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THE INFLUENCE OF WIND AND TOPOGRAPHY ON PRECIPITATION DISTRIBUTION IN SWEDEN: STATISTICAL ANALYSIS AND MODELLING

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ABSTRACT

To estimate daily catchment precipitation from point observations there is a need to understand the spatial pattern, particularly in mountainous regions. One of the most important processes occurring there is orographic enhancement, which is affected by, among other things, wind speed and wind direction. The objective of this paper was to investigate whether the relationship between precipitation, airflow and topography could be described by statistical relationships using data easily available in an operational environment. The purpose was to establish a statistical model to describe basic patterns of precipitation distribution. This model, if successful, can be used to account for the topographical influence in precipitation interpolation schemes. A statistical analysis was carried out to define the most relevant variables, and, based on that analysis, a regression model was established through stepwise regression. Some 15 years of precipitation data from 370 stations in Sweden were used for the analysis. The geostrophic wind, computed from pressure observations, was assumed to represent the airflow at the relevant altitude. Precipitation data for each station were divided into 48 classes representing different wind directions and wind speeds. Among the variables selected, the single most important one was found to be the location of a station with respect to a mountain range. On the upwind side, precipitation increased with increasing wind speed. On the leeward side there was less variation in precipitation, and wind speed did not affect the precipitation amounts to the same degree. For ascending air, slope multiplied by wind speed was another important factor. The effect of slope was enhanced close to the coast, and reduced for mountain valleys with upwind barriers. The stepwise procedure led to a regression model that also included the meridional and zonal wind components. Their inclusion might indicate the importance of air mass characteristics not explicitly accounted for. Copyright © 2003 Royal Meteorological Society.

KEY WORDS: precipitation; orographic enhancement; regression analysis; topography; airflow; spatial distribution; Sweden

1. INTRODUCTION

The assessment of water resources is often based on estimates of areal precipitation, due to the lack of runoff observations. Rainfall-runoff models are common tools, both for long-term planning and for hydrological forecasting (Singh, 1995). In recent years, the applications have widened to include hydro-chemical modelling (Arheimer and Brandt, 1998) and human impact studies (Parkin *et al.*, 1994; Bergström *et al.*, 2001). Generally, estimates of areal precipitation for hydrological applications are made from point observations, although radar measurements are now available in some regions. To be able to interpolate precipitation there is a need to understand the spatial pattern and the influence of topography. It is particularly important in mountainous regions with complex precipitation gradients, where the use of radar is problematic, the station density is low, and stations are located in valleys with easy access but a low precipitation compared with the surrounding higher terrain. Data from meteorological stations must then be supplemented by other information to account for the influence of topography (Martinez-Cob, 1996; Prudhomme and Reed, 1999; Goovaerts,

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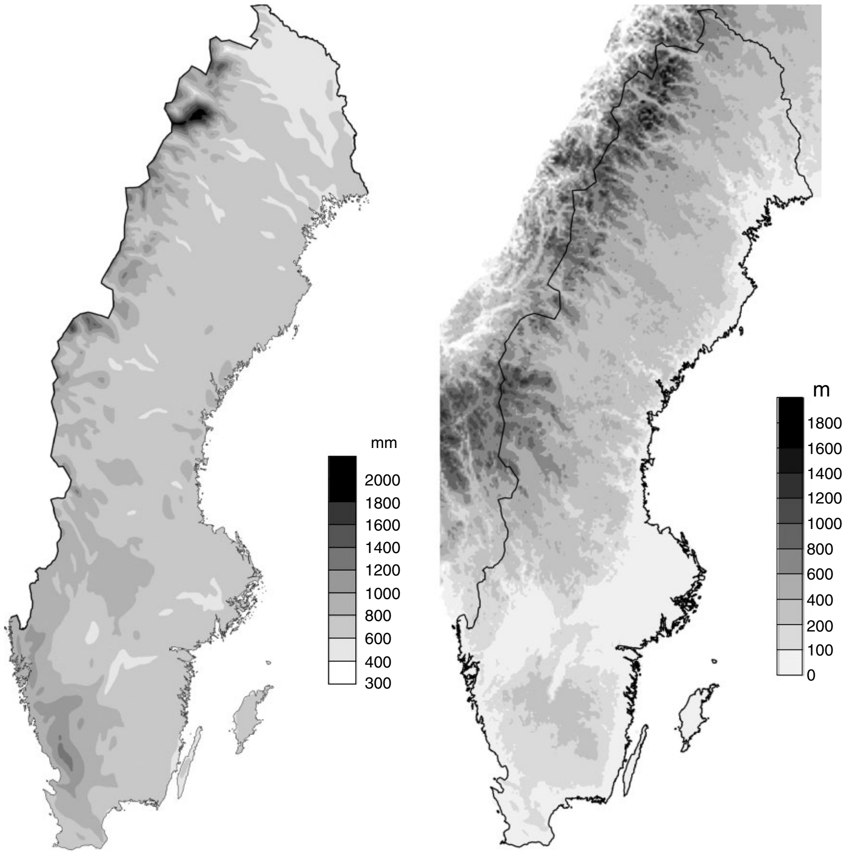
2000). Adjustments of precipitation for topography are often based on studies of annual precipitation, but, in truth, the effects vary between precipitation events (Peck, 1973; Konrad, 1996).

