Studies of the Martian atmospheric boundary layer and global circulation from combined use of spacecraft data and numerical circulation models

a) Project description: The climate of Mars has played a critical role during the planet’s history in determining its potential habitability, and continues to be of crucial importance (a) for understanding its near-surface environment, both now and in its geological past, and (b) for designing and planning spacecraft missions to explore it. Numerical models of the atmospheric circulation and its interactions with the surface have become essential tools for studying these systems, and have now reached an advanced state of development whereby they are able to simulate in some comprehensive detail both the day to day weather across the planet and (at least to some extent) the seasonal and interannual variability of its climate. This has led in recent years, for example, to the compilation of the ESA Mars Climate Database (MCD), widely acknowledged as a major resource for science and mission planning, to which, together with their collaborators at LMD, IAA and the Open University, Read’s team at Oxford have been major contributors [1].

The validation and continued improvement of models and facilities such as the MCD rely heavily on detailed, quantitative comparisons between model simulations and measurements of the Martian environment, both direct and indirect. With the advent of spacecraft platforms in low altitude, short period orbits (notably Mars Global Surveyor –MGS – and Mars Reconnaissance Orbiter - MRO) it has been possible recently to collect highly detailed sets of remote sensing measurements that allow systematic mapping of at least some atmospheric variables with more complete coverage on a daily basis. The asynoptic (non-simultaneous) nature of such measurements from a single orbiting platform (especially in sun-synchronous orbits), however, still leads to ambiguities that may be hard to unravel for certain features (especially if time-varying).

The UK team of Prof. Read and Dr Stephen Lewis at the Open University have recently pioneered the use of meteorological data assimilation techniques to overcome some of these difficulties [2,3]. Data assimilation is a statistical-dynamical technique that combines the use of a numerical simulation and sets of measurements to produce a complete, 3D, multivariate reconstruction of the state of the atmosphere, effectively by using the model to connect disparate measurements whilst ensuring that the resultant solution is fully consistent with those measurements to within their intrinsic uncertainty. Such an approach was originally developed by the operational community in terrestrial meteorology to obtain accurate and complete initial conditions for numerical weather forecasts. By utilising a similar approach, the terrestrial community has also developed long-term

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1 Laboratoire de Météorologie Dynamique, Paris, France
2 Instituto de Astrofisica de Andalucia, Granada, Spain
databases of assimilated atmospheric observations\textsuperscript{3} that provide highly detailed, four-dimensional global records of the Earth's climate over periods of decades. Read and Lewis have now begun to achieve a similar goal for Mars, initially through assimilation of the Thermal Emission Spectrometer (TES) temperature and dust measurements from MGS, covering a continuous period of around 3 Mars years (sampled 4 times per day)\textsuperscript{[3]}. This is now being continually extended and updated through assimilation of new data from the Mars Climate Sounder (MCS) instrument on MRO, such that the current 'reanalysis' record for Mars covers nearly 6 Mars years in total \textsuperscript{[4]} (see Fig. 1). Parts of this dataset (known as MACDA) are also now being made publicly available through the British Atmospheric Data Centre\textsuperscript{4}.

In the present project, we propose to exploit this dataset (a) to verify and extend it using new data from other missions, especially including the REMS instrument package on the Curiosity MSL Rover, (b) to utilise the extended MACDA dataset to diagnose seasonal and interannual variations in global transport of heat, mass and dust within the Martian climate system and to quantify the contributions to these transports by different components of the climate system, especially within the atmospheric boundary layer, and (c) to explore and extend the capability of the UK-LMD Mars model to make deterministic boundary layer, and (c) to explore and extend the capability of the UK-LMD Mars model to make deterministic

The long-term presence of the MSL rover at the Martian surface at the same time as the MRO spacecraft continues its mapping operations provides a unique opportunity to validate the assimilated analyses systematically against an independent data source that measures all of the key meteorological variables (albeit at just one location). The REMS package is providing continual records of atmospheric and surface temperature, pressure, wind and humidity from its vantage point in Gale Crater, as well as measurements of atmospheric opacity. Some of this data will shortly become available via NASA's PDS, but we also have good collaborative links with members of the REMS team in Madrid (J. Martin-Torres) and in the US (Richardson, Renno). At the same time, MCS continues to observe the atmosphere from low orbit. The MACDA analyses of MCS data can therefore provide a global context for the variability observed by REMS, which is \textit{essential} for its physical interpretation, and provide predictions/inferences of the conditions encountered by Curiosity which can be directly tested against REMS measurements. Systematic differences are expected to lead to new insights into potential deficiencies in the UK-LMD model's representation of Martian meteorology, especially within the near-surface boundary layer, which is still a relatively unexplored part of the Martian environment \textsuperscript{[5]} yet plays a critical role in governing the exchange of mass, heat and momentum between atmosphere and surface.

