\partial(\rho q_c)}{\partial t} + \nabla\cdot(V\rho q_c) = \rho C_d - \rho A_p - \rho C_p \qquad (1b)$$

$$\frac{\partial(\rho q_r)}{\partial t} + \nabla\cdot(V\rho q_r) = -\frac{\partial(\rho q_r V_T)}{\partial z} + \rho A_p + \rho C_p - \rho E_p \qquad (1c)$$

where q_v=water vapor mixing ratio, q_c =cloud water mixing ratio, q_r=mixing ratio of hydrometeors. The source/sink terms on the right-hand side (r.h.s.) are: C_d=condensation rate, E_p=evaporation rate of hydrometeors, A_p=auto-conversion rate, C_p=accretion rate. The 1st term on the r.h.s. of (1c) is precipitation, the final loss to the system. The other symbols follow normal conventions.

Herein, we limit ourselves to only a brief derivation of the characterizing measures: Essentially, (1) is assumed steady-state and integrated over a control volume V, Fig.1. The Gauss-theorem is applied for the 2nd terms on the l.h.s. giving a net flux into the volume F_2-F_1.

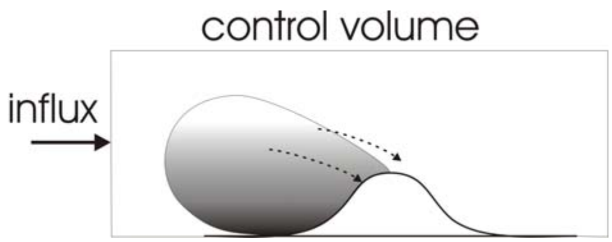

FIGURE 1: Condensation upstream the hill enclosed in a control volume.

Adding the three equations together and neglecting fluxes of cloud water or hydro-meteors through the walls, (1) may be written as

$$DR \equiv \frac{P}{F_{1v}} = 1 - \frac{F_{2v}}{F_{1v}} \qquad (2)$$

were DR is the drying ratio of the system. The area integrated precipitation P is normalized with the influx of water vapor F_{1v}. DR is a global measure characterizing the system. However, DR does not tell us anything about the interior mechanisms. To address this issue, we rewrite a steady-state version of (1) in terms of positive defined volume integrated quantities,

$$F_{2v} - F_{1v} = -Co^c + Ev^c + Ev^r \qquad (3a)$$

$$0 = Co^c - Aut - Acc - Ev^c \qquad (3b)$$

$$0 = -P + Aut + Acc - Ev^r \qquad (3c)$$

"Ev" / "Co" denote evaporation and condensation of water vapor and superscripts denote to which water species the term links to. We define the precipitation efficiency (PE) as a measure of conversion from cloud water to precipitation,

$$PE \equiv P/Co^c = \frac{P}{\int_V \max(\rho C_d, 0)dV} \qquad (4)$$

and a similar ratio for condensation,

$$CR \equiv Co^c / F_{1v} = \frac{\int_V \max(\rho C_d, 0)dV}{F_{1v}} \qquad (5)$$

so we get

$$PE \cdot CR = DR \qquad (6)$$

With the PE-measure, we have isolated the micro-physical part of the system from the one of airflow dynamics (CR). DR shows the effect of the two combined. The remaining terms on the r.h.s. of (3) may be normalized with P to find their effectiveness producing precipitation. Herein, we limit ourselves to a measure of the re-evaporation of hydro-meteors;

$$HYRE = Ev^r / P \qquad (7).$$

enabling us to identify re-evaporation of hydro-meteors as they fall into dry air.

In case of a ice-phase scheme, the analysis must at least have a growth term in (1c) receiving water directly from (1a), thus (3a),(4) and (5) will have additional terms.

