Tellus (1994), 46A, 4–13
Printed in Belgium – all rights reserved

TELLUS
ISSN 0280–6495

Precipitation from convective boundary layers in arctic air masses

By HARALDUR ÓLAFSSON*[,1] and HANS ØKLAND, *Institute of geophysics, University of Oslo, PO Box 1022 Blindern, N 0315 Oslo, Norway*

(Manuscript received 20 February 1992; in final form 15 June 1993)

ABSTRACT

Cold air mass formed over the ice-covered polar area during the winter season often moves southward over the Norwegian Sea. The heat flux from the water produces a CBL (convective boundary layer) with increasing thickness and temperature in the downstream direction. Usually, snow showers are observed over the sea and at the coast of Norway. The object of this investigation is to examine the amount of precipitation measured at the coast in relation to the temperature and thickness of the CBL. A sample consisting of 37 cases is collected and a positive correlation is established between the precipitation measured by 5 coastal stations and the CBL thickness, while the temperature seems to be of minor importance. Some of the data indicates a two-regime precipitation pattern, divided by a threshold value in the thickness of the CBL. This is discussed in relation to microphysical precipitation processes. Peculiar differences in the records from the observing stations indicate interesting orographic shadow effects.

1. Introduction

During the winter season, strong and very cold airstreams from the ice-covered polar area frequently blow southward over the open water of the Norwegian Sea toward Northern Scandinavia. A layer of slightly unstable stratification forms in the originally stable air mass, a so-called convective boundary layer (CBL). The major cause for the development of this layer is thermal convection, although turbulence caused by the wind shear in the surface layer may be of some importance, especially in the initial stage. As the air mass moves south over water of increasing surface temperature, the convection gradually entrains and mixes the ambient air, creating a layer of increasing thickness and higher mean temperature in the downstream direction. This change along the trajectory depends on several parameters, such as the length of the trajectory over open water and the air-sea temperature difference (Fig. 1 shows a typical example of the sea surface temperature). Important is also the initial stability of the air mass. In fact, although in the source area the arctic air mass is extremely stable in the lower part, say up to 500 m, the stability in the middle troposphere may vary widely.

Apart from sea smoke which may be present along the ice-edge, the first traces of clouds in a developing convective boundary layer are normally small cumuli, sometimes forming clusters or long rolls. As the water vapor content increases and the layer itself becomes thicker, some cumuli grow to become precipitation producers, cumulonimbi or showering cumuli. Precipitation at this stage of the development is the prime topic of this paper. We shall be interested in the amount of precipitation in a specific location during a period of time which is so short that the weather situation may be considered as stationary for our purpose.

The major source of the water substance for the precipitation is evaporation from the sea, since the vapor content of the arctic air is originally very small. However, only a portion of the evaporated

---

* Corresponding author.

[1] Present affiliation: Vedurstofa Islands, IS 150 Reykjavik, Iceland.

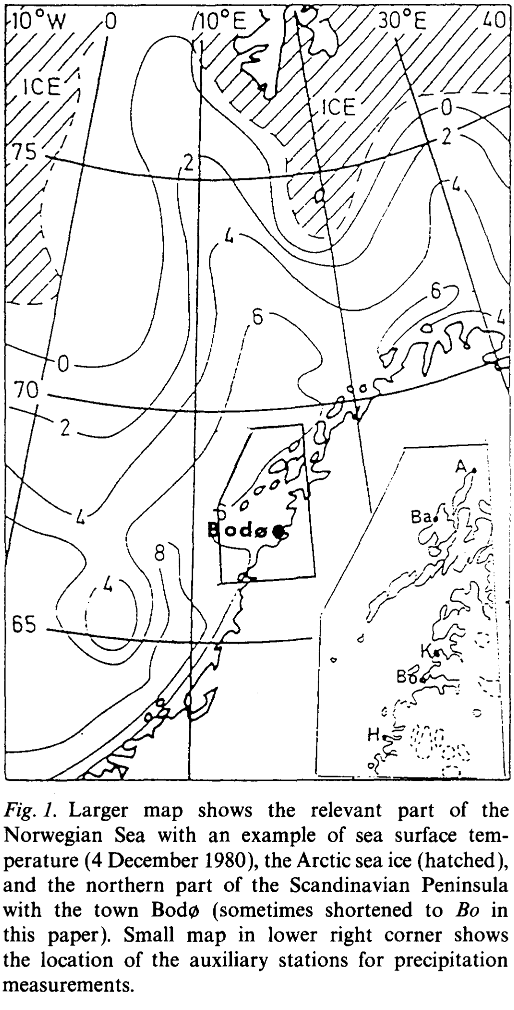

Fig. 1. Larger map shows the relevant part of the Norwegian Sea with an example of sea surface temperature (4 December 1980), the Arctic sea ice (hatched), and the northern part of the Scandinavian Peninsula with the town Bodø (sometimes shortened to *Bo* in this paper). Small map in lower right corner shows the location of the auxiliary stations for precipitation measurements.

