Interaction between the Atmosphere and the Underlying Surface

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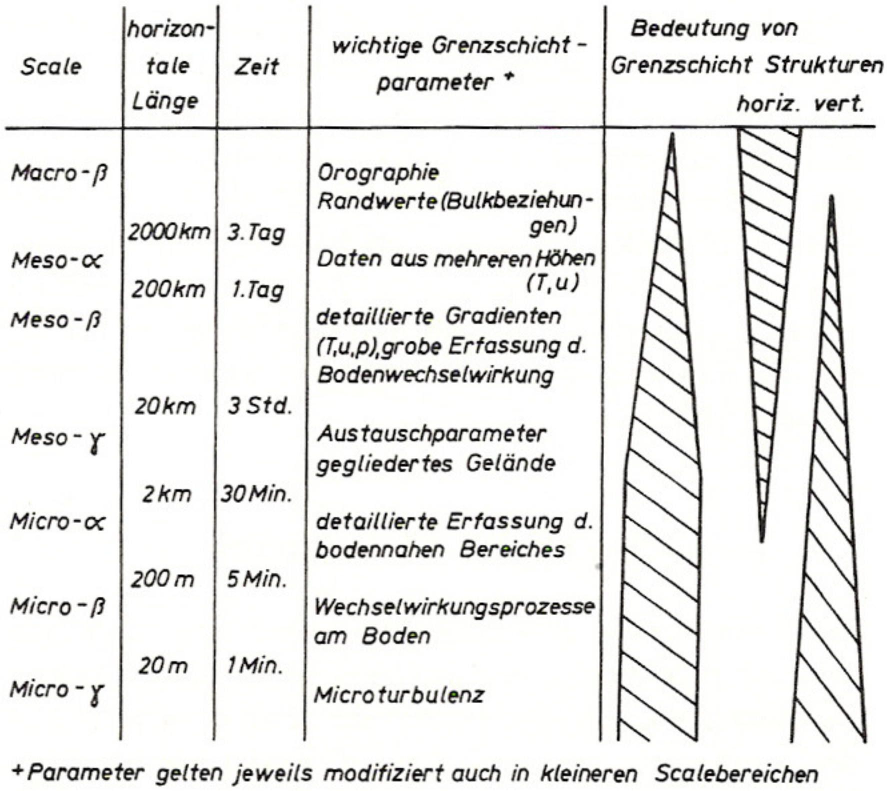
This chapter includes investigations of processes of the atmospheric boundary layer and the interaction between the atmosphere and the underlying surface - land and water surfaces. Most of the investigations were not made in a climatological context, but they are highly relevant for climate modelling and understanding of climatological processes. After an introduction of the terminus Boundary-Layer climate, relevant studies of this topic in the former GDR are presented.

Boundary-Layer climate

The terminus boundary-layer climate, the climate of the lowest kilometre of the atmosphere, is not very well decribed, because the temporal and spatial classification of the climate is more focussed on horizontal scales (Hupfer, 1989). Climatological investigations in aerology often did not include the atmospheric boundary layer because radio sounding of the boundary layer is very expensive and the layer near the surface is excluded. Measurements within the 10-50 m thick surface layer are in the typical range of climatological measurements, but in this chapter of boundary-layer processes the focus will be orientated on the determination of turbulent fluxes of sensible and latent (evapotranspiration) heat. The available measurements were made during short-term experiments, which did not fulfil the typical “climatological” scale, although they were the basis upon which climatology of the evaporation in the territory of the GDR could be presented (Richter, 1984).
The conference ”Meso-Meteorology“, held in Castle Reinhardsbrunn near Friedrichroda from December 8 to 11 (Abhandl. Meteorol. Dienst DDR, Nr. 141, 1989), was remarkable for the presentation of a boundary-layer climatology of the GDR. This conference opened the way to a future mesoscale orientation of future meteorology, as well as for the weather forecast and for the climatology.