Smith (1979) gives a comprehensive review on the complex subject of orographic rain. On the windward side, forced lifting of approaching air masses causes the release of rainfall and an increase in precipitation with elevation. Depending on the mountain size and the efficiency of the release processes, precipitation will decrease on the leeward side. Smith (1979) presents a simple prototype model of upslope rain, based on the assumption of an adiabatic temperature lapse rate. The assumption leads to a model where rainfall intensity depends on the speed by which an air parcel is forced to rise, which in turn is expressed by horizontal wind speed and mountain slope. Weston and Roy (1994) used a similar approach to model orographic rain in Scotland, but they also considered the gradual decrease in cloudwater. The enhanced rainfall over a range of hills or mountains removes cloudwater, which results in reduced orographic enhancement for downwind hills. Observations in the South Wales, by Hill *et al.* (1981), support the assumptions made in the models. They found that orographic enhancement was well correlated with wind speed, and that the existence of high relative humidity in the lowest 1.5 km of the atmosphere was important. However, rainfall rates do not only depend on the condensation rate, but also on the availability of initial particles on which raindrops can grow. Bergeron (1968) noted a large increase in precipitation over low hills, and explained it with a seeder–feeder mechanism. Feeder clouds are low-level clouds forming over the hills. The clouds are not dense enough to cause precipitation by themselves, but precipitation from high-level (seeder) clouds is amplified by these clouds through washout of cloud droplets. Over the surrounding valleys, precipitation from the high-level clouds partly evaporates before hitting the ground, resulting in large differences in precipitation. According to Browning *et al.* (1974), the upwind speed, and thereby the condensation rate, can be increased by the existence of moving convective cells within a front, probably formed in unstable layers and triggered by orographic lifting.

Mountains may also facilitate the formation of convective rainfall (Smith, 1979). As sun heats the mountainside, the air near the surface is heated by conduction and small-scale convection. The warm air rises, and at the mountain tops it breaks away from the surface and clouds starts to form. The clouds are then carried downwind, producing rainfall on the leeward side, as opposed to frontal systems where precipitation is usually higher on the windward side.

Hill (1983) used the wind at 600 m a.s.l. to represent wind direction and wind speed in a study of orographic enhancement over England and Wales, and considered that to be well represented by the geostrophic wind. In a study in central and southern Norway, Nordø and Hjortnæs (1967) found a strong correlation between rainfall distribution and the component of the geostrophic wind directed against the mountain. Within the lowest levels of the atmosphere (the friction layer), the wind speed and direction are affected by friction against the Earth's surface. Above 500 to 1000 m this effect is negligible, and the airflow direction and speed are mainly governed by the pressure gradients and the Coriolis force, which balance each other. The airflow direction becomes parallel to the isobars, and the geostrophic wind can be computed from pressure observations. Airflow indices computed from sea-level pressure have been used to study temporal and spatial distribution of precipitation (e.g. Conway *et al.*, 1996; Busuioc *et al.*, 2001a; Linderson, 2001; Phillips and McGregor, 2001). The studies have often aimed at the development of downscaling procedures for global climate models (Busuioc *et al.*, 2001b) and have been based on data with a low spatial resolution (grid sizes of 5–10°). The airflow indices thus describe a large-scale circulation. Generally, a good correlation is found between precipitation and such airflow indices, but results from Sumner (1996) and Olsson *et al.* (1999) indicate that they do less well in describing the local orographic influence.

Precipitation distribution in Sweden is strongly influenced by topography (Figure 1). It is closely related to the passage of cyclones, normally following westerly–easterly tracks across Scandinavia (Ångström, 1974). The highest annual precipitation is found in the Scandinavian mountain range and along the west coast. Convective rainfall mainly occurs in summer. In Sweden, estimates of areal precipitation for operational runoff modelling are normally based on fixed relationships with elevation. One should be able to provide more accurate daily estimates if information on airflow and topography are combined. The objective of this paper was to investigate to what extent the influence of wind and topography on precipitation can be described by statistical relationships, using data easily available in an operational environment. The aim was to define



a) b)

Figure 1. (a) Mean annual precipitation in Sweden 1961–90 (Raab and Vedin, 1995); (b) elevation map (database from the National Land Survey of Sweden)

the most relevant variables and to establish an empirical model that describes typical precipitation patterns. Ultimately, the intention is to use this model in an interpolation scheme for estimation of areal precipitation.

2. DATA AND METHODS

The applicability of the empirical model in an operational environment was considered important. It led to the decision to seek relationships valid for the whole of Sweden, as local relationships are time consuming to develop.

The analysis of precipitation distribution was based on daily data from 1981 to 1995 from 370 rainfall stations run by the Swedish Meteorological and Hydrological Institute (SMHI; Figure 2(a)). Another 80 stations were used for verification. The stations selected were located at the same site for the whole period, which guaranteed well-defined long-term mean values. Most of the stations were so called Type 3 stations, where accumulated rainfall is measured once a day. There were 97 Type 1 stations, where, in addition to accumulated daily precipitation, 3-hourly observations of a weather code were available. The code is a measure of rainfall intensity. This information was important in order to define the relevant wind speed and wind direction during the precipitation event. Precipitation was corrected for observation losses by station-specific loss factors (Eriksson, 1983; Hans Alexandersson, SMHI, personal communication). There was a seasonal variation in the factors, but neither actual wind speed nor precipitation type were taken into consideration.

