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Application of a "generalized hydraulic theory" to the severe northern Adriatic bora

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Summary. The "generalized hydraulic theory" (Smith and Sun [10]) is applied to eight severe northern Adriatic bora cases, which consist of two layers, each with constant static stability in the upstream region. The agreement between values derived from the theory and the observations is reasonably good, especially in consideration of the often complicated vertical structure in the atmosphere and the high sensitivity of theoretical results on input data.

Anwendung einer „verallgemeinerten Hydraulik-Theorie" auf starke Boras in der nördlichen Adria

Zusammenfassung. Eine „verallgemeinerte Hydraulik-Theorie" nach Smith und Sun [10] wird auf solche acht Stark-Borafälle in der nördlichen Adria angewendet, die einem 2-Schichten-Modell mit jeweils konstanter statischer Stabilität im stromaufwärtigen Gebiet entsprechen. Die Übereinstimmung zwischen den aus der Theorie und aus den Beobachtungen abgeleiteten Werten ist zufriedenstellend, insbesondere wenn die große Annäherung der meist komplizierteren vertikalen Schichtung und die große Empfindlichkeit der theoretisch abgeleiteten Werte von den Eingangsdaten berücksichtigt werden.

1. Introduction

Strong downslope winds, often gusting to well above 30 m/s, are observed in many mountainous regions on the world. One of them is the bora wind which blows across a mountain barrier parallel to the eastern Adriatic coast of Yugoslavia. Although bora events have been studied extensively for more than 10 years, their dynamic is not satisfactorily understood.

Recently there have been three major attempts to construct a theory of downslope windstorms. Klemp and Lilly [1] have proposed a mechanism of severe downslope wind generation which is based on the linear theory of internal gravity waves in a continuously stratified, semi-infinitive fluid. The second attempt is based on the results obtained from numerical integrations of the equations which govern the dynamics of the flow for spatial initial conditions [2, 3, 4, 5]. The third way of constructing such a theory is Smith's mathematical model [6]. This links downslope windstorms to breaking waves in a continuously stratified atmosphere by solving Long's equation [7, 8] subject to the assumption that the overturning region is well mixed, so that the density in that region is constant. Long's equation is a differential equation for the displacement of the streamlines from their elevation far upstream. It is linear even for finite amplitude disturbances and therefore gives a procedure for calculating the complete flow field without approximation. The presupposition is: two-dimensional incompressible (or Boussinesq), inviscit, hydrostatic and steady flow with kinetic energy (approximately the horizontal wind) independent of the height far upstream.

Smith derived an upper-boundary condition for these solutions by assuming that the disturbance is in hydrostatic balance, that turbulence produces a well-mixed stagnant region within the breaking layer, that no disturbances are transmitted through this layer and that it is possible to identify a streamline which separates the well-mixed region from the laminar flow below (Fig. 1). Under these assumptions the horizontal velocity is constant along the dividing streamline. The transition in Smith's solution that allows the dividing streamline to continue descending on the lee side of the mountain has qualitative similarities with the transition of supercritical flow that occurs in hydraulic theory. In a recent paper by Smith [9] the subject is dealt with in more detail and to a broader extent.

The theory was improved four years ago by Smith and Sun [10]. They found nonlinear steady-state solutions of Long's equations for a stratified two-layered flow over a ridge which encompass any distribution of stability. In parameter space these solutions lie between the interfacial case of Long [7] and the constant stratification case of Smith [6]. The theory provides a reasonable prediction of the dividing streamline height, the flow field beneath the dividing streamline and the drag. It has supplemented earlier linear theories of severe downslope winds.

The results of the theory applied to five ALPEX bora cases by Smith and Sun [10] indicate an internal hydraulic mechanism for the limiting forms used in Smith's earlier paper [6]. Unfortunately, the five ALPEX bora cases considered fell close to the constant or the interfacial stratification limit. Thus, those cases did not provide a wholly satisfactory test of the theory extension.

In this paper, the results of the theory applied to some stratified two-layer bora cases will be shown. But, before that, the model sensitivity for the input data will be discussed.

