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Fog and Boundary Layer Clouds: Fog Visibility and Forecasting

Edited by
Ismail Gultepe

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COST- the acronym for European **CO**operation in the field of **S**cientific and **T**echnical Research- is the oldest and widest European intergovernmental network for cooperation in research. Established by the Ministerial Conference in November 1971, COST is presently used by the scientific communities of 35 European countries to cooperate in common research projects supported by national funds.

The funds provided by COST - less than 1% of the total value of the projects - support the COST cooperation networks (COST Actions) through which, with only around €20 million per year, more than 30.000 European scientists are involved in research having a total value which exceeds €2 billion per year. This is the financial worth of the European added value which COST achieves.

A "bottom up approach" (the initiative of launching a COST Action comes from the European scientists themselves), "à la carte participation" (only countries interested in the Action participate), "equality of access" (participation is open also to the scientific communities of countries not belonging to the European Union) and "flexible structure" (easy implementation and light management of the research initiatives) are the main characteristics of COST.

As precursor of advanced multidisciplinary research COST has a very important role for the realisation of the European Research Area (ERA) anticipating and complementing the activities of the Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of "Networks of Excellence" in many key scientific domains such as: Biomedicine and Molecular Biosciences; Food and Agriculture; Forests, their Products and Services; Materials, Physics and Nanosciences; Chemistry and Molecular Sciences and Technologies; Earth System Science and Environmental Management; Information and Communication Technologies; Transport and Urban Development; Individuals, Society, Culture and Health. It covers basic and more applied research and also addresses issues of pre-normative nature or of societal importance.

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Pure and Applied Geophysics

Fog and Boundary Layer Clouds: Introduction

This special issue of the Journal of Pure and Applied Geophysics contains 15 papers related to fog, visibility, and low clouds that focus on microphysical and conventional surface observations, satellite detection techniques, modeling aspects, and climatological and statistical methods for fog forecasting. The results presented in this special issue come from research efforts in North America and Europe, mainly from the Canadian Fog Remote Sensing And Modeling (FRAM) and European COST-722 fog/visibility related projects. COST (http://www.cost.esf.org/) is an intergovernmental European framework for international cooperation between nationally funded research activities. COST creates scientific networks and enables scientists to collaborate in a wide spectrum of activities in research and technology. COST activities are administered by the COST Office.

Fog affects human being in various ways, both from a negative point of view (hazard to aviation, land and marine transportation) and in a positive way (fog water harvesting in arid regions). Our understanding of the physics of fog remains incomplete due to the time and space scales involved in the numerous processes influencing fog formation, development, and decay (e.g. nucleation, radiative processes, surface turbulent fluxes, mesoscale circulations, etc.). Because of this complexity, the accurate forecasting/nowcasting of fog remains difficult and related issues need to be further studied in detail. We do not know accurately how basic physical processes interact to determine the timing and location of fog formation, impeding our ability to provide accurate forecasts. Presently, typical numerical forecast models lack sufficient resolution and appropriate physical parameterizations to represent fog and use a simple approach in estimating visibility that leads to uncertainty of more than 50% in many conditions. Better forecasts would help mitigate the financial losses associated to delays at airports as well as the human and financial losses due to accidents, which can be comparable to losses resulting from tornadoes.

From an analysis perspective, the modeling issue of fog needs to be further developed because surface observations are too sparsely distributed to adequately capture the spatial variability of fog, and satellite retrievals have serious limitations in the presence of mid- and high-level clouds. Although various methods were developed for fog remote sensing from satellites, they can be limited when visibility channels are not available at night and contributions from shortwave radiation affect the near infrared channels during the day time. This implies that integrated methods need to be developed. When observations are integrated with model based output, better methods for fog nowcasting/forecasting can be developed.

Careful analysis of climatological data can serve as a basis for the better understanding of the various conditions that led to fog formation in the past. Also, if any trend occurred in the past, the fog occurrence may be predicted in the future when similar conditions occur. This defines an approach where artificial neural networks, ruled-based climatological methods, and some other statistical methods (e.g. tree approaches) can bring added-value to fog forecasting.

In this special issue, various contributions related to the above issues are included. These are the result of various COST-722 meetings and FRAM workshops, and this collection of various articles presents a cutting edge research in the field. Although the works presented here suggest that fog/low cloud visibility calculations have improved significantly, there are still issues to be resolved and it is hoped that this special issue will facilitate future works on this subject.

We wish to thank the scientific contributors to this book and members of the FRAM, and COST-722 groups, and specifically to Dr. Pavol Nejedlik who was a science officer for the Earth System Science and Environmental Domain at the COST office in Brussels. The COST is operated under the auspices of the European Science Foundation and the European Commission. We also gratefully acknowledge funding support for this work provided by the Canadian National Search and Rescue Secretariat and Environment Canada. Additional funding was also provided by the COST-722 project office. Technical support for the data collection was provided by the Cloud Physics and Severe Weather Research Section of the Science and Technology Branch, Environment Canada, Toronto, Ontario. In addition, I like to sincerely thank Prof. Renata Dmowska, Editor in chief for topical issues at Pure and Applied Geophysics, inviting our working group to prepare this special issue, handling the review process and providing invaluable advice during the preparation of this special issue. Many thanks also to Prof. Brian Mitchell for valuable suggestions during the course of this work with whom I work as an editor in Atmospheric and Ocean Sciences of the Pure and Applied Geophysics.

The editor is indebted to the reviewers who took the time and effort to carefully review the manuscripts and make suggestions for improvements. The following reviewers were involved in the review process: N. Ahmad, A. Bott, J. Bendix, T. Bergot, A. Cannon, J. Cermak, Z. Boybeyi, L. S. F. Fuente, M. Gordon, I. Gultepe, B. Hansen, P. King, S. C. Michaelides, M. Pagowski, G. Pearson, R. Tardif, A. Tokay, G. Toth, and Z. Vukovic.

I. Gultepe
Environment Canada
Dec. 15 2006

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Pure and Applied Geophysics

Obituary

This special issue on fog, low clouds and visibility is dedicated to the memory of Professor Peter Zwack, who passed away prematurely on November 8, 2005, after a courageous bout with cancer.

As a curious child, Peter was fascinated by a wide variety of weather phenomena. It is no wonder he graduated in 1966 from the renowned City College of New York with a Bachelor's Degree in Meteorology. He later went on to tackle the practical aspects of the field by working as a weather forecaster at the National Weather Service in New York City. Given his curious nature, it did not take long for Peter to reconnect with the joys of scientific discovery. He completed a Master's Degree in meteorology at New Jersey's Rutgers University in 1968 while working in the New York weather office. He then moved to Montreal to pursue a Ph.D. in radar meteorology at McGill University under the supervision of J.S. Marshall. Shortly after graduating in 1973, Peter was among the first professors hired to create the Atmospheric Sciences program at the Université du Québec à Montréal (UQAM). Part of the original mandate of the program was to provide professional training to upcoming weather forecasters hired by the Meteorological Service of Canada (MSC). At UQAM, in 1976, Peter also contributed to the creation of North America's only graduate program in Atmospheric Sciences available to French-speaking students.

Teaching and research activities geared toward the needs of the weather forecasting community would become the central themes of Peter's career. In the mid-eighties, he and a graduate student developed diagnostic equations describing in intuitive ways the mechanisms responsible for the development of large-scale weather systems and associated vertical motions in the atmosphere. The so-called "Zwack-Okossi" equations became a fixture among the practices of Environment Canada's (EC) weather forecasters and were the basis for the prototype of the DIONYSOS software, which has been developed by Peter and his students over several years. This software provides insights into the physical mechanisms influencing the vertical motions associated with synoptic weather systems and the cyclogenesis of such systems, as simulated by numerical weather prediction models. It has been implemented at operational weather centers in Canada, France and the United States.

Throughout his career, Peter had a profound desire to teach. He was renowned for his ability to illustrate difficult subjects in lucid and simple ways. Classes he taught ranged from "Introduction to Meteorology," taken as an elective by numerous students from other programs, to undergraduate and graduate-level "Synoptic Meteorology." He also taught the meteorology fundamentals to UQAM students who studied to become high school science teachers. Peter also remained involved in the professional training world for most of his career. He was among the developers of the EUROMET project which culminated in the availability of online interactive training modules used by European weather forecasters. The EUROMET project was awarded, in 1998, the prize for best European educational software.

From the nineties onward, aviation meteorology became one of the main thrusts of Peter's efforts. He recognized that the prediction of low cloud ceilings and fog remained among the most challenging tasks performed by forecasters. Peter was instrumental in establishing the STRATUS project, which involved a wide spectrum of experts in meteorology, artificial intelligence and software engineering. The project led to the development of an expert system for the short-term forecasting of low cloud ceilings and produced a number of spin-off projects that developed software applications currently in use at EC's weather offices. These efforts were followed by Peter's involvement in a project aimed at providing improved guidance to personnel tasked with forecasting the dissipation of marine stratus in the approach zone of the San Francisco airport. Peter provided scientific leadership on the application of high-resolution one-dimensional numerical modeling to that specific problem. In 2002, the Federal Aviation Administration awarded Peter and the other members of the development team a certificate of recognition for their efforts resulting in the operational Marine Stratus Forecast System for the San Francisco International Airport.

