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A TAILORED OBSERVATIONAL CAMPAIGN OF OROGRAPHIC PRECIPITATION -STOPEX phase I

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1. INTRODUCTION

As moist air is forced over mountains, orographic precipitation (OP) is formed (e.g. Smith 1979). Recently, the severity of freshwater supply and problematic flooding situations has directed attention to OP.

Numerical models are helpful as they may simulate the physical process, and thereby provide forecasts and climate predictions of the water cycle. Our ability to successfully forecast OP relies upon understanding of the phenomenon. This is because the parametrization in models is based on understanding and logical reasoning. As the process in question often is buried in a complex weather situation, simple models may be helpful to clarify the picture. In addition, simple models are often very cost efficient which allows high resolution. Further development of models will benefit from constrains given by observational data from tailored campaigns.

2. BACKGROUND

The scientific motivation for the observational campaign described in this paper arises from the recent developed of a simple, physical-based linear theory (Smith and Barstad; 2004). Previous studies seeking to evaluate this theory (e.g. Barstad and Smith, 2005; Smith et al. 2005), did not have sufficient details in the precipitation measurements to produce conclusive results. This gave incentives to a tailored observational campaign. The first phase of an observational campaign will hopefully identify information needed for such an endeavor.

The linear theory is an extension of the vertically integrated expression of condensation rate (S) in saturated, moist neutral airflow by Smith (1979). For wind speed U, impinging on a slope, he derived the expression,

$$S = \rho_0 q_0 U \cdot \nabla h, \quad (1)$$

where $\rho_0 q_0$ is the water vapor density at the surface, and *h* denotes the terrain. Simple microphysics is included by using vertically integrated, linearized steady-state advection equation of cloud water and hydrometeors,

$$U \cdot \nabla q_c = S - q_c / \tau_c \quad (2a)$$

$$U \cdot \nabla q_r = q_c / \tau_c - q_r / \tau_f \quad (2b)$$

where q_c and q_r are cloud water and hydrometeor content, τ 's are conversion and fall-out times. Upslope a mountain top, *S* becomes positive and transformation from cloud water (2a) to hydrometeors (2b) is delayed by the conversion time-scale (τ_c). In the lee, negative S first of all evaporates the cloud water and subsequently the hydrometeors. Smith and Barstad (2004) extended the theory to include airflow dynamics, and their expression of precipitation (P) in Fourier space can be written as:

$$\hat{P}(k,l) = \frac{C_w i \sigma \hat{h}(k,l)}{[1 - imH_w][1 + i\sigma\tau_f][1 + i\sigma\tau_c]} \quad (3)$$

Table 1:

$C_w = \rho_s \Gamma_m / \gamma$	Uplift sensitivity factor
$\sigma = uk + vl$	Intrinsic frequency
m	Vertical wave number
$H_w = -\frac{R_v T^2}{L\gamma}$	Scale height of water vapor in the atmosphere
τ_f, τ_c	Conversion and fall-out time
$\hat{h}$	Fourier transformed terrain
Γ_m / γ	The ratio of moist adiabatic to environmental lapse rate
$\rho_s = q\rho$	Saturated water vapor density
R_v	Gas constant for water vapor
L	Latent heat

Table 1 explains symbols used. The theory predicts high level of detail due to high-resolution terrain. Sharp gradients in precipitation, typically across the top of narrow mountains, are predicted. Accordingly, extremes with large magnitudes may be found. Given the correct water influx towards the mountain, the microphysical delays control the level of detail and the extremes. Further details and elaboration on the theory may be found in cited literature.

3. THE CAMPAIGN

Across the mountains at the west coast of southern Norway (Figure 1), typically 1000 to 2000 m high, large gradients of annual precipitation are found. The precipitation magnitudes typically range from 2000-3000 mm on the west coast to 400-500 mm in the lee, 300 km further to the east. On a more local scale at the west coast, historical records of precipitation across the island Stord, show about 1000 mm difference in annual precipitation. The height of the mountains are 500-600 m, and the island is about 10 km east-west and 30 km in the north-south direction. The western side (Fitjar) has about 1500 mm while the eastern side (Børtveit) has about 2500 m in annual precipitation. This might be a bit surprising knowing that the main airflow comes from the southwest sector, which generally should indicate larger amounts on the west side. In relation to (2), this may be explained by the time delays in the microphysics. The residence time for a particle in the orographic cloud is sufficient to generate hydrometeors, and drift brings the particles to the top or into the lee of the mountains.

