Journal of Quantitative Spectroscopy & Radiative Transfer 168 (2016) 176–192

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Neural network radiative transfer solvers for the generation of high resolution solar irradiance spectra parameterized by cloud and aerosol parameters

M. Taylor [a,*], P.G. Kosmopoulos [a], S. Kazadzis [a,b], I. Keramitsoglou [c], C.T. Kiranoudis [c,d]

[a] Institute for Environmental Research and Sustainable Development (IERSD), National Observatory of Athens (NOA), Metaxa & Vas Pavlou, Penteli, GR-15236 Athens, Greece
[b] Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center (PMOD/WRC), Dorfstrasse 33, CH-7260 Davos Dorf, Switzerland
[c] Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing (IAASARS), National Observatory of Athens (NOA), Metaxa & Vas Pavlou, Penteli, GR-15236 Athens, Greece
[d] School of Chemical Engineering, National Technical University of Athens (NTUA), GR-15780 Athens, Greece

ARTICLE INFO

Article history:
Received 30 June 2015
Accepted 28 August 2015
Available online 30 September 2015

Keywords:
Solar radiation
Clouds
Aerosol
Neural networks
Radiative transfer

ABSTRACT

This paper reports on the development of a neural network (NN) model for instantaneous and accurate estimation of solar radiation spectra and budgets geared toward satellite cloud data using a ≈ 2.4 M record, high-spectral resolution look up table (LUT) generated with the radiative transfer model libRadtran. Two NN solvers, one for clear sky conditions dominated by aerosol and one for cloudy skies, were trained on a normally-distributed and multiparametric subset of the LUT that spans a very broad class of atmospheric and meteorological conditions as inputs with corresponding high resolution solar irradiance target spectra as outputs. The NN solvers were tested by feeding them with a large (10 K record) "off-grid" random subset of the LUT spanning the training data space, and then comparing simulated outputs with target values provided by the LUT. The NN solvers demonstrated a capability to interpolate accurately over the entire multiparametric space. Once trained, the NN solvers allow for high-speed estimation of solar radiation spectra with high spectral resolution (1 nm) and for a quantification of the effect of aerosol and cloud optical parameters on the solar radiation budget without the need for a massive database. The cloudy sky NN solver was applied to high spatial resolution (54 K pixel) cloud data extracted from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the geostationary Meteosat Second Generation 3 (MSG3) satellite and demonstrated that coherent maps of spectrally-integrated global horizontal irradiance at this resolution can be produced on the order of 1 min.

1. Introduction

The 5th assessment report of the International Panel on Climate Change [21] has highlighted a need for increasing the breadth of studies into the impact of clouds, aerosols and their feedback processes on climate change. The main reason for this emphasis is that there is uncertainty in the sensitivity of the Earth climate system to the global

* Corresponding author. Tel.: +30 2108109170; fax: +30 2108103236.
E-mail address: mtaylor@noa.gr (M. Taylor).

http://dx.doi.org/10.1016/j.jqsrt.2015.08.018

radiation balance [51]. Questions are also being raised about the reliability of assessments of the level of uncertainty associated with direct aerosol radiative forcing [23]. Importantly, clouds are known to affect the energy balance of the Earth system by influencing both shortwave solar radiation and longwave terrestrial radiation [1,37]. The radiative properties of clouds depend on their height, the size of constituent water or ice droplets and optical properties. An increase of cloud top height reduces outgoing infrared radiation and leads to an increase in tropospheric and surface temperature, which in turn can affect the radiative interaction of clouds with solar and terrestrial radiation [5]. For example, the introduction of solar UV flux into a spectral GCM coupled to a chemical transport model was shown to lead to an intensification of the polar vortex and a statistically significant surface warming of up to 1.2 K over North America and Siberia [11]. Importantly, cloud optical properties have been found to have a direct influence on climate via various feedback mechanisms [3]. While changes in cloud water content are known to have a strong impact on different environmental scenarios, large uncertainty has been found to be associated with cloud optical properties and cloud-climate feedback mechanisms in particular. Moreover, because clouds and aerosols are closely related in the climate system [26,3], the influences of internal/external mixing of aerosol need to be considered since they may significantly alter cloud optical properties and their influence on the radiation budget [28].