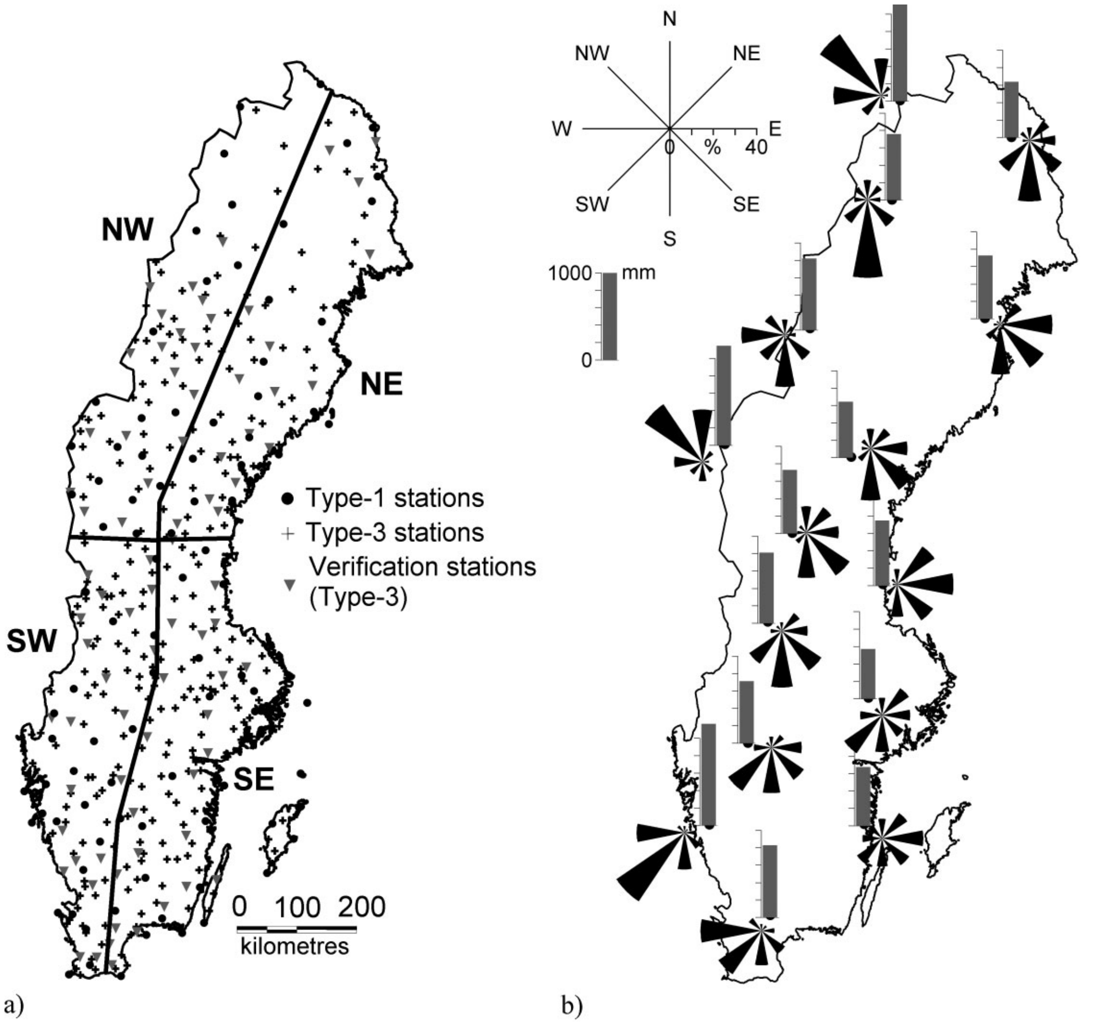


Figure 2. (a) Rainfall stations used for statistical analysis; (b) precipitation distribution by wind direction (wind roses) and mean annual precipitation (bars). Examples from some of the Type 1 stations, based on data from 1981–95

Geostrophic wind was available on a 1° × 1° grid for 3-hourly intervals (Omstedt *et al.*, 1997). It was originally computed by interpolating 3-hourly sea-level pressure observations to a 1° × 1° grid mesh. The u and v components of the geostrophic wind for each grid were then computed from the pressure gradient between the neighbouring east–west and north–south grids. As sea-level pressure was used, the assumption was made that the isobars do not change with altitude. During the passage of a cyclone, wind direction may vary considerably. Therefore, the weather code from the Type 1 stations was used to estimate average daily wind speed and wind direction. Usually, the wind direction did not vary by more than 90° during the actual precipitation event. If the 90° interval was exceeded, then it was not considered possible to compute an average wind direction. The 90° interval with most precipitation was then selected to represent the wind of that day. Very little precipitation was classified in the wrong interval by using this procedure. At none of the Type 1 stations did it exceed 3%. For the Type 3 stations, wind speed and wind direction were assumed to be the same as at the nearest Type 1 station. Figure 2(b) shows the distribution of precipitation by wind direction for some of the Type 1 stations included in the analysis.

Elevation data were taken from the 50 × 50 m^2 elevation database of the Swedish National Land Survey. It was resampled to a 4 × 4 km^2 grid mesh.

Precipitation events were divided into classes according to wind speed and wind direction. There were eight classes for wind direction (N, NE, E, SE, S, SW, W, NW) and six for wind speed (0–5, 5–10, 10–15, 15–20, 20–25, >25 m/s). For each class and station, the mean precipitation for the years 1981–95 was computed. Only mean values based on at least 20 observations were included. With 370 stations and up to 48 values per station, the total number of values used for the analysis was about 12 000.

2.1. *Selected topographical and airflow variables*

A number of variables were assumed important for the precipitation amounts at a specific location under specific wind conditions. They were selected on a theoretical and empirical basis, but also from an initial analysis of different data subsets (Table I).

Slope and the slope multiplied by wind speed were selected to represent the ascent and descent of the air mass. As air starts to ascend some distance ahead of a mountain range (Smith, 1979), both the upwind and the downwind slope were selected as variables. A distinction was made between the windward and the leeward side of a mountain (ascending/descending air). Wind speed itself might be an indication of the intensity of the frontal system, and thereby of the precipitation amounts. Conway *et al.* (1996) found a correlation between strength of flow and daily precipitation amounts.

