RADIATIVE TRANSFER MODELING OF THE MARTIAN ATMOSPHERE. E. Mlawer[1], J. Eluszkiewicz[1], K. Cady-Pereira[1], M. J. Iacono, and J.-L. Moncet[1], [1]Atmospheric and Environmental Research, Inc., 131 Hartwell Ave., Lexington, MA 02421, emlawer@aer.com.

Introduction: Studies of the past and current climate and weather on Mars depend on accurate calculations of the radiative properties of the Martian atmosphere. Atmospheric and Environmental Research, Inc. (AER) is the source of the state-of-the-science radiative transfer codes for terrestrial applications [1] and these models are continuously updated and validated [2]. Recently, they have been modified to extend their applicability to conditions other than found on current-day Earth, such as those relevant to paleo-Earth and current and ancient Mars. This presentation will describe these developments, in the hope that they will contribute to achieving broad Mars research and exploration goals via modeling and remote sensing.

LBLRTM: In our radiative transfer work, AER's well-known LBLRTM model [1, 2] serves as the foundational line-by-line reference. LBLRTM participates in on-going radiative closure studies [3, 4] enabling it to be quickly and rigorously updated as our knowledge of the fundamental spectroscopic parameters improves. A recent example involves the implementation of new P and R branch line coupling coefficients for CO_2 [5, 6]. The inclusion of this work in the EOS-Aura Tropospheric Emission Spectrometer forward model (for which AER has primary responsibility [7]) has led to improvements in the atmospheric temperature retrievals in the most recent data version release. Of particular relevance to the proposed work is our on-going NASA-funded work that has enhanced the capabilities of LBLRTM specifically for the development of GCM-suitable radiation codes for studies of the climate of paleo-Earth, -Mars, and other terrestrial planets. This development has involved a number of upgrades to the model. First, newly calculated CO_2-broadened line parameters (half-widths, line shifts, and temperature dependence of widths) of water vapor lines [8, 9] have been incorporated. Since these calculations did not cover numerous water vapor lines of interest (e.g. near-infrared bands, weaker lines, most isotopologues), a scheme was developed to estimate the CO_2-broadened line parameters of these lines. Second, the water vapor continuum model, MT_CKD [1] has been adjusted to account for the difference between air- and CO_2-broadening of water vapor lines and their relative efficiency in generating collision-induced absorption. Finally, the CO_2 collision-induced absorption parameterization presented in [10] has been added to the MT_CKD continuum model. In our presentation, we will provide details of these modifications and their effect on the relevant radiative transfer calculations. For example, preliminary results indicate a change of 10-20% in the retrieved column water vapor under current Martian conditions (compared to calculations employing the more basic spectroscopic modifications [11]), with most of this difference stemming from changes to the water vapor continuum.

Another effort in which we are centrally involved and that has the potential to affect the spectroscopic parameters that underlie the modeling of water vapor continuum are two field campaigns co-led by AER and U. Wisconsin under the sponsorship of the U.S Department of Energy Atmospheric Radiation Measurement (ARM) program. These campaigns aim to improve our knowledge of water vapor spectroscopy in spectral regions that are normally opaque at the Earth's surface, including the far-infrared band used to retrieve water vapor abundances from the MCS and TES measurements. The first of these campaigns, RHUBC-I (Radiative Heating in Underexplored Bands Campaign - I), was held in February-March 2007 in Barrow, Alaska, and has led to revised water vapor line widths and continuum coefficients in the 390-550 cm^{-1} spectral region. The second RHUBC campaign will be held in the Atacama Desert of Chile during August-November 2009, at which time the water vapor column amounts are expected to be 5-10 times smaller than during RHUBC-I. These low column amounts result in the usually opaque regions of the far-IR (and other water vapor bands) becoming semi-transparent, thus allowing critical spectroscopic information in the 200-550 cm^{-1} region to be determined from the measurements taken during the campaign.