Scale	horizontale Länge	Zeit	wichtige Grenzschicht-parameter +	Bedeutung von Grenzschicht Strukturen horiz.	vert.
Macro-β			Orographie Randwerte (Bulkbeziehungen)		
	2000km	3.Tag			
Meso-α			Daten aus mehreren Höhen (T,u)		
	200km	1.Tag			
Meso-β			detaillierte Gradienten (T,u,p), grobe Erfassung d. Bodenwechselwirkung		
	20km	3 Std.			
Meso-γ			Austauschparameter gegliedertes Gelände		
	2km	30Min.			
Micro-α			detaillierte Erfassung d. bodennahen Bereiches		
	200m	5Min.			
Micro-β			Wechselwirkungsprozesse am Boden		
	20m	1Min.			
Micro-γ			Microturbulenz		

+Parameter gelten jeweils modifiziert auch in kleineren Scalebereichen

Fig. 1: Scales of boundary-layer processes (Foken, 1987; Foken, 1989), translation of important phrases: wichtige Grenzschichtparameter: important boundary layer parameter; Bedeutung von Grenzschicht-Strukturen, horiz., vert.: importance of boundary layer structures, horizontal, vertical; Orographie, Randwerte (Bulkbeziehungen): orography, marginals (bulk approach); Daten aus mehreren Höhen: data from different heights; detaillierte Gradienten, grobe Erfassung der Bodenwechselwirkung: detailed gradients, pure application of surface interaction; Austauschparameter im gegliederten Gelände: exchange parameters in heterogeneous landscape; detaillierte Erfassung des bodennahen Bereiches: detailed coverage of the near surface layer: Wechselwirkungsprozesse am Boden: interaction processes near the surface; Microturbulenz: micro-turbulence; Parameter gelten jeweils modifiziert auch in kleineren Scalenbereichen: parameters are valid in modified form also for lower scales.

Mesometeorology means a new orientation of meteorological measurements with more attention to vertical fluxes in the boundary layer (Fig. 1). This was the start of a development which became reality in Germany about 10 to 20 years later. Therefore, it may be interesting to investigate this nucleus of boundary-layer climatology. In the following sections this investigation is done for the boundary layer and the turbulent fluxes near the surface.

Climatology of vertical boundary-layer processes

Early aerological investigations in the context of this description of the vertical structure of the atmospheric boundary layer were measurements made in 1950-1951 with a 80-m-lift at the Aerological Observatory Lindenberg (Rink, 1953). But the available analysis unfortunately did not permit climatological or boundary-layer meteorological conclusions.

First investigations of boundary-layer climatology were focussed on the upper part of the boundary layer and the inversion layer. Investigations of the geostrophic drag coefficient, the ratio of the surface and geostrophic wind and an important parameter to characterize the shear included the whole boundary layer. These investigations were based on carefully made analyses of radio sounding profiles over Lindenberg and showed variations within the daily cycle (Bernhardt, 1975, see also Bernhardt, this issue, 52 - 579). Some special boundary-layer soundings were made in the 1980s near Greifswald to investigate possible internal boundary layers near the Baltic coast in the region of the former atomic power station Greifswald-Lubmin. No report about these measurements is available.

Besides short-term experiments at tall towers, mostly in Czechoslovakia (Table 1), systematic investigation of the wind shear between 30 and 60 m were done at the 60 m shear-wind tower of the Berlin-Schönefeld airport (Graebe, 1984) in the period from March 13, 1980 to December 31, 1983. The measurements were continued up to 1990 only for operational purposes. The main aim was the determination of the frequency of wind shears and the identification of situations of possible wind shears, which are risky to the landing of aircrafts. In the period of investigation, within the height interval between 30 and 60 m, 15548 two minute intervals with wind shear $\geq$ 3,0 m s^{-1} (Table 2) were found. Additionally, the dependence of wind shear on the weather situation was investigated. About 36 % of strong shear-wind situations were found under low wind conditions with inversion and only 18% for high wind conditions.

