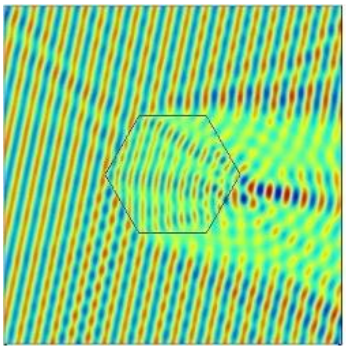

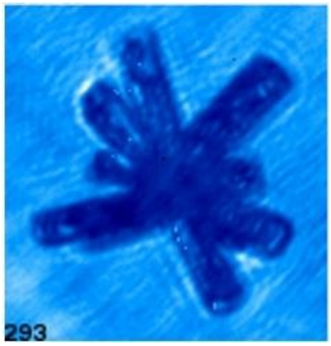

Scattering, Clouds & Climate: A Short Workshop of Exploration

Mathematical Institute, University of Oxford

24th - 25th March 2014

A two-day workshop bringing together mathematicians and atmospheric physicists working on problems related to scattering of electromagnetic radiation by atmospheric ice crystals. The aim is to identify areas where advances in mathematical methods, such as high frequency asymptotics, homogenisation, and numerical schemes, may be useful in climate modelling, and, in so doing, nucleate future collaborative efforts.

Workshop programme and book of abstracts

www.maths.ox.ac.uk/~hewett/scatteringcloudsclimateworkshop.htm

UNIVERSITY OF OXFORD

OCCAM

OXFORD CENTRE FOR COLLABORATIVE APPLIED MATHEMATICS

Background:

The accurate prediction of the Earth's radiation balance requires an understanding of the way that electromagnetic radiation is scattered by ice crystals in clouds. Accurately modelling this scattering is challenging because of the multiscale nature of the problem, and because of the complexity and variation in the size, shape and distribution of ice crystals within clouds. Current climate models cannot produce cloud covers that accurately agree with (a) observations and (b) other climate models. The principal methods to probe the microphysics of clouds are remote-sensing retrievals, either active (radar, lidar) or passive (radiometry/imaging), and in-situ measurements by aircraft. A central feature of the cloud components of climate models involves the interpretation of such measurements, ranging from basic scattering physics (for example the investigation of ice crystal size and distribution) to the implementation of algorithms and instrument corrections.

Focus of workshop:

The key goals of the workshop are:

1. To identify the basic scattering questions that currently limit the quantitative interpretation of remotely sensed and in situ data;
2. To identify model scattering problems that are relevant to the meteorological community and involve interesting mathematical challenges.

For example, possible topics for discussion may include:

- How does polarization figure into retrieval schemes?
- Which is more important: ice crystal size distribution or shape variation?
- How useful are two-dimensional approximations?

Outcomes:

Currently, advances in mathematical scattering theory and in remote sensing appear to be progressing in parallel, but given the richness of the former and the increasing importance of the latter it is hoped that a principle consequence of this workshop will be the formation of new collaborations and research proposals based on a mutually beneficial union of both.

Organisers:

David Hewett, John Ockendon and John Wettlaufer

Acknowledgements:

The organisers are grateful to the Oxford Centre for Collaborative Applied Mathematics and the Oxford Mathematical Institute for funding this workshop, to Chris Westbrook, Robin Hogan and Steven Langdon (University of Reading) and Anthony Baran (Met Office) for their assistance in planning the workshop, and to Anthony Baran (Met Office) for supplying the image of the ice crystal rosette at the top of the first page.

Programme

Registration, lunches, and tea/coffee breaks will take place under the North Crystal on the Mezzanine. Talks will take place in lecture room L4.

Mon 24th

1300-1400	Lunch and registration
1400-1415	Welcome and introduction – David Hewett (Oxford) and Chris Westbrook (Reading)
1415-1500	Anthony Baran (Met Office) – "*A unified approach to cirrus microphysics, remote sensing and climate prediction, and its impact in a climate model*"
1500-1545	Helen Smith (Manchester) – "*Laboratory measurements and modelling of the scattering properties of hollow and solid ice crystals*"
1545-1615	Tea/coffee
1615-1700	David Bebbington (Essex) – "*Advances in polarimetric radar scattering - modelling and analysis*"
1700-1745	Cathryn Fox (Imperial) - "*CIRCCREX: A new cirrus dataset for model evaluation*"
1745-1830	Discussion
1830-1900	Free time (opportunity to check in at Somerville College)
1900	Reception and dinner at Somerville College

