The Oxford 3D Thermophysical Model with application to the Lunar PROSPECT Mission. T. Warren[1], N. Bowles[1], O. King[2], E. Sefton-Nash[3], R. Fisackerly[3], R. Trautner[3]. (1) Atmospheric, Oceanic and Planetary Physics, University of Oxford, UK, (tristram.warren@physics.ox.ac.uk neil.bowles@physics.ox.ac.uk), (2) Department of Physics & Astronomy, University of Leicester, UK (ortk1@leicester.ac.uk), (3) ESTEC, European Space Agency, Keplerlaan 1, Noordwijk 2201AZ, Netherlands (e.sefton-nash@cosmos.esa.int).

Overview: To investigate potential in-situ near surface volatiles that might be present in the lunar Polar regions, the European Space Agency (ESA) is developing the PROSPECT instrument package to fly to the South Polar region of the Moon on-board Russia's Luna-27/Luna Resurs mission, which is scheduled to launch in the next decade [1,2]. PROSPECT will consist of a drill (ProSEED) that will collect samples from the regolith at depths of up to 1 m below the lunar surface and transfer them into a miniaturised chemical laboratory (ProSPA), where samples will be heated up to ~1000° C in the presence of different reagent gases to extract a range of different volatiles including water.

To help investigate potential landing sites we have developed the Oxford 3D Thermophysical Model (O3DTM) [3]. Using the O3DTM, we have modelled the lunar surface and subsurface (<2.5 m) temperatures for the South Polar Region (<-75° latitude) at a resolution of ~2 km^2. As an example Figure 1 shows the maximum surface temperature map of the simulated region. The O3DTM has been written in MATLAB and all the code and data files are available on GitHub[1].

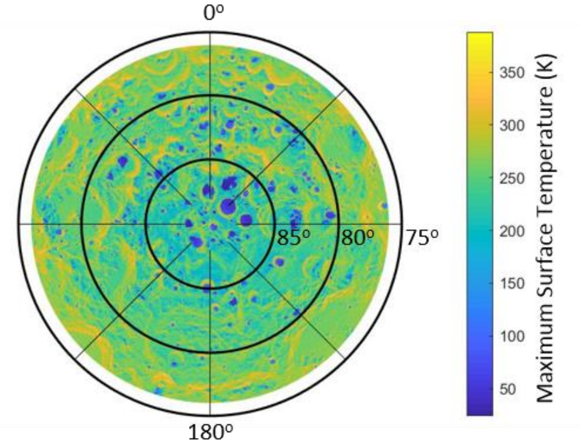

Figure 1 : Simulated maximum surface temperature map of the lunar South Pole

Oxford 3-D Thermophysical Model: One dimensional thermophysical models are poor predictors of the lunar polar surface and subsurface temperatures at high latitudes due to the importance of shadowing and scattering. In shadowed regions one dimensional models can predict surface temperatures to be >100 K too warm [3] and in the extreme case of permanently shadowed regions one dimensional models are unable to predict the surface temperature since they do not include scattered radiation. To model accurately the surface and subsurface temperatures at the lunar poles requires a 3-D thermophysical model (3DTM). A new 3DTM that includes a discreet subsurface exponential density profile, surface shadowing and scattering effects has been developed at Oxford University to simulate the lunar surface and subsurface temperatures to account for these environmental effects at the poles [4,5,6]. The Oxford 3DTM combines the one-dimensional subsurface heat flow from the model described in [6] and the 3-D shadowing and scattering effects used in standard 3DTMs such as [4,5]. To compute the shadowing and ray tracing the Oxford 3DTM uses the LOLA topography and albedo datasets. However, since the LOLA albedo measurements are performed using a 1064.4 nm laser the albedo values are scaled to represent the broadband solar albedo value using the method described in [6]. All other thermophysical modelling parameters are taken from [6].

Model Validation: Validation of the model's subsurface temperature estimates are currently limited as there is no in situ data for the Polar Regions to compare to our modelled values. The simulations have been compared to surface temperature measurements from the Lunar Reconnaissance Orbiter's Diviner Lunar Radiometer instrument ("Diviner") for validation [7]. The O3DTM is in good agreement with the Diviner measurements with the absolute temperature deviation being typically less than 5 K. The absolute temperature deviation is defined as being the time averaged absolute difference between the modelled temperature and the Diviner measured temperature.

Ice Stability Depth: From the thermal model it was possible to define the minimum depth required to drill to reach subsurface temperatures where water ice would be expected to be stable by using the theoretical sublimation rate taken from [8] and shown in Figure 2. The O3DTM splits a single surface element into several (>10) model layers at different depths. The O3DTM calculates how the temperature of each layer varies throughout the lunar day night cycle which is modulated by a smaller seasonal cycle.

