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RESEARCH INTO ATMOSPHERIC DYNAMICS AT TARTU OBSERVATORY

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Abstract. The paper presents an overview of recent development of atmospheric dynamics at Tartu Observatory. This scientific trend, new in Estonia, was initiated owing to the need to provide graduate courses in meteorology and environmental physics at the University of Tartu and to create a scientific basis for numerical weather forecast in Estonia. Scientific projects in progress are synoptic-scale dynamics, mesoscale modelling, and modelling of air pollution from local sourses.

Key words: meteorology, atmospheric dynamics, education, forecast.

1. INTRODUCTION

Contemporary atmospheric sciences, which came into being through the use of computers, celebrate the fiftieth anniversary these days. Rapid development of atmospheric sciences has taken place during this period in close relationship with the evolution of the computer science. The development of atmospheric sciences in turn has had an effect on the computer science. Thus it is impossible to treat contemporary atmospheric sciences separately from computers and the computer science. The backbone of atmospheric sciences is atmospheric dynamics (AD) (dynamic meteorology), a science of movement and processes in the atmosphere. It is namely AD that represents a branch of atmospheric sciences which has taken particular advantage of the progress in the computer world.

If somebody wishes to characterize AD with a single word, this word should be *model*. Most of contemporary AD is presented in the model form. A dynamic model of the atmosphere is a complex formation which includes concepts, theories, and mathematical models on the one hand, and a sophisticated computing environment (hard- and software) for the realization of these concepts, theories, and mathematics on the other hand. The model represents an open system, it utilizes input data on the initial and boundary conditions at the moment. These data are provided by the World Meteorological Organization (WMO) network and by climatic databases (which are mainly a product of WMO, too). The output of dynamic models results in weather forecasts, forecasts of the consequences of disastrous events (tropical cyclones) or accidents (like Chernobyl), and predictions of climatic changes and responses of climatic systems to human activities.

If AD is treated as a scientific topic, the main accent lies on the conceptual side of the model. In this paper we will also concentrate on this side of the topic. Still, we should not forget for a moment the decisive role of the computing environment in the realization of conceptual AD models.

2. AD FORMATION IN ESTONIA

AD is quite a new branch of science in Estonia. There have been several related studies, Letzmann's tornado research [1], for instance, but the main scientific interests of Estonian atmospheric researchers have been elsewhere – in the realm of radiation transfer and radiation climatology. Close connection of Estonian atmospheric physics with Estonian astronomy, the radiation transfer school of which is well known, has had certain influence here. The first papers on AD in Estonia [2–4] came out at Tartu Observatory (TO)[1] less than ten years ago.

For two reasons the development of AD became really important for Estonia after gaining independence. First, every modern industrial country ought to have an advanced environment, climate, and weather monitoring system, which includes dynamic modelling and weather forecasting. Estonia as a maritime country cannot be an exception in this respect. Weather and environment monitoring systems, however, cannot operate without AD. Second, the AD science is essential for the graduate and postgraduate level education in atmospheric sciences at the universities, aimed to train modern specialists (no matter how they are called: meteorologists, environmental scientists or something else). AD plays the central role among environmental sciences and it is impossible to teach and develop environmental sciences without it.

To make progress in this strategically important trend, the joint Chair of Dynamic Meteorology of the University of Tartu and the IAAP was established at the Institute of Environmental Physics of the university in 1993. The adjective "dynamic" was included in the chair's name to underline the contemporary character of the curriculum and draw a demarkation line with the traditional meteorology lectured at the university during the long postwar period [5]. The chair is financed by TO as a scientific unit but, as far as lecturing is concerned, it acts as a part of the Institute of Environmental Physics. Its task by the statute is to

[1] The former name of TO was the Institute of Astrophysics and Atmospheric Physics (IAAP) of the Estonian Academy of Sciences.

provide (along with other chairs of the institute) the graduate curriculum in environmental physics with special accent on numerical AD. Beside the postgraduate study the chair is responsible for teaching meteorology at the institute. The curriculum includes general meteorology, AD, boundary layer physics, synoptic meteorology, physical climatology, numerical methods in AD, and air quality and pollution. Three students have successfully defended their MSc theses at the chair, in preparation are two MSc and two PhD theses.

3. MAIN RESEARCH TRENDS

The AD research at the Chair of Dynamic Meteorology is carried out in three main trends: synoptic-scale dynamics, mesoscale dynamics, and air pollution modelling. While the first two trends deal with the theoretical investigation of adiabatic processes in an ideal (dry and non-viscous) atmosphere, the last one represents mainly applied science.