Peter received individual honors and prizes during his career. In 1992 he was awarded the Dr. Andrew Thomson Prize from the Canadian Meteorological and Oceanography Society for his innovative contributions to the field of applied meteorology. He was also recognized in 1997 by the Association Professionelle des Météorologistes du Québec with the "Alcide Ouellet" prize for his contribution to the meteorology profession.

Always active in the community, Peter served as the president of the Canadian Meteorological and Oceanography Society in 1996–1997. He also served on many committees and advisory boards on a range of subjects dear to him, from artificial intelligence to the role of the private sector in meteorology. These activities underscored Peter's eagerness to collaborate with others and his constant desire to exchange ideas with members of the atmospheric science community.

Perhaps Peter's greatest achievements were outside meteorology. As a father with a son diagnosed with autism, Peter became a determined advocate for the rights of autistic people and their caretakers, and raised awareness and understanding about the disorder. He was vice-president of the Montreal Autism Society from 1990 to 1995, president of the Québec Society for Autism from 1995 to 2000, and joined the Board of Autism Society Canada in 2000. He became vice-president in 2001 and president in 2004. Throughout this period, he spearheaded numerous initiatives to better the lives of autistic children and adults alike, as well as family members providing constant care.

The passing of Peter represents a great loss not just for science, but for the autism community as well. We have lost an exceptional colleague and a good friend. He will be remembered by many colleagues and numerous students for his communicative laughter, enthusiasm, intellectual mind, and kind heart.

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Dec. 15 2006

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Pure and Applied Geophysics

Fog Research: A Review of Past Achievements and Future Perspectives

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Abstract—The scientific community that includes meteorologists, physical scientists, engineers, medical doctors, biologists, and environmentalists has shown interest in a better understanding of fog for years because of its effects on, directly or indirectly, the daily life of human beings. The total economic losses associated with the impact of the presence of fog on aviation, marine and land transportation can be comparable to those of tornadoes or, in some cases, winter storms and hurricanes. The number of articles including the word "fog" in Journals of American Meteorological Society alone was found to be about 4700, indicating that there is substantial interest in this subject. In spite of this extensive body of work, our ability to accurately forecast/nowcast fog remains limited due to our incomplete understanding of the fog processes over various time and space scales. Fog processes involve droplet microphysics, aerosol chemistry, radiation, turbulence, large/small-scale dynamics, and surface conditions (e.g., partaining to the presence of ice, snow, liquid, plants, and various types of soil). This review paper summarizes past achievements related to the understanding of fog formation, development and decay, and in this respect, the analysis of observations and the development of forecasting models and remote sensing methods are discussed in detail. Finally, future perspectives for fog-related research are highlighted.

Key words: Fog review, fog observations, fog modeling, fog remote sensing, fog forecasting.

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1. Introduction

The effect of fog on human life was recognized in the early ages of mankind but its impact has significantly increased during recent decades due to increasing air, marine, and road traffic. In fact, the financial and human losses related to fog and low visibility became comparable to the losses from other weather events, e.g., tornadoes or, in some situations, even hurricanes. The purpose of this review is to summarize the earlier works on fog and to lay a basis for the articles presented in this special issue and outline perspectives for future fog research.

The earliest works on fog can be traced back to Aristotle's Meteorologica (284–322 B.C.). These were extensively referenced by NEUMANN (1989) in his study of early works on fog and weather. This paragraph is mainly based on his detailed work. In the English translation by H.D.P. Lee (1962, ARISTOTLE), a statement is given on the relationship between fog and good weather. Also, NEUMANN (1989) relates a poem by ARATUS (315–240 B.C.), which was referred to as Prognostication Through Weather Signs, in an English translation by G.R. Mair (ARATUS, 1921). The poem reads " *If a misty cloud be stretched along the base of a high hill, while the upper peaks shine clear, very bright will be the sky. Fair weather, too, shall thou have, when by sea-verge is seen a cloud low (fog) on the ground, never reaching a height, but penned there like a flat reef of rock"*. In this regard, Pliny the Elder (A.D. 23–79, PLINY, 1971), a Roman historian, admiral, scientist and author, states in his work of Natural History "....... *Mist (fog) coming down from the mountains or falling from the sky or settling in the valleys will promise fine weather."* These works suggested that fog was recognized for use as a fair weather predictor.

The influence of fog was also felt on historical events. LINDGREN and NEUMANN (1980) describe one such event during the Crimean War, when the Russian empire faced the alliance of Britain, France, and Turkey. The allied forces landed in Crimea in September 1854. Intense fog developed early on the morning of the 5th, just when the Russian forces were launching their first major offensive. The allied forces could not realize what was occurring on the other side. It was stated that "*...for the vapors, fog, and drizzling mist* obscured the ground to such an extent as to render it impossible to see what was going on at a distance of a few yard." This suggests that fog was a major player in this historical event.

The formation of fog and its extent at the surface are not easy to predict. The fog formation does not always occur in calm windless conditions. In fact, the formation of fog associated with turbulent windy conditions was studied at the end of 18th century. SCOTT (1896) stated that fogs with strong winds occurred in the British Isles, and sometimes lasted a month. He also mentioned that the strong wind fogs were accompanied by rain which was frequently heavy. SCOTT (1894) showed that fog occurrence was correlated to strong winds (Beaufort scale of 6), and that there was no clear relationship between weather patterns (e.g., cyclonic or anticyclonic) and fog formation. Scott also stated that the total number of fog cases with strong wind was estimated to be about 135 over 15 years. The role of aerosols in fog formation was recognized by MENSBRUGGHE (1892) who stated that "*aqueous vapor condenses in the air only in the presence of solid particles around which the invisible vapor becomes a liquid.*" The heavy London fog on 10–11 January, 1925 followed the great fog of December 1924 (BONANCINA, 1925). During this episode, two types of fog occurred: 1) unsaturated haze without condensation and 2) fog with liquid characteristics. These fog episodes paralyzed the entire city with very low visibility values. This discussion shows that fog formation and its relation to environmental conditions were known early on but detailed field and modeling works were limited.

The importance of fog and low ceiling in weather forecasting was studied by WILLETT (1928). In his detailed work, he emphasized the importance of condensation nuclei for fog formation. He listed that dust particles with some degree of surface curvature, particles having an electric charge or ions, and hygroscopic particles were facilitating agents to droplet formation. He also proposed a classification for fog and haze based on causes and favorable synoptic conditions. Overall, fogs were classified into two groups: 1) airmass fogs and 2) frontal fogs. Subsequently, he emphasized the importance of all meteorological parameters affecting fog formation. For each group, he then sub-classified them, e.g., advection type, radiation fog, and marine fog, etc. He also summarized the works done by others such as KÖPPEN (1916, 1917), TAYLOR (1917), and GEORGII (1920).

Numerous field studies with a focus on fog and other boundary layer clouds were performed over the last few decades. Among the regions where these experiments took place are the coastal regions off the California coast in the western United States. Review articles on issues of fog that focused on West Coast marine fog and stratocumulus were presented by LEIPPER (1994) and KLOESEL (1992). Among the noteworthy experiments was the CEWCOM project (1977) which consisted of a major set of experiments off the California coast conducted during the 1972–1982 time period under the US Navy Naval Air Systems Command. These series of meso- and micro-meteorological experiments involved a land and sea network of radiosonde observations, ships, aircraft, balloons, and kites. Studies based on observations were complemented by modeling studies. An investigation of low-level stratus/fog was performed by KORACIN *et al.* (2001) using a one-dimensional (1-D) model and observations with results suggesting that radiative cooling and large-scale subsidence was an important factor for fog formation. The interactions between radiative and turbulence processes studied in detail by OLIVER *et al.* (1977; 1978) suggested that radiative cooling at fog top was an important process in the fog life cycle. Similarly, it was shown by WELCH and WIELICKI (1986) that ~5C°/hour cooling occurred during a simulation of warm fog layer in which the liquid water content (LWC) reached 0.3 g m^{-3}. These results were found to be comparable with observations. Radiation fog studies using detailed surface observations were lead by MEYER *et al.* (1986), ROACH *et al.* (1976), and CHOULARTON *et al.* (1981). These authors also focused on various aspects of fog formation and its evolution by using numerical models. FUZZI *et al.*

(1992) carried out the Po Valley Fog Experiment which was a joint effort by several European research groups from five countries. The physical and chemical behavior of the multiphase fog system was studied experimentally by following the temporal evolution of the relevant chemical species in the different phases (gas, droplet, interstitial aerosol) and the evolution of micrometeorological and microphysical conditions, from the pre-fog state, through the whole fog life cycle, to the post-fog period. FUZZI *et al.* (1998) also conducted a second field project called CHEMDROP (CHEMical composition of DROPlets) that took place in the Po Valley region. Their project focused mostly on fog microphysics and chemistry as in the previous field experiment. Ice fog studies (BOWLING *et al.*, 1968; GIRARD and BLANCHET, 2001; GOTAAS and BENSON, 1965) were limited due to the difficulties of measurement ice particles at sizes less than 100 μm (GULTEPE *et al.*, 2001). However, Gotaas and Benson results showed that 10°C/day cooling was due to ice fog occurrence on January 1962. More recently, GULTEPE *et al.* (2006a) and GULTEPE and MILBRANDT (2007) conducted a field project over Eastern Canada for marine fog studies and at a site in the Ontario region for winter warm fog studies with a focus on nowcasting/forecasting issues. These projects contributed to the better understanding of fog physics, and the development of parameterizations for numerical models and remote sensing studies.

