MESOSCALE PHENOMENA INDUCED BY MOUNTAINS OVER SCANDINAVIA AND SPITSBERGEN

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Summary: An overview of mesoscale phenomena induced by the mountains of Scandinavia and Spitsbergen is given. Observations are few to reveal the phenomena, and most of the information is found in studies based on high resolution simulations. On the largest scales, the rotation of the earth plays a significant role. Lee cyclones occur in Skagerrak, but the event is rare. Coastal jets on the left side of the mountains and wake-like areas with weak wind on the lee side are very common. In winter, static stability is usually high near the ground in easterly flows over Scandinavia and in flows from the sea ice over Spitsbergen. High amplitude lee waves, coastal jets, wakes and strong lee winds are then formed. At Spitsbergen the jets and wakes might extend for several hundred, may be 1000 km downstream in the Norwegian Sea. The thermal wind in such cases is opposite to the surface wind and a critical layer might be found aloft. However, large amplitude mountain waves might also be found when no critical layer is present. Strong lee effects might also be observed when warm fronts are passing South-Norway from south-west. Orographic precipitation is high at the west coast which is exposed to travelling cyclones from west. Release of latent heat plays a significant role on the mountain flow. The effect reduces the upstream positive pressure perturbations, while the negative perturbations on the lee side are increased. On smaller scales, separation phenomena might cause strong wind speeds in lee of very steep topography.

1. INTRODUCTION

The Scandinavian mountains and the mountains at Spitsbergen, with the highest tops reaching between 1500 and 2400 m, make an interesting test-area for the study of topographical meteorological effects. The mountains are surrounded by oceans which give rather well defined up-stream conditions of wind, static stability and humidity, conditions which might show a large range of variation. Orographic precipitation is often plentiful, which indicate that release of latent heat might have a significant influence on the flow. The strongest stratification is found in easterly winter flows when cold continental polar air masses are formed east of Scandinavia. At Spitsbergen the dominating flows in winter are from the ocean ice over the Arctic Sea, characterised by strong surface inversions reaching heights around 850 hPa. In both cases the thermal wind at the surface typically has a large component opposite to the surface wind, which gives a tendency for a critical layer aloft. Large amplitude mountain waves and strong lee wind are common, particularly at Spitsbergen.

The largest scale of the mountains - as measured by a half width L - is a few hundred km. With an up-stream wind speed U of the order of 10 ms^{-1}, the Rossby numbers (Ro=U/fL) connected to the mountain flows are around one. This means that the effect of the rotation of the earth is significant, but not dominating for the mountain phenomena in question. On smaller scales there are valleys, fjords and steep mountains. For instance at the coastal islands of North-Norway, narrow valleys and fjords are found, where mountain tops are 500-1000 m high and distances between the mountain tops on each side of the valley/fjords might be down to 2-3 km. In such topography separation phenomena might take place (see Baines, 1995), and forceful winds might be observed (Andresen & Harstvedt, 1993a).

In this paper an overview of the different mesoscale phenomena is given, ordered according to their main horizontal scale. A schematic indication of the different phenomena is found in Figure 1. Some are partly resolved by the ECMWF operational model and some are not resolved at all. On the largest scale, the mountains modify the tracks of cyclones passing (section 2). At Spitsbergen the cold air over the sea ice might have a similar steering effect. The largest scale of the mountains of South-Norway might form lee-cyclones in Skagerrak (Bjerknes & Solberg, 1921, 1922) (section 3). In this respect, these mountains might represent the smallest scale supporting lee-cyclones. The rotational effect gives frequent low-level jets on the left side of the mountain flows, a phenomenon which in Norway is called a coastal jet (section 4). In this way the wind is often stronger at the coast than over open sea. The same upstream conditions might give wakes and areas with weak wind in the lee of the mountains. In particular, wakes in flows from the sea ice over Spitsbergen might be found for distances of several hundred km downstream, despite of intensive heat fluxes from the sea. Normally, the non-dimensional mountain height ($\hat{h}$=hN/U, where h is the height of the mountain, U the up-stream wind speed and N the Brunt-Väisälä frequency) is small enough to give a flow regime characterised by gravity waves (Smith, 1989). However, as already indicated, sometimes in winter other flow regimes with stagnation points are present, since the static stability might be very high. Large amplitude mountain waves, which sometimes probably break, are frequent over Spitsbergen (Grønås & Skeie, 1997) (section 5), and in easterly cold flows over North Norway, where the slopes are much stronger on the western side than on the eastern side (Andræ, 1997). On the northern slopes of South-Norway, similar conditions are observed when warm fronts are crossing from south-west (Harstveit et al., 1995, Doyle et al., 1996) (section 6). Orographic precipitation is large at the west coast and release of latent heat plays a significant role on the mountain flow (section 7). On the smallest scales, mountain separation might give rotors and corkscrew structures (Cook et al., 1978) behind steep mountains (Harstvedt & Andresen, 1994; Sandvik & Grønås, 1997) (section 8). Severe damages might then take place. The need for mesoscale observations is stressed in the concluding remarks in section 9.

2. MODIFICATION OF THE LOW TRACKS

To a modest degree, our mountains modify the track and the low-level structure of extratropical cyclones passing Scandinavia. Some of the influence is caused by local thermal circulations. Occasionally in winter, cold air and high pressure cover Scandinavia, with winds along the coast with land to the right, to some extent prevent the lows to cross. In summer the opposite effect brings lows onshore.