Upfront of phase I of STord Orographic Precipitation Experiment (STOPEX), the linear model was run in quasi-operational modus producing a strong gradient in precipitation across Stord Island. Guidance from this effort assisted the deployment of rain gauges.

The STOPEX I took place between the 23rd September and 15th of November 2005. Data from 12 rain gauges ('tipping-buckets'), 3 weather stations and a dual GPS vertically integrated water vapor measurer were collected. Additionally, the synoptic network, a near by weather radar (Bømlo), continuous meteorological measures at Stord airport, upstream soundings (every 12th hour) and satellite information were collected, see Fig. 2.

Fig.3 shows the calculated water vapor influx at Stord during the campaign. The data are taken from ECMWF analysis, and only the component parallel to the wind direction at 850 hPa is used. We see that moist winds from the south dominate. Due to southern Norway's influence on the wind field (Barstad and Grønås; 2005), the wind will gain a more southerly component closer to the ground, near the coast line.

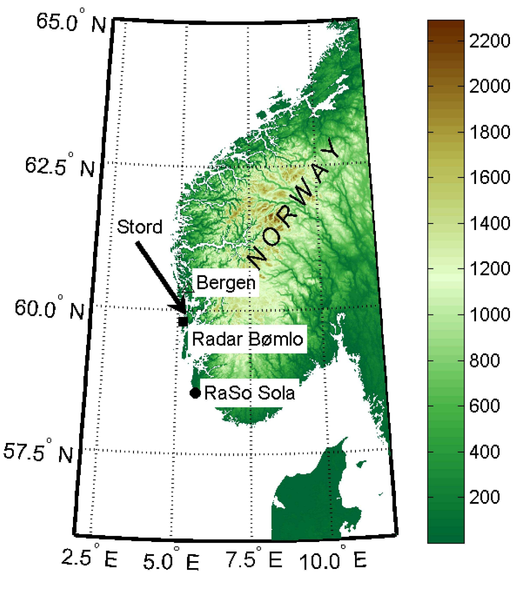

FIGURE 1: The terrain (m) in southern Norway.

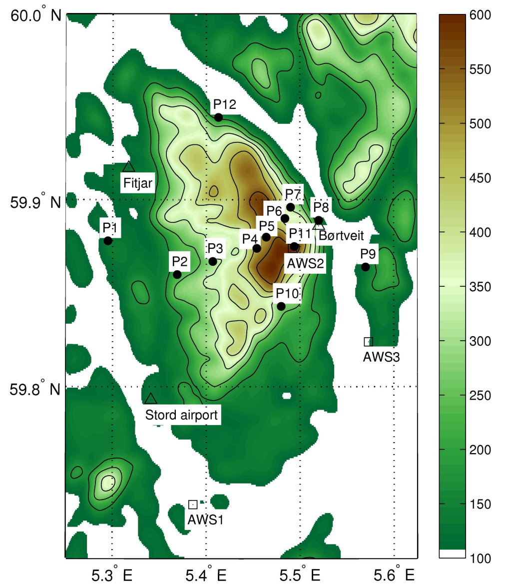

FIGURE 2: The terrain (m) at the Stord site.

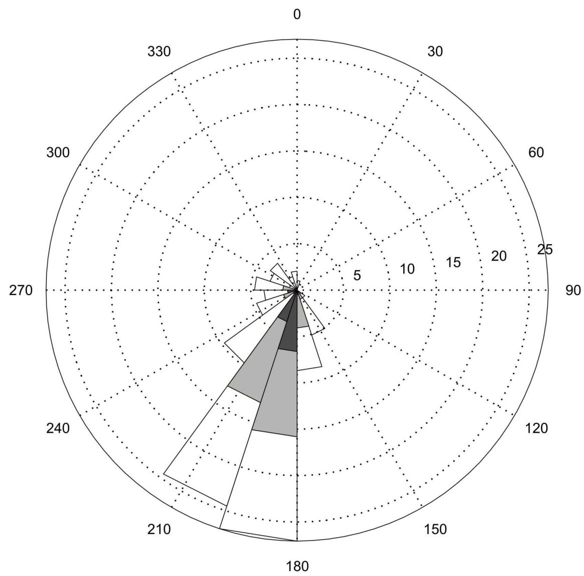

FIGURE 3: Frequency of water vapor flux of various strengths throughout the campaign. Only the component parallel to the wind speed in 850 hPa is used. Dark shading >500 kg/ms, light shading >200 kg/ms.