Tues 25th

0915-1000	Steven Dobbie (Leeds) – "*An estimate of the optical significance of trigonal ice particles*"
1000-1045	Joseph Ulanowski (Hertfordshire) – "*Non-idealized ice crystal geometries*"
1045-1115	Tea/coffee
1115-1200	Robin Hogan (Reading) – "*Coherent backscattering effects for single particles and distributions of particles*"
1200-1245	Ivan Graham (Bath) – "*On shifted Laplace and related preconditioners for finite element approximations of the Helmholtz equation*"
1245-1345	Lunch
1345-1430	Timo Betcke (UCL) – "*The BEM++ boundary element library and applications*"
1430-1515	David Hewett (Oxford) – "*Hybrid numerical-asymptotic methods for high frequency scattering*"
1515-1600	Discussion
1600-1630	Tea/coffee
1630	Close

Participants

Abrahams, David	University of Manchester	i.d.abrahams@manchester.ac.uk
Allwright, David	University of Oxford	allwrigh@maths.ox.ac.uk
Baran, Anthony	UK Met Office	anthony.baran@metoffice.gov.uk
Bebbington, David	University of Essex	david@essex.ac.uk
Betcke, Timo	University College London	t.betcke@ucl.ac.uk
Chandler-Wilde, Simon	University of Reading	s.n.chandler-wilde@reading.ac.uk
Chapman, Jon	University of Oxford	chapman@maths.ox.ac.uk
Connolly, Paul	University of Manchester	paul.connolly@manchester.ac.uk
Dobbie, Steven	University of Leeds	j.s.e.dobbie@leeds.ac.uk
Fox, Cathryn	Imperial College London	c.fox11@imperial.ac.uk
Gibbs, Andrew	University of Reading	A.J.Gibbs@pgr.reading.ac.uk
Graham, Ivan	University of Bath	i.g.graham@bath.ac.uk
Groth, Samuel	University of Reading	s.groth@pgr.reading.ac.uk
Hannay, John	University of Bristol	j.h.hannay@bristol.ac.uk
Hesse, Evelyn	University of Hertfordshire	e.hesse@herts.ac.uk
Hewett, David	University of Oxford	hewett@maths.ox.ac.uk
Hogan, Robin	University of Reading	r.j.hogan@reading.ac.uk
Langdon, Stephen	University of Reading	s.langdon@reading.ac.uk
Ockendon, John	University of Oxford	ock@maths.ox.ac.uk
Pickering, Juliet	Imperial College London	j.pickering@imperial.ac.uk
Poulsen, Caroline	Rutherford Appleton Laboratory	caroline.poulsen@stfc.ac.uk
Rawlins, Anthony	Brunel University	anthony.rawlins@brunel.ac.uk
Smith, Helen	University of Manchester	helen.smith-3@manchester.ac.uk
Smyshlyaev, Valery	University College London	v.smyshlyaev@ucl.ac.uk
Stein, Thorwald	University of Reading	t.h.m.stein@reading.ac.uk
Ulanowski, Joseph	University of Hertfordshire	z.ulanowski@herts.ac.uk
Westbrook, Chris	University of Reading	c.d.westbrook@reading.ac.uk
Wettlaufer, John	University of Oxford	wettlaufer@maths.ox.ac.uk

Abstracts

A unified approach to cirrus microphysics, remote sensing and climate prediction, and its impact in a climate model

Anthony Baran and Paul Field
Met Office, Exeter, United Kingdom.

The most recent report of the Intergovernmental Panel on Climate Change (IPCC) published in 2013 concluded that the coupling between clouds and the Earth's atmosphere is still one of the largest uncertainties in predicting climate change. One such cloud type that compounds this uncertainty is cirrus. In this talk, the overarching philosophy adopted by the Met Office of implementing consistent cirrus microphysics and radiation parametrizations into its series of climate models will be discussed. In particular, the importance of the size spectrum of ice crystals and ice crystal shape to the radiative properties of cirrus will be demonstrated through twenty-year climate model runs. The talk will demonstrate that well chosen cirrus microphysics applied to an idealized model of cirrus ice crystals, optimized through global remote sensing, can improve a climate model. The need for the development of fast, accurate, frequency near-independent methods to calculate the single-scattering properties of ice crystals will be discussed, a latest electromagnetic result will be presented.