In addition to fog formation, development and decay, the artificial dissipation of fog was also studied in the early 1970s. The main objective of these works was to study how fog can be eliminated from a specific area such as over an airport or a shipping port. Because the fog droplets are found in a narrow drop size range e.g., 4–10 μm, by somehow increasing droplet size, the dissipation of fog can occur through coalescence processes. The work by HOUGHTON and RADFORD (1938) was the first to use hygroscopic particle seeding to dissipate fog droplets. JIUSTO *et al.* (1968) studied the possibility of fog dissipation by giant hygroscopic nuclei seeding and stated that the use of carefully controlled sizes and amounts of hygroscopic (NaCl) nuclei can produce significant improvements in visibility. KORNFELD and SILVERMAN (1970) and WEINSTEIN and SILVERMAN (1973) also indicated similar results and stated that if the fog droplet size distribution is known, the seeding nuclei are to be chosen carefully for dissipating the fog. These works suggested that fog dissipation seems possible but its detailed microphysics should be known. Another method used helicopters to dissipate fog on the theoretical basis of turbulent mixing of dry air into the fog layer by the helicopter's downwash (PLANK *et al.*, 1971).

The increased fog water content as dripping water, opposite to the fog dissipating idea, was used as a resource for the ecosystem hydrology and water resources. The Standard Fog Collector (SFC) was developed by SCHEMENAUER AND CERECEDA (1994) which is a 1 m^2 frame with a double layer of 40% shade cloth mesh. It is set up perpendicular to the prevailing wind direction. The collected fog water is routed from the collection trough to a large-capacity tipping bucket gage with data logger to measure the amount and frequency of precipitation. The polypropylene nets similar to the original SFC over the coastal cliffs and desert areas transform windborne fog and mists into water. Fog catchers use a simple idea in which a fine-mesh netting is placed against the wind that carries fog droplets, so that water would condense on the filaments. At the arid stretches of coastal Chile, Peru, Ecuador, and several other countries around the world, this method was utilized to obtain water from fog droplets. Trees also serve as natural fog catchers (AZEVEDO and MORGAN, 1974); a forest growing in an arid area can provide as much water as rain into the dry soil. They suggested that fog drifting inland is caught by plant leaves, the nutrients contained in the fog as nuclei and dissolved gases become available to the plants. Some nutrients may be absorbed directly by the leaf and the rest become available to the plants via the soil as water drips to the ground.

The number of articles that includes the word "fog" in the American Meteorological Society (AMS) published journals was found to be about 4700, suggesting that there is an abundance of works on this subject. In spite of this extensive body of work, concerns related to fog forecasting/nowcasting still remain because of fog's considerable time and space variability related to interactions among various processes.

Among the reasons behind the difficulties in accurately forecasting/nowcasting fog are the difficulties in detecting fog and representing the physical processes involved. Remote sensing of fog using satellites is very useful but more spectral channels compared to the ones available are needed to improve detection algorithms (ELLROD and GULTEPE, 2007). Lately, a Moderate Resolution Imaging Spectroradiometer (MODIS) base algorithm (BENDIX *et al.*, 2006) for fog detection has been developed and includes more channels in the near IR and better resolution (of about 100 m). Although various methods were developed for forecasting and nowcasting applications, the accuracy of these algorithms needs to be assessed further, especially over snow and ice surfaces. From the numerical modeling point of view, important issues are related to the horizontal (PAGOWSKI *et al.*, 2004) and vertical (TARDIF, 2007) resolutions, and physical parameterizations (GULTEPE *et al.*, 2007b). For instance, if the total droplet number concentration (N_d) is not obtained prognostically, it can be obtained diagnostically as a function of supersaturation or simply fixed (GULTEPE and ISAAC, 2004). It is a well known fact that visibility in fog is directly related to N_d. In the large-scale models, N_d is either not considered or is simply fixed. In most models, visibility is obtained from extinction versus LWC relationships (KUNKEL, 1984), in turn, LWC is obtained using either a simple LWC-T relationship (GULTEPE and ISAAC, 1997) or a prognostic equation (TEIXEIRA, 1999; BERGOT and GUÉDALIA, 1994; BOTT and TRAUTMANN, 2002; PAGOWSKI *et al.*, 2004). Therefore, detailed three-dimensional cloud/fog models are needed to better understand issues related to fog, but they are not used extensively because of the computational cost involved in producing operational forecasts (MÜLLER *et al.*, 2007; GULTEPE *et al.*, 2006b). One-dimensional (1-D) models are cheaper to run and can prove to be useful in certain situations (BERGOT and GUÉDALIA, 1994; BERGOT *et al.*, 2005; BOTT, 1991). However, their applicability becomes limited in regions of complex and heterogeneous terrain (MÜLLER *et al.*, 2007). The applicability of the different modeling strategies for fog forecasting and various parameterizations requires extensive research.

In order to better evaluate forecasts of fog formation, development, and decay, field observations should be used for verification purposes. This can be done: 1) using carefully analyzed climatological surface data (TARDIF and RASMUSSEN, 2007), 2) *in situ* observations (GULTEPE *et al.*, 2006; GULTEPE *et al.*, 2007b), and 3) remote sensing data (CERMAK and BENDIX, 2006). Detailed studies by TARDIF and RASMUSSEN (2007), HANSEN *et al.* (2007), and HYVARINEN *et al.* (2007) suggest that the climatological data can help in developing better understanding of fog formation, forecasting methods, and organize better field programs (GULTEPE *et al.*, 2006b). In the following sections, fog definition and types, observations (including field and remote sensing observations), models, climatology and statistical methods, and concluding remarks together with discussions will be given in the context of prior achievements and future works.

2. *Definition and Fog Classification*

The international definition of fog consists of a collection of suspended water droplets or ice crystals near the Earth's surface that lead to a reduction of horizontal visibility below 1 km (5/8 of a statute mile) (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1995). If the visibility is greater than 1 km, then it is called mist (WMO, 1966). Prevailing visibility is the maximum visibility value common to sectors comprising one-half or more of the horizon circle (MANOBS, 2006). Water droplets and ice crystals, typically 5 to 50 μm in diameter (PRUPPACHER and KLETT, 1997), form as a result of supersaturation generated by cooling, moistening and/or mixing of near surface air parcels of contrasting temperatures. The presence of suspended droplets and/or crystals can render an object undistinguishable to a distant observer and thus causes poor visibility conditions. This occurs through a reduction in the brightness contrast between an object and its background by particle concentration and size-dependent scattering losses of the light propagating between the object and the observer (GAZZI *et al.*, 1997; 2001) and through the blurring effect of forward scattering of light due to the presence of the droplets/crystals (BISSONETTE, 1992).

Several approaches have been used in the classification of fog. It can be based on physical (freezing fog), thermodynamical (mixed phased fog) properties, dynamical processes (mixing and turbulence fog), chemical composition of particles (dry fog), physiographic character of the surface (valley fog), and meteorological features (frontal fog). An earlier work by PETTERSSEN (1956) suggested that fog can also be divided into three subsections: 1) Liquid fog ($T > -10°C$), 2) mixed phase fog

($-10°C > T > -30°C$), and 3) ice fog ($T < -30°C$). These fog types can occur under the various scenarios listed above. One should recognize that the criteria used in this respect do not always occur in a clear-cut fashion as implied by the classification. For example, ice fog may occur at $T = -20°C$ when excessive vapor is used by ice nuclei within a steady-state condition occurring with no mixing processes (GULTEPE *et al.*, 2007b). Usually freezing fog occurs when T gradually decreases below 0°C.

As suggested by the discussion above, fog does occur in a wide variety of conditions. These conditions can be described using various fog types. WILLETT (1928) study, later modified by BYERS (1959), established a classification describing eleven types of fog, each defined by the main physical processes responsible for their formation as well as circumstances in which these processes occur.