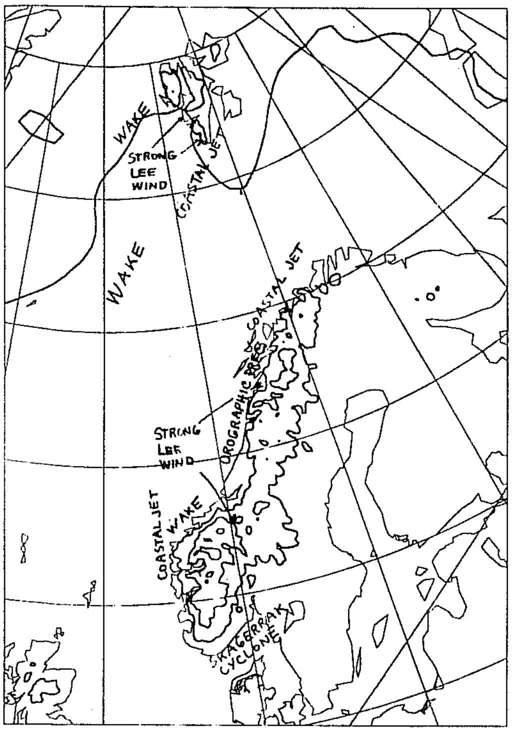

Figure 1. The orography of the DNMI HIRLAM 10 km grid (contours for 500, 1000 and 1500 m). Different mesoscale phenomena induced by the mountains are indicated.

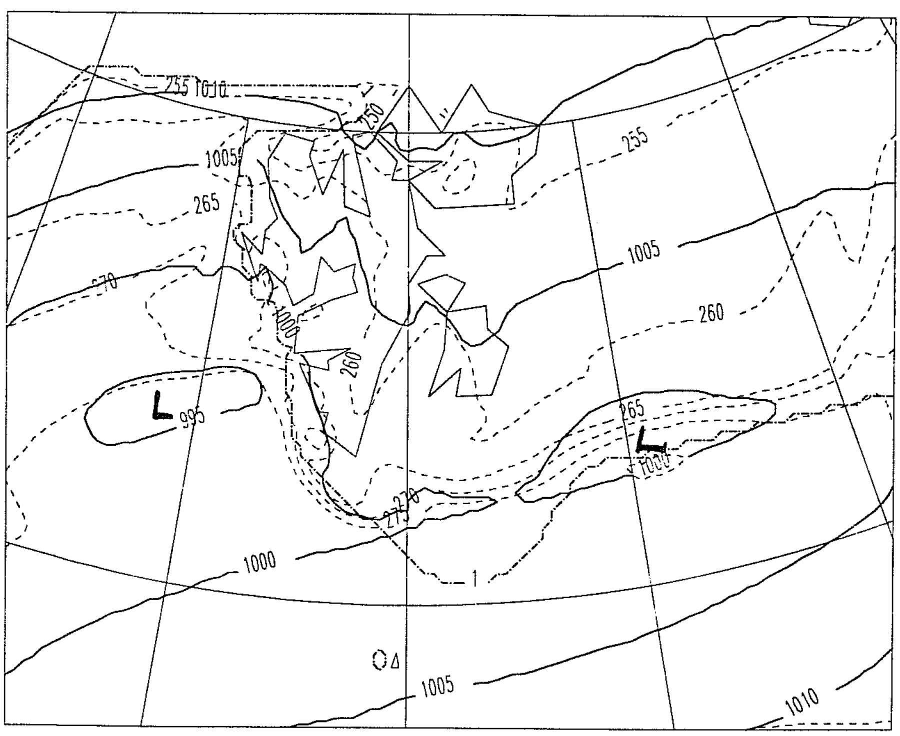

Figure 2. Sea level pressure (hPa) and temperature (K) at the lowest model level in a 24 h simulations valid at 18 February 1984 12 UTC, after simulations by Skarstein (1997). A low approaching Spitsbergen from south-west is regenerated further south at the edge of the sea ice.

Lows crossing the middle of Scandinavia from south-west and west are often split in two low centres. Production of anti-cyclonic vorticity over the mountains removes some of the signatures of the low at the ground. A regeneration occurs on the lee side over the northern end of the Baltic. Yet, since the scale of the low generally is larger than the scale of the mountain, a secondary low remains for a while on the Norwegian coast. It is interesting that this low has a rather fixed position.

Lows approaching Spitsbergen from south-west in winter have difficulties to enter the sea ice. The cold air over the ice acts like a mountain and modifies the track of the cyclone, and a regeneration is often found along the ice edge further south. An example is given in Figure 2. It is also found that the cold air, separated from the warmer air over the ocean by the Arctic Front, acts like a mountain so that gravity waves are formed. This has been revealed by high resolution simulations showing waves with upward energy transfer, when warmer air is climbing the Arctic Front (Skarstein, 1997).

3. THE SKAGERRAK CYCLONE

Skagerrak cyclones were studied by the Bergen School meteorologists and a conceptual model (see Figure 3) was given for the development (Bjerknes & Solberg, 1922). According to this model, when a frontal wave is approaching from west, the warm front is halted by the mountains of South-Norway. The cold front has a freer approach, overtakes the warm front and a new warm wave, and a pressure anomaly, is formed in Skagerrak. Such developments seem to be rare. I found an example a few years ago, but the low did not stay long in the area.