2. Model sensitivity for the input data

In the two-layer hydraulic model, Smith and Sun [10] considered an incompressible flow approaching a ridge with

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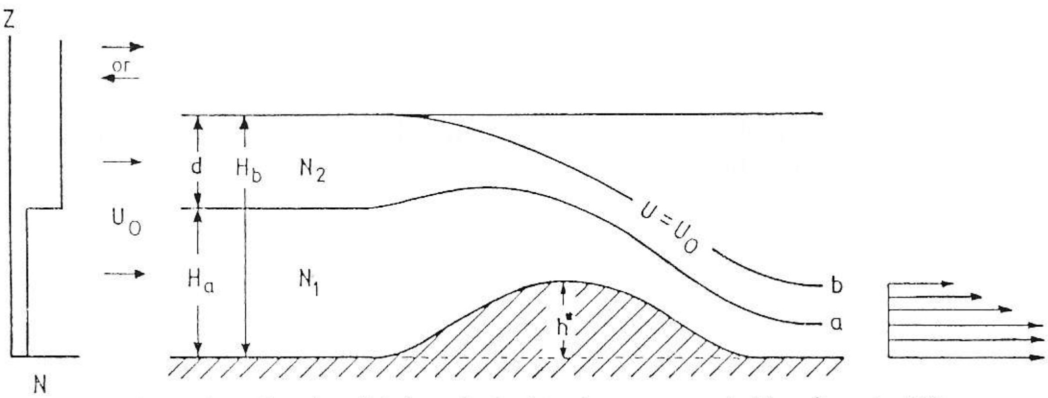

Fig. 1. Schematic review of the hypothesized steady-state severe wind f configuration [10].

uniform speed U_0 (Fig. 1). The stability profile consists of two layers, each of constant stability. For the present purpose, we restrict the problem by assuming a neutral lower layer.

According to the hydraulic theory, a certain relationship must exist among upstream wind, depth, stratification and mountain height, whenever the airflow accelerates over the ridge crest. For a two-layer atmosphere this is given by (see [10], p. 2935, eq. (16) and [7], p. 108, eq. (12)):

$$\frac{h^*}{H_{eff}} = 1 + \frac{1}{2} F_0^2 - \frac{3}{2} F_0^{2/3} \qquad (1)$$

where h* is the critical mountain height for transition flow (see [10], eqs. (30, 32, 33)):

$$H_{eff} = H_a + 0.5\, d \qquad (2)$$

$$F_0^2 = \frac{U_0^2}{N_2^2\, d\, H_{eff}} = \frac{(1+r)^2}{r\,(1+r/2)\,\hat{H}_b^2} \qquad (3)$$

$$\hat{H}_b = H_b \frac{N_2}{U_0} \qquad r = d / H_a \qquad (4)$$

$$N_2^2 = \frac{g}{\rho}\frac{d\rho}{dz} \cong \frac{g}{\rho}\frac{\Delta\rho}{d} = \frac{g'}{d} \qquad (5)$$

In equations (1)—(5), d is the depth of the upper stable layer, H_a is the depth of the lower neutral layer, H_{eff} is the effective altitude of the stable layer, F_0 is the Froude number and N_2 is the Brunt-Väisällä frequency in the upper layer. The authors presumed that the fluid selects a certain critical streamline in the upper layer to serve as the top of the disturbed flow (H_b on Fig. 1). Knowing the lower neutral layer depth H_a, the upper layer stability N_2 the uniform upstream wind speed U_0 and critical mountain height h*, we may apply the theory in order to obtain the predicted depth of the upper layer d_p. The second possibility is to obtain the predicted mountain height d^*_p knowing N_2, U_0, H_a and the observed upper layer depth d. If the observed values of H_a, N_2, U_0, d and h were in absolute agreement with the theoretical approximation, the observed values of the upper layer depth (d) and the critical mountain height (h*) would be the same as the predicted d_p and h^*_p.