water is precipitated. What remains is used to increase the mean mixing ratio of the CBL (we do not distinguish between vapor, droplets and crystals in this context). The relative size of the precipitated part depends on the precipitation efficiency of the cumulonimbi or showering cumuli, which again is a function of the environment in which the clouds form. Thus, the whole process of precipitation in the CBL is very complicated, and we shall make no attempt to discuss it in detail. Instead, we shall try through an observational study to reveal possible connections between the intensity of the precipitation and some easily observable properties of the CBL. For reasons which will be clarified presently, we consider especially the thickness of the CBL, often designated as Z_i, and a characteristic temperature of the CBL.

Known facts about the dynamics and physics of clouds support the idea of such a dependence. High cloud base temperature increases the amount of moisture entering the cloud (Cotton and Anthes, 1989). High temperature, on the other hand, reduces the temperature gradient between the air and the sea surface and weakens thereby the updraft. A thick convective layer lowers the temperature of the cloud tops, and presumably increases the efficiency of ice phase precipitation processes. Accretion, which probably is a dominating factor in production of precipitation particles in our cases, is a nonlinear process, i.e., it increases as the falling particles become larger and the liquid water content is greater (Wallace and Hobbs, 1977).

According to Økland (1989), precipitation from the CBL may be a factor in the enhancement of polar lows in this area, and the study at hand may be useful in this connection. The amount and intensity of precipitation that can be expected from a CBL under such conditions is of interest for forecasters. Moreover, such a study might have considerable general interest, since it concerns the dynamics and microphysics of clouds. Lastly, as it turned out, the investigation uncovered interesting features of the orographic influence on precipitation.

2. Case studies

Our strategy is to compare measurements of the CBL thickness (Z_i) and its characteristic temperature to precipitation intensity measured at certain observing stations. Some of the processes mentioned above, especially accretion indicate that the cloud thickness above the CCL (convective condensation level) should be used, instead of the total thickness. However reasonable this may be for a single cloud, it may not be quite relevant to the present case. The 24-h precipitation depends also on the number and size of the precipitating clouds, which presumable is coupled to the total amount of humidity available. Anyway, our choice of Z_i as parameter has also been influenced by the fact that actual values of CCL are not recorded, and that determinations the usual way from the soundings has proved to be inaccurate, mainly because the humidity appears to be inaccurately measured, and in some cases obviously wrong.

In a marine CBL, the surface fluxes of heat and vapor are strongly interconnected. Økland (1983) studied the gross feature of a developing marine CBL, and showed that the CCL may be derived from the relative humidity near the sea surface, U_0. Under certain simplifying assumptions, he found that U_0 increases asymptotically toward a value determined by the turbulent fluxes from the sea, the entrainment through the top of the CBL and, in the case at hand, the water removed by precipitation. It may be shown that the CCL has only a moderate variation from case to case in our sample. From characteristic values, we have computed CCL to be between 400 and 500 m (from Økland (1983), his eq. (19)). This agrees well with experience.

Accordingly, since the cloud base height is only a small fraction of the total boundary layer thickness, and since it also has a relatively modest variation, we do not think that our use of Z_i as a parameter will cause serious errors in our statistics.

For practical reasons, we choose to use the 850 hPa temperature to represent the temperature of the CBL in each case. Since the 850 hPa level is in all cases inside the CBL and above the CCL, cloud base temperature as well as cloud top temperature are related to the T (850 hPa) by the wet-bulb adiabatic lapse rate.