The magnitude of the uncertainty due to the effect of clouds on large-scale radiation budgets is much less well constrained than that due to aerosol and has motivated a number of studies. As part of the International Satellite Cloud Climatology Project (ISCCP), Zhang et al. [60] estimated top of the atmosphere and surface radiative fluxes using a radiative transfer model, and used the derived radiation budget to analyze the distribution of cross-zonal heating and cooling; an important input in climate models. Surface radiation budgets have also been estimated in the context of global surface temperature by capitalizing on the full-Earth viewing potential offered by geostationary satellite observations in conjunction with general circulation models (GCM) and/or online coupled numerical weather prediction models [42,43,59], and have been shown to be sensitive to cloud feedback processes [52,55]. This has also been confirmed by radiative-convective models which have demonstrated the sensitivity of climate to cloud optical properties and the related feedback processes [19].

Findings such as these highlight the need for more detailed studies of the influence of clouds and aerosol and their feedback processes on the Earth system and on radiation budgets. To achieve this, new and efficient parameterizations in terms of cloud and aerosol are required to reduce the uncertainty associated with radiative forcing. An important step in this direction was the work of Takenaka et al. [53] who developed a customized neural network (NN) solver based on radiative transfer calculations from the radiative transfer code RSTAR5b [35,36] to estimate downward and upward shortwave fluxes at the surface and the top of the atmosphere from combined aerosol and cloud parameters with high speed and accuracy. It should be borne in mind that there is a growing number of radiative transfer codes which vary substantially in the numerical approximation method used (e.g. discrete ordinates and/or 2-stream), their spectral resolution (UV, visible, near-IR, thermal-IR, mm/sub-mm and microwave), their treatment of cloud properties and gas absorption (principal and/or trace), the complexity of their aerosol models, whether or not they perform line-by-line (LBL) flux or band integration, their inclusion of scattering and polarization, the geometry adopted as well as atmospheric profiles and surface characteristics. The Intercomparison of Radiation Codes in Climate Models (ICRCCM; http://gcmd.nasa.gov/records/GCMD_CDIAC_ICRCCM.html) under the auspices of the World Meteorological Organization (WMO) produced benchmark longwave LBL fluxes to allow for their assessment [12]. However, researchers have had to deal with the trade off between calculation speed and accuracy. On the one hand, the estimation of radiances for finite spectral intervals (e.g. to estimate solar energy budgets) with LBL calculations is precise but computationally intensive, while on the other hand, band-integrated irradiances are faster but imprecise. The Continual Intercomparison of Radiation Codes (CIRC; http://circ.gsfc.nasa.gov/) has emphasized the importance of using observations to constrain and define intercomparison cases [40] and more recently, emphasis has been placed on computational speed with new parameterizations of bands and channels to accelerate radiance calculations and to provide a good compromise between computation time and uncertainty for a range of typical radiative transfer problems, in particular, for satellite radiometer simulations [15]. Current trends suggest that the greatest gains in speed are expected to come from NN models or hybrid approaches that incorporate NNs.

Building on the work of Lopez et al. [30], Dorvlo et al. [10], Zarzalejo et al. [58] and Takenaka et al. [53] which pioneered the development of NN models of solar radiation, here we report on the development of NN solvers for radiance spectra parameterized in terms of cloud and aerosol:

i. that are based on large state-of-the-art LUTs calculated with libRadtran that span a very broad range of cloud and atmospheric conditions,
ii. that include cloud optical parameters which are derived from a new tailor-made satellite product for the development of radiation budget applications,
iii. that recover the UV, visible and near-IR radiation spectra at high resolution (1 nm),
iv. and which, once trained, can produce almost instantaneous output.

To train and validate the NN, we constructed two high resolution LUTs from a total of ≈ 2.5 million runs with the radiative transfer code, libRadtran [32] for clear sky and cloudy conditions (separately) using distributed computing over a network of 8 high-end workstations running continuously in batch mode for ≈ 3 months. The trained NNs developed here behave like fast radiative transfer solvers and have been designed to meet the need for both