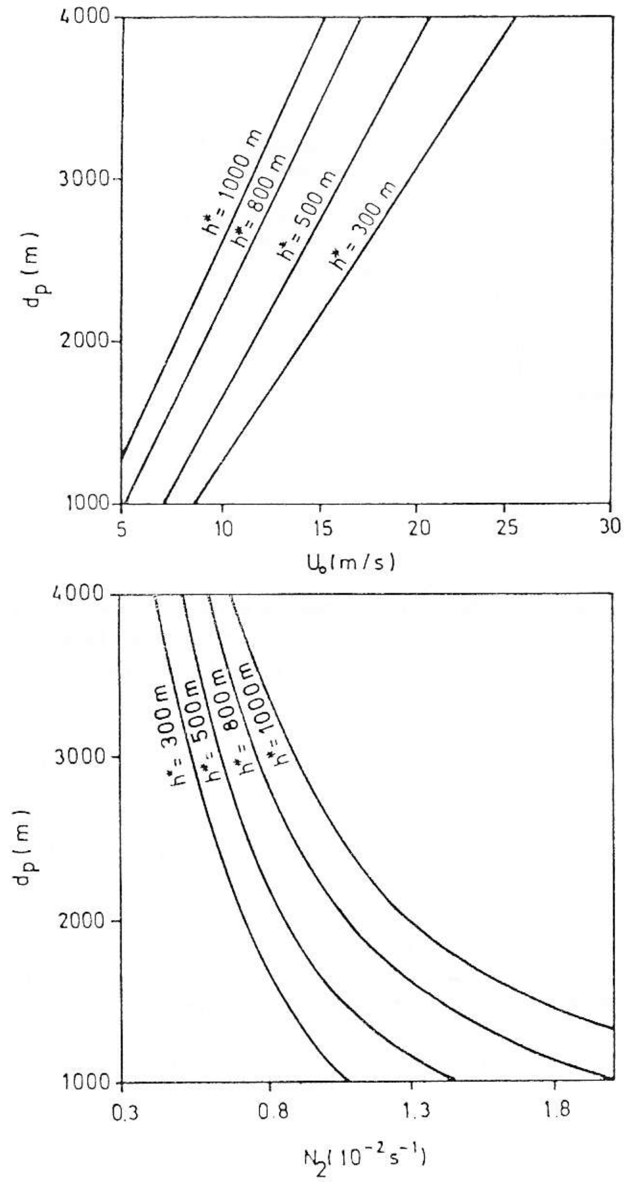

Fig. 2. Predicted split streamline height d_p in dependence on: (above): critical mountain height h* and mean wind speed U_0 (with $H_a = 2000$ m, $N_2 = 0.01$ s^{-1}); (below): critical mountain height h* and upper layer stability N_2 (with $H_a = 2000$ m, $U_0 = 10$ m/s).

How much the stability N_2 and the wind speed U_0 as input data influence the predicted upper layer depth d_p, can be seen in Fig. 2. The flow approaching the mountain with the same critical height with only 5 m/s difference in speed causes a difference of more than 1000 m in the predicted upper layer depth. The situation is similar when the stability is used as input parameter. Relatively small changes in the stability value ($0.8—1.0 \times 10^{-2} s^{-1}$) result in differences of a few hundred meters in the upper layer depth.

This sensitivity demands great caution with input data determination. Because of a very complicated atmospheric structure the accurate wind speed and stability determination are rather difficult, as will be seen in the next section.

3. The data selection and preparation

The meteorological station on the northern Adriatic with the longest period of registered wind data is Senj which is the most famous bora place in the northern Adriatic. The results of basic statistical analysis of bora occurrence in Senj are described in a paper by Bajić [13]. In the 30-year period (1957—1986) 434 situations with severe bora have been observed in Senj. A situation with severe bora is defined by a wind direction continuously between 360 ° and 90 ° and the mean hourly wind velocities 17.0 m/s in at least one hour. In 10 % of such situations maximum hourly bora gusts in Senj were ≧ 35.0 m/s.

The upstream flow parameters which we need for the theoretical application in such a severe bora situation are available from one sounding station only at the time intervals of 12 hours. This station is Zagreb, located approximately 10 km northeasterly from Senj (Fig. 3). The height of the top of disturbed flow beneath the critical streamline (upstream bora layer depth H_b) can be defined only by using the sounding data so far upstream from the mountain top. In our analysis we have defined H_b as a level where the wind component normal to the mountain ridge U_B became equal to zero. This definition is in accordance with the Durran and Klemp suggestion [11, 12] that the height of the dividing streamline can be related to the elevation of the critical layer in the upstream flow and the upper boundary of the critical layer is taken at that height where the cross-mountain wind reverses its direction. By using only the U_B wind component we adapt our consideration to the applied two-dimensional hydraulic theory.

If we want to apply the two-layer hydraulic theory to severe bora situations we should find upstream stability profile which consists of approximatively two layers of constant stability with a neutral lower layer. In the majority of severe bora situations the upstream stability profile in the bora layer consists of one or more than two layers of constant stability [14, 15, 16, 17]. In the period 1957—1986, only 8 observations were made which met the requirement of the two-layer hydraulic theory and these were related to different bora stages. One of them is presented in Fig. 4. The detailed synoptic and mesoscale bora characteristics in the 8 situations considered are described in [14, 15, 18]. Here we will pay most attention to the results of theory.