The linear model (Smith and Barstad, 2004) is briefly described as follows: The model has vertical integrated cloud water and hydrometeors advected by a homogeneous background flow. The transformation to and the fall-out of hydrometeors is linked to a cloud delay constants (τ), see J14.2 in this proceeding. The PE, CR and DR for the linear model of Smith and Barstad (2004) are:

$$PE^l = \frac{P}{S} \qquad (8)$$

$$CR^l = \frac{S}{UH_w \rho q_{0s}} \qquad (9)$$

$$DR^l = \frac{P}{UH_w \rho q_{0s}} \qquad (10)$$

where S is the condensation rate without airflow dynamics (Smith, 1979), U the horizontal wind, q_{os}=saturate mixing ratio of water vapor at the surface and H_w is the scale height of water vapor.

The main free parameters in the linear model are the two τ's controlling the spill-over into drying regions. In order to compare the two models, some over-all residence time for the cloud water must be estimated for the non-linear system. From volume integrated quantities of the linear model, the following equivalent expressions may be derived for the non-linear system:

$$\tau_c = \frac{Mass\,of\;cloud\;water}{Co^c + Ev^c} \qquad (11)$$

$$\tau_f = \frac{Mass\,of\;hydro-met.}{P} \qquad (12)$$

3. DESIGN OF THE EXPERIMENTS

The response from the nonlinear system (1) was simulated as uniform air (U=15m/s, N=0.012s^{-1}, Rh=100%) flowed over a Gaussian shaped ridge. The standard height of the ridge is 500m and half-width is 30km. The lower boundary had free-slip condition, and the simulations had no explicit diffusion. A numerical model based on non-oscillatory MPDATA advection scheme (Smolarkiewicz and Margolin, 1998) conserving transported quantities (e.g.water) was used. The grid distance was 300m both vertically and horizontally. The simulations started from potential flow and any perturbation towards the upper and lateral boundaries were dampened. The linear model was run correspondingly for similar set-up.

In linear theory of airflow dynamics, the non-dimensional mountain height (h_m=Nh/U) is the controlling parameter. Smith and Barstad (2004) and Barstad and Smith (2004) found that the linear micro-physics depends on Uτ/a, when the τ's are set equal. Therefore, it is natural to first of all vary the mountain height (h) and the half-width (a) of the mountain to test the sensitivity to characteristic measures derived.

4. RESULTS

Fig.2 shows that CR^l (linear model; broken line) is unaffected by the non-linearities (solid line) as the mountain becomes tall. The effective stability is about N=0.009s^{-1}, so the non-linear behavior becomes increasingly important after Nh/U=0.45 (h=750m). The DR-measure responds directly to the wave dynamics, following the same pattern. The black solid straight line in Fig.2, is condensation without airflow dynamics (i.e. perfect penetration of forced ascent). In the non-linear model, the PE (eq. 4) drops and increases the gap between CR and DR for taller mountains.

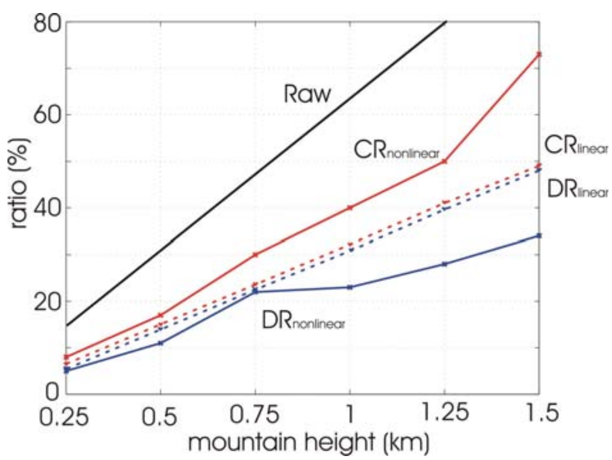

FIGURE 2: Efficiency ratio versus mountain height. Solid line represents the non-linear model, and broken line the linear model. The “Raw” is the condensation without airflow dynamics.

We now turn to variations in mountain half-width. Fig.3 shows that the linear model has high efficiency in precipitating water for short tau (200s). The quick rise in PE is distinct. The longer tau runs are similar to the non-linear model; a gentler rise for wider ridges. The re-evaporation (HYRE) of hydro-meteors drops significantly around 15-30km. For half-widths less than 5km, HYRE rises sharply due to larger amount of hydro-meteors carries over into the drying regions.