The accumulated precipitation for the 12 rain gauges is shown in Fig.4 (rain gauge P2 failed). The labeling is in accordance with Fig.2. From Fig.3, we see that the rain gauges on the top and on the eastern side receive the most. The station far to the west has the minimum with less than 350 mm. The gauge furthest to the east has significant less than those on the eastern side of Stord. This indicates that the spill-over effect is pronounced at this island. In this paper, we will continue by a taking a closer look at 3 events which are indicated by shading on Fig.4.

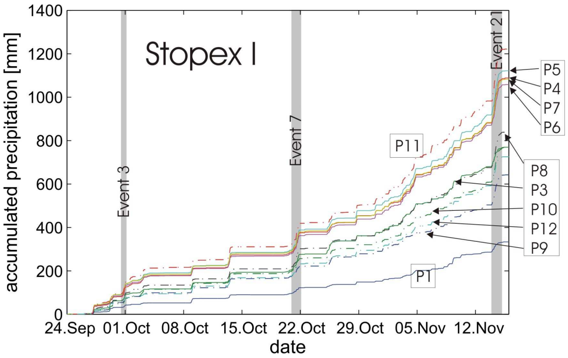

FIGURE 4: The overall accumulated precipitation during STOPEX I. Eleven rain gauges are listed (P2 failed).

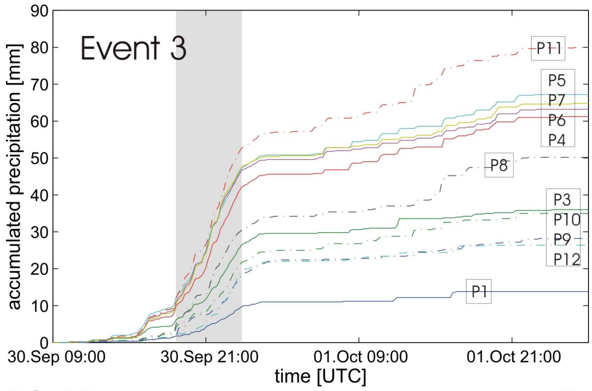

FIGURE 5: Accumulated precipitation during event 3. The shaded region is the focus for comparison with the linear theory.

4. RESULTS – OBSERVATIONS AND MODELING

Table 2 shows winds, surface temperature, stability along with microphysical delays for the three events. The latter has been obtained by fitting the linear model results to recorded precipitation rates. The former comes mainly from Sola sounding (12 hourly) next to the city of Stavanger. Most variables vary significantly through the lower atmosphere, and values are chosen conservatively.

TABEL 2: Three events of intense precipitation. Winds (ff/dd), surface temperature (T_0), stability (N_m) and microphysical delays for the linear model simulations (Tau).

Even	ff [ms^{-1}]/ dd [^{0}]	T_0 (K)	N_m [s^{-1}]	Tau [s]
3	19 / 180	286	0.006	370
7	11 / 205	284	0.0	500
21a	19 / 220	283	0.0	350
21b	25 / 260	284	0.008	350
21c	19 / 270	285	0.010	500

The linear model was run for three of the events, listed in Table 2. The results are shown in Figures 6, 8 and 10.

Event 3 was associated with a passage of a frontal system. The precipitation rate varied with range 2-8 mm/h stations in between, Fig.5. The four stations clustered to the northwest of P11, including P11 had similar rain rate (8 mm/h). The stations in the periphery, excluding P1, have a rate of 4-5 mm/h. P1 had 1-2 mm/h. According to Fig.6 showing the simulated amount by the linear model using values in Table 2, the comparison with observations is good, except for the P12 which is located in the lee. The linear theory is known to have problems with steep lee-sides like these of Stord. This is due to vertically integration method which assumes that the sum of condensation in the column, produce the precipitation. Consequently, in the lee, dry air aloft will cancel supersaturated air next to the ground. This is a questionable assumption, and constrains the use of the model to windward sides, or to coarser resolved terrain.