Previously, we should remark that in none of the 8 situations was the lower layer stability N_1 strictly equal to zero. However, the lower layer in each case was nearly neutral with a stability $N_1 < 0.6 \times 10^{-2} s^{-1}$ in comparison with the upper layer stability $N_2 > 1.2 \times 10^{-2} s^{-1}$. Such a stability profile most fits the requirements of the theory.

The upper (d) and lower (H_a) layer thicknesses, together with the upper layer stability N_2 and the mean wind speed U_0 in the upstream bora layer (layer beneath the critical streamline) for the 8 considered observations, are given in Table 1. The assumption that the upstream flow has a constant speed is questionable because of the relatively pronounced wind speed maximum in the bora layer (which can be noticed in the vertical profile given in Fig. 4 too). Such an upstream wind profile is a common characteristic for the majority of severe bora situations [15, 16, 17, 18]. The way of mean wind speed determination could lead to differences in the theoretically obtained results. The wind speed U_0 used in this paper as an input data for the theory application, represents the weighted average throughout the layer:

$$U_0 = \frac{1}{H_b} \int_{z=0}^{H_b} U \, dz \tag{6}$$

or in finite difference form:

$$U_0 = \frac{\sum_{i=1}^{n} \Delta z_i \, U_i}{H_b} \qquad H_b = \sum_{i=1}^{n} \Delta z_i \tag{7}$$

where z_i are the differences between the two altitudes of successive significant levels in the upstream wind profile and U_i are the mean wind speeds in each z_i layer.

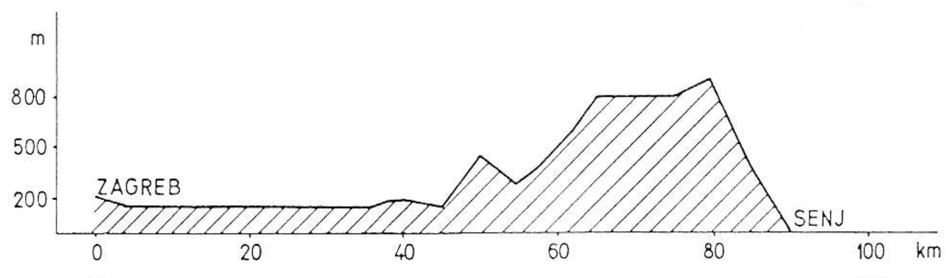

Fig. 3. Zagreb — Senj vertical cross section.

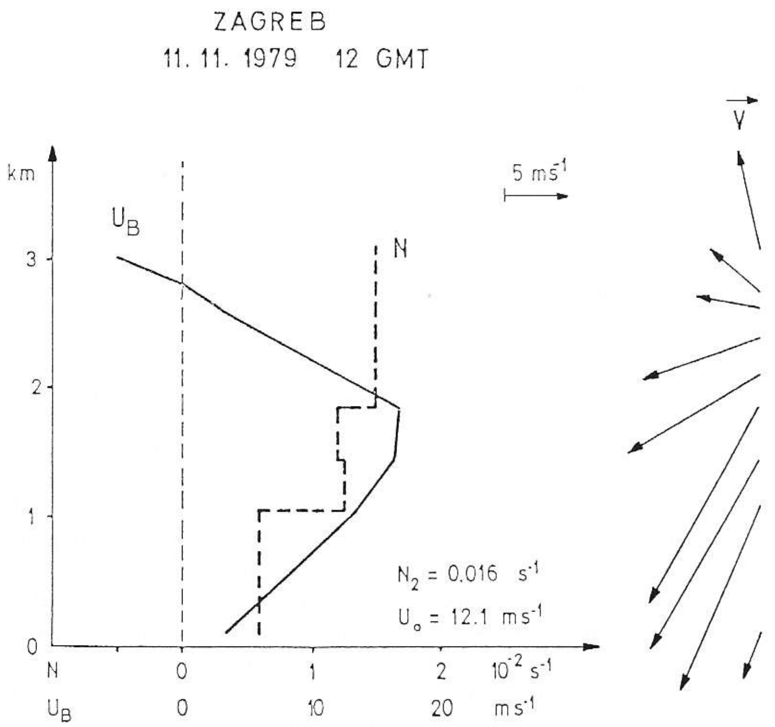

Fig. 4. Vertical profile of Brunt-Väisälä frequency (N_2), cross-mountain wind component speed U_B and wind vector V over Zagreb in the case acceptable for use of the two-layer hydraulic model.