Synoptic-scale dynamics

A model for the description of extra-tropical dynamics within the framework of the quasi-geostrophic (QG) theory has been developed in [6, 7]. QG models were in operational use at weather forecasting until around 1995, when they were replaced by more sophisticated and exact models. At present the QG models are applied as convenient tools for qualitative study and lecturing on extra-tropical synoptic- and planetary-scale dynamics [8]. The main advantage of QG models compared to the recent ones is their simplicity. The dynamics of the atmosphere in the QG framework can be completely described by modelling the evolution of a single scalar field. Usually this field is either the height of isobaric surfaces, the stream function of the geostrophic wind, or the potential vorticity [8]. Unlike common QG models, the Tartu Observatory model employs temperature T and the ground surface pressure p_s as primary fields, the evolution of which determines whole dynamics. The new approach has several advantages: (1) the main fields of the model T and p_s have a clear physical meaning and are measured strictly from observations; (2) prognostic equations for T and p_s are extremely simple; (3) the model emphasizes the role of the ground surface pressure in the formation and development of mid-latitude synoptic systems. Due to its simplicity the model presents a convenient lecture tool. A one-level baroclinic model using T and p_s fields was developed in [6], a two-level generalization has been studied in a BSc thesis by Männik [9].

Mesodynamics

A major trend has been the foundation and quality investigations of adiabatic nonhydrostatic mesomodels. Mesodynamic processes constitute a wide range of atmospheric movements with characteristic scales from 100 m to 100 km. Most of local atmospheric phenomena, such as orographically induced winds, cumulus convection, thunderstorms, surface fronts, represent mesodynamic events. "Adiabatic" means that the models we treat do not include turbulent friction, radiation, and "moist" processes. In physics and mechanics such systems are often called conservative models. The most important results, obtained in that trend, are as follows.

I. A representation of complete, nonhydrostatic, nonfiltered AD equations in pressure coordinates has been deduced in [2–4]. The equations obtained generalize the Miller–Pearce model elaborated earlier [10].

Pressure coordinates represent a variety of curvilinear coordinate systems where the pressure in the air particle is in the role of the vertical coordinate instead of common height above sea level. The representation of equations of motion in pressure coordinates is very popular in AD as measurements of hydrodynamic fields are usually carried out in this coordinate frame. Pressure coordinates were initially introduced in large, synoptic-scale dynamics, where the atmosphere is with high accuracy in the hydrostatic equilibrium and the barometric formula holds, establishing the relationship between height and pressure fields. Recently this coordinate system has been employed in different nonhydrostatic models.

By the classical use of pressure coordinates in nonhydrostatic models the pressure coordinate is treated as a mere convenient mathematical abstraction which does not represent necessarily the real pressure in an air particle. In our case, however, the pressure coordinates are introduced for the most general AD equations without any preliminary simplification whereas the pressure coordinate of an air particle always coincides with the actual pressure in that particle. Such general approach enables a unified treatment of all pressure coordinate models.

II. From the general nonhydrostatic pressure coordinate model an acoustically filtered set of equations has been derived in pressure coordinates for slow mesoscale dynamics. These equations can be applied in the full range of slow processes from microturbulence to planetary-scale movements [11–14]. The use of the Lagrangian function and variational technique enables optimum filtering: the filtered model is represented by equations which are of maximum precision in comparison with the exact, nonfiltered equations.

Acoustic filtering is in some way used in all AD models. The aim of filtering is to get rid of fast acoustic-wave processes which are not activated in slow dynamics, to eliminate parasite acoustic noises (different numerical "acoustic" modes which have no physical relevance) from the model, and to enhance the integration time-step. In the present case a novel method is proposed to obtain filtered equations of maximum accuracy. As model calculations (buoyancy wave generation by orography) demonstrate, compared to other filtered models the optimally filtered equations really enable higher precision in a shorter mesoscale, $l <$ 1 km, and on the passage to the synoptic domain, especially within the region 100 km $< L <$

300 km. In addition, modelling has also shown that the ordinary hydrostatic primitive equations yield erroneous solutions for buoyancy waves in this domain.[2]

III. On the ground of the described filtered nonhydrostatic equations and the adiabatic numerical package created by Miranda and James [15], a numerical model NHAD has been developed. The model was realized on the SUN Spark-Station 20/51. Large models cannot be loaded into that computer as its RAM is 96 Mb and the operation performance is about 20 Mfl. The maximum model launched has 40×40×40 grid points in the domain 200×200×20 km^3. Some modelling was performed on the DEC Alpha-Station of the Lisbon University. Modelling consisted mainly in testing where the numerical filtered model was compared with analytical solutions. The modelled objects were stationary mountain waves, which represent significant agents realizing the interaction of free atmosphere with the underlying surface.