Laboratory measurements and modelling of the scattering properties of hollow and solid ice crystals

Helen Smith[1], Paul Connolly[1], Ann Webb[1] and Anthony Baran[2]
1. University of Manchester
2. Met Office, Exeter, United Kingdom

The International Panel on Climate Change, 2013, concluded that the coupling of clouds with the Earth's atmosphere is the biggest uncertainty in predicting climate change today. Ice clouds are of particular interest due to their diverse microphysical properties. The large range in crystal shape and size leads to considerable variations in the net radiative effect. In current light scattering models, ice particles are often represented by simplified geometric shapes such as the simple hexagonal column. These simplifications may lead to errors in the predicted phase function and asymmetry parameter. Many recent studies have highlighted the sensitivity of scattering behaviour on small scale features such as surface roughness and internal structure, and therefore more accurate representations are sought.

This work focuses on experimentally measuring the scattering properties of ice crystals, with particular emphasis on particles with hollow cavities. Experiments were conducted in the Manchester Ice Cloud Chamber (MICC). The facility comprises a 10 meter fall tube and can produce clouds with a variety of ice crystal sizes and shapes. The cloud falls out of a sampling port into a smaller scattering chamber, it is here that the scattering experiments are conducted. Laser radiation is directed horizontally along the 0.3m diameter of the cloud. The detector optics samples the portion of light scattered in a horizontal plane at a range of angular bins from 0-150^{o}. The cloud is monitored using a Cloud Particle Imager (CPI) in conjunction with formvar replicas. The measured data was combined with theoretical results in order to normalise them. From this, the phase function, P_{II}, and asymmetry parameter, g, were found. Results from Ray Tracing and Ray Tracing with Diffraction on Facets (RTDF) are compared with measured results for both solid and hollow ice particles.

Advances in polarimetric radar scattering - modelling and analysis

David Bebbington
University of Essex

Hydrometeors span a wide range of sizes, exhibit a range of morphologies, and are in many cases materially inhomogeneous. It is necessary to characterize their scattering properties over a broad range of the electromagnetic spectrum. The first part of the talk is focussed on work in progress to revive a computational approach to scattering developed in the 1970's based on the Fredholm Integral Method. More recently, for raindrop scattering this has been almost ubiquitously superseded by the T-matrix approach. What makes the FIM attractive is that it appears to be adaptable to treat inhomogeneous scatterers, such as melting snowflakes. Such particles comprise ice/water/air mixtures, and as yet there appears to be no consistent way to characterise such mixtures using effective medium theory. An interesting question is whether, in practice, the rank of matrix to be solved can be reduced when the particle texture is highly granular. The latter part of the talk will describe recent work on the formalism of polarimetric scattering algebra, which better integrates the geometrical nature of the scattering and the analytic signal representation used for harmonic wave representation. This has led to new insights into the characterization of bistatic scattering.

CIRCCREX: A new cirrus dataset for model evaluation

Cathryn Fox and Juliet Pickering
Imperial College London

CIRCCREX, a new NERC-funded airborne research campaign, aims to understand the link between evolving ice cloud microphysical properties and cirrus radiative signatures at the macrophysical scale. CIRCCREX will obtain for the first time radiation measurements across the electromagnetic spectrum (visible to sub-mm wavelengths) together with state-of-the-art cloud microphysical measurements. These datasets will be utilised to achieve the overall goal of an accurate parameterisation of cirrus optical properties in global climate modelling and NWP, through testing and facilitating improvement of cirrus scattering models and investigation of the sensitivity of the radiance to PSD, habit types and crystal complexity.

Presented here is an overview of CIRCCREX, the relevant background and previous results. Preliminary findings from the first stage of the research campaign, which took place in Prestwick, November 2013 are reported.

An estimate of the optical significance of trigonal ice particles

Steven Dobbie
University of Leeds

Most people readily identify with the six fold symmetry of ice and snow particle shapes which derive from the hexagonal crystalline structure of water molecules; however, there is significant evidence for the occurrence of ice particles that exhibit a three-fold symmetry, referred to as trigonal ice particles. In this talk, I'll show evidence for the existence of trigonal ice particles from current observations as well as from the literature dating back many years, and I'll show results from simple calculations that will allow us an understanding of the optical importance of these ice particle shapes for halos and radiative properties of clouds.