Any attempt to represent wind shear as velocity discontinuities between layers would lead to instability in the upstream state [10].

Besides the mentioned hydraulic parameters, we have to define the critical mountain height as an input data for the application of the theory. Other authors [6, 10] have used a mountain height of 800 m. This altitude is realistic (Fig. 3) and it will be used in our cases, too.

4. The application of the theory and concluding remarks

The results of the application of the theory to 8 severe bora cases are given in Table 1. According to Smith and Sun [10], the theory overestimates the split streamline altitude especially in the large $r = d/H_a$ cases. In our cases this overestimation of d_p ranges from 40 m to nearly 1200 m and there are no regularities between r and overestimated d_p. The theoretically predicted critical mountain height h^*_p reaches values between 330 m and 850 m. The smaller h^*_p than h^* values point to the possible formation of the stagnant upstream layer (as a consequence of the upstream blocking) which influences the reduction of observed critical mountain height [18]. By using a higher critical mountain we obtained values which are, according to theory [7, 8, 10], good indicators of possible critical flow over the mountain top and an unsteady state flow. A steady state will be established with a lee jump.

However, all obtained values presented in Table 1 show reasonably good agreement with the theory, considering the complicated vertical structure in the real atmosphere and the theory's sensitivity to input data.

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Table 1. *Hydraulic parameters for two-layer severe bora cases (symbols are explained in the text).*

date	H_a (m)	d (m)	r	N_2 (s^{-1})	U_o (m/s)	d_p (m)	h^*_p (m)
8. 12. 1969	1570	920	0.59	0.021	7.6	850	850
9. 12. 1969	1100	1750	1.59	0.018	16.0	2730	390
20. 12. 1969	680	2060	3.03	0.018	11.9	2690	540
2. 1. 1979	1120	2840	2.54	0.013	11.5	2630	860
11. 11. 1979	920	1730	1.88	0.014	12.1	2890	330
12. 11. 1979	1430	970	0.68	0.016	10.4	1760	380
30. 11. 1980	1030	1730	1.68	0.014	11.5	2770	410
27. 12. 1980	1080	3470	3.21	0.012	13.7	3430	850

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The challenge of designing and operating ground-based observational instruments in Alpine terrain

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Summary. On the basis of the network of automatic weather stations in Switzerland some experience and problems in designing, testing, operating, maintaining and finally interpreting the results from observations of instruments in an Alpine country are presented. Apart from logistic problems, effects of icing, lightning, wind and radiation need special attention when designing instruments and networks of automatic stations to monitor the weather reliably and with minimum effort all year round in Alpine terrain.

Entwicklung und Betrieb von Instrumenten für automatische Wetterstationen in den Alpen — eine Herausforderung

Zusammenfassung. Fragen und Probleme betreffend Entwicklung, Erprobung, Betrieb, Unterhalt und schließlich auch der Interpretation von Resultaten werden anhand von Erfahrungen mit dem schweizerischen Netz von automatischen Wetterstationen diskutiert: Will man das Wetter in den Alpen rund um die Uhr und in allen Jahreszeiten zuverlässig und mit minimalem Aufwand beobachten, so benötigen Einflüsse von Vereisungen, Blitz und Strahlung, neben logistischen Fragen, unsere besondere Aufmerksamkeit.

1 Introduction

In 1972 the Swiss Meteorological Institute started to develop a network of automatic weather stations, the ANETZ. Today about 70 stations are reporting every 10 minutes. Doessegger [4] gives an overview on the network, the data transmission and presents analyses and some applications. Gutermann [5] discusses as an example the THYGAN-sensor for measuring temperature and humidity of the air and some real-time applications such as the automatic generation of warnings for Föhn winds on the Urnersee in the Swiss Alps.

In order to upgrade measurements of wind and snow in severe weather conditions and for avalanche forecasting, an extension of the Swiss network of automatic weather stations (ENET) is being realized within the next two years. ENET will consist of 50 stations, including 10 in the Alps and 10 for special applications [14].

