Institution: University of Oxford

Unit of Assessment: 9 – Physics

Title of case study: [10] The Mars Climate Database for spaceflight missions

1. Summary of the impact

The Mars Climate Database (MCD), based on research at the University of Oxford, has been used to inform the entry, descent, landing and operation of past and future Mars landers. The MCD has been provided to 112 users, including NASA, the European Space Agency (ESA) and Astrium. The MCD has directly contributed to the successful landing and operation of NASA's *Curiosity* Mars Rover, and ESA have required Astrium, lead contractor for the ExoMars mission, to use it for the design of components and systems. The impacts of the MCD include (1) contributions to preventing failures of billion-dollar space missions and thus financial savings for space agencies and (2) enabling viability studies of spacecraft designs by industrial contractors.

2. Underpinning research

The climate and atmospheric circulation of Mars have many features in common with the Earth, in terms of the mechanisms driving atmospheric motions and of the roles played by planetary rotation, small-scale turbulent mixing and the topography of its underlying surface. Professor Peter Read (appointed 1991) and his group at the University of Oxford adapted numerical circulation models, originally developed for the Earth's atmosphere, for use in studies of the Mars climate system. Initial studies focused on investigating the role of surface topography on the atmospheric circulation, including the identification of 'Western boundary currents' (WBCs), which are intensifications of north-south flow adjacent to an eastward-facing meridional boundary. Although most familiar in the oceans, where the Gulf Stream is the best known example, WBCs also occur in the Earth's troposphere in the form of an intense jet stream, such as the one associated with the Indian monsoon producing a seasonal jet close to the Ethiopian Highlands.

In 1994, Professor Peter Read's group identified WBCs for the first time in numerical simulations of the atmosphere of Mars [1,2], and demonstrated that features of WBCs were consistent with observational evidence. The intensity of WBCs is dependent on surface drag, and frictional forces were shown to dominate the WBC's behaviour. Slope winds were found to have a profound effect on WBC structure, especially where they have a component parallel to the jet. In these cases, slope winds can cancel out or reinforce WBCs, depending on their direction. Read determined that enhanced low-level winds associated with WBCs are an important mechanism in the generation of the dust storms on Mars and the transport of dust and water vapour across the planet.

With this new insight, the Oxford team went on to collaborate with Laboratoire de Météorologie Dynamique du CNRS (LMD) in Paris to develop comprehensive climate and circulation models of Mars [3,4] and to publish a database of statistics of global Mars climate and variations [5]. The Oxford team primarily worked on the atmospheric dynamics, while LMD worked primarily on improving the representation of physical processes (e.g. radiative transfer, boundary layer turbulence) in the combined model. The development of database tools and the online variability model were led by Oxford.

The research was carried out in Oxford and was led by Professor Read with Lewis (postdoctoral researcher 1990 – 2001 then lecturer 2001 - 2005), Catling (graduate student 1990 – 1994), Joshi (graduate student 1990 – 1994) and Collins (postdoctoral researcher 1993 – 1997).

3. References to the research (Oxford authors, * denotes best indicators of quality)

*[1] Joshi MM, Lewis SR, Read PL & Catling DC, (1994), Western boundary currents in the atmosphere of Mars, *Nature*, 367, 548-551, doi: 10.1038/367548a0, citations: 17 (WoS).

[2] Joshi MM, Lewis SR, Read PL & Catling DC, (1995), Western boundary currents in the Martian atmosphere: Numerical simulations and observational evidence, *Journal of Geophysical Research (Planets),* 100, 5485-5500, doi: 10.1029/94JE02716, citations 37 (WoS).

[3] Collins M, Lewis SR, Read PL and Hourdin F, (1996), Baroclinic wave transitions in the Martian atmosphere, *Icarus*, 120, 344-357, doi: 10.1006/icar.1996.0055, citations: 46 (WoS).