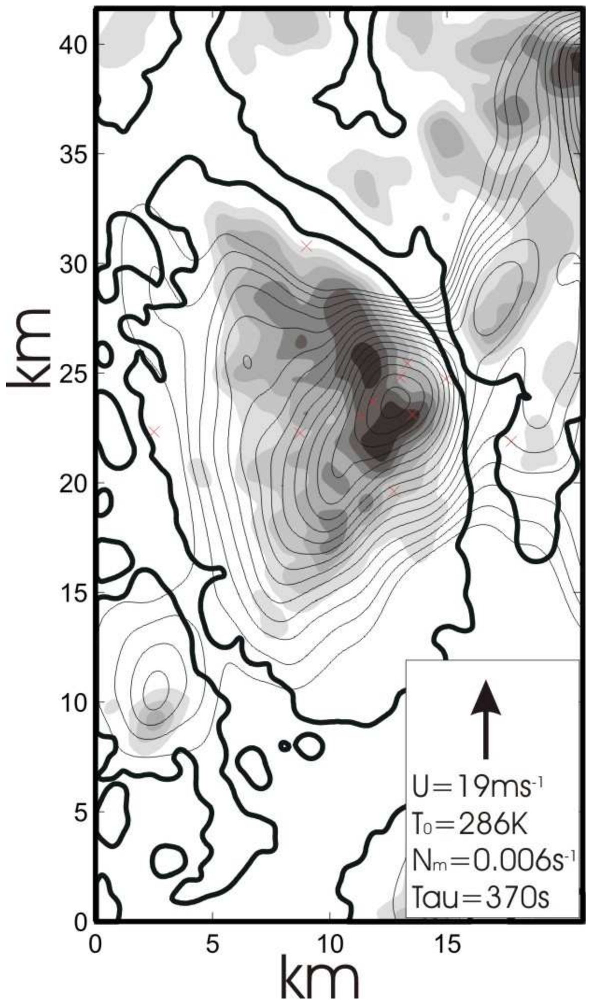

FIGURE 6: Performance of the linear model. The terrain is shaded (every 100 m) and the precipitation intensity is contoured every 0.5 mm/hr. The 10 m terrain contour is indicated with a heavy line.

Event 7 comprises a complicated situation with several fronts. We focus on the latter part of the event, and strongest rain intensities were about 6-10 mm/h, Fig.7. The air was a little cooler than for the previous case, and the wind was significantly weaker. In addition, the wind direction was a bit more westerly (Table 2). The cooler air and the weaker wind suggest that the linear model should give a weaker intensity. However, the stability was weaker (near-neutral), and according to air flow dynamics, vertical velocity generated at the surface, may penetrate deeper, producing more condensate. Nevertheless, the linear model did not simulate the full amounts as collected in event 7. Only 50% was reproduced, Fig.8. A much shorter Tau was needed to obtain observed rain rates (Tau=150 s). For such short Tau's, the simulated spatial rain pattern was poor. According to our weather stations, the lower atmosphere was instable in the time of maximum rain rate, suggesting that convection might be active.

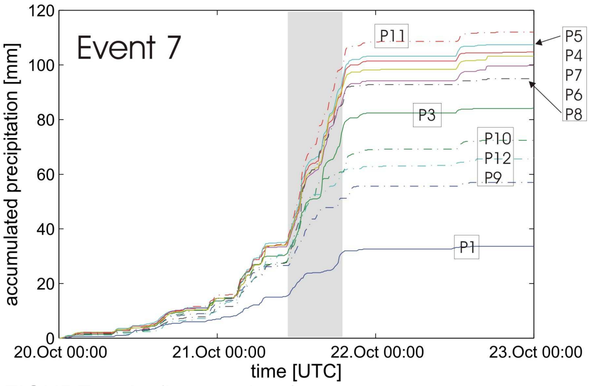

FIGURE 7: As figure 5, but for event 7.