Heilund (1996) has investigated a case from August 1988, which was not predicted by the numerical models and which, without warning, gave close to 100 mm of precipitation in the Oslo area. Simulations with NORLAM (Grønås & Hellevik, 1982; Nordeng 1986; Grønås et al., 1987), with 25 and 10 km horizontal grid distance, gave rather successful predictions. A low developed on a secondary cold front passing South-Norway from north. The development seemed to take place according to theory of Smith (Smith 1984, 1986). The mountains formed a wave on the cold-front and a warm low-level anomaly over eastern Norway and Skagerrak. The wave propagation along the cold front had a component toward the mountains and for a period of 12 hours, and a quasi-stationary cyclone developed. Release of latent heat was considerable and played a substantial role in the development. The low-level cyclonic disturbance worked together with an upper-level positive PV-anomaly. Still, the initiation of the cyclone came from the lower levels. A simulation, without mountains in the numerical model, gave no cyclonic development. Figure 4 shows the low, with fronts and trajectories at the surface.

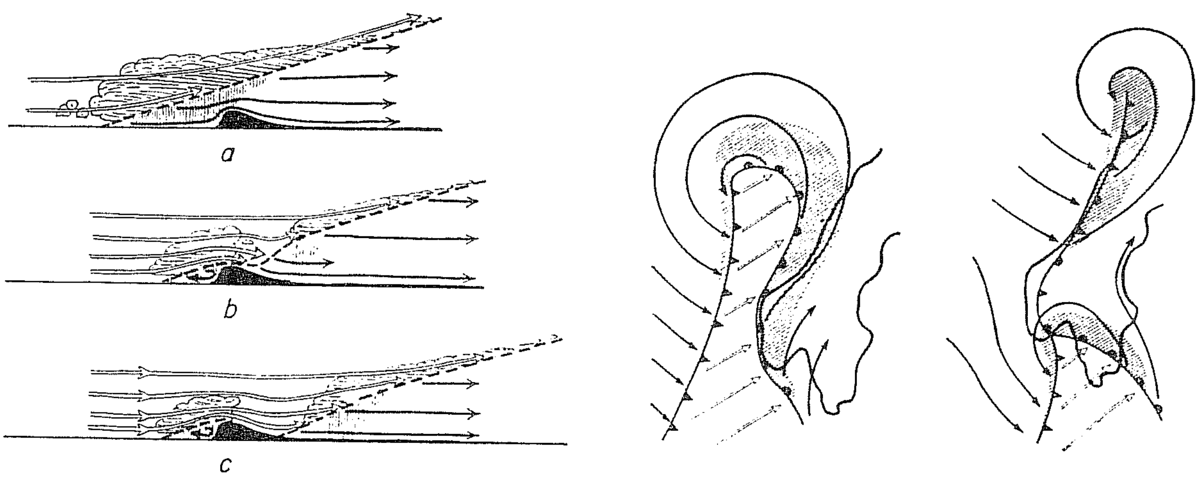

Figure 3. Conceptual models of the Skagerrak lee cyclone and a warm front passing mountains. After Bjerknes & Solberg (1921,1922).

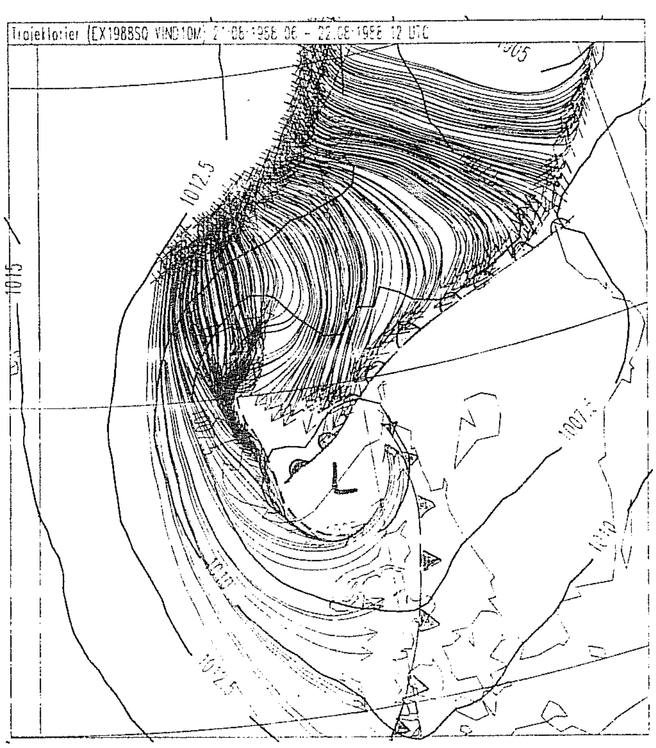

Figure 4. Sea level pressure (hPa), fronts and surface trajectories in the cold air in a 36 h simulation valid at 22 August 1988 12 UTC, after simulations by Heilund (1997). The frontal wave is made on a cold front as it passes the mountains of South-Norway from north.

The development did not follow the conceptual model of the Bergen School. This means that there might be at least two kinds of Skagerrak lows. It is interesting that no lee-cyclones are observed elsewhere in Scandinavia. It is probably only in Skagerrak disturbances on a cold front, induced by the mountain, can get a propagation component towards the mountain, so that a quasi-stationary lee-cyclogenesis might take place. Cyclogenesis has also been observed in coastal troughs in easterly surface flows over Norway (Økland, 1990), but such developments are not classical lee-cyclogenesis.