Non-idealized ice crystal geometries

Joseph Ulanowski
University of Hertfordshire

The knowledge of properties of ice crystals such as size, shape, concavity and roughness is critical in the modelling of the radiative properties of ice and mixed phase clouds. Limitations of current cloud probes to measure these properties can be circumvented by acquiring two-dimensional (2-D) light scattering patterns instead of particle images. Such patterns were obtained in situ for the first time using the Small Ice Detector 3 (SID-3) probe during FAAM flights in a variety of mid-latitude mixed phase and cirrus clouds. In contrast to earlier results from cloud chambers which typically indicated crystal shapes based broadly on the hexagonal prism, the 2-D patterns were characterized by the presence of pronounced speckle, which is representative of irregular particles. The patterns can be analysed using measures of pattern texture, selected to reveal the magnitude of particle roughness or complexity. The retrieved roughness was compared to values obtained from a range of well-characterized test particles in the laboratory and found to correspond to the roughest subset. Thus the in situ data, together with other results obtained from remote sensing, is consistent with ice particles with highly irregular or rough surfaces being dominant. Overall, the roughness is expected to lead to significantly larger shortwave cloud reflectivity, in comparison with cirrus composed of more regular, smooth ice crystal shapes. The challenge now is to establish the precise impact of the roughness on the scattering and radiative properties of cirrus. However, the SID-3 study did not differentiate between small-scale, fine surface roughness, and large-scale crystal complexity. While it is likely that both can have broadly similar manifestations in terms of light scattering, this gap in knowledge will make the task of quantifying the impacts more difficult. Therefore, progress is needed in two overlapping areas. New inverse-scattering techniques are needed on the one hand, so that details of ice particle shape can be retrieved from in situ data, and perhaps also from remote sensing observations. On the other hand, efficient computational techniques need to be developed or adapted so that libraries of scattering properties can be built.

On shifted Laplace and related preconditioners for
finite element approximations of the Helmholtz equation

Ivan Graham[1], Paul Childs[2], Martin Gander[3], Euan Spence[1] and Douglas Shanks[1]
1. University of Bath
2. Schlumberger Gould Research, Cambridge
3. University of Geneva

As a model problem for high-frequency wave scattering, we study the boundary value problem

$$\left.\begin{aligned} -(\Delta + k^2)u &= f \quad \text{in } \Omega, \\ \frac{\partial u}{\partial n} - \mathrm{i}ku &= g \quad \text{on } \Gamma, \end{aligned}\right\} \tag{1}$$

where Ω is a bounded domain in R^d with boundary Γ. Our results also apply to sound-soft scattering problems in truncated exterior domains. Finite element approximations of this problem for high wavenumber *k* are notoriously hard to solve. The analysis of Krylov space-based iterative solvers such as GMRES is also hard, since the corresponding system matrices are complex, non-Hermitian and usually highly non-normal and so information about spectra and condition numbers of the system matrices generally does not give much information about the convergence rate.

Quite a lot of recent research has focussed on preconditioning (1) using (approximate) solution of the "shifted Laplace" problem

$$\left.\begin{aligned} -(\Delta + k^2 + \mathrm{i}\epsilon)u &= f \quad \text{in } \Omega, \\ \frac{\partial u}{\partial n} - \mathrm{i}\mu(k,\epsilon)u &= g \quad \text{on } \Gamma. \end{aligned}\right\} \tag{2}$$

It is generally observed that if the "absorption" parameter ε > 0 is taken large enough, then problem (2) becomes "easier" to solve, but if ε is not taken too large then (2) is a good preconditioner for (1).

Using techniques from PDE analysis (in fact extensions of the high frequency asymptotics literature) we prove that when Ω is a star-shaped Lipschitz domain, then the choice ε/*k* sufficiently small ensures *k*-independent convergence (as $k \to \infty$) for GMRES when the FEM approximation of (1) is preconditioned by the FEM approximation of (2). We also present an analysis of optimised Schwarz domain decomposition methods for (2), proving estimates on the rate of convergence explicitly in terms of *k* and ε. We also give numerical illustrations of the solution of (1), preconditioned by approximations of (2), in 2D for some constant and variable wavespeed problems.

The analysis is driven by estimates for the field of values of the preconditioned matrices. Some interesting special cases of trapping domains for which the problem possesses pseudomodes are encountered along the way.

Related references:

1. E.A. Spence, S. N. Chandler-Wilde, I. G. Graham, V. P. Smyshlyaev, *A new frequency-uniform coercive boundary integral equation for acoustic scattering*, Communications on Pure and Applied Mathematics 64(10) (2011) 1384-1415.