The most studied and therefore well-described fog types are those associated with radiative cooling over land. These can be divided among: 1) radiation fog, 2) high-inversion fog, and 3) advection-radiation fog. Radiation fog usually forms near the surface under clear skies in stagnant air in association with an anticyclone. Numerous researchers have devoted efforts to understanding the relationship between the occurrence of this type of fog with the various mechanisms known to influence the evolution of the nocturnal boundary layer. The main mechanism is radiative cooling, but the opposing influences of upward soil heat flux, as well as warming effects and moisture losses through dew deposition from turbulent mixing in the stable boundary layer largely determine the likelihood and timing of radiation fog formation (TAYLOR, 1917; LALA *et al.*, 1975; ROACH, 1976; ROACH *et al.*, 1976; BROWN and ROACH, 1976; PILIÉ *et al.*, 1975; FINDLATER, 1985; TURTON and BROWN, 1987; FITZJARRALD and LALA, 1989; BERGOT and GUÉDALIA, 1994; ROACH, 1995a; DUYNKERKE, 1999). Advection-radiation fog is a coastal phenomenon and results from the radiative cooling of moist air that has been advected over land from the ocean or from any large water body during the previous daylight hours (RYZNAR, 1977). So-called high-inversion fog usually forms in valleys within a deep moist layer capped by a strong inversion (HOLETS and SWANSON, 1981). The inversion results from prolonged radiative cooling and subsidence associated with a persistent anticyclone. This type of fog is common during winter in the Central Valley of California (UNDERWOOD *et al.*, 2004).

Another relatively well-studied fog type is associated with the advection of a moist airmass with contrasting temperature properties with respect to the underlying surface and is therefore referred to as advection fog. BYERS (1959) makes the distinction between sea fog, land- and sea-breeze fog, and tropical-air fog even though all are associated with advection of moist warm air over a colder water surface. Sea fog typically occurs as a result of warm marine air advection over a region affected by a cold ocean current, and thus, it is common at sea in locations where boundaries with cold ocean currents can be found, such as the Grand Banks of Newfoundland and areas over the coastal northeastern United States, in the North Pacific, off the west coast of North America and over the British Isles (LEWIS *et al.*, 2004). The frequency of this type of fog is maximized when air with a high dew point initially flows over a sea-surface with a few degrees colder (TAYLOR, 1917; FINDLATER *et al.* 1989; KLEIN and HARTMANN, 1993; ROACH, 1995b; CROFT *et al.*, 1997; CHO *et al.*, 2000). In contrast to this, PILIÉ *et al.* (1979) reported cases where marine fog patches are associated with regions having a warmer ocean surface, where buoyant mixing of the moist near surface air results in saturation of the low-level air. Adding to the complexity, TELFORD and CHAI (1993) report on the dissipation of an existing fog layer over warmer water, with a sensitivity of the fog behavior on the temperature and moisture structure above the fog layer. Once fog has formed, its evolution is largely determined by the influences of radiative cooling at fog top, subsidence, drizzle and the evolution of surface heat and moisture turbulent fluxes as the air flows over sea-surface temperature gradients (FINDLATER *et al.*, 1989). Furthermore, it has been shown that the origin and history of air masses are important factors in the observed variability in the spatial distribution of fog/stratus in the coastal zone (LEWIS *et al.*, 2003). Land- and sea-breeze fogs are purely coastal phenomena and occur when warm moist air over land is transported offshore over the cool coastal ocean, leading to fog formation. This fog may subsequently move over land under the influence of a sea-breeze circulation that sets up during the following afternoon hours. Tropical-air fog is another advection fog type and is associated with long-range transport of tropical air pole-ward along the large-scale latitudinal ocean temperature gradient leading to gradual cooling of the air mass. Advection fog has also been observed over land in winter in the central United States as warm moist air flows over the cooler (sometimes snowy) surface (FRIEDLEIN, 2004).

Another type of fog associated with advection and mixing is the so-called steam fog. It tends to be observed in the Arctic and results from cold air with a low vapor pressure being advected over a relatively warm water surface. The difference in vapor pressure between the air and the water surface leads to evaporation, and mixing of water vapor into the cold air leads to supersaturation and fog (SAUNDERS, 1964; ØKLAND and GOTAAS, 1995; GULTEPE *et al.*, 2003).

Fog may also form as a result of a cloud base lowering all the way to the surface. Some influences have been cited by various authors, mainly dealing with conditions out over the open ocean. For instance, the presence of a sufficiently shallow cloudy marine boundary layer capped by a strong inversion and a sufficiently moist subcloud layer (dew point higher than the sea-surface temperature by a few degrees) have been cited by PEAK and TAG (1989) and TAG and PEAK (1996) as important factors. Furthermore, cloud base lowering has been shown to be tied to the diurnal cycle of stratiform boundary layer clouds related to the interaction of the cloud with radiation (DUYNKERKE and HIGNETT, 1993). The coupling of the cloud layer with the subcloud layer occurs as top-down turbulent mixing is generated by the destabilization induced by the radiative cooling at cloud top. Radiatively cooled air is transported downward by the turbulent eddies, cooling the subcloud layer and thus leading to a lowering of cloud base (OLIVER *et al.*, 1978; PILIÉ *et al.*, 1979). It has been hypothesized that this process can be aided by the moistening of the subcloud layer by the evaporation of settling cloud droplets or drizzle drops (PILIÉ *et al.*, 1979). Adding to this complex picture, KORAČIN *et al.* (2001) and LEWIS *et al.* (2003) have shown that stratus lowering can occur under the influence of persistent subsidence leading to a decrease in the depth of the marine boundary layer.

Fog forming together with precipitation, often referred to as frontal fog, is described as a common occurrence ahead of warm frontal boundaries (GEORGE, 1940a,b,c; BYERS, 1959; PETTERSSEN, 1969). Its presence has also been documented in regions of extra-tropical cyclones characterized by a transition in precipitation type (STEWART, 1992; STEWART *et al.*, 1995) presumably due to the evaporation of melting or freezing precipitation hydrometeors (DONALDSON and STEWART, 1993). BYERS (1959) further divided the precipitation fog type into three subcategories: pre-frontal, post-frontal and frontal passage fogs. Pre-frontal fog is usually associated with an approaching warm front. The textbook explanation involves the evaporation of warm rain into the stable cold air near the surface, leading to saturation and fog formation. Post-frontal fog usually occurs behind a cold front and is much like pre-frontal fog as the main mechanism is the evaporation of falling precipitation, but is less likely to be widespread as the precipitation bands associated with cold fronts occur over a smaller spatial scale. Frontal passage fogs are said to be associated with the mixing of near saturated air from the warm and cold air masses. This further separation of precipitation-induced fog into subcategories merely describes the various scenarios under which fog is observed and does little in terms of providing a comprehensive description of the physical processes involved.

Finally, upslope fog is associated with the cooling of near-surface moist air resulting from an adiabatic expansion as it is forced to higher elevations, and thus lower pressure, by topography.

This discussion confirms that fog is influenced by numerous factors, spanning multiple spatial and temporal scales. This complexity is central to the persistent difficulty associated with providing accurate fog forecasts.

3. Observations and Models

3.1. Microphysics and Nucleation Processes

Fog formation typically occurs in aerosol-laden surface air under high relative humidity conditions, ranging from undersaturated to slightly supersaturated conditions (PRUPPACHER and KLETT, 1997). Fogs are typically composed of a mixture of micron-size haze (unactivated) particles and activated droplets reaching tens of microns in size (PINNICK *et al.*, 1978; HUDSON, 1980; GERBER, 1981). Compared to convective cloud types where strong updrafts generate higher levels of supersaturation, fog droplets are generally smaller than cloud droplets and the resulting LWC generally remain small. Most fogs have LWC ranging from 0.01 to 0.4 g m^{-3} (GULTEPE *et al.*, 2007b).

Significant variability has been observed in the droplet size distribution (DSD) in fog. For instance, KUNKEL (1982) reports various shapes in DSDs measured in advection fogs. Some DSDs were characterized by continuous decrease of droplet concentration with size which can simply be parameterized by a power law. Other DSDs were observed to be distinctly bi-modal (GULTEPE *et al.*, 2007b) while others exhibited hybrid characteristics, with the presence of a nearly constant droplet concentration for droplet size between 20 and 30 μm in diameter. Other studies have shown the development of mostly bi-modal DSDs in mature radiation fogs (PILIÉ *et al.*, 1975; ROACH *et al.*, 1976; PINNICK *et al.*, 1978; MEYER *et al.*, 1980; WENDISCH *et al.*, 1998). Processes shaping the microstructure of fog include activation and diffusion growth of droplets, droplet growth related to radiative cooling, as well as turbulent mixing and differential gravitational settling of drops of different size.

Intricate relationships exist between aerosols and fog characteristics since the activation and diffusion growth of droplets depends on the physico-chemical character of the ambient aerosols. For instance, fog is more likely to appear in an environment with large concentrations of aerosols characterized by a low activation supersaturation. Early efforts were performed by J. Aitken in 1880s (KNOTT, 1923). NEIRBURGER and WURTELE (1948) and ELDRIDGE (1966) studied aerosol characteristics and droplet nucleation related to various environmental conditions and they established a dependency between fog microstructure and the characteristics of condensation nuclei. This was later confirmed by HUDSON (1980), who found systematic differences in fog microstructure between polluted urban and cleaner maritime air masses. Fog which formed in polluted environments was characterized by DSDs for which the distinction between inactivated haze particles and activated droplets was not as straightforward as for other clouds types, whereas a clearer demarcation existed in the case of fogs forming in the cleaner maritime air. The complexity of the aerosol-fog microphysics interdependence is an important process in the understanding of fog processes. It has been shown that the occurrence of fog also has an impact on ambient aerosols (YUSKIEWICZ *et al.*, 1998) who summarized aerosol characteristics related to fog formation from measurements of particles in various size ranges (from 0.003 μm up to 47 μm) covering the ultra fine, Aitken, and accumulation modes as well as the activated fog droplets. A comparison of particle number concentrations during fog and clear air conditions suggested a 78% and 65% decrease in ultra fine and accumulation mode particles, respectively. This points out the important scavenging influence of fog.

