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Determining the Growth-Rate Law of the Atmospheric Boundary Layer: One Step Closer to Ensuring the Accuracy of Weather Models

Euan MacDonald

Scientists seeking to develop accurate weather, climate and air quality prediction models have long been confronted with a difficult yet important problem: how to accurately forecast the height of the atmospheric boundary layer as it develops during daytime heating. Using DEISA resources, a team of scientists from the Delft University of Technology in the Netherlands, Imperial College London and the National Center for Atmospheric Research in Colorado initiated the PINNACLE project in order to resolve this longstanding controversy.

The atmospheric boundary layer (ABL) is the part of the atmosphere in which we live. It is the essentially turbulent lower layer of the atmosphere, connecting the Earth's surface to free atmosphere (troposhere). A typical daytime boundary layer (also known as the "convective boundary layer") grows from a few hundred meters in the morning to one kilometre or more in the afternoon. The top of the boundary layer is clearly identifiable by a so-called capping inversion, a sudden sharp increase with height in the (potential) temperature profile. Due to solar heating of the surface, hot air will be formed which, due to its lower density, will rise in the form of thermals all the way to the top of the boundary layer. Owing to the large Reynolds number (a dimensionless number used in order to represent how many scales of motion are involved in the turbulence under study) associated with atmospheric flow, the motion in the boundary layer is highly turbulent. Understanding the atmospheric boundary layer is of crucial importance if scientists are to be confident in the accuracy of the weather and climate predictions that they make.

"Turbulence in the atmospheric boundary layer mixes heat, momentum, and bio(chemical) species originating on the surface throughout the entire boundary layer; any inaccurate calculation of the boundary layer height will result in flawed predictions of – for example – temperature and pollutant concentrations", notes Dr. Harm Jonker of the Delft University of Technology in the Netherlands, and the lead researcher on the PINNACLE project. "Therefore, for weather, climate, and air quality models, it is of vital importance to correctly forecast the height of the boundary layer as it develops under daytime heating. To put it bluntly: if a model cannot get the boundary layer height correct, it cannot get anything correct".

Fig. 1. A photograph of a real inversion, as taken by a glider pilot. The inversion is topped by very small cumulus clouds; however, the "misty" band that is associated with the top of the boundary layer can clearly be identified here.

Ascertaining the growth-rate law of the atmospheric boundary layer: A long-standing problem

A key issue in weather modelling is, therefore, the so-called "growth-rate law" for the evolution of the daytime atmospheric boundary layer; this, however, remained a highly controversial question.

"The most widely employed growth rate law for the atmospheric boundary layer is riddled with controversy", continues Jonker. "Results from atmospheric observations, large-eddy simulations and laboratory experiments are mutually inconsistent, and display substantial scatter; which, of course, renders predictions of the boundary layer height based on these results of somewhat questionable accuracy."

The PINNACLE project was carried out in order to confront this controversy directly. The project, led by Jonker, brought together a number of other scientists from the US and Europe: Dr. Maarten van Reeuwijk of Imperial College London, who co-developed the computer code used in the project, and Dr. Peter Sullivan and Dr. Ned Patton from the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, whose years of experience with high-performance computers was essential to its success. The project was largely carried out between June 2008 and January 2009, when Jonker was a visiting researcher at the NCAR.

"Our goal was to put an end to this controversy by conducting "ground truth" (that is, departing from first principles) Direct Numerical Simulation (DNS) of convective boundary layers. DNS employs no empirical rules whatsoever and explicitly calculates the full spectrum of turbulent motions in three dimensions. Of course, it is simply not possible at present to simulate the high Reynolds number of atmospheric tur-