As a base for the investigation, cases of major outbreaks of arctic air over the Norwegian Sea have been studied. The CBL thickness was evaluated by means of ascents from the radiosonde station Bodø, located on the coast of Northern Norway (Fig. 1). A sample consisting of 37 winter cases between 1976 and 1987 was collected. The cases were chosen by inspection of analyzed weather maps, taking care that low level trajectories were running from the source area north of the ice border to Bodø, with no major perturba-

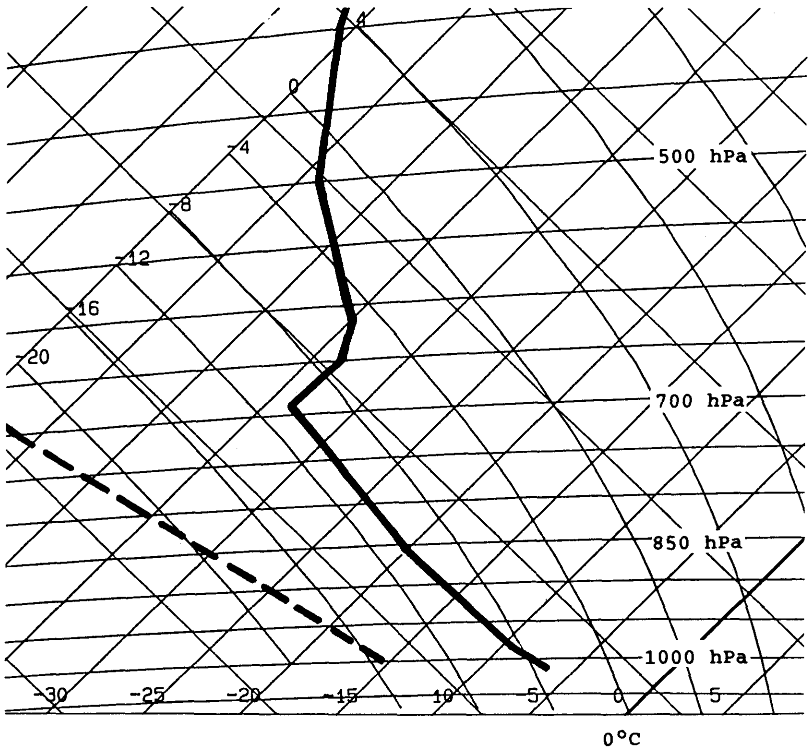

Fig. 2. A radiosounding from *Bo* on 21 January 1980 at 00 UTC, featuring a relatively shallow CBL.

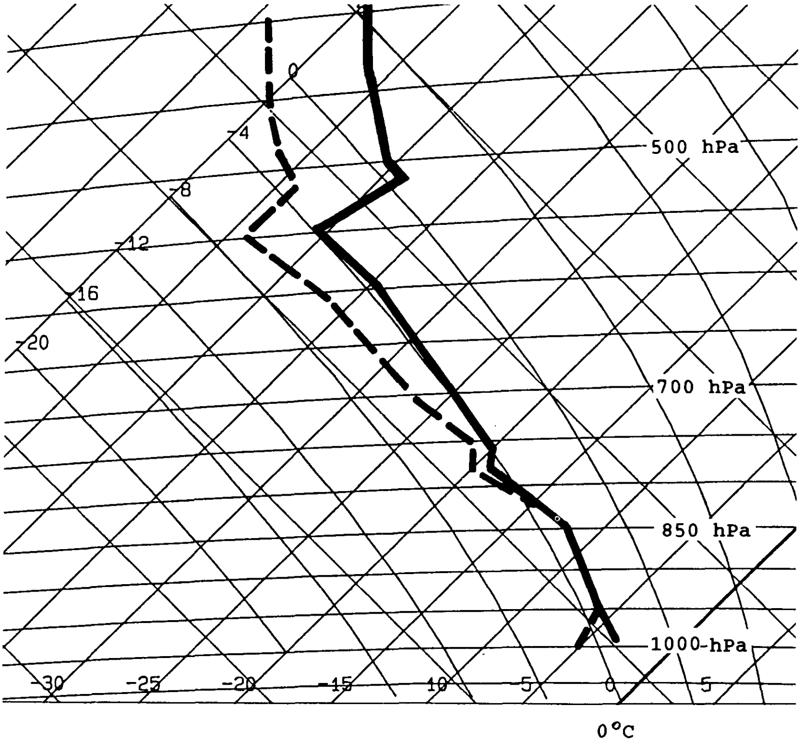

Fig. 3. A radiosounding from *Bo* on 17 December 1981 at 00 UTC, featuring a relatively deep CBL.

tions, like polar lows, in between. In all cases the wind direction in the convective layer was between west and north over Bodø.