4. COASTAL JETS

Old forecasting rules based on surface analyses and observations (Spinnangr, 1942), tell us that the wind at the coast is stronger than over open sea when the wind is blowing along the coast with land to the right. This is in line with more recent theory (Smith, 1982), which predict low-level jets on the left side of flows across mountains with scales like South-Norway, where rotational effects are significant. Wind statistics from SYNOP stations in different large-scale wind directions (Andersen, 1975) and computations of so-called return periods for strong wind (Harstveit & Andresen, 1994), confirm the existence of such low-level jets. High resolution NWP products from DNMI (Grønås, 1990), with a horizontal grid length of 25 km, has for a long time demonstrated such winds, which have been called coastal jets, since they first of all are noticed at the coast, where surface friction is relatively low. Yet, the low-level jets are found over the mountain slopes from the ocean and inwards.

A new operational routine at DNMI with the HIRLAM model, with 10 km between the grid points for an area covering Scandinavia and the Nordic Seas (224*324 points), frequently shows coastal jets and areas with weak winds over land on the right side of the flow and on the lee side. Examples are shown in Figure 5. The preditions show that coastal jets extend far downstream from the mountains over the sea. An area with weak wind is found for southerly flows from the corner Stadt and north-eastwards for 200 km. This calm area is well known to Norwegian meteorologists. Normally, no stagnation points are found in the flow and gravity and inertia-gravity waves are dominating. Nevertheless, the wake-like area with weak winds is verified by observations at the coast. Still, due to few observations, little has been verified of the downstream extension of this wake-like phenomena.

Coastal jets in cases with cold air outbreaks in winter over North-Norway is likely to exist, but so such cases have not been investigated. However, similar phenomena have been studied at Spitsbergen.

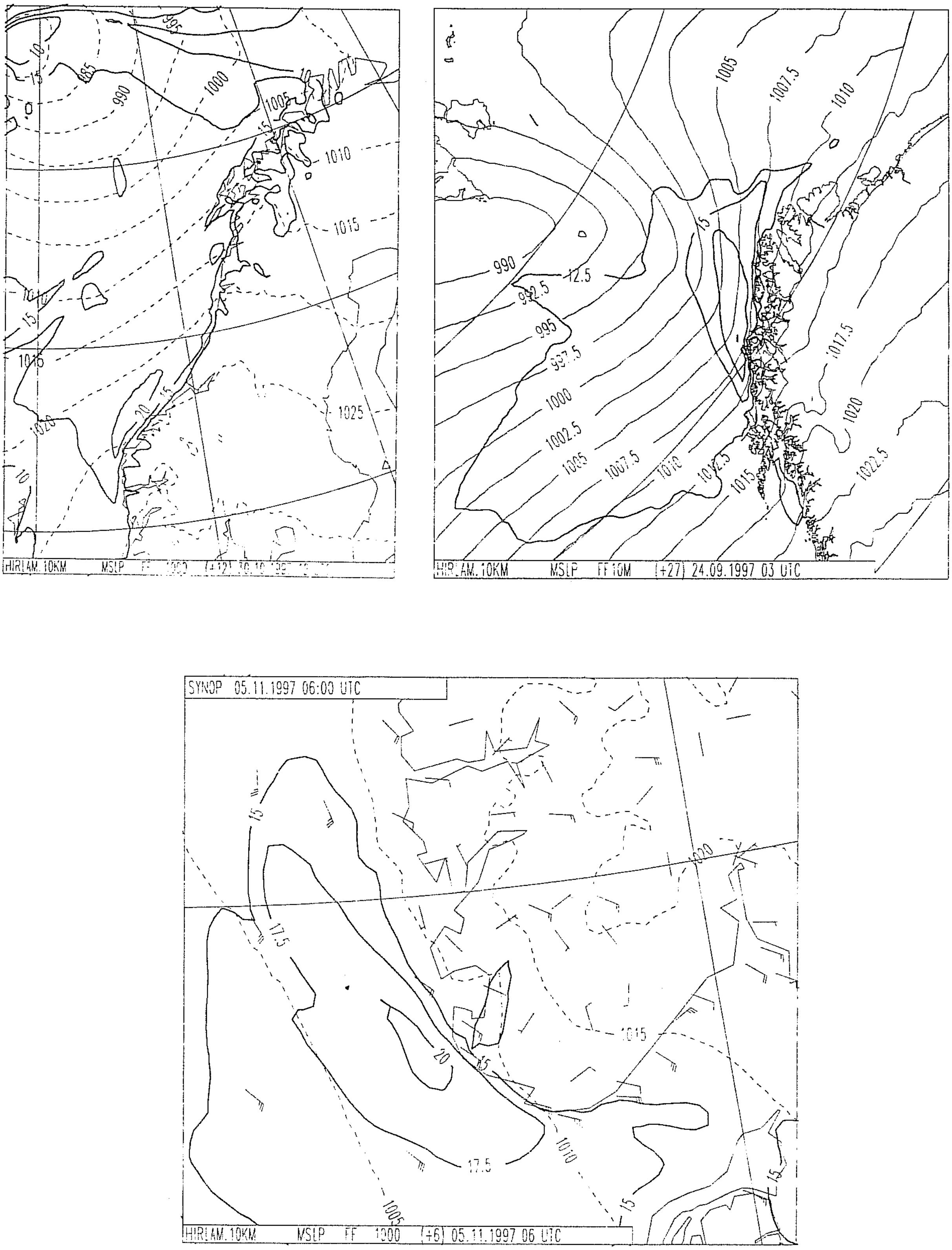

Figure 5. Three examples of prediction with the DNMI HIRLAM 10 km operational model. Sea level pressure (hPa) and contours of wind speed (ms^{-1}) at the lowest model level are shown. Coastal jets are demonstrated.