The temperatures for each model layer inside every surface facet was binned in 1 Kelvin bins. This was then convolved with the theoretical sublimation rate given in Figure 2, to give a total sublimation rate for each layer in every facet. We assumed as in previous

[1] https://github.com/tw7044/O3DTM/

works [3,4] that the water delivery rate is much greater than 1 $Kg/m^2/Ga$ and hence water ice could exist at a given depth if the total sublimation rate is less than 1 $Kg/m^2/Ga$. The predicted ice stability minimum depth map using this method is shown in Figure 3.

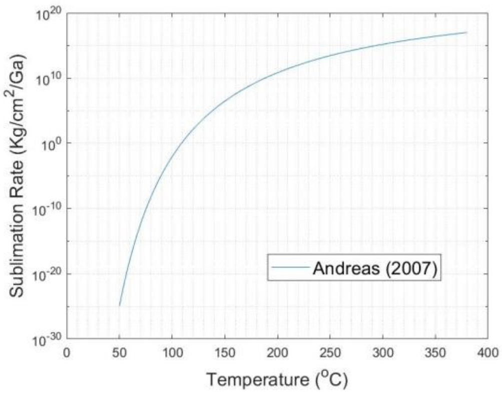

Figure 2 : Theoretical sublimation rate of water ice

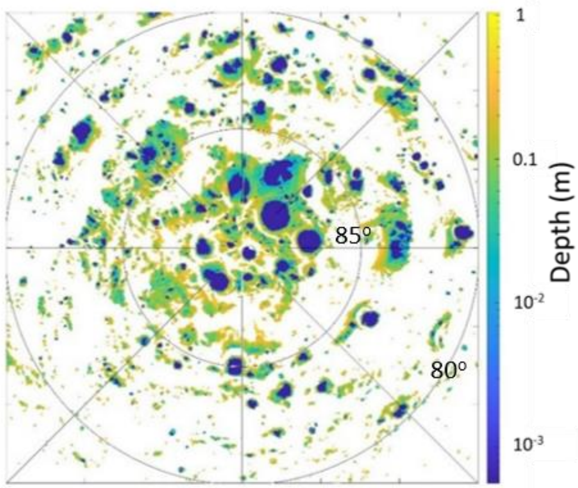

Figure 3 : O3DTM predicted ice stability map of the lunar South Pole

This method does not account for diffusion or potential pumping of water ice to greater depths [9] and is therefore just a guide to demonstrate where temperatures remain cold enough for water ice to exist. We are currently working on coupling a diffusion model with the O3DTM to make a more physically accurate model.

However, at the moment the expected stable ice depth for the lunar South Pole shown in Figure 3 is our best estimate of water ice distribution. It shows there are large regions where ice is not stable at any depths and in those locations where ice is stable the ice stability depth is relatively shallow (< 0.5 m). These results show that, assuming careful selection of landing site the current design depth of the PROSPECT drill (~1 m) should be sufficient to sample trapped water ice.

Comparison to Previous Models: Predicted stable water ice depths have been previously generated by other 3DTM such as [4] and we will present a comparison between the two models. The models agree to within 1 mm of expected stable water ice depth in 90% of the simulated region, but in some specific locations disagree. In the regions of disagreement the O3DTM generally predicts water ice should not be present, but the Paige model [4] predicts water ice at medium to high depths (> 0.2 m). Currently, the difference in the predicted water ice location is believed to be due to difference in the layering between the two models. The O3DTM use a discreet subsurface exponential density profile with multiple layers (> 10) whereas [4] used two discrete layers with different densities.

Model Summary: Compared to other 3DTM such as the Paige model the O3DTM also has several other differences. Most 3DTM's assume isotropic scattering, however, the O3DTM assumes non-isotropic scattering with scattering functions taken from laboratory measurements [10,11,12]. The O3DTM does not account for Earth shine radiance and the sun is assumed to be a single point.

Conclusions: The Oxford 3DTM is available to download and new surface and subsurface temperature simulations for the lunar South Polar Region are available to download from GitHub - https://github.com/tw7044/O3DTM/

Simulations show depths at which ice would be expected to be stable are generally near the surface (< 0.5 m), so for the Luna-27 lander mission the choice of landing site location and the precision landing capability of the lander are essential given the engineering constraints on the sampling system.

There is an obvious correlation between the illumination fraction and the volatile stability conditions. Luna-27/PROSPECT will therefore have a trade-off to select a site that will satisfy both critical power/operations requirements and science objectives of the PROSPECT mission.

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References: [1] Trautner, R. et al. (2018) IAC-18, 42773 [2] Sefton-Nash, E. et al. (2018) LPSC 2740 [3] King and Warren. et al. (2019), PSS 104790 [4] Paige, D. A. et al. (2010), Science, 330, 479. [5] Vasavada, A. et al. (1999) GJR, 193. [6] Hayne, P et al. (2017) Space Sci Rev. [7] Paige, D. A. et al. (2009), Space Sci. Rev.150, 125-160. [8] Andreas et al . (2007) Icarus 186. [9] Schorghofer and Aharonson (2014) AAS 788(2). [10] Warren et al. (2019) JGR 124(2). [11] Warren et al. (2017) Rev Sci 88(12). [12] Foote et al. (2020) Icarus 336