A numerical study performed by BOTT (1991) provides further insight into the dependence of the fog's microstructure and life cycle on the properties of aerosols. He performed simulations using aerosol size distributions and properties typical of urban, rural and maritime environments and showed that aerosols have a direct influence on the life cycle of a fog layer. In urban environments fog is characterized by the presence of absorbing aerosols and its formation is delayed by small aerosol number concentrations while higher number concentrations of aerosols yield the highest vertical extent of the fog layer and highest fog water contents. This is related to the radiative effects of absorbing particles, decreasing the incoming solar radiation at the surface and leading to an early initiation of the evening transition of the boundary layer and earlier formation of fog. The fog layer then is allowed to deepen over a longer time period and generate higher LWC under the influence of prolonged cooling at fog top.

In terms of DSD, the main difference between urban and other aerosol models has been found in droplet concentrations for the submicron-size droplets. The concentration of inactivated drops was found to be roughly an order of magnitude higher for the urban aerosols compared to the rural aerosols. Similar results were obtained for rural aerosols compared to maritime aerosols. Supersaturation within the fog was also found to be strongly dependent on aerosol properties. The higher the particle concentration, the lower supersaturation are. However, supersaturation levels have also been found to depend on dynamical processes, such as large supersaturations resulting from turbulent mixing processes (PILIÉ *et al.*, 1975; GERBER, 1991).

Significant high frequency variability in fog droplet concentration and LWC has also been reported in the literature. Observations from GARCÍA-GARCÍA *et al.* (2002) suggest that fog layers are heterogeneous in nature. Small–scale variability in fog microstructure has been observed, with regions of decreased droplet concentration corresponding to broader DSDs. Rapid temporal variations in droplet concentrations, sometimes with amplitudes corresponding to two orders of magnitude (GERBER, 1981; 1991), and LWC from near zero up to 0.5 g m^{-3} have been observed (FUZZI *et al.*, 1992). Some fluctuations are seemingly random while others are found to be quasi-periodic in nature. Random fluctuations are thought to be related to intermittent turbulent mixing events (PILIÉ *et al.*, 1975; GERBER, 1991) while some evidence points to the fact that quasi-periodic oscillations are the result of the interaction between the radiatively induced droplet growth and subsequent depletion of LWC by the enhanced gravitational settling of the larger droplets (BOTT *et al.*, 1990).

Lower frequency variations in the microphysical character of fog layers have also been tied to the various stages defining the life cycle of fog by some authors (PILIÉ *et al.*, 1975; KUNKEL, 1982). Concurrent increases in droplet concentration, mean droplet size and LWC have been observed to occur gradually during the formation stage of fog. This is followed by the mature stage, generally characterized by nearly constant mean droplet concentration and LWC, and a gradually decreasing mean droplet size. JIUSTO (1981) suggested a relationship for visibility as a function of both droplet size and LWC, showing that LWC was directly related to droplet size. The dissipation stage typically occurs as the droplet concentration, mean droplet size, and LWC all decrease.

generation. Thus fogs are generally less likely to occur over rough (e.g., urban) than over smooth (e.g., field) terrain but either way the air parcel needs to be saturated. Surface processes are rather easier to parameterize for marine fogs which are usually associated with advection of warm air over colder waters and vapor condensation in the cooled surface layer. A reverse process can also occur when cool and relatively dry air is brought over warm waters leading to evaporation from the surface and vapor condensation.

Turbulence and radiative processes can have an important role in fogs characteristics that can be both constructive to their formation, or destructive leading to their dissipation. Observations as well as modeling provide sometimes contradictory answers with regard to this problem (e.g., BROWN and ROACH, 1976; ROACH *et al*., 1976; LALA *et al*., 1982), depending on atmospheric conditions. For example, for radiative fogs, enhanced vertical mixing in strong turbulence can lead to droplet evaporation when they mix with the drier air above. On the other hand, fog can form after dew having evaporated from the surface is carried upward with turbulence, and then condenses in the air above. Destabilization of the atmosphere via radiative cooling of stratus tops can also lead to enhanced turbulence and downward mixing of cloud droplets leading to fog as mentioned in section 2.

As of now, modeling often does not provide a clear answer to the role of turbulence since results depend on the parameterization of turbulence and radiative processes, both burdened with significant uncertainty. Development and improvement of turbulence parameterizations in stable stratifications might lead to better understanding and forecasting of fogs. Complexity of turbulence and surface parameterizations plus the required high vertical and horizontal resolutions pose a major obstacle for successful and timely fog forecasts. For this reason, surface conditions and turbulence flux parameterizations will remain a significant research area for fog research and its modeling.

3.3. Remote Sensing Applications

The first goal in the investigation of radiative processes in natural fogs was to learn about the propagation and modification of electromagnetic radiation, and then develop and optimize optical systems to measure horizontal visibility. Pioneer work by GRANATH and HULBURT (1929), HOUGHTON (1931) and STRATTON and HOUGHTON (1931) dealt with absorption and transmission of light by/through fog in solar wavelengths. In the 1960s and 1970s, several studies addressed the relationship between fog properties and broad band extinction/horizontal visibility (e.g., DICKSON and VERN HALES, 1963; ELDRIDGE, 1971). The work was done to better understand the applicability of Koschmieder's law (KOSCHMIEDER, 1924) for various drop size distributions (DSD). To address the needs of the air traffic industry, slant visibility was investigated to find relations to horizontal visibility at ground level, required to estimate the visibility along the touch down path of aircraft through

with the atmospheric radiation field. Later, BALLARD *et al.* (1991) used a 3-D numerical weather prediction model to simulate sea fog and they pointed out the importance of initial conditions and vertical resolution. GOLDING (1993) stated that the development of local nocturnal winds in complex terrain often determines the location and timing of fog formation. GUÉDALIA and BERGOT (1994) illustrated in their one-dimensional fog model the importance of advection terms and their role in fog formation and evolution. In addition to the above studies, SIEBERT *et al.* (1992a, b) and VON GLASOW and BOTT (1999) included the new modules into their fog models to simulate the influence of vegetation on the evolution of radiation fogs. In these later models, the evolution of the droplet size distribution and cloud condensation nuclei is explicitly calculated although even today such an approach is computationally very expensive. For a better understanding of the three-dimensional structure of radiation fog and its generation mechanisms, NAKANISHI (2000) applied a large-eddy simulation and found distinct flow regimes in the various stages of the fog layer's evolution. Based on these results, NAKANISHI and NIINO (2004, 2006) developed a second-order turbulence closure appropriate for fog modeling that was used for forecasting in a regional model. Other applications of 3-D models for fog forecasting include PAGOWSKI *et al.* (2004).

In addition to the one-dimensional models, single-column versions of existing 3-D models have been frequently used for the fog studies. (e.g., BRETHERTON *et al.*, 1999; DUYNKERKE *et al.*, 1999; TEIXEIRA, 1999). Recently, the 1-D models have been developed for research and operational purposes e.g., TEIXEIRA and MIRANDA (2001) who combined a set of established parameterizations with the finite-element methods for the vertical discretization. In fact, the microphysical and turbulence parameterizations for numerical weather prediction and climate models were first used as a part of the 1-D forecasting models.

The coupling of 1-D and 3-D models and their integration with observations lead to promising results for fog forecasting. BERGOT *et al.* (2005) clearly demonstrated the necessity of using surface measurements in 1-D models with a local assimilation scheme. CLARK and HOPWOOOD (2001) used a modified single column version of the UK Meteorological Office Unified Model which is driven by an operational 3-D forecasting model. Similarly, MÜLLER (2006) developed a 1-D variational assimilation scheme for surface observations and coupled two 1-D models with several operational 3-D models to produce an ensemble forecast. Currently, parameterized versions of detailed fog microphysics originating from 1-D models were incorporated into 3-D models and were able to improve visibility forecasts (MÜLLER, 2006; GULTEPE *et al.*, 2006b; GULTEPE and MILBRANDT, 2007).

Successful numerical modeling and forecasting of fog depends on the fog type that has to be predicted. Some fog events are largely driven by dynamic processes, such as advection fog and orographic fog (PEACE, 1969; WEICKMANN, 1979; MARKUS *et al.*, 1991; TJERNSTROM, 1993). The results of a study by PEACE (1969) suggested that orographic effects associated with the foothills of the Rocky Mountains tend to

However, new data driven methodologies are now available which can handle the inherent uncertainty in the analysis. The concept of statistical modeling is now-a-days more generic, in the sense that it encompasses a wider range of procedures for treating uncertainty and which have been devised as a result of modern computational methodologies. It is within this context that the term *statistical forecasting* is used in this section and some newer methodologies are reviewed briefly.