Only those cases were used where the depth of the layer could be determined with reasonable accuracy. The upper boundary of the layer, Z_i, was chosen to be at the level separating conditionally unstable or neutral lapse rate below, from conditionally stable stratification above. A sharp temperature inversion which generally is assumed to be at the top, was missing in the majority of the cases. A probable reason for this is the absence of large scale subsidence. Also, although in theory there should be a drop in the specific humidity at the top, this was not always the case. This is however in accordance with the cumuli or cumulonimbi formations, which do not give a spatially continous drop in the specific humidity in the same way as a CBL capped by a layer of stratocumulus. Figures 2 and 3 show radiosoundings from two different cases. Figure 2 shows a case with a relatively shallow CBL, 2800 m deep and reacting up to about 690 hPa. Fig. 4 shows on the other hand a relatively deep CBL, 4400 m and reaching up to 550 hPa.

The frequency distribution of convective layer thickness in the sample is shown in Table 1. Note the cut-off at about 1500 m, below which there are no cases. This corresponds to the shortest possible trajectory from the ice-edge to Bodø, assuming initial stability and the air-sea temperature difference to be within their typical limits.

Table 1. *Number of cases in different thickness intervals*

thickness (m × 10^2)	15–20	20–25	25–30	30–35	35–40	40–45	45–50	50–55
no. cases	4	5	6	7	8	5	1	1

Similarly, there must be a maximum length of the trajectories in the sample, which explains the small frequency of thicknesses above 4000 m.

Precipitation is measured at Bodø twice a day (at 0600 and 1800 UTC). Since a cold air outbreak usually lasts for no more than one or two days in fairly unchanged form, we have used the precipitation in the 24 hour period beginning at 0600 UTC. The corresponding CBL thickness was determined from the radiosonde ascent the following midnight. For such a relatively short period, the measured precipitation has a considerable deviation from the ensemble mean of the daily precipitation in this type of weather situation. One way of minimizing the variation is to use measurements from additional stations with similar topographic locations. Ideally, the stations should be located so closely together that no significant variation in the depth of the convective layer should be expected between them. This has been possible only to a certain extent, since the number of suitable observing stations is limited.

The stations that we have chosen are all from the regular observation network. They are all located at the coast, exposed to winds from the sea in the sector between west and north. We also wanted the stations to have unbroken records of measurements through the period from 1976 to 1987. When these requirements were considered, we ended up with 4 stations in addition to Bodø. The exact location of each station is as follows: *Bo* (67°17′N, 14°25′E), *A* (69°18′N, 16°07′E), *Ba* (68°49′N, 14°48′E), *H* (66°45′N, 13°34′E), *K* (67°33′N, 14°53′E). Two of the stations are at the main coast, on either side of Bodø. The others are located on a chain of islands (Lofoten and Vesterålen) north of Bodø and separated from the main coast by a fairly broad fjord (see separate map on Fig. 1).

Another source of error is that strong wind affects the amount of precipitation which comes into the gauge, especially when it is snowing, which is mostly the case. An empirical formula for correcting this error is available (Førland and Aune, 1985).

3. Precipitation and CBL temperature

The stability in the CBL layer is close to the dry adiabat below the level of condensation and to the moist adiabat above. However, the temperature at 850 hPa varies considerably from case to case. The possibility that the precipitation may be a function of this temperature was mentioned above. In an attempt to verify this hypothesis we have prepared the scatter diagram pictured in Fig. 4. Here the horizontal axis represents the 850 hPa temperature over Bodø while the vertical axis shows the mean precipitation for the 5 stations, what we shall call station mean.

The sample mean of temperature is −12.8°C and the standard deviation is 2.7°C. Note that outside a distance of one standard deviation from the mean, there is somewhat more precipitation on the warmer side than on the colder side, but the central part of the diagram does not give the impression of a dependence like the one we are looking for. In fact, the coefficient of correlation is not significantly different from zero.

The explanation of the lack of functional dependence may be a partial balance between 2 counteracting effects already mentioned; high cloud base temperature increases the amount of vapor entering the cloud, while the air-sea temperature difference is smaller in this case, leading to less convection.