Table 1: Short-term boundary-layer experiments using tall towers

Year	place	Scientific goal	Reference
1980-1983	Airport Berlin-Schönefeld, GDR	Wind shear	Graebe (1984)
1985	Tusimiče near Kaden, Czechoslovakia	Calibration of sodar technique	Keder et al. (1989)
1986	Kopisty near Most, Czechoslovakia	Calibration of sodar technique, exchange processes in a heterogeneous industrial area	Pretel (1988)
1987	Juliusruh, Rügen, GDR	Calibration of sodar technique	Neisser et al. (1990)
1989	Jaslovske Bohunice, Czechoslovakia	Control of the monitoring system of the atomic power station	Zelený and Foken (1991)

Table 2: Cumulative frequency of wind shear between 30 and 60 m (2-minutes-interval in the period 1980–1983 at the airport Berlin-Schönefeld according to Graebe (1984).

Wind shear in m s^{-1}	$\geq$ 3.0	$\geq$ 3.5	$\geq$ 4.0	$\geq$ 4.5	$\geq$ 5.0	$\geq$ 3.5	$\geq$ 6.0	$\geq$ 6.5
Number of cases	15548	4279	1136	362	115	43	24	4

At the conference of the Meteorological Society of the GDR in 1986 mentioned above, the direction that a meso-scale meteorology needs the development of ground based remote sensing technique was shown/demonstrated (Foken, 1987; Foken, 1989). In 1983 a project management led by Peters and Foken started to develop the sodar technique. This technique was developed at the Heinrich-Hertz-Institute of the Academy of Sciences of the GDR. The first device was a vertical sodar to measure the backscatter intensity (Gronak and Kalaß, 1986). The version of a doppler sodar was finished after 1989 but thereafter no longer used in the GDR. To use the vertical sodar in the network of the meteorological service a special weather code was developed (Foken et al., 1987). The first operational application was in winter 1985/86 at the weather bureau in Leipzig. The height distribution of the inversion is shown in Table 3. In the following years a network of vertical sodar devices was installed. They were used to observe the inversion height for a better forecast of inversion situations. A further application was the determination of the cloud base for military aircrafts. In winter 1989/90 a network of six civil and five military stations (Foken et al., 1997, see Fig. 2) was installed. Consequently, information regarding the inversion height was available every hour especially in the industrial areas in the south of the GDR. Still, in winter 1990/91 the network was switched off by the German Meteorological Service and only the devices at Potsdam und Leipzig-Schkeuditz worked “illegally” some years longer. Only in 2005, 15 years later in reunified Germany, was a network of six wind profiles installed for a continuous observation of the atmospheric boundary layer and for meso-meteorological application.

Table 3: Percentile frequency of the height distribution of ground inversion (thickness) and free inversions (lower base) in winter 1985/86 in Leipzig (Foken et al., 1997).

Thickness or height in m	00 – 49	50 – 99	100 – 149	150 – 199	200 – 249	250 – 299	300 – 349	350 – 399	> 400
Surface inversion	15.9	28.0	18.2	12.1	6.8	3.8	3.8	1.5	9.8
Free inversion	19.7	30.3	17.8	6.6	4.0	1.3	4.0	2.6	19.7

Fig. 2: Vertical sodar network in winter 1989/90 (Foken et al., 1997)
●: civil station with real-time communication
○: civil station without communication
■: military station with real-time communication

Turbulent fluxes in the surface layer

Immediately after the Second World War the ideas of Albrecht (1940) about the investigation of the heat budget of the Earth were revived. This was mainly done at the Meteorological Main Observatory at Potsdam of the Meteorological Service of the GDR. According to the character of research at this observatory, investigations were mainly done in campaigns and not made under climatological points of view. But they were used to generate long-term measuring programmes at other institutions.

Under the leadership of Skeib, investigations of the heat budget of the near surface layer in Potsdam were started, first with a forest climate station (Heckert, 1955). At the Aerological Observatory Lindenberg, the micro-aerological measurements by Rink (1953) were also a contribution to this research topic.