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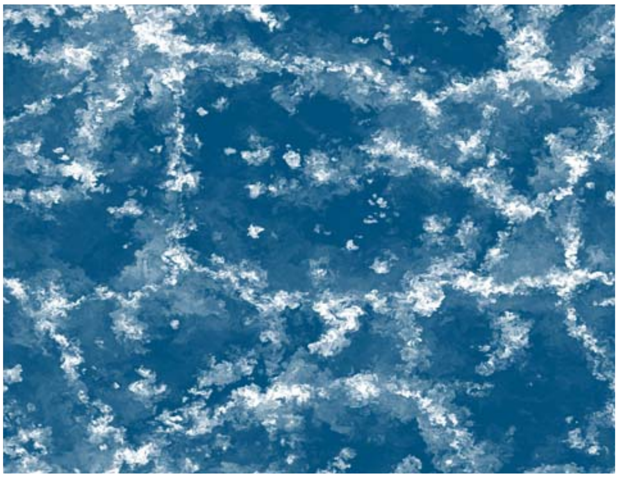

Fig. 2. and 3. Both figures display the simulated temperature field: figure one is a horizontal (xy) cut, while figure 2 is a vertical (xz) cut. Darker colours represent cooler zones. In the horizontal cut, the large-scale organization of the temperature field can be observed, whilst in the vertical cut a thermal can be seen impacting upon the inversion (on the left), lifting it up and generating lateral motions

bulence; this would require the simultaneous simulation of kilometre-sized motions and millimetre-sized motions and every size in between (that is, cover six orders of magnitude of scale in three directions). However, current computing capabilities do enable us to accurately simulate the classical laboratory experiments on the basis of which the existing growth-rate laws for the atmospheric boundary layer were proposed – indeed, we can now reach Reynolds numbers that are some ten times higher than those of the original experiments. Our hope was that, by varying the Reynolds number over three orders of magnitude and analysing in detail its impact on the growth-rate law, many of the key controversies could be resolved."

A controversy laid to rest

"The PINNACLE project was a tremendous success, as it explained why the previous experimental results had yielded apparently confusing and inconsistent results", notes Jonker. "It showed that, in general terms, the original experiments had been well conducted; but also, however, that the common assumption that fluid properties play only a minor role on the growth of the boundary was demonstrably false".

"Most importantly, the project revealed which of the competing growth-rate laws was, in fact, the correct one in the context of atmospheric boundary layers. This law can now be used with full confidence in weather, climate and air quality models. Secondly, the project results also shed light on why different laboratory experiments, conducted in the past by various groups using different methods, gave different growth-rate laws. By mimicking these experimental conditions in our simulations, we were able to exactly reproduce those historical experiments and get insight into how the properties of the fluid in question (in particular its viscosity, conductivity/ diffusivity) had influenced previous findings on the boundary layer growth-rate"

"Indeed, one of the most interesting outcomes of the project is our finding that the experiment that historically was most influential in the field was actually right – but for the wrong reasons. In that experiment, the fluid used was heated water in a tank. Compared to the atmosphere, the Reynolds number was too low; however, compared to the fluid in the atmosphere (air), the water's conductivity was also too low. We found that these two elements effectively cancelled each other out, so that the correct 'atmospheric' growth law emerged – somewhat fortuitously – from the experiment."

The PINNACLE project is now almost entirely complete: all that remains to be done is some final post-processing, before the results are written up for publication in an academic journal. "The next step", according to Jonker, "is to apply the same strategy to the more complex atmospheric situations in which wind shear (difference in wind speed and direction over relatively short distances) and/or the presence of boundary layer clouds (cumulus or stratocumulus) are known to significantly alter the growth-rate of the boundary layer. Simulations of this sort will be even more computational resource-heavy than those we carried out in the PINNACLE project; but the new generation of supercomputers will, we think, be equal to the task".

Fig. 4. Doctor Harm Jonker, taking a break from the PINNACLE project in the Colorado mountains. The project was largely conducted while he was a visiting researcher at the National Center for Atmospheric Research there during 2008.

DEISA Resources: Essential to the PINNACLE project's success

The DEISA framework was crucial to the PINNACLE project as the total computational cost of the simulations exceeded by far anything that can normally be requested at the national level.