Before we proceed, a few remarks on the influence of the *local* topography may be appropriate. Take for instance station *Ba* (Fig. 5, upper left map). This station may be suspected to be in the "shadow" of two mountain peaks, one to the W and the other to the NW. Notice, however that precipitating cumuli, triggered by the peaks,

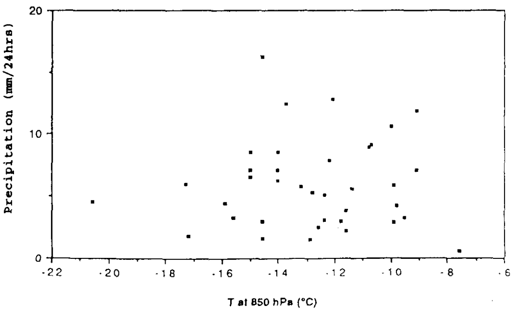

Fig. 4. Scatter diagram showing corresponding values of 24-h precipitation and 850 hPa temperature, for a sample of 37 cases of arctic air outbreak. The precipitation is an average of measurements at the 5 stations indicated on Fig. 1 ("station mean"), while temperature is measured over Bodø.

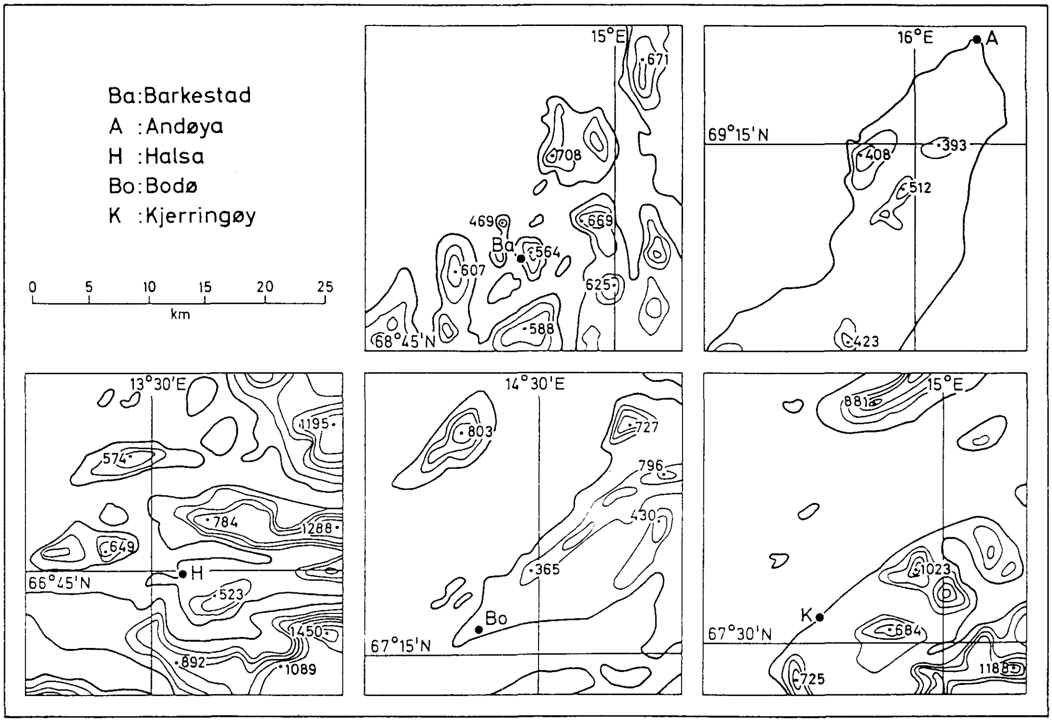

Fig. 5. Maps showing the topography of an area approximately 25 × 25 km surrounding each of the 5 stations (200 m contours).

drift toward *Ba* in 10 to 15 min with the prevailing wind. Therefore, instead of being sheltered, the station may experience increased precipitation. That this actually is the case is supported by the fact that *Ba* has larger mean precipitation than *A* (9.1 mm against 6.2 mm, which is statistically significant). This example shows how difficult it is to draw conclusions about the precipitation at a specific place from the topography in the immediate surroundings.

On a somewhat larger scale, a general rule is that the higher and more rugged mountains, the greater the precipitation. This is the reason why we in the following sections attempt to explain certain peculiarities in the measurements by the shadow effects from the chain of islands, on which *A* and *B* are located.