The modern era of turbulence research at Potsdam began with the procurement of the first modern sonic anemometer in 1968 at the Meteorological Main Observatory (Beyrich and Foken, 2005). A huge number of national and international experiments were done in the following 20 years (Table 3). There were three main focusses, which were partly realized in cooperation with other institutes. Parallel measurements on a raft at lake “Stechlinsee” were made in 1977 and 1983 together with the Research Institute for Hydrometeorology of the Meteorological service of the GDR to update parameterizations for the calculation of evaporation (Richter, 1984).

The contacts to the Research Institute for Agrometeororology of the Meteorological Service of the GDR at Halle-Kröllwitz and its research station Müncheberg were very intensive. At both places a profile measuring program of wind, temperature and humidity to calculate the sensible and latent heat flux.there was running. These measurements were compared with direct turbulence technique with the eddy-covariance method in 1976 and 1984 at Halle-Kröllwitz and in 1978, 1979 and 1982-84 in Müncheberg (Fig. 3). Not only a remarkable measuring methodical paper resulted from this (Koitzsch et al., 1988), but also a data set for a computer-based agriculture advice system for sprinkling and harvest forecast (Forschunsgzentrum, 1985). Unfortunately, this data set was not investigated under climatological focusses.

Furthermore, a system for the routine determination of turbulent fluxes with measurements of temperature, wind and humidity at two levels was developed (Foken, 1991) and in 1985 successfully applied at the Berlin-Schönefeld Airport (Fig. 4, Richter and Skeib, 1991). The method was based on theoretical investigations by Skeib and Richter (1984) and was included into a possible meso-meteorological network (Foken, 1989). The strong recommendations for a homogeneous measuring field, the manpower and the missing application of the data were reasons that this technique was not used in the routine network. This was only possible from 1998 on at the Meteorological Observatory Lindenberg with an updated measuring technique (Beyrich and Foken, 2005).

Table 3: Short-term experiments with direct turbulence measurements

Zeitraum	Ort	Zweck	Quelle
1971-1975	Potsdam, Schlaatz	Turbulence and profile measurements, long-term measurements	Gerstmann (1973)
1973	Zingst	Air-sea interaction in the coastal zone Küstenbereich, Experiment EKAM	Mücket and Gerstmann (1975)
1976, 1984	Halle-Kröllwitz	Intercomparison with measurements of the Agrometeorological Research Institute	Wendling et al. (1980)
1977, 1983	Stechlinsee	Intercomparison with measurements of the Hydrometeorological Research Institute	
1978, 1979, 1982, 1983, 1984	Müncheberg	Intercomparison with measurements of the Agrometeorological Research Institute, research station Müncheberg	Koitzsch et al. (1988)
1981	Tsimlyansk, Soviet Union	International turbulence intercomparison experiment, determination of universal functions, ITCE-81	Tsvang et al. (1985)
1985	Berlin-Schönefeld Airport	Test of parameterization equations	Foken (1991)
1987	Tautenburg	Investigation of astro-climate	Foken et al (1990)
1988	Kursk, Soviet Union	Turbulence experiment in heterogeneous areas, KUREX-88	Tsvang et al. (1991)
1990	Brocken, Harz mountains	Test of turbulence devices, measurements in sloppy terrain	Richter et al. (1990)
1990	Töravere/Tartu, Soviet Union (Estonia)	Turbulence measurements at a sudden change of surface roughness TARTEX-90	Foken et al. (1993)

Fig 3: Sonic anemometer and Lyman-alpha-hygrometer of the Meteorological Main Observatory Potsdam during intercomparison measurements at Müncheberg (photo: Th. Foken).

Fig. 4: Mast for the parameterization of turbulent fluxes of the Meteorological Main Observatory at Potsdam, consisting of anemometers at three and psychrometers at two heights, during measurements at the Berlin-Schönefeld Airport in 1985 (photo: Th. Foken).

Energy exchange measurements above ice and in mountain regions

This topic was already reviewed by Foken (1999) on the occasion of the 70th anniversary of the first German-Soviet-Pamir expedition in 1928 by Finsterwalder and the second 30 years later in 1958. When scheduling the International Geophysical Year in 1958-1959, research activities were focussed on ice regions. Supported by Prof. Boulanger (Moskau), Prof. Philipps (Potsdam) and also Prof. Finsterwalder (Munich) the second expedition was planned (Skeib and Dittrich, 1960). The meteorological investigations were made by Skeib (1961; 1962) in 1958 on the Tujuksu glacier near Alma-Ata.