5. STRONG LEE WIND, COASTAL JETS AND WAKES IN FLOWS OVER SPITSBERGEN

Cold air at the surface and strong low-level inversions endure every day over most of the Arctic sea ice through the long winter. Typical heights of the inversions are 1000-1500 m (Serreze et al., 1992). The conditions result in a persistent Arctic high. In the Nordic Seas, the winter climate is dominated by cyclonic activity and low tracks towards the Kara Sea. In this way there normally is a north-easterly flow from the sea ice and over the sea. The surface temperature gradients are often strongest at the ice edge, from the ice edge and northwards (Skarstein, 1997), and here the strongest pressure gradients are also found. Consequently, the strongest east and north-east winds are found at the surface just inside the edge at the top of a shallow boundary layer (2-300 m). These climatic conditions give frequent north-easterly cold flows with strong stratification in the Arctic Inversion over Spitsbergen in winter (Grønås & Skeie, 1997) . The thermal wind is opposite to the surface wind and a critical layer with no wind is often found in the middle troposphere. In particular, this is the case when there is a baroclinic layer above the Arctic Front which gives a westerly jet at the tropopause.

The sea level pressure and wind representing the top of the neutral, shallow boundary layer are shown for a typical winter case in Figure 6. For upstream wind speeds of approximately 20 ms^{-1}, local wind speeds over Spitsbergen vary from calm to 37 ms^{-1}. Strong wind is found as jets on both sides of the island and downstream from the fjords, and on the lee side of the mountains. Weak wind is found upstream on the right side of the flow and in wakes behind the main mountains resolved by the model. In particular, there is a major wake behind the highest mountains north of Isfjorden, extending about a few hundred km downstream. In this wake, a turbulent, weak return flow is found.

There seem to be a rotational effect, since the southern jet is strongest and the upstream minimum wind area in front of the mountains is found on the northern side. However, the strength of the upstream flow is decreasing northwards and a substantial part of the southern jet is simply the extension of the upstream jet inside the ice edge. While upstream stagnation is not clear, stagnation is observed in high amplitude lee waves over the mountains (see Figure 7). Clearly, little wave energy is transferred across the critical layer. The 280 K surface drops from the 700 hPa level upstream to nearly 900 hPa above the lee slope where the topography reaches the 950 hPa level. The height of the 280 K surface above the ground upstream exceeds the height above the lee slope by a factor of roughly 5. In a two-dimensional stationary case, conservation of mass would require the vertically averaged velocity above the lee slope to exceed the upstream value with the same factor. In the simulation a factor of two seems more appropriate, and it is clear that a large portion of the air is being diverted south of the mountains.