The resource allocation was the equivalent of 1.9 million CPU-h (Power5, 1.9 GHz). It was equally divided over a number of the different supercomputing centres that constitute the DEISA consortium: SARA (Amsterdam, the Netherlands); CINECA (Bologna, Italy); HPCX (Edinburgh, Scotland); FZJ (Jülich, Germany); and LRZ (Munich, Germany). When, during the course of the project, it transpired that it would be necessary to conduct at least one massive simulation that exceeded the resource allocation on each individual platform, the researchers were able to overcome this problem by transferring the resources allocated at HPCX to FZY at the Jülich Research Centre. This meant that a "super-run" on the Jülich Bluegene supercomputer was possible, which made use of 32.768 processors (i.e. fully half of the machine's capacities).

Joint DEISA and HPC-Europa BoF Session at ISC'09: "EU Support for HPC Users"

David Henty, EPCC

Together with the HPC-Europa project, DEISA organised a BoF session at the recent International Supercomputing Conference held in Hamburg on 23-26 June.

The aim of the session was to promote the support available to HPC researchers provided by EU-funded projects. It seemed natural to talk about both HPC-Europa and DEISA in the joint session. HPC-Europa enables transnational visits to HPC centres in Europe to develop computational science research projects. DEISA is an obvious next step for successful collaborations, for example providing access to world-leading supercomputing resources via the DEISA Extreme Computing Initiative, DECI.

During the session, Sanzio Bassini from CINECA gave a talk on the opportunities available under HPC-Europa, explaining how EU researchers can apply for visits to work with research groups in a number of HPC centres around Europe. HPC-Europa project covers travel and accommodation costs, as well as access to local HPC facilitites. David Henty from EPCC then covered the facilities available in DEISA, and the process of applying for a DECI project which can provide substantial amounts of computational resources on the DEISA platforms together with technical assistance from DEISA staff. The BoF finished with a question and answer session.

The BoF organisers were very pleased with the attendance, with around 35 ISC'09 delegates present at the session. This will hopefully lead to new users and application areas applying for the computational resources in the next DECI call.

For more information see:

ISC09: http://www.supercomp.de/isc09/

DECI: http://www.deisa.eu/science/deci/

HPC-Europa: http://www.hpc-europa.eu/

DEISA presented at TeraGrid´09

Hermann Lederer, RZG

This year's TeraGrid Conference took place in Arlington, Virginia, from June 22 - 25 and coincided with ISC'09. Keynotes came from the National Science Foundation (Ed Seidel), the Open Science Grid (Paul Avery), and the University of Utah (Thomas Cheatham). Most presentations were organized in tracks for technology, science and education/outreach/training.

A "Global Grid Perspectives" panel was scheduled for June 23. From the TeraGrid Blog: "Tuesday: Wild World of Grids: Tuesday morning's panel on "Global Grid Perspectives" gave a taste of the future while, at the same time, acknowledging some of the obstacles, such as the importance of standardization and the difficulties of funding.

Geographically, the panel circled the globe. It comprised leaders of grids in the European Union, Japan and the United Kingdom — Hermann Lederer of DEISA (Distributed European Infrastructure for Supercomputing Applications), Kenichi Miura of Naregi (Japan's National Research Grid Initiative Project), and Peter Coveney of the UK's eScience. John Towns of the TeraGrid moderated."

Further reading:
http://www.teragrid.org/tg09/blog/?p=123

http://www.hpcwire.com/blogs/Wild-World-of-Global-Grids-49005416.html

DEISA MiniSymposium at forthcoming ParCo 2009 Conference

DEISA will have a Mini Symposium in the ParCo 2009 Conference
3 September, 2009 in Lyon.

"DEISA: Extreme Computing in an Advanced Supercomputing Environment"

More information: *gentzsch@rzg.mpg.de*

Conference web site: http://www.ens-lyon.fr/LIP/ParCo09-3/

Fig. 3. Sanzio Bassini, CINECA from HPC-Europa project in front and David Henty, EPCC from DEISA at the back.