Locally, there is usually a clear relationship between elevation and mean annual precipitation (Lauscher, 1976; Raab and Vedin, 1995). Several authors have shown that the mean elevation for an area with a radius

Table I. Variables selected for statistical analysis

Variable name	
SL_U$_>$/SL_U$_> \cdot V$	Upwind slope, ascending air/multiplied by wind speed
SL_U$_<$/SL_U$_< \cdot V$	Upwind slope, descending air/multiplied by wind speed
SL_D$_>$/SL_D$_> \cdot V$	Downwind slope, ascending air/multiplied by wind speed
SL_D$_<$/SL_D$_< \cdot V$	Downwind slope, descending air/multiplied by wind speed
V	Wind speed
ELEV4	Elevation of 4×4 km^2 grid around rainfall station
ELEV12	Elevation of 12×12 km^2 grid around rainfall station
SEAD_U	Distance to the sea in the upwind direction.
SEAD_U45	Distance to the sea, 45° clockwise to the upwind direction.
MIN_SEAD	The minimum of SEAD_U and SEAD_U45
MRDIF_U	Elevation difference to the highest upwind mountain range. Elevation of mountain range computed as the mean elevation for a stretch of 160×4 km^2 perpendicular to the wind direction
MRDIF_U45	Same as MRDIF_U, but 45° clockwise to the upwind direction
MIN_MRDIF	The minimum of MRDIF_U and MRDIF_U45
MEAN_MRDIF	The mean of MRDIF_U and MRDIF_U45
$V \cdot$MRF	Wind speed multiplied by a mountain range factor: MRF = MIN[(250 − MIN_MRDIF)/250, 0]
BRDIF	Elevation difference to highest upwind barrier within 50 km of the station. Elevation of barrier computed as the mean elevation for a stretch of 80×4 km^2 perpendicular to the wind direction
$V \cdot$SL_D$_> \cdot$BRF	Downwind slope, ascending air, multiplied by wind speed and a barrier factor: BRF = MIN[(250 − BRDIF)/250, 0]
$V \cdot$SL_U$_> \cdot$CF	Upwind slope, ascending air, multiplied by wind speed and a coast factor: CF = MAX[(40 − MIN_SEAD)/40, 0]
$V \cdot$VDIR	Meridional wind component (equals V for southerly winds)
$V \cdot$UDIR	Zonal wind component (equals V for westerly winds)
X, Y	Station location

of a few kilometres is more representative for precipitation amounts than the actual station elevation (Chuan and Lockwood, 1974; Hill *et al*., 1981).

Distance from the sea is used as an indication of air humidity. The geostrophic wind follows the isobars, and as the isobars close to the cyclone centre are often curved, the straight upwind distance may not be representative, particularly not if the coast is some distance away. Consequently, the distance 45° clockwise to the upwind direction was included among the variables. The same reasoning was applied to the distance to upwind mountain ranges.

The importance of upwind barriers is often stressed in studies of the topographical influence (Schermerhorn, 1967; Konrad, 1996; Prudhomme and Reed, 1998). There are two possible effects: first, the gradual decrease in moisture content as the air passes over one or several mountain ranges; second, the blocking of air by a nearby upwind barrier. The two variables MRDIF and BRDIF were intended to represent these two effects. In both cases, the elevation of the upwind barrier was computed over a fairly long stretch of land in order to avoid discontinuities with great differences in values for neighbouring grids.

Wind direction might indicate different air mass characteristics. In Sweden, southerly and easterly winds often appear together with warm and occluded fronts, northerly and westerly winds together with cold fronts (Ångström, 1974).

The three variables $V\cdot\mathrm{MRF}$, $V\cdot\mathrm{SL\_D}_{>}\cdot\mathrm{BRF}$ and $V\cdot\mathrm{SL\_U}_{>}\cdot\mathrm{CF}$ were selected after an initial analysis of the data. After plotting daily mean precipitation against MIN_MRDIF, it was seen that most of the variation occurred for MIN_MRDIF less than 250 m (Figure 3). Furthermore, no correlation between wind speed and precipitation was found for MIN_MRDIF greater than 250 m. As a result, the variable $V\cdot\mathrm{MRF}$ was introduced. A special analysis of stations located in narrow mountain valleys revealed a much weaker relationship with downwind slope. This led to the variable $V\cdot\mathrm{SL\_D}_{>}\cdot\mathrm{BRF}$. Along the coast, precipitation was found to increase more strongly with upwind slope than for inland stations. Thus, the variable $V\cdot\mathrm{SL\_U}_{>}\cdot\mathrm{CF}$ was introduced.

Several approaches were tested to determine upwind and downwind slope. The one finally chosen is illustrated in Figure 4(a). Slope is computed as the difference in elevation between a 12×12 km^2 grid around the station and the weighted mean of a number of upwind/downwind grids. The correlation between upwind slope and daily mean precipitation increased for up to seven upwind grids in the wind direction (84 km, Figure 4(b)). Pedgley (1970) found that the orographic influence on precipitation was best described by a smoothed topography. This is in agreement with the upwind elevation being computed over a large area. On the other hand, the estimated slope largely depends on the elevation of the station grid, and this suggests a strong local influence. In steep mountainous terrain, the difference in elevation between neighbouring 12×12 km^2 grids is considerable. The use of an original 4×4 km^2 grid ensured that the station location was in the centre of a 12×12 km^2 grid.

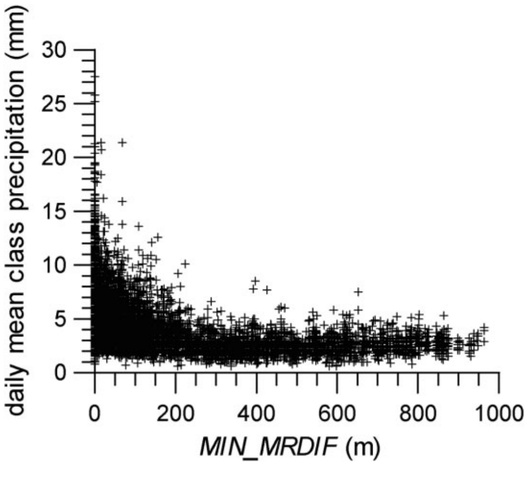
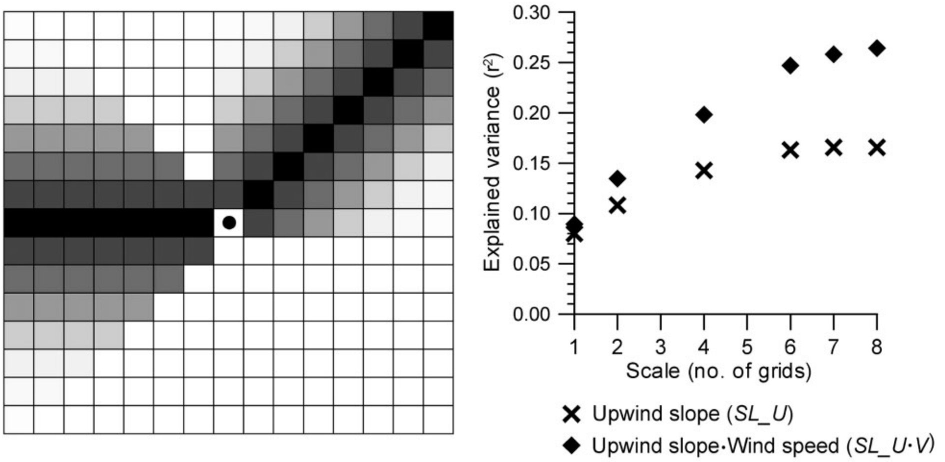