4. Precipitation and CBL thickness

Fig. 6 displays a scatter diagram of station mean precipitation against CBL depth. Here, the thickness is measured in hundreds of meters and precipitation in millimeters. Indeed, the dependence shows up quite clearly. The equation of the linear regression line is $y = -2.85 + 0.27x$. The coefficient of correlation, which is 0.71, shows that the "explained" variance is about half of the

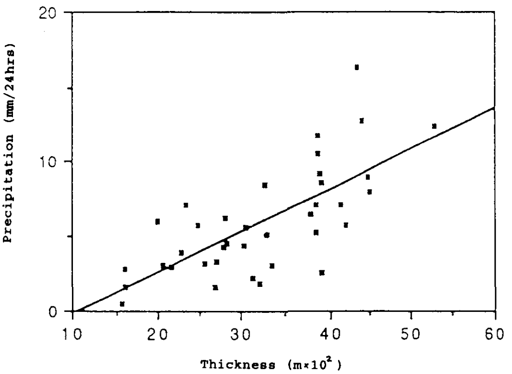

Fig. 6. Precipitation as in Fig. 2, and the thickness of the CBL (Z_i).

total variance, which is 12.9, when precipitation intensity is measured in mm per day. Under the condition that the theoretical population from which the sample is drawn is normally distributed, that the errors are mutually independent and independent of the thickness, the Student t-distribution may be used to evaluate the confidence of the coefficient in the regression equation (Bhattacharyya and Johnson, 1977). It turns out that within the 95% confidence limit the population coefficient is between 0.18 and 0.37. Here, the thickness is measured in hundreds of meters and precipitation in millimeters per day. A discussion of the above assumptions is included in the last section of this paper.

We have also attempted a logarithmic transformation of the thickness, suggested by the idea that the increase of the precipitation with increasing CBL thickness might be non-linear. However, the result was negative, since the latter coefficient of correlation became slightly less than the former (0.69). Reduction of some of the scatter in the left part, where the convection is shallow would, on the other hand, give a substantially higher correlation for the logarithmic transformation. In this context, one should bear in mind that the subsaturated layer and the variation in CCL is a relatively bigger fraction of the total CBL thickness in the shallow cases, than in the deep ones. Consequently, errors due to the neglect of these factors are more likely to hurt in the cases of shallow convection, and may cause the scatter in the left part of Fig. 6.

5. Orography

As mentioned, our selection of auxiliary stations for precipitation measurements is not ideal, since we were forced to choose from the regular observing network. A closer look at our records for the 5 stations is therefore appropriate and as we shall see reveals interesting facts.

Since the whole area is mountainous, orography is expected to be important. Accordingly, we have provided maps showing the topography of an area approximately 25 × 25 km surrounding each of the 5 stations (Fig. 5). Vertical distance between the height contours is 200 m. Station A, located on the NE point of an island with low terrain within a distance of 10 km from the station, is the one least affected by orography and presumably represents conditions over the open ocean best. On the other hand, it has the largest distance from Bo where the characteristics of the CBL are measured.

5.1. *Shadow effects from the islands*

Table 2 contains the sample mean, standard deviation and correlation coefficient for each station, and also for the mean of their measurements (the station mean). Clearly, stations A and Ba have the largest sample mean, while H, Bo and K have considerably less (see Fig. 1 for identification of the stations). The reason may be that the main coast where the 3 latter stations are located, is sheltered by the chain of islands. The islands are mountainous with tops up to 1000 m, so it is quite possible that they may trigger increased convection, which removes water from the air and depletes the moist convection farther downstream. This idea is supported by the fact that the mean decreases from station H to Bo and still more to K. This may be explained by considering that the sheltering influence of the islands on air streams of directions between west and north increases toward northeast along the main coast. Local topography differs however from one station to another, and in particular station H has mountainous surroundings. Consequently, these results remain rather speculative.

Note also that the standard deviation is smaller and the correlation coefficient larger when computed from the station mean than for any of the individual stations. This shows the expected result, since the mean for several stations does not feature peaks that occur at each station, caused by the random nature of convective precipitation.