Artificial Neural Networks (ANN) are computational methodologies capable of establishing associations between the independent variables (i.e., the predictors) and the dependent variable (i.e., predictand), through the experimentation of a multitude of situations (i.e., learning data set). Information on the relationship between the predictors and the predictand is placed in a net of interacting nodes. Although ANN have been extensively used in atmospheric science (for a review see HSIEH and TANG, 1998; GARDNER and DORLING, 1998; MICHAELIDES *et al.*, 2006), their application in ceiling and visibility forecasting is rather limited. It is only very recently that a rather restricted number of researchers have adopted the use of ANN in the area of statistical ceiling and visibility forecasting (PASINI *et al.*, 2001; COSTA *et al.*, 2006; BREMNES and MICHAELIDES, 2007). A natural question arising is whether ANN have any advantages over the traditional statistical tools mentioned above. MARZBAN *et al.* (2006) compared neural network with linear and logistic regression in forecasting ceiling and low visibilities, and they concluded that the ANN approach yields superior forecast quality.

Fuzzy logic is a methodology to treat uncertainty in systems whose variables are rather qualitative, imprecise or ambiguous. Over the past few years, this methodology has been increasingly adopted as a favorable technique in a variety of environmental issues but has found limited applications in weather prediction. The appropriateness of fog occurrence for treatment with fuzzy logic has been tested with promising results (SUJITJORN *et al.*, 1994; MURTHA, 1995). More recently, PETTY *et al.* (2000) describe a fuzzy logic system for the analysis and prediction of cloud ceiling and visibility. Also HANSEN (2000) reports on the use of such a forecasting system to forecast ceiling and visibility and concludes that the fuzzy system outperforms persistence-based forecasts.

In a decision-making process, a *Decision Tree* is defined as a graphical representation of all the alternatives and the paths by which they may be reached. Decision trees are quite popular tools in many domains and can be powerful prediction tools (see ALMUALLIM *et al.*, 2001). In contrast to neural networks, decision trees represent sets of comprehensible rules. Despite the potential attractiveness of decision trees for weather prediction, there are few examples of applying them; COLQUHOUN (1987) lists a few such applications to meteorological issues. The complexity of the phenomena discussed in this paper makes the determination of "rules" a very difficult task. It is probably for this reason that examples of the application of decision trees in forecasting ceiling and visibility are also limited. WANTUCH (2001) presents one such successful attempt.

Apart from surface-based observations, data from polar-orbiting satellites have been successfully used by BENDIX (1994, 2002) for fog mapping and to derive the climatology of fog physical parameters for Germany and adjacent areas. Significant spatial variability was observed in microphysical properties between continental radiation fog and the coastal sea fog.

The study of interannual trends in frequency can also yield significant insights into the complex nature of fog. However, great care must be taken in extracting meaningful information from climatological time series. For instance, HANESIAK and WANG (2005) describe procedures for mitigating the effects of "artificial step changes" in long-term climatologies. Such changes are often plainly visible in time series plots of obscuration frequency, appearing as sharp discontinuities in trends and moving averages. Such changes can often be attributed to changes in instrumentation or changes in instrumented site. HANESIAK and WANG (2005), using the logistic regression technique, reported long-term trends in fog conditions in the Canadian Arctic, specifically, decreasing in the east and increasing in the southwest. FORTHUN *et al.* (2006), using simple linear regression, reported finding a variation of trends in the southeast U.S. (decreasing, flat, increasing); however, decreasing trends predominate. LADOCHY (2005) also found decreasing trends in the Los Angeles area on the West Coast of the United States and attributed them to the urbanization of the area and its associated urban heat island. Similar findings have also been reported by WITIW and BAARS (2003) for various cities in South and North America and the United Kingdom, while some cities in the United States and Asia are characterized by increasing trends. Some evidence points to increasing air pollution as a possible reason for fog increase. In many instances, decadal trends at individual sites are often quite distinct, which implies that knowledge of such trends should always be factored into any fog climatology-based forecast application.

The information extracted from fog climatologies can serve as a basis for the development of forecast decision support and guidance tools. For example, MARTIN (1972), using data from 15 airports in the U.S., comprising in excess of 340 years worth of hourly observations, showed how large amounts of climatological data can be condensed into a small amount of relevant conditional climatology information which is useful for short-term forecasting at airports. Frequencies of ceilings in various important flight categories were graphed as a field bounded by two axes: Time of year (month) and time of day (hour UTC). When the data for specific airports were thus graphed, seasonal and diurnal site-specific features in the climatology were revealed. Such seasonal-diurnal (SD) graphs were further refined to display probabilities of various ceilings given additional conditions, such as, probability of persistence of a category of ceiling at 2 hours, and probability of a ceiling category when the wind direction is from a given sector. This work was advanced for its time, however its applicability was limited mainly by two factors: 1) Low computing power meant that analyses for individual airports took a long time and had to be completed manually, and 2) forecasters still had to manually search

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used by the model in the simulation, discussed below, predicts N_d and LWC independently, from which Vis is then obtained diagnostically. The visibility observations from ground-based instruments were then compared to the results of MC2 simulations. The new microphysical parameterizations for the settling rate and droplet terminal velocities were also developed for future applications.

2. Observations

Observations were collected during FRAM (GULTEPE *et al.*, 2006b) from 1 December, 2005 to 18 April, 2006 but the data only from 4 January, 2006, representing warm fog conditions, were used in the analysis because of availability of the complete observations. The instruments used in the data collections were the Droplet Measurement Systems (DMT) Fog Measuring Device (FMD), Vaisala ceilometer (CT25K), York University Ice Particle Counters (IPC, SAVELYEV *et al.*, 2003; BROWN and POMEROY, 1989) mounted on a 10 m tower, DRI Hot Plate, Radiometrics microwave radiometers (MWR; profiling and regular ones), radiometers (profiling and regular ones), Vaisala FD12P, and the Precipitation Occurrence Sensor System (POSS). Observations of sizes and number concentrations of liquid droplets, ice crystals, and aerosols were collected using optical probes; visibility was observed with a Vaisala FD12P; LWC, relative humidity with respect to water (RH_w), temperature (T), and liquid water path (LWP) were observed with a profiling MWR. Details on the FRAM field project and instruments used to collect data can be found in GULTEPE *et al.* (2006b).

3. Parameterization of Visibility

The extinction parameter (β_{ext}) used to get Vis was calculated from FSSP probe measurements by

$$\beta_{ext} = \sum Q_{ext} n(r) \pi r^2 dr, \tag{1}$$

where n is the number density of particles in a bin size represented by radius (r) and Q_{ext} is the Mie efficiency factor calculated from the Mie theory. For large size parameters, it can be taken to be approximately 2 (KOENING, 1971). It is converted to Vis using the following equation (STOELINGA and WARNER, 1999)

$$Vis = -\ln(0.02)/\beta_{ext}. \tag{2}$$

Using the *in situ* observations collected during Radiation and Aerosol Climate Experiment (RACE), LWC, N_d, and β_{ext} are used to obtain a relationship between Vis_{obs} and $(LWC{\cdot}N_d)^{-1}$ (referred to as the fog index) as

$$Vis = \frac{1}{(LWC \cdot N_d)^{0.65}}. \tag{3}$$

This fit indicates that Vis is inversely related to both LWC and $N_{d.}$. The maximum limiting LWC and N_d values used in the derivation of Eq. (3) are approximately 400 cm^{-3} and 0.5 g m^{-3}, respectively. The minimum limiting N_d and LWC values are 1 cm^{-3} and 0.005 g m^{-3}, respectively.

4. Model Description and Set-up

The simulation in this study was performed using the Canadian Mesoscale Compressible Community (MC2) model. This model is based on the fully-compressible Euler equations, solved on a Mercator projection, and is a limited-area model capable of one-way self-nesting. The model dynamics are discussed in detail in BENOIT *et al.* (1997) and THOMAS *et al.* (1998). The MC2 uses a comprehensive physics package (MAILHOT *et al.*, 1998) which includes a planetary boundary layer scheme based on turbulent kinetic energy (BENOIT *et al.*, 1989), implicit (explicit) vertical (horizontal) diffusion, and a detailed land-surface scheme (BELAIR *et al.*, 2003a,b). The solar (FOUQUART and BONNEL, 1980) and infrared (GARAND and MAILHOT, 1990) schemes in the radiation package are fully interactive with the model clouds.