RRTM: LBLRTM has provided the foundation for the development of the fast radiative transfer code RRTM [12] that is used primarily for radiative flux and heating rate calculations. The RRTM model is based on the correlated-*k* method and has been developed specifically with the ability to handle gas mixtures, a feature particularly relevant to the modeling of the Mars paleo-climate. The terrestrial GCM version of this model, RRTMG [13], is currently in use operationally or is being tested in several general circulation models for weather forecasting and climate research. At the European Centre for Medium-Range Weather Forecasts (ECMWF), the longwave version RRTMG_LW has been running in the operational weather forecast model since June 2000 [14] and it was a component of the global model used to generate the ERA40 Reanalysis. ECMWF began using the shortwave version RRTMG_SW operationally in June 2007 [15]. The National Centers for Environmental Prediction (NCEP) has been utilizing RRTMG_LW operationally in the Global Forecast System (GFS) model since August 2003 and the Climate Forecast System

(CFS) model [16] since 2004. It is anticipated that NCEP will begin using RRTMG_SW in the GFS and CFS during 2008. The next version of the National Center for Atmospheric Research (NCAR) climate model (CAM4) is currently in development, with RRTMG as a likely replacement for the present radiation in CAM3 [17]. RRTMG is also being evaluated at the Geophysical Fluid Dynamics Laboratory (GFDL) for application to the GFDL AM2 climate model [18]. The NCAR version of the advanced research Weather Research and Forecasting (WRF) model [19] has included RRTMG_LW since 2004, and this model runs as an ensemble forecast among the daily operations at NCEP. The shortwave model is presently being implemented in WRF. Other models currently utilizing RRTMG_LW include the ECHAM5 model of the Max Planck Institute [20] and the NCAR/PSU regional forecast model MM5 [21]. Finally, the AER longwave and shortwave radiation codes are a component of the Visible Infrared Imager/Radiometer Suite (VIIRS) net heat flux and ocean albedo algorithm for the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

Parallel to the planetary modifications to LBLRTM listed above, an enhancement of RRTM and RRTMG is under development to make them appropriate for use in studies of paleo-Earth and studies related to the outer edge of the habitable zone. The plan is to further adapt these codes to studies of paleo and current Mars.

OSS: Our retrieval and radiance assimilation work is based on the Optimal Spectral Sampling (OSS) method [22-24]. The theoretical basis and implementation of the OSS method are described in [25]. The OSS approach is an extension of the Exponential Sum Fitting Transmittance (ESFT) method [26], applicable to vertically inhomogeneous atmospheres, and consists of approximating radiances in each spectral channel as linear combinations of radiances computed at selected monochromatic locations. The spectral locations and their statistical weights are selected by comparing the resulting channel radiances against LBLRTM calculations performed over a wide range of atmospheric profiles. The training profiles are chosen to be representative of the expected variability, including atmospheric temperature and composition, surface pressure, surface emissivity and reflectivity, and viewing and solar angles. Being a physics-based approach, the OSS method is robust with respect to the range of atmospheric conditions to which the model is applied, including profiles outside of the training set. Furthermore, the method very accurately takes into account variations in temperature and gaseous and aerosol absorption along inhomogeneous vertical paths. A distinct advantage of the method is that its error tolerance (versus LBL calculations) is selected *a priori* by the user, even in the multi-layer case. This feature provides flexibility to tailor the fitting to balance the radiometric accuracy requirements dictated by the application and the algorithm run-time constraints. Specifically, while an LBL model uses hundreds of thousands of monochromatic calculations to simulate a 10 cm^{-1} channel, the OSS model requires only a dozen or fewer monochromatic points to achieve a level of accuracy appropriate to the instrument noise. In doing so, the OSS method exploits the spectral redundancies between monochromatic lines within each channel. In other words, a few (optimally chosen) lines represent the variability of absorption in each layer of all spectral lines present in the channel. The RMS accuracy of the OSS is typically set to 0.1 K (in brightness temperature) or better and may be tailored to the application (retrieval or radiance assimilation). Since the OSS approach is based on monochromatic calculations, it is applicable to non-positive instrument line-shape functions (interferometers) and different viewing geometries, including nadir, limb, and EPF sequences. For the same reason, the modeling of scattering effects can be included in an accurate and computationally efficient way. Multiple scattering calculations at nadir are performed in OSS using an adding/doubling algorithm code based on CHARTS (Code for High Resolution Accelerated Radiative Transfer) that has been developed specifically to provide scattering radiative transfer capability for LBLRTM and used for validation purposes at the ARM/Southern Great Plains site [27]. In the limb, our plans are to use OSS in conjuction with the Gauss Seidel Spherical RTM (GSSRTM) code [28-30].