Table 2. *Sample mean and standard deviation of 24-h precipitation (mm) for each of the 5 stations indicated in Fig. 1, together with the correlation coefficient between precipitation and CBL thickness (Z_i); last column contains the same parameters for the station mean*

Station	A	Ba	H	Bo	K	Mean
mean	6.2	9.1	5.6	5.1	3.8	6.0
S.D.	4.5	4.9	4.9	5.6	4.9	3.6
corr.	0.43	0.58	0.37	0.64	0.51	0.71

5.2. *A non-linear dependence on thickness*

The lower left part of Table 3 shows the correlation coefficient for precipitation for all pairs of the observing stations. An interesting discovery is that the correlation between *Bo* and *K* is by far the best one, indicating that the measurements at these two stations are comparatively similar. It should be added that by omitting the "worst" case of the total of 37 increases the correlation between *Bo* and *K* to 0.80 and by omitting the two "worst" cases the correlation increases to 0.89. One reason why this is so may be that neither *Bo* nor *K* have mountains in their immediate surroundings, but another reason may be that these two stations are the ones which have the smallest separation distance (see upper right part of the table). In fact, the distance is 35 km, compared to 70 km between *Bo* and *H*, 75 km between *A* and *Ba*, and still greater for the other pairs. Nevertheless, the similarity is remarkable, especially since the other pairs do not show the same relation to the distance.

Since we have established that *Bo* and *K* behave similar to each other, yet different from the other stations, we shall study their distribution separately. For reasons previously mentioned we prefer to use the average precipitation for the two stations, as shown in Fig. 7. However, each of the two has basically the same characteristic distribution. It is remarkable that there seems to be two different "regimes", separated by a "threshold" value of the thickness, which we have placed at 3200 m. The lower regime (18 cases) contains no values greater than 4 mm and small standard deviation. In the upper regime where the convection is deeper the precipitation is greater than 4 mm in 11 out of 19 cases, and the standard deviation is large.

Table 3. *Upper right. Distance (km) between all pairs of the 5 stations measuring precipitation; lower left: correlation coefficients for precipitation for all pairs of stations*

	A	*Ba*	*H*	*Bo*	*K*
A	—	75	310	240	210
Ba	0.49	—	230	170	150
H	0.28	0.26	—	70	100
Bo	0.50	0.54	0.33	—	35
K	0.27	0.40	0.29	0.62	—

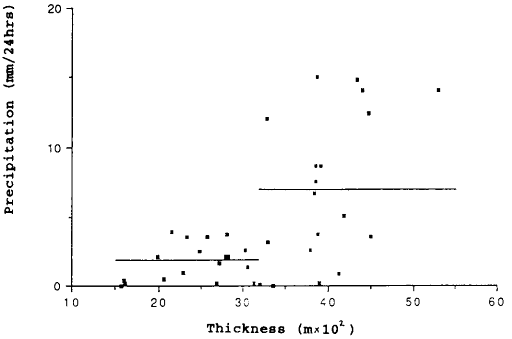

Fig. 7. Plot as in Fig. 3, but with precipitation as an average of the measurements at *Bo* and *K*. The two "regimes" are separated by the 3200 m thickness. Regression lines are at constant precipitation levels, equal to the mean in each regime.

Separate regression analyses for the two regimes show small correlation coefficients, which according to the *t*-test are not significant. Therefore, it may be more appropriate to model this bivariate distribution as two rectangular parts; one of mean m and standard deviation s for thickness less than 3200 m, and another of mean M and standard deviation S for greater thickness. In other words we choose the regression lines $v = m$ for $x < 3200$ m and $v = M$ for $x > 3200$ m (see Fig. 7). Again, a *t*-test assures that the population mean of the two parts are different with a high degree of confidence. The numerical values are $m = 1{,}74$, $M = 7.00$, $s = 1.34$ and $S = 5.43$. Note that the ratio of the mean to the standard deviation is almost exactly the same for the two regimes. The "unexplained" variance turns out to be 16.0 in the same units. This is a rather large value compared to the station mean case, but may in part be explained as an effect of the different averaging (cf. Figs. 6, 7).

One may wonder why the station mean (Fig. 6) does not show clear signs of the threshold, although the stations *Bo* and *K* are included. A partial reason is that the 3 stations *A*, *Ba* and *H* together have more than twice as much precipitation as the remaining two.