Figure 3. Daily mean precipitation for each wind class and station plotted against elevation difference to upwind mountain range (MIN_MRDIF)



a) b)

Figure 4. (a) Grids used for computation of slope towards the west and northeast. Slope computed as the difference in elevation between station grid (in the centre) and a weighted mean of upwind/downwind grids. The shade of grey represents the size of the weights, so that the greatest weight is given to grids marked in black. Grid size is 12 × 12 km^2. (b) Variance in daily mean precipitation explained by upwind slope. Upwind elevation computed over a different number of grids in the wind direction

Stepwise regression was used to select an optimal set of variables reflecting the topographical and wind effects. This method adds additional independent variables one at a time, in successive stages, each raising the dimensions of the analysis by one. The most promising independent variable, i.e. the one that provides the greatest reduction in the unexplained variation in the dependent variable (precipitation), is selected at every stage. Then there is a re-examination of all the variables included in the previous steps. A variable that becomes superfluous because of its relationship with other variables in the model is excluded.

3. RESULTS

3.1. *Variance explained by single variables*

The variance r^2 explained by each single variable is listed in Table II. It appears that the most important factors affecting precipitation amounts are the wind speed V and whether a station is located upwind or downwind of a mountain range (MRDIF_U/MRDIF_U45/MIN_MRDIF/MEAN_MRDIF). Combined ($V\cdot$MRF) they explain 42% of the variance. Other important factors are the upwind and downwind slopes for ascending air ($\mathrm{SL\_U}_{>}\cdot V$, $\mathrm{SL\_D}_{>}\cdot V/V\cdot\mathrm{SL\_D}_{>}\cdot\mathrm{BRF}$). Precipitation amounts are higher for events with easterly and southerly winds than for westerly and northerly winds. Elevation does not explain any of the variance in precipitation. This is not wholly surprising considering the large study area and the subdivision of data into different wind classes (Smith, 1979; Phillips *et al*., 1992).

A comparison regarding topography variables for two wind classes shows that the influence of topography is hard to discern at low wind speeds but visible at high wind speeds (Table III). For a certain distance, the correlation between stations is also lower for the wind class 0–5 m/s than for the wind class 10–15 m/s (Figure 5), indicating that precipitation is less widely spread at low wind speeds.

3.2. *Regression model*

The stepwise regression was performed with the variables marked in bold in Table II. It was decided not to use variables that explained less than 5% of the variance, and the variables MIN_SEAD, MIN_MRDIF and MEAN_MRDIF were preferred to SEAD_U, SEAD_U45, MRDIF_U and MRDIF_U45. However, it was not possible to select only variables that were totally independent. To limit the number of variables in the linear

Table II. Variance in precipitation explained by single variables: (+) indicates a positive correlation, (−) a negative correlation. Variables in bold explain more than 5% of the variance. Analysis based on daily station mean precipitation for 48 different wind classes and 370 stations

Variable	r^2 (%)	Variable	r^2 (%)	Variable	r^2 (%)
SL_U$_>$	11 (+)	ELEV4	0.1 (−)	**V·MRF**	42 (+)
SL_U$_>$·V	26 (+)	ELEV12	0.1 (−)	**BRDIF**	11 (−)
SL_U$_<$	13 (+)	SEAD_U	5 (−)	**V·SL_D$_>$·BRF**	22 (+)
SL_U$_<$·V	7 (+)	SEAD_U45	4 (−)	**V·SL_U$_>$·CF**	10 (+)
SL_D$_>$	6 (+)	**MIN_SEAD**	7 (−)	**V·VDIR**	7 (+)
SL_D$_>$·V	15 (+)	MRDIF_U	15 (−)	**V·UDIR**	10 (−)
SL_D$_<$	4 (+)	MRDIF_U45	14 (−)	X	3 (−)
SL_D$_<$·V	1 (+)	**MIN_MRDIF**	16 (−)	Y	2 (−)
V	19 (+)	**MEAN_MRDIF**	20 (−)		

Table III. Variance in daily mean precipitation explained by topographical variables for two different wind classes (all wind directions)

Wind class 0–5 m/s		Wind class 10–15 m/s	
Variable	r^2 (%)	Variable	r^2 (%)
SL_U$_>$	2 (+)	SL_U$_>$	17 (+)
SL_U$_<$	7 (+)	SL_U$_<$	23 (+)
SL_D$_>$	0	SL_D$_>$	19 (+)
MIN_SEAD	3 (−)	MIN_SEAD	10 (−)
MIN_MRDIF	8 (−)	MIN_MRDIF	28 (−)
MEAN_MRDIF	9 (−)	MEAN_MRDIF	36 (−)
BRDIF	8 (−)	BRDIF	19 (−)