Event 21 is the record high precipitation event on the 14th of Nov. As most of the strong precipitation events, the air in event 21 had tropical origin. A high pressure system west of Iberian peninsula (45N,30W) directed tropical air northward nearer the American continent, into the westerlies the 12th of Nov. A rapidly deepening low emerged south of Greenland the 13th, bringing the warm and moist air westward hitting the Norwegian mainland early the 14th of Nov. Tracking the origin of an air parcel at 850 hPa 06 UTC 14th Nov., show that it started 63 hours earlier at (35N,40W). Comparing the soundings at Bermuda 1-2 days before with the sounding at Sola the 00UTC, 14th Nov., the air mass near the ground (below 900 hPa) has adjusted to the cooler sea-surface, but the inversion at 800 hPa was still present at landfall. The vertically integrated water vapor found from the GPS, was steady high throughout the event (quantitative values waits for data processing). The first part of the event (21a), had the largest rain rates, ranging 3-16 mm/h for the various stations, Fig.9. For reasonable input values (Table 2), the linear model produced about half the observed amounts (not shown). In order to obtain the observed rain rates, Tau's as low as 200 s were needed. However, the fit of the simulated spatial precipitation was poor. Estimates based on information from our weather stations, indicates that the lower atmosphere was instable during the first part (21a). Convection is likely, and this might explain the large difference.

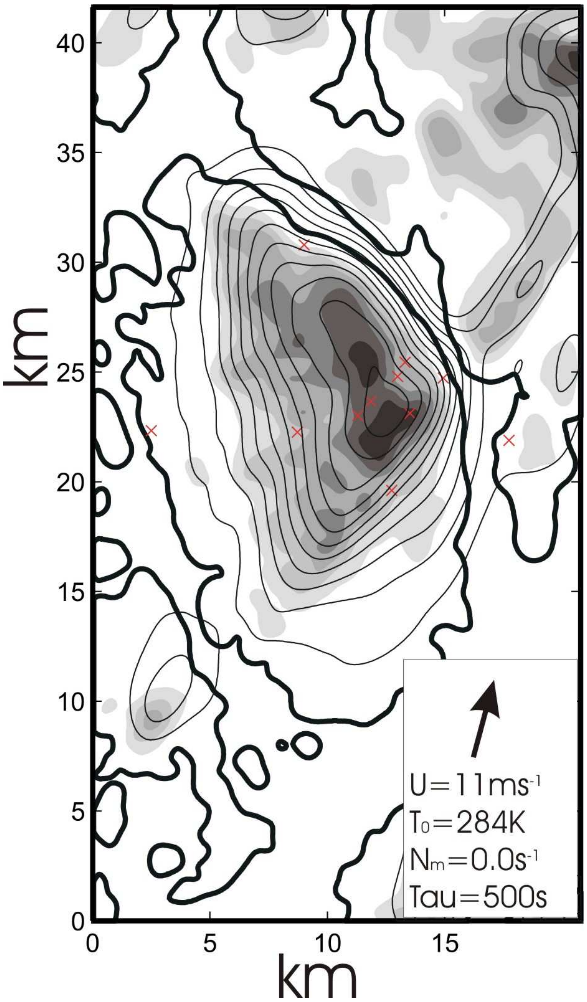

FIGURE 8: As figure 6, but for event 7.

In the second part of the event (21b), the wind shifted more to the west, and the wind speed increased. The air mass became more stable near the ground. The resulting rain intensities ranged from 2-13 mm/h. The linear model (Fig.10) was able to reproduce the amounts if the Tau's where about 300-350 s, indicating rapid conversion from cloud water to rain.

The third part of the event (21c) was characterized by weakening westerly flow. The temperature continued to rise, and stability was increasing in the lower levels. The rain rates decreased to 1-8 mm/h. The linear model was able to produce nearly the amounts observed. The Tau's had to be around 500 s to match the spatial rain patterns observed.

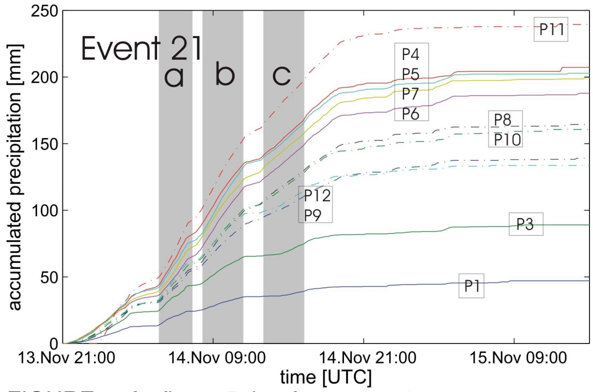

FIGURE 9: As figure 5, but for event 21.