Local air pollution dispersion

The applied numerical packages AEROPOL and AEROFOUR are being created for local air pollution dispersion and deposition modelling. The first model is based on the concept of the standard Gauss distribution [16], the second uses a mixed-spectral numerical algorithm, which is probably the first attempt to apply the Fourier transform to the pollution transport modelling [17]. The advantage of the mixed-spectral model is in faster performance in comparison with the traditional grid-point methods.

The models are tested in collaboration with the Norwegian Air Research Institute using the results of field measurements of pollution loads in North-East Estonia in 1994 and 1996 [18]. They were applied for modelling the North-East Estonian pollution loads [19]. A project of the Institute of Ecology (Tallinn), participated by M. Kaasik, during which the model AEROPOL will be integrated into the North-East Estonian pollution monitoring system, is at the launching stage.

4. PERSPECTIVES

Keeping in mind vital needs of Estonia, continuing efforts in mesodynamics and air pollution modelling are necessary.

The Chair of Dynamic Meteorology has gained sufficient experience in mesodynamics which permits us to supplement the existing adiabatic model NHAD with diabatic and sub-grid parametrizations, to include real orography and surface processes into it, and get a realistic mesoscale model for Estonia and its nearest surroundings. Such a model can be employed

[2] These results are part of the MSc thesis by Ü. Lindmaa which will be finished in the near future.

further for regional climate modelling and local weather forecast. In the latter case it is necessary to link it with a larger dynamic model (the ECMWF global model or the local area model HIRLAM) to get boundary and initial data. The mesomodel will then represent an extension to larger models, which, like a magnifying glass, enables high-resolution modelling and forecast of local weather phenomena in the regions of interest. The creation of analogous models is presently topical in the world. The PSU-NCAR mesomodel [20] and the Advanced Regional Prediction System [21] can be mentioned as examples.

The elaboration and development of applied air pollution dispersion models is to be continued in parallel with the improvement of the mesomodel and as a part of it, with a special accent on physical parametrization of pollutant sedimentation and pollution load. As the comparison of experimental data and model predictions (both by us and other researchers) has shown, the load parametrization is the weakest part of the existing models which needs essential improvement.

The present overview has been prepared for the Conference of Estonian Scientists, Tallinn, 11–15 August 1996. Supplementary information on AD research at Tartu Observatory and opportunities to study dynamic meteorology at the University of Tartu may be found on the Internet address http://apollo.aai.ee/. The Chair of Dynamic Meteorology has an Internet weather-window on the address http://apollo.aai.ee/~ilmatark/.

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ATMOSFÄÄRIDÜNAAMIKAALASEST UURIMISTÖÖST TARTU OBSERVATOORIUMIS

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Tegu on uue ja olulise teadussuunaga Eestis. Selle teke ja areng on olnud tugevasti mõjutatud keskkonnafüüsika ja meteoroloogia (atmosfääriteaduse) õpetamise vajadusest Eestis, eriti Tartu Ülikoolis. Dünaamiline meteoroloogia, ühendades süsteemselt teoreetilise ja matemaatilise füüsika, hüdrodünaamika, keskkonnaprotsesside füüsikalise parameetrimise ja numbrilise modelleerimise elemente, moodustab kogu nüüdisaja atmosfääriteaduse selgroo. Suuna tugevdamiseks on TÜ keskkonnafüüsika instituudi juurde loodud Tartu Observatooriumi initsiatiivil ning sellega koostöös dünaamilise meteoroloogia ühisõppetool. Uurimistöö on toimunud kolmes valdkonnas.

1. Sünoptilise skaala dünaamika. On loodud kvaasigeostroofiline numbriline mudel, mis kasutab peaväljadena atmosfääri temperatuuri- ja aluspinna rõhujaotust ning võimaldab sünoptiliste protsesside (polaarfrondi areng, tsüklogenees) kvalitatiivset modelleerimist. Mudelit rakendatakse õppevahendina TÜ-s.

2. Mesoskaalaprotsesside modelleerimine. Teoreetilise tulemusena on saadud mittehüdrostaatilise dünaamika esitus rõhukoordinaatides ja testitud selle täpsus. Käivitatud on Eesti esimene numbriline mesodünaamika mudel. On alustatud võrgualuste protsesside lisamist sellesse.

3. Lokaalne saastelevi. On saadud punktallikatest (näit. tehasekorstnad) lähtuva atmosfäärse saaste levi ja väljasadenemise numbrilised mudelid, mida on rakendatud Ida-Viru tööstusrajooni saastekoormuste modelleerimiseks. Jätkub piirikihi ja väljasadenemise parameetrimine.

Perspektiivide osas on Eestile olulisteks väljunditeks Läänemere regiooni mesokliima modelleerimine, lühiajalise ilmaprognoosi arendamine koostöös Eesti Meteoroloogia ja Hüdroloogia Instituudiga ning saastelevi mudelite edasine täiustamine. Arvestatavalt head on olnud väliskontaktid.