The fog case simulated was that of 4 January, 2006 during which a warm front moved across the Ontario region. The model was initialized on a coarse-resolution domain (10-km grid-spacing, 301 × 301 points; not shown) using the 15-km regional analyses from the Canadian Meteorological Centre (CMC) at 00:00 UTC 4 January, 2006. Lateral boundary conditions from the CMC analyses were supplied every 6 h for a 24 h simulation. Using the output from the 10-km simulation, the model was then nested to a high-resolution domain (2-km grid-spacing, 251 × 251 points; see Fig. 5) for an 18-h simulation, starting at 06:00 UTC 4 January, 2006, 6 h after the initial time of the 10-km run. The purpose of this nesting strategy is to generate initial conditions for the 2-km simulation at higher resolution than are provided for by the regional analyses in order to reduce the model spin-up time for the 2-km run. Also, experience with the MC2 model has provided a rule-of-thumb for users, stating that jumps in model grid-spacing for nested runs should be limited to a factor of 5. Both simulations had 41 modified Gal-Chen levels (unevenly spaced) with 12 levels in the planetary boundary layer and a model lid at 30 km. The 10-km run employed the Kain-Fritsch scheme to parameterize subgrid-scale convection and a Sundqvist-type scheme to treat grid-scale condensation (see MAILHOT *et al.*, 1998).

The 2-km simulation, discussed below, used the triple-moment version of the multi-moment bulk scheme described in MILBRANDT and YAU (2005a,b) to parameterize cloud microphysical processes at saturated grid points. The scheme

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Table 1

Available observations at and in the vicinity of the Zürich airport

Parameter
visibility (spatially aggregated)
precipitation rate
precipitation type
soil temperature (−0.05, −0.1,−0.2,−1.0 m)
soil moisture (−0.01, −0.02, −0.1, −0.25, −0.6, −0.98 m)
"surface" temperature (0.02 m)
temperature (0.5 m)
temperature (all heights of virtual profile)
temperature profile (MTP−5)
wind profile
humidity (all heights of virtual profile)
u−wind (all heights of virtual profile)
v−wind (all heights of virtual profile)
cloud base
cloud cover
longwave radiation LW↓
longwave radiation LW↑
shortwave radiation SW↓
Radiosonde from Payerne (150 km away)

For temperature it was possible to use an MTP-5 microwave profiler (Kadygrov and Pick, 1998) but nothing comparable was available for humidity. In order to obtain entire profiles of temperature and humidity, an assimilation scheme is necessary to initialize the forecast models.

3. The Ensemble Forecast System

Fog forecasting is a threshold problem, namely a small difference in temperature and/or humidity determines if condensation occurs and thus fog forms or not. Keeping in mind the difficulties of providing good temperature and humidity

Table 2

Statistics of temperature deviations between the MTP−5 and the stations of the virtual temperature profile. Height in m above sea level (m a.s.l.), also indicated is the number of 10 min intervals with positive or negative temperature deviation from the MTP−5 profile

Station	Height (m a.s.l.)	RMS (K)	Mean (K)	negative	positive
Zürich airport	432	0	0	0	
Bühlhof	520	0.77	0.44	586	2745
Gubrist	640	0.79	0.28	955	2453
Zürichberg	730	0.90	0.37	922	2486
Lägeren	870	1.21	−0.56	2137	1194

Table 3

*Monthly frequencies (%) of low visibility (vis) as observed between 1993 and 2002 at Zürich airport. (*Schmutz *et al. 2004)*

	vis <800 m	vis <1500 m
Jan.	6.0	8.8
Feb.	2.5	4.1
Mar.	1.4	2.2
Apr.	0.9	1.2
May.	1.0	1.2
Jun.	0.4	0.6
Jul.	0.4	0.6
Aug.	0.9	1.3
Sep.	4.0	4.9
Oct.	7.2	8.7
Nov.	5.4	7.6
Dec.	3.5	5.2

forecasts and the dependence of theses forecasts on initial conditions, a deterministic forecast incorporates rather large uncertainties. This problem can be addressed with ensemble forecasting, which not necessarily provides a more accurate forecast for all conditions although it can provide a likelihood of fog occurrence and thus also inform about the predictability of a particular situation.

The developed ensemble forecast system consists of an assimilation system to generate a set of initial conditions based on prior forecasts and current observations, two distinct 1-D forecast models and a post-processor.

Data Assimilation Strategy

An important part of every ensemble forecast is the derivation of a set of initial conditions representative of the current uncertainty of the initial state.

The process of data assimilation optimally combines observations with a first guess or background estimate. In this case data have to be assimilated by a 1-D model, and it seems natural to use a previous forecast of that model as background state. There are however several reasons for using the 3-D model forecasts, having resolutions between 2 and 7 km, as a first guess. In 1-D it is not possible to simulate horizontal gradients which are responsible for advection and wind so that the 1-D model cannot simulate its own background state needed in the data assimilation process. Basically the 1-D model is unaware of changes in temperature, humidity and wind caused by advection so that large errors develop over time. Since the 1-D model is operated at a location where observed humidity and wind is based on measurements taken only a few meters above ground, the assimilation process cannot correct the background state in most parts of the vertical profile. Another big problem is the limited vertical extent of the 1-D model, which currently simulates the lowest 2000 m of the atmosphere. Thus mid-and high-altitude clouds and their effects on radiative

In order to solve the assimilation problem it is necessary to precondition **B** and reduce the number of elements, which is done by the so-called control variable transform.

$$\mathbf{U}^T\mathbf{B}^{-1}\mathbf{U} = \mathbf{I}. \tag{2}$$

It is thus necessary to transform the model variables (actually perturbations) $\vec{x'}$ into control variables $\vec{v'}$, the so called T-Transform and *vice versa* using the so called U-Transform:

$$\vec{x'} = \mathbf{U}\vec{v'}, \tag{3}$$

$$\vec{v'} = \mathbf{T}\vec{x'}. \tag{4}$$

By doing so the cost function to be evaluated becomes

$$J(\vec{v'}) = \frac{1}{2}(\vec{v'}^T\vec{v'}) + \frac{1}{2}(\vec{y'} - \mathbf{HU}\vec{v'})^T R^{-1}(\vec{y'} - \mathbf{HU}\vec{v'}). \tag{5}$$

During the minimization process, the cost function and the gradient of (5), as derived by Bouttier and Courtier (1999) and transformed into the incremental form in $\vec{v'}$-space (6), have to be evaluated during every step of the minimization.

$$\nabla_{\vec{v'}}J(\vec{v'}) = \vec{v'} - \mathbf{U}^T\mathbf{H}^T\mathbf{R}^{-1}(\vec{y'} - \mathbf{HU}\vec{v'}). \tag{6}$$

In the current implementation, the Broyden-Fletcher-Goldfarb-Shanno variant of the Davidon-Fletcher-Powell method, as described in Press *et al.* (1988), is used to compute the minimization of the cost function with the help of its gradient.

The quality of the assimilation relies on an accurate estimation of **B**. This is a difficult task since it cannot be observed directly and hence has to be estimated in a statistical sense. Here, the "NMC" or NCEP Method (Parrish and Derber, 1992) is used which is independent of measurements.

$$\mathbf{B} \approx \alpha\frac{1}{n}\sum_{i=1}^{n}\Big((\vec{x_f}(t_1) - \vec{x_f}(t_0))(\vec{x_f}(t_1) - \vec{x_f}(t_0))^T\Big), \tag{7}$$

where $\vec{x_f}$ represents the forecast state vector and α is an empirical scaling factor. As can be seen in (7) **B** is estimated as the average over n differences between two short-range model forecasts verifying at the same time. Normally $t_1 = 48$ h, $t_0 = 24$ h and about 50 different forecasts representative for the season are used.

The estimates of **B** obtained for different 3-D models using the NMC-Method (7) and corresponding correlations are shown in Figure 2. The statistics are based on the vertical profiles of the 3-D models from October 2004 to February 2005. In Figure 2, it is evident that variances are largest close to the surface, where a small change in e.g., predicted cloud cover results in a large temperature difference. This means that in this region, the background term will have relatively little influence compared to the observations. Fortunately most observations are available close to the surface