The OSS technique has been developed and extensively validated for a wide range of terrestrial applications. The method was initially applied to Earth-orbiting infrared and microwave sounders [22, 23], with the most recent applications involving the NPOESS/CrIMSS, NPOESS/CMIS, EUMETSAT, and CLARREO projects, and has since been adapted to Mars [24, 31]. Currently, the OSS method is being implemented at NCEP for operational numerical weather prediction and data assimilation [32] and serves as the observational operator in the assimilation of TES radiances as part of the Mars data assimilation system being developed at the University of Maryland.

Acknowledgements: This work has been supported in part by the NASA Terrestrial Planet Finder, Mars Fundamental Research, and Mars Data Analysis Programs.

References: [1] Clough S. A. et al. (2005) *JQSRT, 91,* 233. [2] http://rtweb.aer.com [3] Clough S. A. et al. (1999) Ninth ARM Science Team Meeting, http://www.arm.gov/publications/proceedings/conf09/abstracts/clough-99.pdf. [4] Turner D. D. et al. (2004) *J. Atmos. Sci., 61,* 2,657. [5] Niro F. et al. (2005) *JQSRT, 95,* 469. [6] Clough S. A. et al. (2008) *Tenth Biennial*

HITRAN Conference http://www.hitran.com [7] Clough S. A. et al. (2006) *IEEE Trans. Geosci. Remote Sens., 44,* 1308. [8] R. Gamache (2008) personal comm. [9] Brown L. R. et al. (2007) *J. Mol. Spectrosc., 246,* 1. [10] Kasting J. F. et al. (1984) *J. Atmos. Chem.,* 1, 403. [11] Smith M. D. (2002) *J. Geophys. Res., 107,* 5115. [12] Mlawer E. J. et al. (1997) *J. Geophys. Res., 102,* 16,663. [13] Iacono M. J. et al. (2008) *J. Geophys. Res.*, *113,* D13103. [14] Morcrette J.-J. (2001) *ECMWF Newsletter*, No. 91. [15] Morcrette J.-J. et al. (2008) *Mon. Weather Rev.*, doi:10.1175/2008MWR2363.1 (in press). [16] Saha S. et al. (2006) *J. Climate*, 19, 3483. [17] Collins W. D. (2006) *J. Climate*, 19, 2144. [18] Anderson J. L. et al. (2004) *J. Climate*, *17,* 4641. [19] Skamarock W. C. et al. (2008) *NCAR Technical Note* NCAR/TN-475+STR. [20] Wild M. and E. Roeckner (2006) *J. Climate*, *19,* 3792. [21] Dudhia J. et al. (2002) Notes and User's Guide: MM5 Modeling System Version 3. [22] Moncet, J.-L. et al. (2001) Algorithm Theoretical Basis Document for the Cross-Track Infrared Sounder (CrIS) Environmental Data Records (EDR). [23] Saunders R. et al. (2007) *JGR, 112,* D01S90. [24] Eluszkiewicz J. et al. (2005) 36th LPSC, Abtract # 2181. [25] Moncet J.-L. et al. (2008) *J. Atmos. Sci.* (in press). [26] Wiscombe, J. W. and J. W. Evans (1977) *J. Comp. Phys.*, *24,* 416. [27] Moncet J.-L. and S. A. Clough (1997) *J. Geophys. Res., 102,* 21,853. [28] Herman B. M. et al. (1994) *Appl. Opt., 33,* 1760. [29] Herman B. M. et al. (1994) *Appl. Opt., 34,* 4563. [30] Eluszkiewicz et al. (2008) this workshop. [31] Eluszkiewicz J. et al. (2008) *J. Geophys. Res.,* doi:10.1029/2008JE003120 (in press) and this workshop. [32] Weng F. (2007) *J. Atmos. Sci., 64,* 3799.