2. S.N. Chandler-Wilde, I.G. Graham, S. Langdon and E.A. Spence, *Boundary Integral Equation Methods for High Frequency Scattering Problems*, Acta Numerica 2012, Published online: 19 April 2012.
3. M. J. Gander, I. G. Graham and E. A. Spence, *How should one choose the shift for the shifted Laplacian to be a good preconditioner for the Helmholtz equation?*, submitted, January 2014.

Coherent backscattering effects for single particles and distributions of particles

Robin Hogan and Chris Westbrook
University of Reading

To infer the properties of clouds from backscattered signals by radar and lidar instruments, we need realistic models not only for the backscatter cross sections of individual cloud particles, but also for the contribution of multiple scattering to enhance the signal received. This talk will discuss the challenge of modelling coherent effects in both these two cases.

I will first consider the mm-wave backscatter of snowflakes, particularly relevant for interpretting spaceborne radar observations at 94 GHz. The complex and irregular shape of snowflakes makes it difficult to derive a general model for their backscatter; rather one tends to resort to very expensive explicit numerical calculations for a large ensemble of particles. It will be shown how an equation can be derived for the mean backscatter cross section of an ensemble of aggregate snowflakes that is valid provided the wavelength is longer than the size of the individual crystals from which the aggregates are composed. This is possible because of the validity of the Rayleigh-Gans approximation in this scattering regime, and because we have found from numerical simulations of the aggregation process that ice aggregates are "self-similar", with a structure that can be described by a power law. (An intriguing theoretical question arises as to why the slope of the power law is the Kolmogorov value of -5/3 when no turbulence is involved in the aggregation process.) The new equation predicts significantly higher backscatter than the commonly made "soft-spheroid" approximation, due to coherent structures within the particle on the scale of half the wavelength that lead to constructive interference in the backscatter direction.

I will then discuss the conditions under which radar and lidar measurements of clouds are influenced by multiple scattering, where the pulse from the instrument can be scattered several times within the cloud before being returned to the instrument and detected. Modelling this process requires careful description of the properties of the cloud and the geometry of the instrument, but is also potentially affected by coherent backscatter enhancement, which could have the effect of doubling the strength of the fraction of the returned signal that is due to multiple scattering. This phenomenon has been studied in depth in the context of light from a spatially extended source (such as the sun, leading to a potential explanation for the increased reflectance of Saturn's rings when the sun is behind the observer), but much less for radar and lidar. I will discuss how geometric considerations should enable the coherent backscatter enhancement to be estimated for radar and lidar platforms, and how this depends on whether they are moving or stationary with respect to the target.

The BEM++ boundary element library and applications

Timo Betcke
University College London

BEM++ is a comprehensive library to solve boundary element formulations of Laplace, Helmholtz, Maxwell, and related problems. It is based on Galerkin discretisation of operators, and supports fast approximate linear algebra for BEM operators via H-Matrix compression. The core of the library is developed in C++, and a Python interface is provided. In this talk we provide a tour through BEM++ and discuss the implementation of Maxwell transmission problems for the computation of electromagnetic scattering from ice crystals.

Hybrid numerical-asymptotic methods for high frequency scattering

David Hewett[1], Simon Chandler-Wilde[2], Stephen Langdon[2], Samuel Groth[2], Markus Melenk[3], Ashley Twigger[2]
1. University of Oxford
2. University of Reading
3. TU Vienna

Conventional numerical methods for linear wave scattering problems (e.g. Finite Element Methods or Boundary Element Methods, with piecewise polynomial basis functions) are prohibitively expensive when the wavelength of scattered wave is small compared to typical lengthscales of the scatterer (i.e. in the so-called "high frequency" regime). This is because the wave solution possesses rapid oscillations which are very expensive to capture using conventional piecewise polynomial approximation spaces. In this talk I will outline some recent work in the development of "hybrid numerical-asymptotic" methods, which incur significantly reduced computational cost by using approximation spaces containing oscillatory basis functions, carefully chosen to capture the high frequency asymptotic behaviour. Such methods have been proven (both theoretically and experimentally) to be very effective for a number of simple scatterer geometries (for example impenetrable convex two-dimensional scatterers). In this talk I will give a brief explanation of the hybrid numerical-asymptotic methodology and discuss some of the interesting challenges arising from attempts to apply it to the nonconvex, penetrable and three-dimensional scatterers arising in meteorological applications, such as the scattering of light by ice crystals in cirrus clouds.