The main focus of the investigations by Skeib (1962) on the Tujuksu glacier were measurements of the radiation balance. The net radiation could be parametrized depending on the albedo. To determine the evaporation wind velocity, temperature und water vapour pressure were measured at heights of 25, 50, 100 and 200 cm and the fluxes were calculated with the logarithmical wind profile. The measurements made from July 12 to September 05, 1958, showed the energy input to the glacier by net radiation and sensible heat flux except for a residual of 4 %, are transferred to ablation and evaporation (Fig. 5). Because of their more than monthly measuring periods they are also relevant to describe the climate of this region.

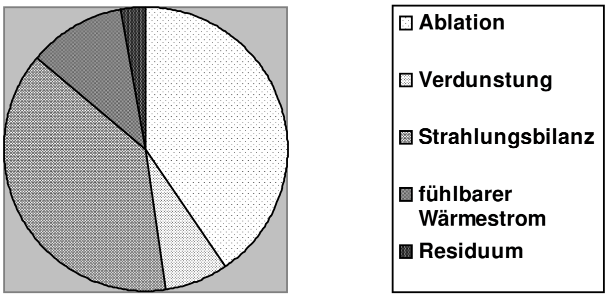


Fig. 5: Energy and water balance of the Tujuksu glacier from July 12 to Sept. 05, 1958 (runoff 113 cm) according to Skeib (1962), Ablation: ablation; Verdunstung: evaporation; Strahlungsbilanz: net radiation; fühlbarer Wärmestrom: sensible heat flux; Residuum: residual.

The Pamir expedition was a test of similar measurements in the years 1959-61 at the Soviet Antarctic station Mirni by Skeib (1968). Both expeditions were one of the first modern measurements of the heat budget of ice and snow regions. Nevertheless, the sonic anemometer technique was at this time not available and therefore the results are limited. Preparations for a new Antarctic expedition for energy exchange measurements were done at the end of the 1980s with sensor tests on Brocken Mountain (Richter et al., 1990), but the experiment took place four years later in 1994 (Foken, 1996).

Air-Sea interaction

There were only a few investigations into the interaction between the atmosphere and the ocean conducted in the former GDR. These were large scale studies of processes of the system ocean-atmosphere, based on the North Atlantic, the Caspian Sea, the Western Baltic Sea and the coastal area of the Baltic Sea near Zingst. But the air-sea interaction as a climate problem was always a topic of high relevance (Hupfer, 1982; Hupfer, 1985).

Michelsen (1989) investigated the effects of global and regional anomalies of the system ocean-atmosphere in the cold water upwelling regions of the Eastern Atlantic, which were mainly investigated by the Institute of Ocean Research, Rostock-Warnemünde. It was found that the seasonal variability is very large and determines the interannual variability. The discovered delay of one year of the parallelism of currents of the East Atlantic to the ENSO years in the Pacific was found to be insignificant because of the data availability. Hagen and Schmager (1991) investigated the relationship between anomalies of the air pressure at the surface in the North Atlantic and European region with anomalies of the sea surface water temperature (SSTA). It was shown that the interannual variations of the zonal averaged SSTA in the subtropical and tropical ocean is influenced by ENSO processes with a delay time of some months due to the anomalies of the air pressure at the surface in the mean latitudes. In cooperation with an international working group, the proposal of the creation of “Phantom Weather Vessels” in this region, which are met continuously by tankers, followed (Dickson, 1977). Harno (1981) evaluated SST observations of weather vessels in the North Atlantic and tried to find a relationship between the change of the SST and the atmospheric circulation. Continuing this direction of research, Schumann (1985) checked the hypothesis by Nikolajev, that in Europe weather relevant changes of the circulation due to SSTA in the North Atlantic depend an the phase difference of the long temperature and pressure wave in the middle troposphere. Hupfer (1988) evaluated long-term SST measurements of the ICES areas in the Northern Atlantic with statistical methods and found as a result the effect of the global warming in the 20th century in this area of the ocean as well as a corresponding phase relation to the air temperature.