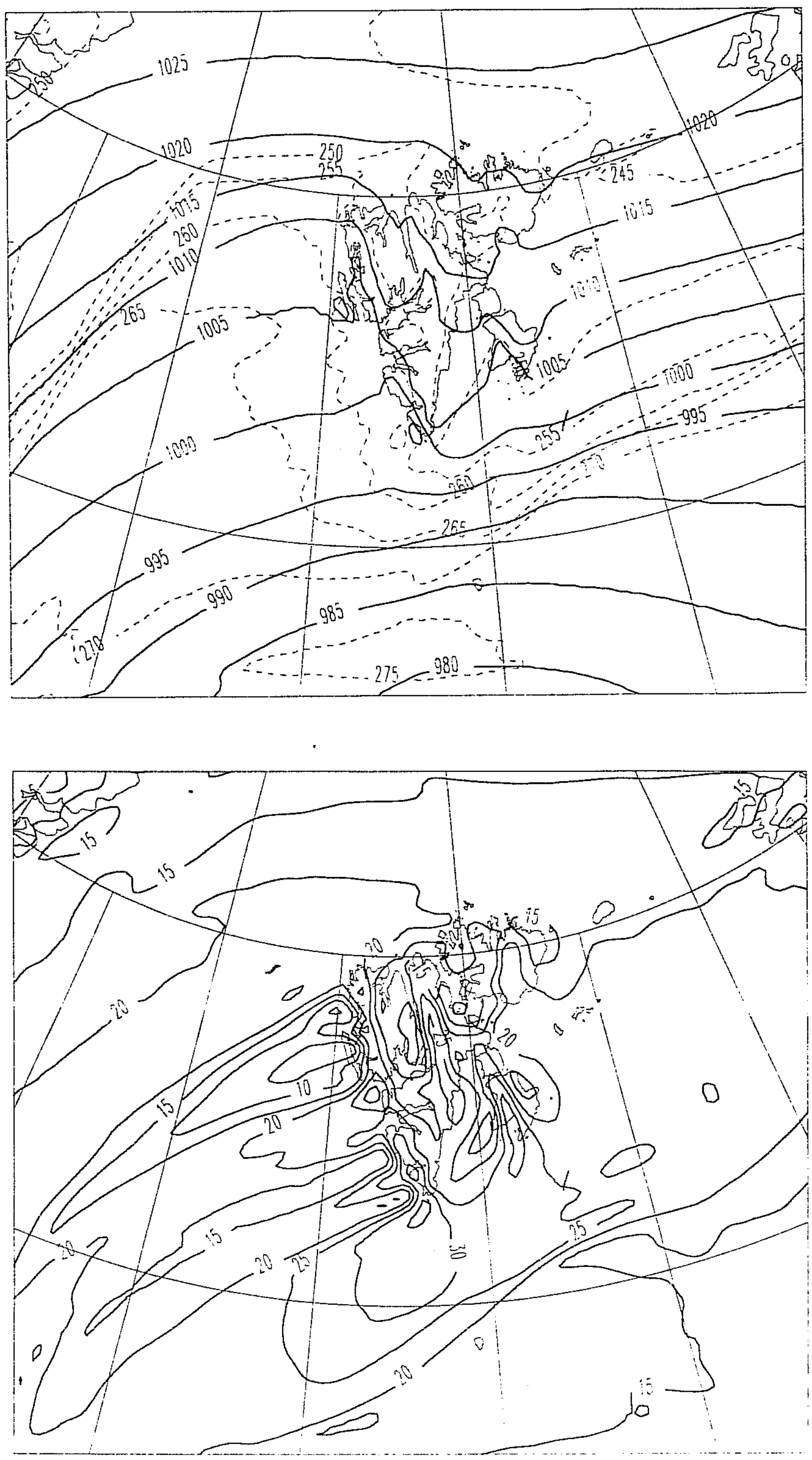

Figure 6. Simulation of surface flow from the sea ice over Spitsbergen after Grønås and Skeie (1997), valid 25 January 1995 00 UTC. a) Sea level pressure (hPa) and temperature (K) at the lowest model level, b) wind speed (ms^{-1}) at the top of the boundary layer (2-300 m). For upstream wind speed of 20 ms^{-1}, the range of wind speeds over Spitsbergen is from calm to 37 ms^{-1}.

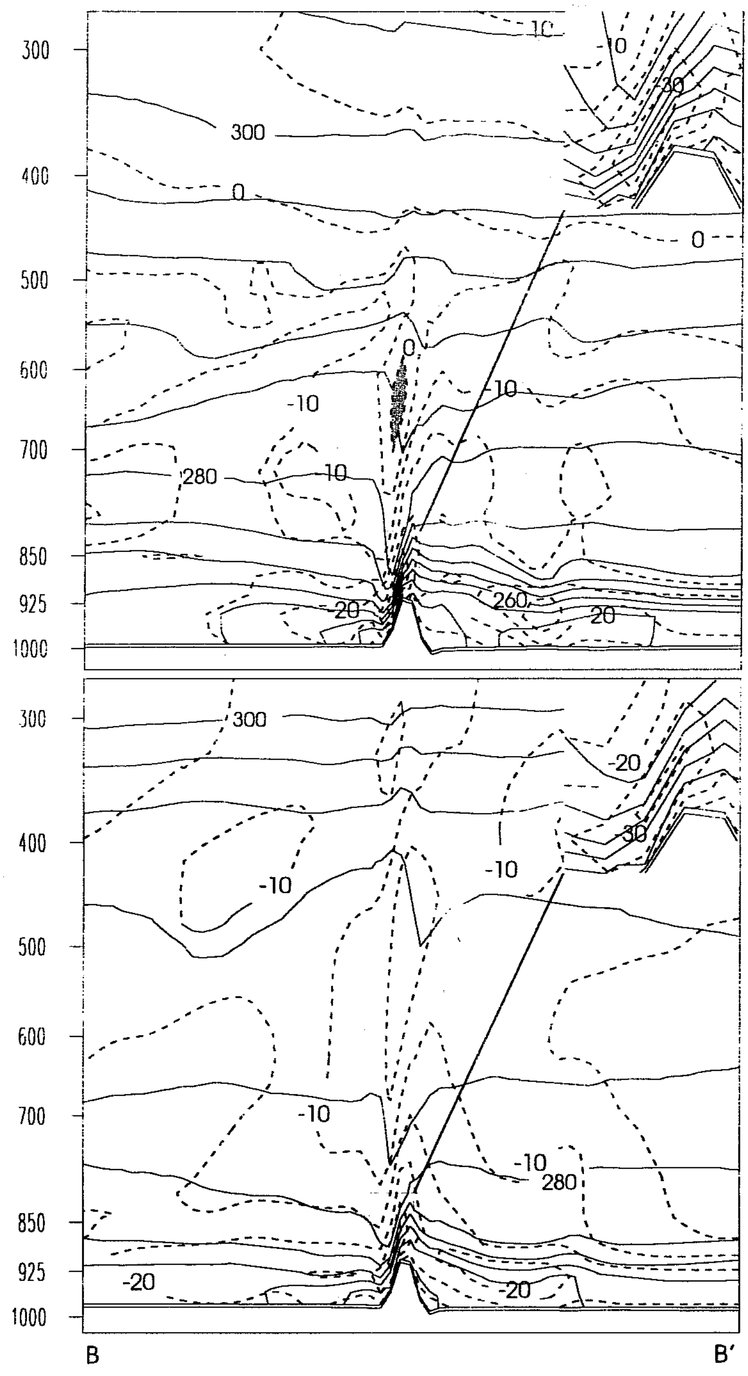

Figure 7 Cross-section west-east across the southernmost mountains of Spitsbergen after Grønås and Skeie (1997). Simulated potential temperature (K) and tangential wind component (ms) are shown. Valid t are 25 January 1995 00 UTC at the top and 9 January 1995 12 UTC below.