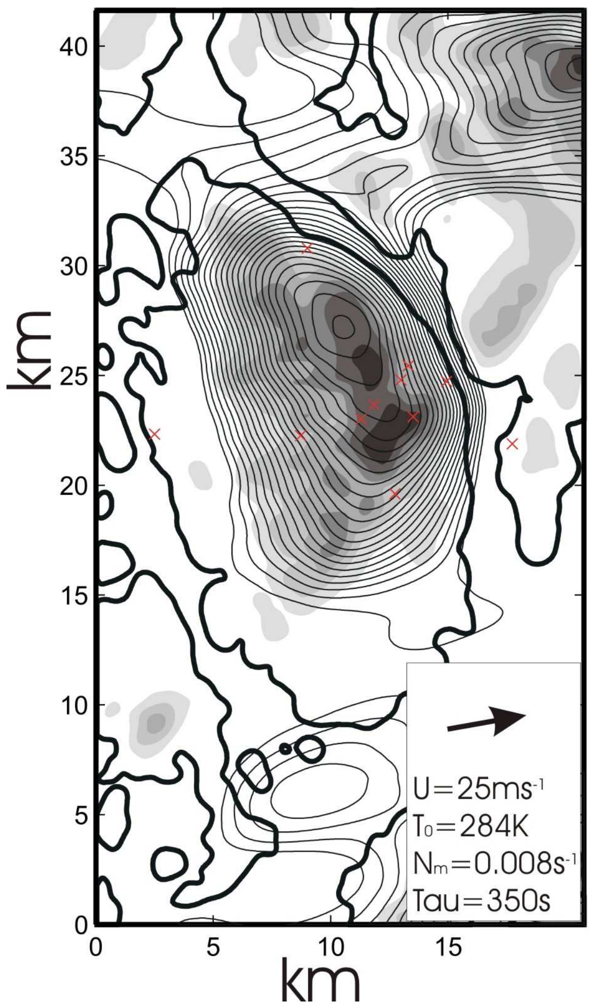

FIGURE 10: As figure 6, but for event 21.

5. DISCUSSION

The stations located on the mountain top, had an overall higher level of relative humidity, indicating that sub-cloud evaporation might play a significant role in resulting precipitation. The data was not corrected for wind drift, suggesting that the actual amounts on the exposed sited, P12 in particular, could be higher.

Instable conditions which were found in many of our events, may have led to embedded convection (e.g. Kirshbaum and Durran, 2005). Convective activity will result in a different precipitation signal.

The linear model's problems having too strong leeside evaporation, was clearly shown. Comparison with detailed numerical modeling will be initiated soon, and microphysical schemes will be tested.

For southerly flows, most of the stations are not located directly in the lee. For westerly cases, this is more the case. The problem in the linear model with too high evaporation on the lee side might have influenced the judgment of the optimal Tau's.

The onset of precipitation is not explained herein. We have only dealt with the intensities, and we see that more work has to be done to achieve a better understanding of the precipitation onset.

6. CONCLUSIONS

An observational campaign of orographic precipitation (STOPEX) has been conducted at the Stord Island, west coast of Norway, between the 23rd of Sept. and 14th Nov. 2005. The detailed observations of precipitation intensities have revealed magnitudes up to 13 mm/h.

The microphysical time delays (Taus) seem to range from 300-500 s. High temporal resolution in the observations is needed in order to identify physical correct Tau's. A long sampling interval (e.g. a day) will lead to weak rain intensities, and longer Tau's will be needed. However, the longer Tau's are then not directly connected to the microphysical process taken place.

Convection due to instable conditions, may have contributed significantly to the overall precipitation signature.

The campaign has revealed potential new location for additional rain gauges and addressed the need of improved upstream information of air masses. The second phase STOPEX will be executed fall 2006.

7. ACKNOWLEDGEMENT

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