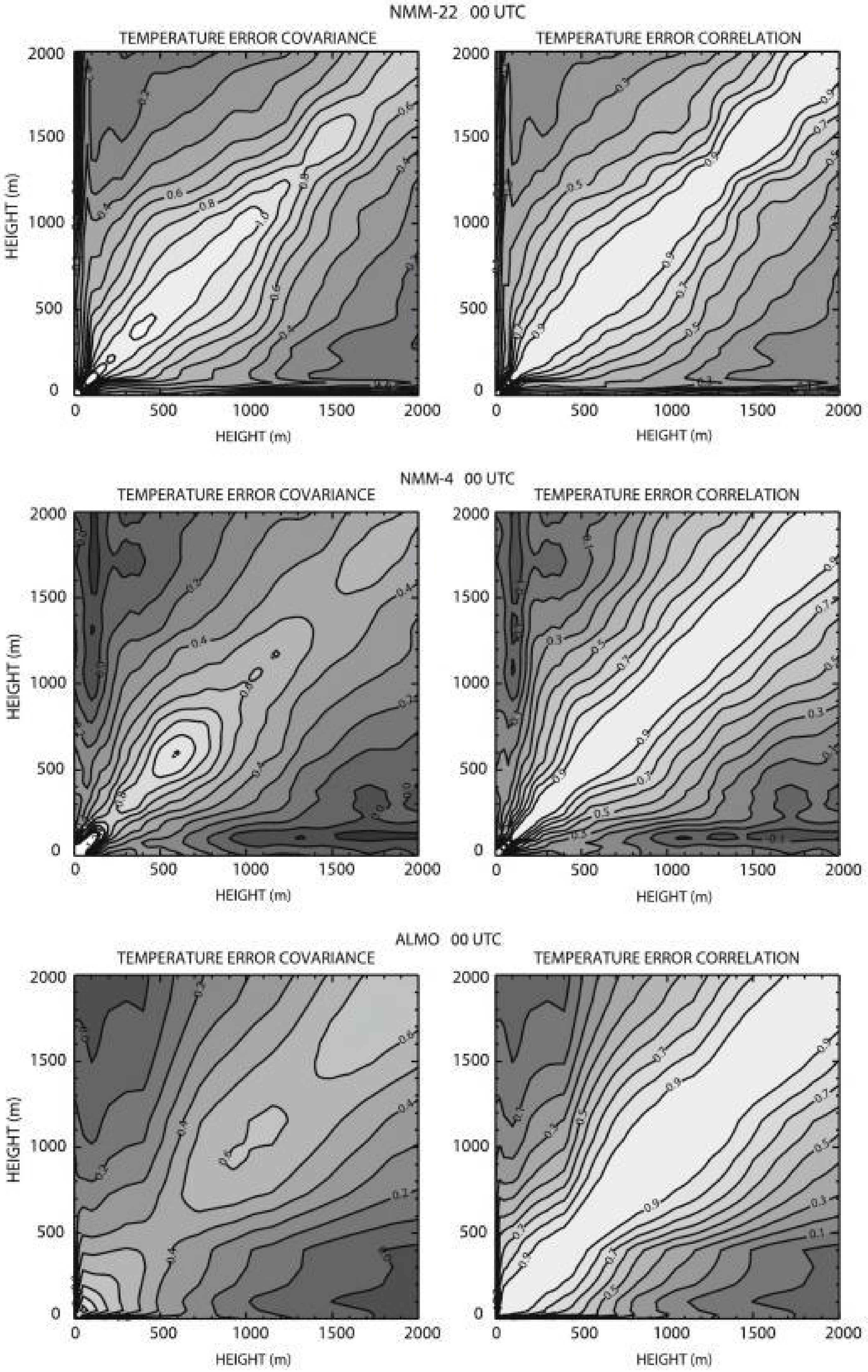

Figure 2

Temperature error covariance and error correlation matrices for the winter season 2004/2005 at 00 UTC for 3 different 3-D models.

and an unreliable forecast for that layer does not pose a problem for data assimilation. For the two resolutions of NMM, a second maximum can be found around 500 m above ground which is not present in the aLMo. The correlations between vertical layers generally increase from ground level to the region of maximum variance. In the aLMo the vertical layers are less independent of each other than in the NMM, which means that the spread and smoothing of information during the assimilation process is larger. Note that the structure of the error covariance is different throughout the day due to the diurnal evolution of the boundary layer, which was also analyzed by HACKER and SNYDER (2005).

Similar to the background error covariance matrix, **R** specifies errors of the observational system. The error is mainly caused by representativeness problems of the observation in model space and only secondly on instrumental characteristic. In contrast to **B**, correlations are assumed to be zero. Concerning the assimilation at Zürich airport, the most difficult part of **R** is assessing representativeness of radiosonde data recorded in Payerne. Because the latter is about 150 km away from Zürich, the lower part of the sounding is expected to be rather unrepresentative. To quantify the similarity between the two locations, model profiles from high resolution numerical weather prediction were analyzed. According to the amount of resolved topography, it is believed that the NMM model run at 2 km resolution is able to capture most spatial differences between Payerne and Zürich. Thus, for the time from October 2004 to March 2005, correlations for humidity as well as temperature, were computed for all vertical layers, respectively. The result is shown in Figure 3 for radiosonde ascent time of 1200 UTC.

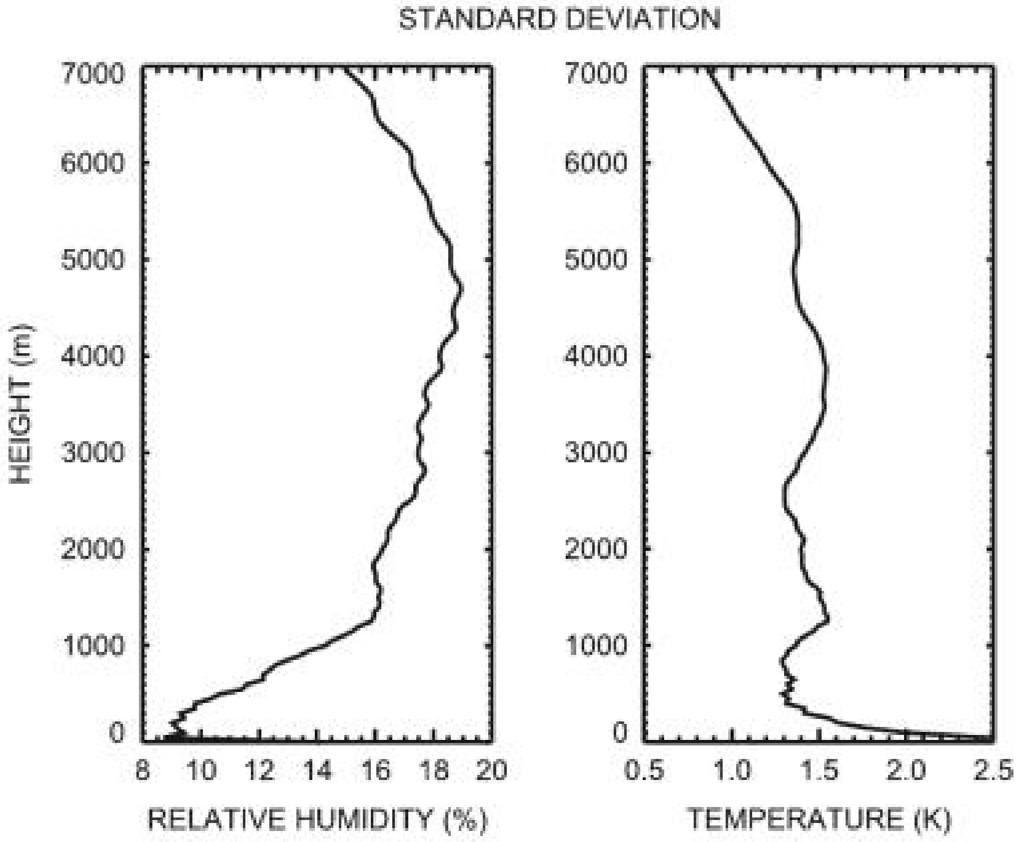

Figure 3
Standard deviations from the observational error covariance matrix **R** of the radiosonde in Payerne.

The virtual profile of temperature and humidity is problematic in that all observations are taken in close proximity to the ground instead of several hundred meters above ground, so that they are especially error-prone under calm conditions when they reflect more the local surface layer conditions than the free atmosphere. To quantify the errors of the virtual profile, mean and root-mean-squares deviations of the virtual profile from the MTP-5 profile at the corresponding height were computed at a temporal resolution of 10 minutes. MTP-5 data were linearly interpolated to the height above sea level where the station measurements took place. Considered are the statistics for each day of the MTP-5 observation period from 26 October, 2004 until 11 April, 2005. In Table 2 the RMS and mean deviations for the whole observation period are listed. Also indicated is the number of ground-based observations with negative or positive deviations from the MTP-5. As can be seen, the virtual profile deviates more as altitude increases. Also the number of cases where the stations measured lower temperatures than the MTP-5 increases with altitude, which shows the important role of radiative cooling of the surface. Thus the stations located at the surface can only provide an estimate of the thermodynamic state of the free atmosphere at that height, nonetheless there is still useful information which can be exploited by data assimilation.

Boundary Conditions

The specification of boundary conditions is used to extend the applicability of the 1-D model to more heterogeneous environments and different synoptic situations. Especially in complex terrain, advection plays an important role and is present even under synoptically calm situations in the form of cold air drainage flows. Advection of a as defined by (8) is specified as an external tendency. It is computed using centered finite differences (9) about the point of interest (i, j), which requires four additional vertical columns from the 3-D model.

$$\frac{\partial a}{\partial t} = -\vec{v}\,\vec{\nabla} a, \tag{8}$$

$$\frac{\Delta a_{i,j}}{\Delta t} = -u_{i,j}\,\frac{a_{i+1,j} - a_{i-1,j}}{2\Delta x} - v_{i,j}\,\frac{a_{i,j+1} - a_{i,j-1}}{2\Delta y}. \tag{9}$$

Another possibility in deriving advection is the use of a total tendency, rather than pure advection. Therefore, the total hourly change of humidity and temperature in the profile of the 3-D model is computed. Of course this change is not solely caused by advection but by all processes, like turbulent mixing, radiative cooling or phase changes. The dominating process depends on the actual situation, but the fog modeling system, which has to produce daily forecasts, needs to be evaluated and tested for all situations in order to be of operational use. This method is beneficial in that it requires only one column of 3-D model data at the point of interest and no neighboring columns. Furthermore temporal discretization errors in the case of

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