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If available, sensors were and are bought off the shelf. But frequently available instruments did not fulfil the desired specifications discussed in Section 2, therefore various sensors were developed in collaboration with the Swiss industry. Very rugged instruments are needed if we want to run such a network with over 1000 instruments at a reasonable price and reliably, instruments being often installed in awkward positions on mountain tops. Various design parameters (ambient conditions) apart from the desired accuracy have to be considered (Section 3). In Section 4 some examples of instruments with their special attributes are discussed. The paper ends with conclusions on the reliability and on the stability of the instruments as indicated by yearly tests.

2 Requirements

2.1 *Specifications*

Apart from the desired range of measurement and error limits which have to be defined for each parameter, the following general specifications must be considered for all sensors in a more or less rigorous way (for more detail see e. g. Hoegger et al. [6]:

1. Windload: horizontal 50 m/s, vertical (at mountain ridge) 35 m/s.
2. Icing: up to 1 g/m^3 of liquid water in a 20 m/s wind at $-20\,^\circ$C.
3. Radiation: no significant reduction of lifetime and accuracy when exposed to radiation of up to 1500 W/m^2.
4. Lightning: full protection against indirect strokes.
5. Electromagnetic compatibility: protection against interference (e. g. from TV-transmitters).
6. EMP/NEMP: protection against electromagnetic pulse (EMP) and nuclear electromagnetic pulse (NEMP).
7. Corrosion: protection against rain and fog in a polluted atmosphere.
8. Life of sensor: over 10 years without significant degradation.

2.2 *Logistics*

1. It is extremely important that the instruments are easily accessible for installation and maintenance. Two types of access must be considered:
   — Access by road or public transport to the station and
   — access to the sensor itself, e. g. on the mast.
2. For more complicated instruments, we need the capability to remotely obtain a health-status of the sensor. The instrument should be equipped with a self-test option, from which the central station must be able to interrogate the results.
3. Calibration and repair of instruments at the site should be avoided. It is usually faster and safer to exchange the entire instrument. If not feasible, the steps necessary for calibration or repair have to be simplified and prepared as far as possible. This task has to be considered already at the design stage of the instrument.

3 Parameters for concern

3.1 *Icing*

Attempts to avoid icing with a special shape of the instrument or with a special treatment of the surface were not successful. According to our experience, the only way to keep the sensors free of ice is to equip them with electric heaters. The heat needed ranges from a few watts for sensors for sunshine and radiation to up to 500 W for wind sensors. The power depends on ambient conditions, whether the instrument must be free of ice all the time, (i. e., whether measurements in icing conditions are mandatory or are required only when the sun shines [measurement of sunshine duration]), and of course it also depends on the size and the complexity of the instrument itself. Two icing mechanisms can be distinguished:

1. Growth of ice through the *vapour phase*: in a supercooled water cloud, i. e., a cloud of waterdrops with temperatures below freezing, the difference of vapour pressure between water and ice creates a supersaturated atmosphere of water vapour over an ice surface. The supersaturation is zero at zero degrees and increases with decreasing temperature. At $-30\,^\circ$ C it reaches 34 %: saturated air in a supercooled water cloud has 100 % relative humidity with respect to water. With respect to ice, however, the relative humidity of the same air is 134 %, corresponding to a supersaturation of 34 %. However, as the absolute vapour pressure over water decreases exponentially with decreasing temperature, the difference of *vapour pressure* between water and ice achieves a maximum which occurs around $-12\,^\circ$C. Its value amounts to 0.3 hPa (super saturation of 12 %, see also Joss and Gutermann [7]. This fact is responsible for the rapid growth of rime at this temperature, which is frequently observed in the Alps at this temperature level. To avoid this type of ice deposition we have to heat the instrument, but it is not necessary to heat it in all conditions to above $0\,^\circ$C. Heating the surface by some degrees above ambient temperature is sufficient.

2. *Accretion of supercooled* water drops, which freeze when they hit the surface of the instrument, can be even more severe than the growth through the vapour phase. This is reflected by the amount of heat needed to avoid the growth of ice in extreme situations (strong winds combined with high concentration of supercooled cloud). For the OWA-windsensor we estimate up to 20 W/cm^2 to keep the measuring section free of water [10].

3.2 *Lightning*

Frequency and characteristics of lightning: Results of the ANETZ lightning sensors distributed all over Switzerland indicate an average density of 12 strokes per year and per