The peculiar records of measurements for stations *Bo* and *K* call for a more thorough discussion. The most intriguing questions are why the two stations show this behaviour and how the distribution can be explained physically. The possibility of a non-linear distribution of precipitation with respect to thickness has been raised before in this paper and the accretion process was mentioned as one possible cause. Another possibility is that the supply of ice nuclei as embryos for precipitation may have this effect. On the basis of the 850 hPa mean temperature (-12.8°C) computed earlier, and a characteristic vertical lapse rate in the CBL, one may derive an approximate mean temperature of about -30°C at 3000 m. Possibly, the ice nuclei become sufficiently abundant around this temperature. However, none of the above hypotheses explain why this particular distribution of precipitation shows up only in the records for *Bo* and *K*. It has already been noted that just these two stations exhibit the least mean precipitation, a fact attributed to the sheltering influence of the mountainous islands. This could mean that a comparatively great part of the cumulonimbi or showering cumuli giving precipitation at *Bo* and *K* are organized on the lee side of the islands, and have not yet reached the stage of heavy precipitating clouds. If, in addition, we assume that clouds with tops above 3000 m are less affected by the mountains and therefore survive on the lee side, the result would be precisely a two-regime distribution. We realize of course that these arguments are rather speculative but see no means to verify them within the framework of the present investigation. Perhaps some mesoscale modeling studies would shed light on the processes affecting precipitation at those stations.

6. Concluding remarks

The number of cases in this investigation is not large. We have, however, used great care in selecting the data. First, the synoptic cases have been chosen on the basis of Europäischer (Täglicher) Wetterbericht, published by Deutscher Wetterdienst, Offenbach, Germany, taking care of the criteria for selection mentioned earlier. Of course, some interdependence cannot be avoided, for instance because of the sea surface temperature which is known to be rather conservative. The upper air measurements and precipitation data come from the regular observation network of the Norwegian Meteorological Institute.

After the selection of the synoptic cases, the radiosonde records were examined to see if the CBL thickness or Z_i could be determined without ambiguity. Finally, the precipitation was obtained from the records and corrected for wind errors.

At all stations and for practically any thickness, there are cases with very little precipitation, or none at all. However, when the mean of the 5 measurements is taken, this is not the case any more, and the error distribution has the appearance of being approximately normal and independent of the thickness (Fig. 6). Therefore, the statistical analysis may be trusted (Bhattacharyya and Johnson, 1977).

As we have seen, the sample mean of precipitation varies from station to station. It may be shown that this variation is not accidental and, as we have indicated, probably is caused by the orography. Therefore, it is not permissible to conclude that the particular regression relation applies to another choice of stations or over the ocean at some distance from land, although there can be little doubt that a positive correlation exists in general.

The non-linear dependence we have uncovered for 2 of the stations also seems to be rather certain. First, we have shown by standard statistical methods that the constructed regression model for the mean precipitation at *Bo* and *K* is valid with a high degree of confidence. Second, inspection of the scatter diagrams for the individual stations reveals that *Bo* and *K* both show the 2 separate regimes very clearly, while none of the other 3 stations do. The fact that 2 stations at a distance of 35 km independently show this structure, strongly supports our belief that it is not accidental but has a real physical cause. However, the location of the threshold indicated by the data must not be taken too literally. A larger sample could show a more gradual change over a certain interval of thickness.

7. Acknowledgements

Professor William R. Cotton and Dr. Michael P. Meyers, who reviewed the manuscript for "Tellus", provided numerous comments and suggestions, for which we are very grateful. We are also indebted to an anonymous referee. The Norwegian Meteorological Institute provided the data.

REFERENCES

Bhattacharyya, G. K. and Johnson, R. A. 1977. *Statistical concepts and methods.* John Wiley & Sons Inc., New York, Santa Barbara, London, Sidney and Toronto. 639 p.

Cotton, W. R. and Anthes, R. A. 1989. *Storm and cloud dynamics, International Geophysics Series,* Academic Press Inc., San Diego, New York, Berkeley, London, Sidney, Tokyo, Toronto. 883 p.

Førland, E. J. and Aune, B. 1985. Comparison of Nordic methods for point precipitation correction. *Züricher Geographische Schriften* **23**, 239–244 p.

Økland, H. 1983. Modelling the height, temperature and relative humidity of a well mixed planetary boundary layer over a water surface. *Boundary Layer Meteorology* **25**, 121–141 p.

Økland, H. 1989. On the genesis of polar lows. In: *Polar and arctic lows* (eds.: Twitchell, Rasmussen and Davidson). A. Deepak Publishing, 421 p.

Wallace, J. M. and Hobbs, P. V. 1977. *Atmospheric science, an introductory survey.* Academic Press, New York, San Fransisco and London, 467 p.