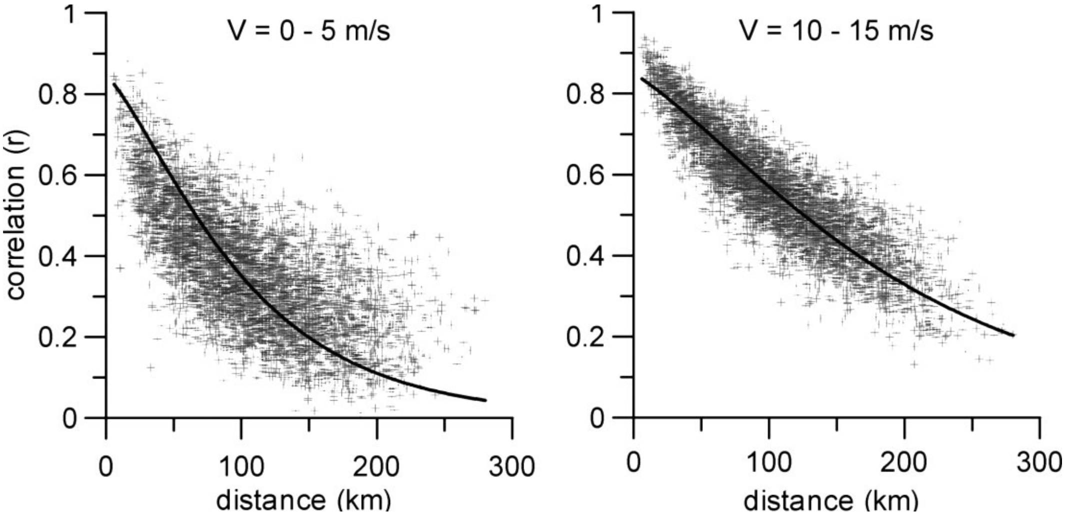


Figure 5. Scatter plot of correlation between daily station precipitation versus distance between stations. Fitted line using exponential expression. Wind speed classes 0–5 and 10–15 m/s shown

regression equation, the p-value (significance level) for inclusion and exclusion of variables was set to 10^{-50}. The result was an equation with six variables:

$$P^m = 2.85 + 0.0335x_1 + 0.125x_2 + 0.0309x_3 + 0.150x_4 + 0.0241x_5 - 0.0583x_6 \qquad (1)$$

where x_1 is the upwind slope multiplied by the wind speed (ascending air, $\mathrm{SL\_U}_{>}\cdot V$), x_2 is the wind speed multiplied by a mountain range factor ($V\cdot\mathrm{MRF}$), x_3 is the downwind slope multiplied by wind speed and a barrier factor (ascending air, $V\cdot\mathrm{SL\_D}_{>}\cdot\mathrm{BRF}$), x_4 is the upwind slope multiplied by wind speed and a coast factor (ascending air, $V\cdot\mathrm{SL\_U}_{>}\cdot\mathrm{CF}$), x_5 is the meridional wind component ($V\cdot\mathrm{VDIR}$) and x_6 is the zonal wind component ($V\cdot\mathrm{UDIR}$).

The regression equation explains 60% of the variance in the data. Table IV also lists the coefficients for the normalized variables. In computing of the daily mean precipitation, there were large differences in the number of observations for each class and station. Thus, the importance of unusual rainfall events may have been overstressed. To investigate this, a weighted regression was carried out, using the number of observations as weights. The coefficients differed only marginally from the original ones.

The three variables, which independently explained more than 20% of the variance in P^m, were included in the regression relationship, confirming the importance of wind speed, slope and barriers. The high humidity along the coast results in a more pronounced orographic enhancement, represented by the variable $V\cdot\mathrm{SL\_U}_{>}\cdot\mathrm{CF}$. The variable differs from zero only for stations close to the coast, which explains its lower coefficient in the equation for the normalized variables. The inclusion of wind direction ($V\cdot\mathrm{UDIR}$ and $V\cdot\mathrm{VDIR}$) was more surprising and difficult to explain satisfactorily. It could indicate a difference in air mass characteristics, e.g. humidity. Southerly and easterly winds are also more common along warm and occluded fronts. Along these fronts, precipitation is often continuous and widely spread, whereas showers are more common along cold fronts. This might result in higher daily precipitation for southerly and easterly winds. The normalized relationship shows that the difference between easterly and westerly winds is particularly

Table IV. Regression coefficients from an analysis based on normalized variables and from a weighted regression analysis (Equation (1))

	Const.	$\mathrm{SL\_U}_{>}\cdot V$	$V\cdot\mathrm{MRF}$	$V\cdot\mathrm{SL\_D}_{>}\cdot\mathrm{BRF}$	$V\cdot\mathrm{SL\_U}_{>}\cdot\mathrm{CF}$	V·VDIR	V·UDIR
Normalized		0.244	0.381	0.173	0.148	0.0985	−0.236
Weighted	2.74	0.0296	0.125	0.0286	0.157	0.0263	−0.0594

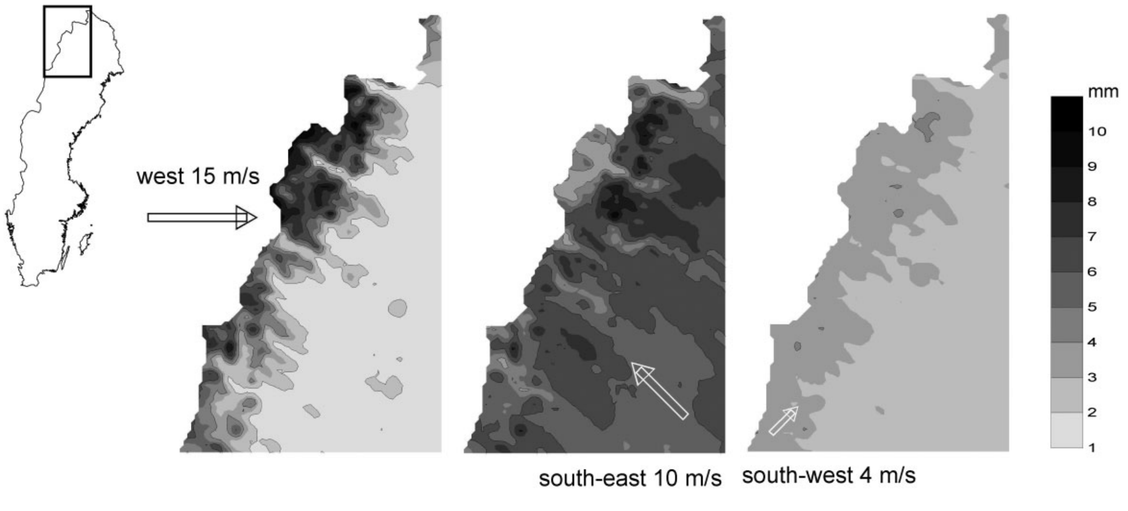


Figure 6. Typical daily rainfall patterns in northwest Sweden for some wind speeds and wind directions. From regression relationship