*[4] Forget F, Hourdin F, Fournier R, Hourdin C, Talagrand O, Collins M, Lewis SR, Read PL and Huot J-P, (1999), Improved general circulation models of the Martian atmosphere from the surface to above 80 km, *Journal of Geophysical Research (Planets),* 104 (E10), 24155-24176, doi: 10.1029/1999JE001025, citations: 295 (WoS). *This paper describes the resulting Mars Climate model and some scientific results.*

*[5] Lewis SR, Collins M, Read PL, Forget F, Hourdin F, Fournier R, Hourdin C, Talagrand O and Huot J-P, (1999), A climate database for Mars, *Journal of Geophysical Research (Planets),* 104 (E10), 24177-24194, doi: 10.1029/1999JE001024, citations: 161 (WoS).

4. Details of the impact

Mars missions cost in excess of $1bn and historically many have failed. An important variable in the success of entry, descent, landing and operation is the climate on Mars and especially the behaviour of dust, which varies widely.

The Mars Climate Database (MCD) described in [5] was made available for wider use in December 2006. The MCD is freely available on the internet through an online version that is intended for light use only. Access to the full database and dedicated software can be requested by advanced users, and is also free of charge. Since 2008, the full database has been provided to 112 users including space agencies NASA and ESA, and contractors Astrium and Thales Alenia Space.

The MCD has been used to produce simulations of spacecraft flight through the Mars atmosphere as well as simulations for surface operations. The MCD can produce profiles of atmospheric density versus height, which is key for producing simulations of flight. It can also produce profiles of the surface temperature and surface pressure over the course of a day and over the seasonal cycle. Dust scenarios are included, providing the ability to account for different dust concentrations and dust storms.

Mars Science Laboratory and *Curiosity* Mars Rover (launched 2011)

In 2011, NASA launched the Mars Science Laboratory (MSL) that successfully landed the *Curiosity* Mars Rover on Mars in 2012. The MSL project cost an estimated $2.5bn and collected information about the habitability, climate and geology of Mars. The MCD contributed to the success of the *Curiosity* Mars Rover by narrowing the options for landing sites without the need for expensive and time-consuming customised models. NASA Jet Propulsion Laboratory used MCD extensively in the early design phase to produce simulations of the MSL's flight through the Mars atmosphere. They also used the MCD to model the surface conditions, and inform the landing site location for *Curiosity.*

NASA say that *"the MCD plays a unique role in providing an easily accessible database, and very importantly one that is constructed and validated by leading Mars atmospheric scientists. This combination allows the engineering teams (with scientific guidance) to quickly narrow the design space. It allows the science team to assess a number of different landing site latitude[s] and elevations, with an idea of the potential consequences to mission operations."*

At the final stages of design, NASA used customised modelling studies but they say that *"such studies are expensive and time consuming, and would not be possible during the design phase when many options are being explored."* [A]

ExoMars (currently in development, due for launch 2015)

ExoMars is a Mars mission that will search for biosignatures of Martian life, past and present. The project, expected to cost a total of $1.3bn, is led by the European Space Agency (ESA), who have used the MCD directly to analyse different atmospheric and dust scenarios to confirm mission feasibility.

ESA required Astrium, the lead contractor on ExoMars, to use the MCD. Astrium used it to develop their aerobraking, a spaceflight manoeuvre that results in drag to slow a vehicle by flying it through the atmosphere to save fuel. At ESA's direct request, Astrium have integrated the MCD with an existing aerobraking simulator enabling them to produce realistic values for density, dynamic pressure and heat flux. Astrium say that *"this allowed tuning [of] the design and demonstrating the viability of onboard algorithms aimed at improving the autonomy level of aerobraking."* [B]

Thales Alenia Space is also a contractor for the ExoMars project and has used the MCD extensively for precision landing studies.

5. Sources to corroborate the impact

[A] Letter from Senior Scientist at the Jet Propulsion Laboratory (held on file) confirming their use of MCD and how it has contributed to the success of the *Curiosity* Mars Rover.

[B] Letter from Advanced Studies Engineer at Astrium (held on file) confirming their use of MCD, the requirement from ESA to use MCD and its impact on their aerobraking design.