The extended MACDA dataset (including MCS data) provides a unique and immensely powerful resource for carrying out quantitative analyses of the climate of Mars and its seasonal and interannual variability. In this project we will carry out a systematic analysis of the seasonal and interannual variations in the global and interhemispheric transports of heat and key tracers, such as CO\textsubscript{2} and dust. With nearly six Mars years of analyses already obtained, this will provide unprecedented quantitative information on how the current climate on Mars is sustained and interacts with other components of the Martian environment and surface.

Finally, we plan to make use of individual analysed states from the extended MACDA dataset to carry out an investigation of the deterministic predictability of Martian meteorology. Our earlier attempts to investigate this problem \textsuperscript{[6]} were dominated by systematic errors in computing the radiative balance of the atmosphere in the model, quickly leading to drifts away from the observed state because of the short radiative timescale. Recent work by the LMD group, however, has led to significant improvements, especially in the representation of dust heating and the radiative effects of water ice clouds, that should substantially reduce these systematic errors. We will therefore investigate the impact of these improvements by carrying out short-term forecasting experiments covering a representative range of conditions and times of year, with the aim of estimating intrinsic limits to deterministic predictability on Mars and determining the feasibility of using models and observations to make forecasts useful for future spacecraft operations.

\textsuperscript{3} known as 'reanalyses', because they entail the application of a modern assimilation technique to historical data

\textsuperscript{4} see http://www2.physics.ox.ac.uk/research/geophysical-fluid-dynamics/macda
b) Supervision: The project will be supervised by Prof. Peter L. Read, who has more than 30 years’ experience of leading research in geophysical fluid dynamics and in studies of the dynamics and circulation of planetary atmospheres. He has successfully supervised more than 20 DPhil students since the early 1990s, many of whom have gone on to flourishing careers as academic researchers (including 3-4 now at Senior Lecturer or Reader level and a Royal Society URF) or in government or industrial research laboratories in the UK and abroad.

c) Monitoring of Progress: In common with the rest of Oxford Physics, AOPP has a well established process for oversight and monitoring of student progress, especially during the first two years of a DPhil programme. The University and Mathematical, Physical and Life Sciences Division has a fully documented code of practice that all Departments adhere to. Students meet with their supervisor at regular intervals throughout the year and supervisors are required to write termly reports on student progress. In addition, students are required to write substantial reports on their research at the end of the first and second years, which are reviewed by two independent academic staff members in a viva interview with the student. Feedback is provided to both student and supervisor from this process, and progression from probationer status to full DPhil student status is contingent on the student satisfying his/her reviewers on progress with their project. Should problems arise, these are picked up and reviewed by the Departmental Graduate Studies committee, which may recommend remedial action and advice for both student and supervisor.

d) Training Opportunities: This project will provide an excellent training in a wide range of atmospheric modelling techniques and in the manipulation and analysis of large datasets of measurements. All graduate students in AOPP are required to complete a basic training course in the Physics of Atmospheres and Oceans during their first year, comprising a set of 40-45 lectures supported by 8-10 tutorial problems classes distributed throughout the year. In addition, students have full access to the range of courses in both scientific/technical disciplines and broader skills training provided within the University’s Mathematical, Physical and Life Sciences Division Graduate School through their Graduate Academic Programme (GAP). Within AOPP, there are also a range of short lecture courses on a rolling series of topics, including statistical methods, geophysical fluid dynamics and data analysis techniques.

e) Research Environment: Oxford’s research programme across all the physical sciences is among the most extensive in the UK. Its research in planetary science, physical climate science and astronomy is world leading in its breadth and quality, with a substantial number of internationally leading researchers among its faculty. Its planetary exploration programme has a long history of direct involvement in NASA and ESA space missions, including the Cassini Orbiter, MRO, Lunar Reconnaissance Orbiter and Venus Express (Read is a Co-I on MRO/MCS, for example). Oxford attracts a large number of high level visitors from across the world, and there are many opportunities for graduate students to attend a rich programme of seminars and lectures across the whole spectrum of Earth and planetary sciences, and astronomy. AOPP typically accepts around 6-10 graduate students per year with 25-30 students in residence at any one time. They form a lively, close-knit and supportive community within the Department. This project will also entail interaction with observational planetary scientists in Oxford, at the Open University and LMD (Paris), as well as with the MSL/REMS team in Madrid and the US.

References

5 http://gradschool.mpls.ox.ac.uk/graduate-school/sites/default/files/Supervision%20Code%20of%20Practice%202012-13.pdf
6 see http://www.mpls.ox.ac.uk/skills