important. Figure 6 gives some examples of typical precipitation patterns according to the regression equation. For westerly winds, the precipitation amounts drop quickly to the east of the mountain range, and the orographic enhancement becomes weak for low wind speeds.

An analysis of the residuals showed that the inclusion of more variables from Table II would only marginally increase the explained variance. A test of the regression relationship for the verification stations revealed no bias, and the explained variance was the same (61%) as for the original stations.

3.3. Seasonal effects

To investigate the seasonal variation in the relationship, a separate analysis was carried out for summer (June to August) and winter precipitation (October to March). Figure 7 further illustrates the distribution of summer and winter precipitation by wind direction. In winter, southerly winds dominate precipitation events at most stations. The daily precipitation is somewhat higher for these wind directions, but their high frequency

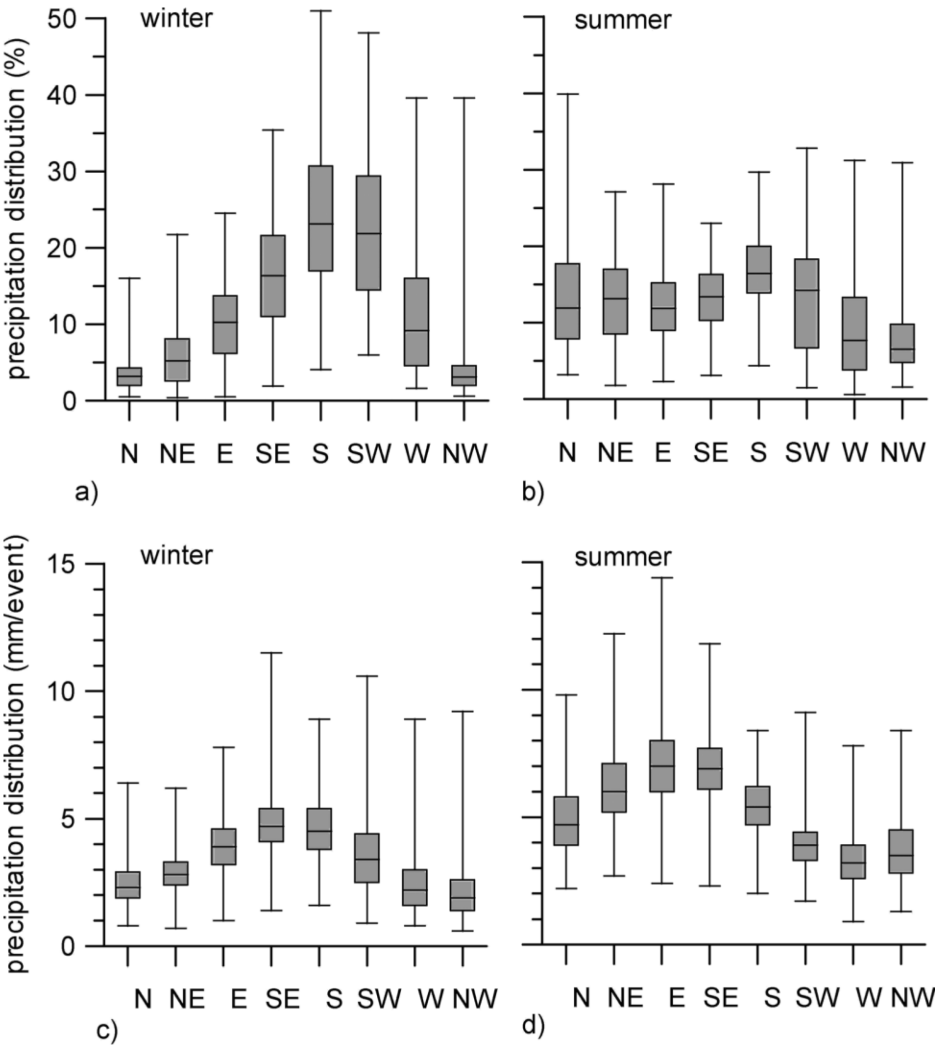


Figure 7. Box–whisker plots illustrating the distribution of precipitation by wind direction for the 370 stations included in the regression analysis (1981–95). June–August (left) and October–March (right). (a, b) Percentage of total rainfall for different wind directions; (c, d) mean precipitation for days with rainfall and different wind directions

is the main reason for the high total amounts (Figure 7(a) and (c)). There is a clear pattern in summer, with higher daily precipitation amounts for easterly than for westerly winds (Figure 7(d)).

The stepwise regression showed that wind speed, slope and barriers are important in both seasons (Table V). One should be careful in interpreting moderate differences in the values of the coefficients in this type of regression relationship, as the variables are not fully independent. For example, except for stations located in valleys or on mountain peaks, the upwind and downwind slopes are either both positive or both negative. A high winter value for the upwind slope coefficients may thus be compensated by a lower value for the downwind slope coefficient. No conclusions should be drawn on the physical relevance of these differences between summer and winter coefficients.

More remarkable is the importance of wind direction. The difference between easterly and westerly winds is very clear in summer, but hardly significant during winter. One reason could be the higher frequency of cyclones moving in a southerly-northerly direction in summer. The fronts bring warm tropical air, causing abundant rainfall, particularly in the eastern part of Sweden.