Hupfer (1970) summarized existing problems and the results of maritime meteorology in the Western Baltic Sea at the end of the 1960s. Sturm (1969) presented a first extensive investigation of the heat budget of this area on the basis of measurements of the light vessel "Fehmarnbelt". The results were a basis for the evaluation of the water temperature and the heat exchange between the Belt Sea and Kattegat during the year. Monthly maps of the sensible heat flux between the atmosphere and the ocean in the region between the North Sea and the Baltic Sea on the basis of Danish light vessels were calculated and published by Helbig und Hupfer (1970).

Hupfer und Schubert (1966) determined on the basis of data of the light vessel "Gedser Rev" the conditions for the generation of sea and evaporation fog over the Baltic Sea and found a close relation to the air-sea interaction. Using data of the station Warnemünde from 1946 to 1970, Tiesel and Foken (Tiesel and Foken, 1987) investigated the energetic conditions for the generation of sea fog due to advection of cold air above the warm sea (sea smoke). Sea smoke is possible for high sensible heat fluxes and free convective conditions, with low wind and lower fluxes.

Since 1963 the main focus of the research activities of the Maritime Observatory of the Leipzig University had been investigations into the "Air-sea interaction in the coastal zone" (Hupfer et al., 2006). Based on the investigations of the heat budget of the coastal zone of the Baltic Sea and the transformation of the components of the heat budget in the zone between land and sea (Hupfer, 1974a) and the water temperature field in shallow water (Hupfer, 1974b) the variation of the wind field depending on the surface conditions were a main focus of research. The micro-structure of internal boundary layers was determined over land and sea by Hupfer et al. (1976). The increase of the drag coefficient with increasing distance to the coast line was calculated by Hupfer (1978) for off-shore winds. An extensive study about the internal boundary layer was presented by Raabe (1981). Most of these extensive investigations, not reported here in detail (Hupfer, 1984; Hupfer and Raabe, 1994), were done within complex international coastal experiments (e.g. Druet et al., 1975). Within these studies the density effect on turbulent fluxes was also investigated (Bernhardt and Piazena, 1988).

In the coastal zone of the Baltic Sea near Zingst as well as on an oil platform in the Caspian Sea near Baku, extensive measurements of the molecular sublayer over the ocean had been made since 1972 with a self-made temperature drop probe (Hupfer et al., 1975). The sensible heat flux could be determined from the temperature gradient of the 1 mm thick sublayer. The variation of the thickness depending on the wave phase is presented in Fig. 6. The study of the dynamic of this layer (Foken et al., 1978) was used for the development of an energy exchange model including molecular and turbulent transport processes (Foken, 1979).

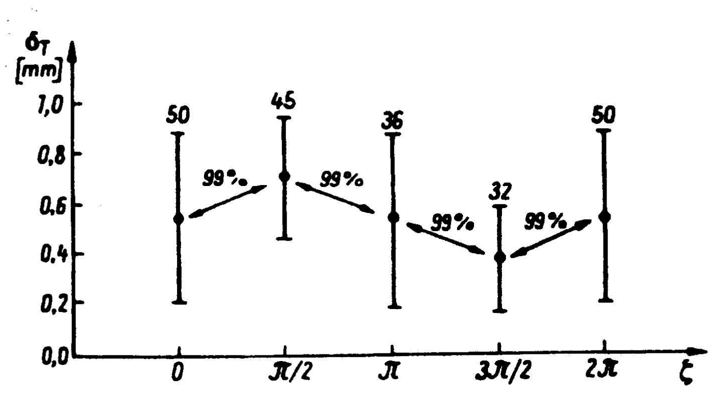


Fig. 6: Averaged heights of the molecular sublayer for temperature depending on the windward (3π/2) and lee (π/2) site of a wave. The measured differences are statistically significant (Foken et al., 1978).

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