A simulation in a similar case, but without a critical layer aloft, gave more or less a similar flow over Spitsbergen. The mountain waves had large amplitudes, and strong lee winds, coastal jets and wakes were found. However, no stagnation points were found in the flow and no return flow in the wake (see Figure 7). A necessary condition for large amplitude mountains waves seems to be the strong stability at the lower levels and not a critical layer aloft.

There were nearly no observations to verify the findings over the sea, but it is known to meteorologists that easterly wind might be very strong south of Spitsbergen. Observations on the western side of Spitsbergen show strong wind in winter (Hanssen-Bauer et al., 1990). In particular, Isfjord Radio, a surface station at the mouth of the major fjord Isfjorden, has a large frequency of strong easterly wind. More than 70 % of the measurements are out the fjord and in 74% of the days, wind speeds of force 6 or stronger have been measured (Hanssen-Bauer et al., 1990). In this way the wind is significantly stronger in the fjords of Spitsbergen than in the fjords of Norway. Isfjord Radio is among the two or three windiest observing stations in Norway.

Sometimes the wakes and the jets on both sides extend southwards for as much as 1000 km. An example is shown in the satellite image in Figure 8. Numerical simulations in the same case verify that the band with deeper cumuli, which extends down to Feroe Islands, is a warm wake formed by the mountains at Spitsbergen (Skeie, personal communication). At each side of the wake, cold advection is much more extensive than in the wake. In this case a polar low developed on the band (Røsting et al., 1996). The jets on either side and the strong stability on the top of the convective boundary layer give anomalies of PV, which seem to be important for the development of polar lows. The jets and wakes over the sea, with a PV reservoir at the top of the convective boundary layer beneath the Arctic Inversion, resembles a shallow troposphere, with a sub-tropopause at say 700 hPa or lower. In this sub-layer mesoscale baroclinic disturbances might be generated.

6. STRONG LEE WIND WHEN FRONTS ARE PASSING SOUTH-NORWAY

As mentioned in the introduction, cold air masses, characterised by a low-level inversion, might also be formed over Scandinavia in winter, in particular over the northern part. Cyclonic activity in the Nordic Seas might force this air to pass the mountains from east. Strong lee winds will then be observed on the western side of the mountains. This has been demonstrated by Andræ (1997) in numerical simulations. He found breaking waves over the steep lee slopes on the west side of the mountains.

Similar strong wind has also been observed on the northern slopes of the main mountains of South-

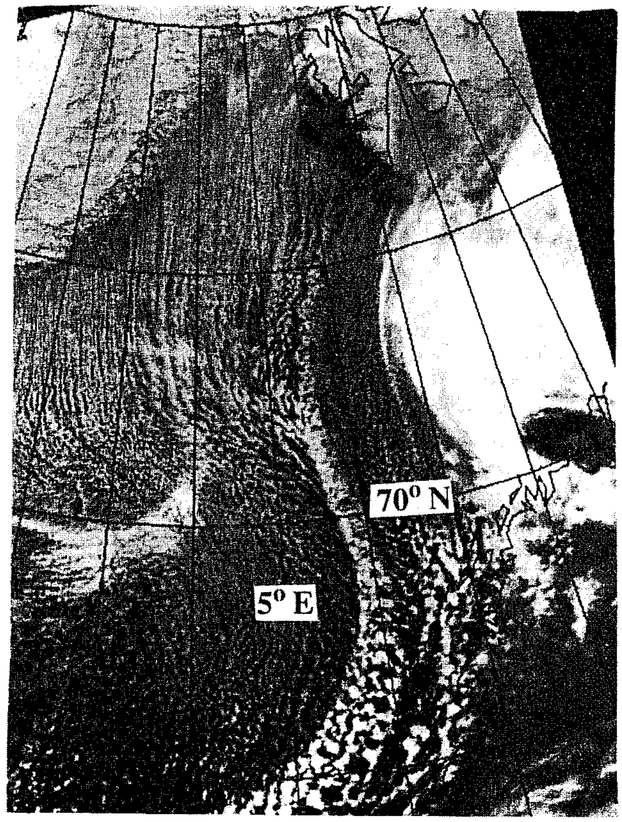

Figure 8. NOAA satellite image, channel 4, 26 March 1995 at 1825 UTC (from Røsting et al., 1996). Note the band of higher cumuli in the Norwegian Sea.

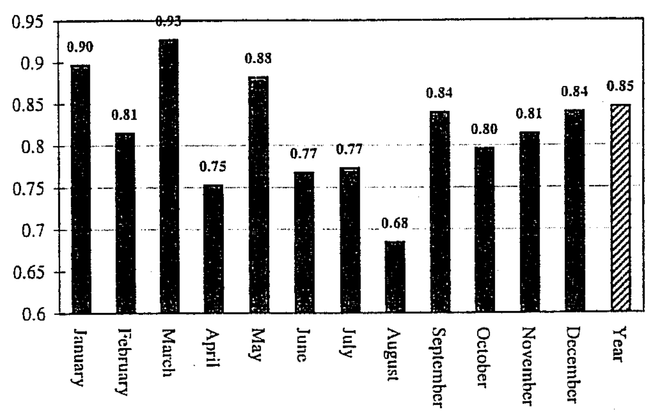

Figure 9. Correlation coefficients between precipitation at Samnanger, Norway (inside Bergen) and sea level pressure difference along the coast between Ona and Utsira (300 km apart) (Tveito, 1996). The data are from 1957 to 1993.