3.4. Regional analysis

The stability of the regression relationship was further investigated by dividing Sweden into four equally large regions: northwest, northeast, southwest and southeast (Figure 2(a)). The relationships appear to be fairly stable with respect to the variables representing the orographic influence (Table VI). The values of the coefficients stay within ±50% of the ones representing the whole of Sweden, and higher values for the upwind slope coefficients are compensated for by lower values for the downwind ones. However, the effect of wind direction is much less significant in the northern part of Sweden, possibly due to the greater differences in elevation and thus a larger orographic influence. In the northwest, as opposed to other regions, northerly winds even appear to give higher daily precipitation amounts.

The northwestern part of Sweden has the most complex precipitation gradients, the highest precipitation and the greatest distances between the rainfall stations. In order, therefore, to interpolate data from this part of Sweden successfully, a good understanding of the spatial distribution is particularly important. However,

Table V. Coefficients of regression equation (Equation (1)) for summer and winter precipitation

Coeff.	Const	$\mathrm{SL\_U}_{>}\cdot V$	$\mathrm{V{\cdot}MRF}$	$V\cdot\mathrm{SL\_D}_{>}\cdot\mathrm{BRF}$	$V\cdot\mathrm{SL\_U}_{>}\cdot\mathrm{CF}$	$V\cdot\mathrm{VDIR}$	$V\cdot\mathrm{UDIR}$	N	r^2
Winter	1.76	0.0349	0.129	0.0295	0.147	0.0656	−0.0063	8145	0.60
p-value	0	0	0	0	0	0	10^{-4}		
Summer	3.99	0.0230	0.130	0.0353	0.102	0.0391	−0.161	4505	0.46
p-value	0	10^{-25}	0	10^{-33}	10^{-9}	10^{-30}	0		

Table VI. Coefficients of regression equation (Equation (1)) for different regions. (There are no coastal stations in the NW region)

Coeff.	Const.	$\mathrm{SL\_U}_{>}\cdot V$	$V\cdot\mathrm{MRF}$	$V\cdot\mathrm{SL\_D}_{>}\cdot\mathrm{BRF}$	$V\cdot\mathrm{SL\_U}_{>}\cdot\mathrm{CF}$	$V\cdot\mathrm{VDIR}$	$V\cdot\mathrm{UDIR}$	N	r^2
NW	2.83	0.0330	0.105	0.0347		−0.0309	−0.0441	2391	0.50
p-value	0	10^{-75}	10^{-46}	10^{-39}		10^{-18}	10^{-22}		
NE	2.32	0.0290	0.144	0.0458	0.163	0.0188	−0.0363	2187	0.77
p-value	0	10^{-36}	10^{-89}	10^{-52}	10^{-66}	10^{-7}	10^{-12}		
SW	3.13	0.0456	0.113	0.0287	0.135	0.0567	−0.0762	3408	0.63
p-value	0	0	0	10^{-35}	10^{-37}	10^{-59}	0		
SE	3.06	0.0303	0.100	0.0367	0.122	0.0378	−0.0606	4286	0.62
p-value	0	10^{-44}	0	10^{-61}	10^{-34}	10^{-77}	0		

the regional analysis shows that the complex gradients are difficult to describe: only 50% of the variance is explained, compared with over 60% in southern Sweden and over 75% in the northeast.

With the exception of the northwestern region, the regression equation fitted to all data explains almost as much of the variance in the data as the regional relationships do (SE region 61%, SW region 61%, NE region 76%, NW region 45%).

4. SUMMARY AND CONCLUSIONS

The aim of this study was to investigate whether statistical relationships could be used to describe typical precipitation patterns related to topography and wind. Daily precipitation data for 15 years, from 370 stations in Sweden, were divided into 48 classes representing different wind speeds and wind directions. The relation between daily precipitation amounts and a number of variables was analysed. The variables were selected on a theoretical and empirical basis. Highly significant relationships were found between daily precipitation amounts and variables representing orography. Among the variables selected, the single most important one was the location of a station with respect to a mountain range. On the upwind side, precipitation was found to increase with increasing wind speed, confirming the assumption that wind speed is an indication of the strength of the frontal system and thereby of precipitation amounts. The influence of wind speed was considerably smaller on the leeward side. For ascending air, slope multiplied by wind speed was another important factor. The effect of slope was enhanced close to the coast, and reduced for mountain valleys with upwind barriers.

A linear regression model was established through a stepwise procedure. It included four variables representing orography and two representing wind directions. The model explained 60% of the variance in the original data. Clearly, there were factors not accounted for. This was underlined by the two wind-direction variables. Their inclusion could not be explained satisfactorily. Precipitation amounts were found to be higher for events with easterly and southerly winds than for events with westerly and northerly winds. Possibly, this is an indication of different air mass characteristics. Humidity and stability are known to affect the generation of precipitation, but these were not part of the analysis. Wind data were taken from a $1^\circ \times 1^\circ$ grid. The scale was deemed appropriate for the orographic influence, but overall precipitation amounts may be better described by large-scale circulation indices. Another source of uncertainty is the estimation of wind speed from sea-level pressure. The geostrophic wind is assumed to represent the airflow above the friction layer, and, properly, it should be computed from the isobars at the relevant level. Particularly along frontal systems, isobars change with altitude due to the strong horizontal temperature gradients.

The regression model was based on data from the whole of Sweden. To investigate its general applicability it was tested using a few subsets of the data. Data were split for summer and winter, and Sweden was divided into four regions. With respect to the four variables representing orography, the model was stable. The variables were highly significant for all subsets of data, and the coefficients varied only moderately. However, there was further indication that the wind direction variables represented factors not accounted for. Their significance differed considerably between summer and winter and between northern and southern Sweden.

The regression model will be further used to support the interpolation of daily precipitation for rainfall-runoff modelling. The main interest is then in the influence of orography. Considering the stability of the model in this respect, it seems safe to conclude that it can be usefully applied.

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