Non-hydrostatic effects will have some influence for narrow ridges. Lee-waves trailing off downstream may produce condensation, but not precipitation. On the other hand, forcing from short wave lengths results in rapid damping of vertical velocity with height limiting the condensation. Both these effects are apparent in the linear model, Fig.4. The maximum CR is located between 3-5km half-width where the lee-waves produce large amount of condensate. The strong damping of the vertical propagation is seen for even shorter wave lengths. The non-linear model does not reach a steady-state because the trailing lee-waves evolve very slowly, and accordingly the maximum of CR does not reach as high.

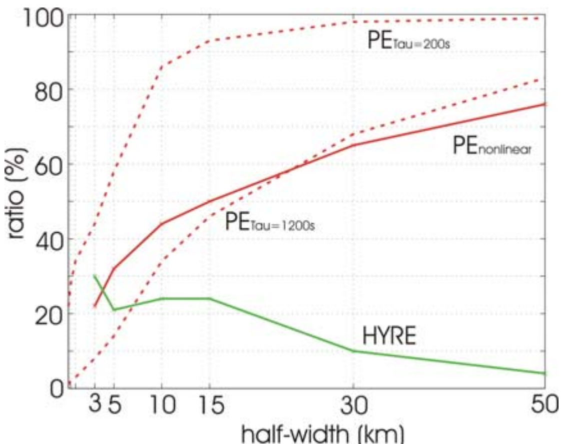

FIGURE 3: Efficiency versus mountain width. PE^l (broken line) for both tau=200s and 1200s is shown. Re-evaporation of hydro-meteors (HYRE) is also indicated.

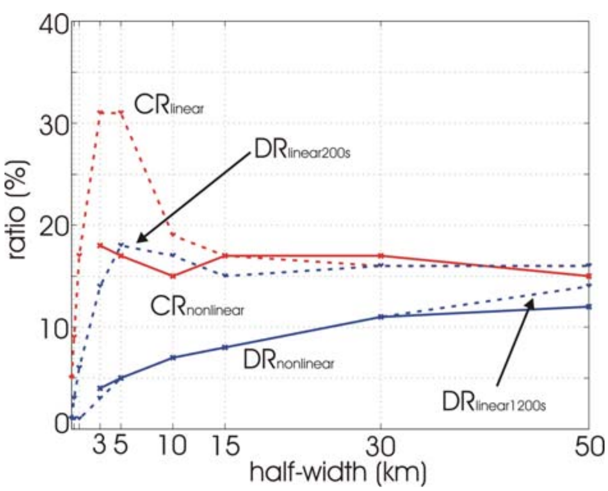

FIGURE 4: Efficiency versus half-width, discussing non-hydrostatic effects.

5. DISCUSSION

Based on (11) and (12), the two cloud delay factors (tau) are estimated in the non-linear model. For the most part, both tau's are found to be in the range from 100-300s. From the figures portrayed herein, the PE becomes too high, or the efficiency is too great compare to the non-linear model. We may search for the reason among the assumptions in the linear model. The bulk value given by the vertically integrated condensation rate in the linear model camouflages the condensation/evaporation in the column. However, in the non-linear model, both evaporation and condensation in a column count separately in the summation procedure. Checks with the non-linear model reveal that this linear model assumption is not the major cause of discrepancy. Another important simplification concerns is the non-linearity in the cloud physics (i.e. accretion-term). Also the evaporation of hydro-meteors in the linear model has the same time delay as condensation.

6. CONCLUSIONS

A water analysis of the orographic precipitating system is undertaken, and some characterizing measures are identified. The effects of cloud-physics and the airflow dynamics are separated with the precipitation efficiency (PE) and the condensation ratio (CR) respectively. The combined effect is represented by the drying ratio (DR).

Two models, a linear and a non-linear, were employed to investigate how characterizing measures changes as mountain half-width and height vary. The linear model seems to represent the airflow dynamics reasonably well. In the cloud-physics, it seems to be larger discrepancy which not yet has been fully explored.

7. ACKNOWLEDGEMENT

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