Norway. Well known in Norway are the strong winds measured in the Otta Valley (Harstvedt et al., 1995). Four cases reported in this report show a warm front or a warm occlusion passing South-Norway from south-west. The warm advection, combined with cold surface air at the eastern side, give a marked low-level inversion (see also the conceptual model in Figure 3). In addition, release of latent heat in connection with orographic precipitation on the western side of the mountain contributes to low static stability in the upper troposphere. In this way the upstream conditions are characterised by a relative high Scorer parameter at lower levels and a low Scorer parameter at higher levels. A high amplitude mountain wave and strong lee wind might develop. Doyle et al. (1996) has used a concept of nested numerical models, with grid distances down to 1 km, to predict the strong lee wind. Encouraging results have been obtained starting from large-scale analyses. The results indicate significant predictability of such mountain effects once the large-scale flow is well predicted.

7. OROGRAPHIC PRECIPITATION

Normally, air passing Scandinavia is humid, maritime polar air masses which give considerable amounts of orographic precipitation. The largest amounts are found on the west coast in south and north, where the slopes of the silhouette/envelope mountains normal to the coast have their maximum a few tens of km from the coast. Maximum mean yearly amounts for the period 1960-1990 are as much as 4 m at the west coast of South-Norway and 3 m further north. Estimated precipitation amounts during the winter at the glacier Åfotbreen north of Bergen might reach 6 m (Østrem, personal communication). At the same time mean yearly precipitation amounts less than 0.4 m are observed on the lee side of the mountains. Since humidity is abundant, there is a strong correlation between the surface pressure gradient along the coast and precipitation amounts. An example is shown in Figure 9, taken from Tveito (1996).

Skeie (1995) investigated the flow from west over North-Norway with numerical simulations. For typical amounts of orographic precipitation, he found maximum heating rates of 2-4 K/hour a few hundred meter above the upstream slopes. He found that the heating decreases the upstream positive pressure perturbation, but increases the negative pressure perturbation on the lee side. When the rate of latent heat release was high, the pressure drag was reduced compared to a flow without release of latent heat. Smaller pressure perturbations in front of the mountain give increased upstream wind speeds. In some cases this might prevent upstream blocking. The momentum budget was investigated after a method used by Bougeault et al. (1990). With 25 km between the grid points, the pressure drag was found to be more or less balanced by the ageostrophic force both in simulations with and without clouds. In comparison, the vertical flux of wave energy was small.

8. EFFECTS ON SMALLER SCALES

Few direct measurements are available to describe wind phenomena, caused by the mountains, which give extreme wind forces. Important observations in Norway are surface wind registrations during a few decades at a dense network of airports. Extreme wind analyses have been made from these stations and light-house stations at the coast, (Harstveit & Andresen, 1994). A few times, denser networks of observations have been established for shorter periods to study variations in valleys and fjords. An extensive campaign with wind measurements took place in the late sixties in the interior of Troms county, North-Norway (Gotaas et al., 1965; Eidsvik et al., 1971, Grønås & Sivertsen, 1971). Interesting steering effects of the mountains and local thermal circulations have been reported.

Frequent wind damages have given proxy data which have been investigated systematically. In particular, damages from the record storm 1 January 1992 (Grønås, 1995) has been extensively studied (Andresen & Harstveit, 1993a, b). The main conclusions in these reports are that the most serious damages take place in the lee side of small mountains (L ~500-2000 m, h ~100-1000 m), when the lee slope is very steep. The experience is that the strongest winds are found when the wind direction at the tops makes an angle with the steep slope rather than being perpendicular. Based on measurements elsewhere (Gibraltar and Ailsa Craig, Cook et al., 1978; Jenkins et al., 1981) and theoretical surveys on separation incidents (see Baines, 1995), Andresen & Harstveit argue that the strong winds are caused by separation of the flow in connection with steep lee slopes. High speed air particles passing a steep lee slope do not longer follow the terrain, but separates from the ground more or less horizontally into the free air. The high-speed air makes a drag on the air underneath and a low pressure anomaly is formed below. Surface air is moving towards the steep slope where pressure is low and a rotor is formed. When the wind direction on the tops makes an angle with the steep slopes, corkscrew circulations are formed instead. Andresen & Harstveit indicate that such corkscrews are more dangerous than the rotors.

Sandvik & Grønås (1997) simulated local wind in rough terrain with steep mountains in North-Norway with a non-hydrostatic numerical model with 270 m between the grid-points. Initial conditions were taken from simulations with the HIRLAM weather prediction model in a storm 12 October 1996 causing severe damages. In a valley where power pylons were broken down in a direction opposite to the main wind, separation and a corkscrew circulation were simulated with return winds reaching 20 ms^{-1} near the valley floor. A gust factor of more than two is possible (Harstveit, 1996).

9. CONCLUDING REMARKS

In this paper a review of mesoscale effects of the mountains in Scandinavia and Spitsbergen has been given. Few papers have been available and most of the existing work has been documented in Norwegian only. Emphasis has been put on dynamical effects simulated in high resolution numerical models. Thermal circulations have not been covered. Some of the phenomena are partly resolved by the ECMWF operational model and some not resolved at all.

Surface observations verify some of the signatures at the ground. Some phenomena, such as jets and wakes from Spitsbergen, are nearly not verified at all by observations, since they are lacking. However, indications are obtained by satellite images. Obviously, there is a need for more mesoscale observations in the lower troposphere. Hopefully, weather radars will be established along the coast in near future. Investigations on the potentials for wind power might also bring forward more resources for new measurements.

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