Atmospheric Research 205 (2018) 18–25

Contents lists available at ScienceDirect

Atmospheric Research

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

# Water vapor radiative effects on short-wave radiation in Spain

Javier Vaquero-Martínez[a,b,*], Manuel Antón[a,b], José Pablo Ortiz de Galisteo[c,d], Roberto Román[e,f], Victoria E. Cachorro[d]

[a] Departamento de Física, Universidad de Extremadura, Badajoz, Spain
[b] Instituto Universitario de Investigación del Agua, Cambio Climático y Sostenibilidad (IACYS), Universidad de Extremadura, Badajoz, Spain
[c] Agencia Estatal de Meteorologia (AEMET), Valladolid, Spain
[d] Grupo de Óptica Atmosférica, Universidad de Valladolid, Valladolid, Spain
[e] Department of Applied Physics, University of Granada, Granada, Spain
[f] Andalusian Institute for Earth System Research (IISTA-CEAMA), Granada, Spain

A R T I C L E I N F O

*Keywords:*
Short-wave
Radiative effect
Radiative efficiency
Water vapor
IWV
Iberian Peninsula

A B S T R A C T

In this work, water vapor radiative effect (WVRE) is studied by means of the Santa Barbara's Disort Radiative Transfer (SBDART) model, fed with integrated water vapor (IWV) data from 20 ground-based GPS stations in Spain. Only IWV data recorded during cloud-free days (selected using daily insolation data) were used in this study. Typically, for SZA = 60.0 ± 0.5° WVRE values are around − 82 and − 66 $Wm^{-2}$ (first and third quartile), although it can reach up − 100 $Wm^{-2}$ or decrease to − 39 $Wm^{-2}$. A power dependence of WVRE on IWV and cosine of solar zenith angle (SZA) was found by an empirical fit. This relation is used to determine the water vapor radiative efficiency (WVEFF = ∂WVRE/∂IWV). Obtained WVEFF values range from − 9 and 0 $Wm^{-2}\,mm^{-1}$ (− 2.2 and 0% $mm^{-1}$ in relative terms). It is observed that WVEFF decreases as IWV increases, but also as SZA increases. On the other hand, when relative WVEFF is calculated from normalized WVRE, an increase of SZA results in an increase of relative WVEFF. Heating rates were also calculated, ranging from 0.2 $Kday^{-1}$ to 1.7 $Kday^{-1}$. WVRE was also calculated at top of atmosphere, where values ranged from 4 $Wm^{-2}$ to 37 $Wm^{-2}$.

## 1. Introduction

The climate system is interactive, and all its elements (atmosphere, Earth's surface and biosphere) are interconnected (Denman and Brasseur, 2007). Water, presented in its three states in the Earth-atmosphere system, is one of the elements of paramount importance. Water vapor is acknowledged as the most important atmospheric greenhouse gas, and although it is not directly involved in climate change since its concentration is regulated by temperature more than anthropogenic emissions, it causes a positive radiative feedback on climate system (Colman, 2003).

Currently, the radiative effect of water vapor is considered a feedback rather than a forcing, since the water vapor concentration is mainly dependent on the temperature on a global scale, and the typical residence time of water vapor is ten days (Myhre et al., 2013). For these reasons, anthropogenic emissions of water vapor have a negligible impact on global climate. The main anthropogenic impact in water vapor content is due to the emission of other greenhouse gases, which cause temperature increase and therefore an increase in water vapor content (Santer et al., 2007). Emissions in the stratosphere, however, can be considered as a forcing (Smith et al., 2001; Forster and Shine, 2002; Zhong and Haigh, 2003; Solomon et al., 2010), because in the stratosphere water vapor emissions (i.e., caused by stratospheric flights) manage to stay in the long term.

Water vapor in the atmosphere can be quantified using the column integrated amount of water vapor (IWV), which is equivalent to condensing all the water vapor in the atmospheric column and measuring the height that it would reach in a vessel of unit cross section. It can be measured in columnar mass density ($g\,cm^{-2}$ or $kg\,m^{-2}$) or in length (height) units (mm) (Román et al., 2015). The instantaneous water vapor radiative effect (WVRE) at surface is defined as the net change in short-wave (SW) solar radiation at surface taking as reference a dry atmosphere (adapted from Mateos et al., 2013a). It can be also calculated at top of atmosphere (TOA) ($WVRE_{TOP}$). Therefore, water vapor efficiency (WVEFF) can be defined as the variation on WVRE that is caused by an increase of 1 unit of atmospheric water vapor, that is to say, the first derivative of WVRE with respect to IWV.

In this work, the WVEFF focused on the SW range is analyzed using a radiative transfer code fed with IWV data recorded from several GPS ground-based stations in the Iberian Peninsula. Although other works

* Corresponding author at: Departamento de Física, Universidad de Extremadura, Badajoz, Spain.
*E-mail address:* javier_vm@unex.es (J. Vaquero-Martínez).

https://doi.org/10.1016/j.atmosres.2018.02.001
Received 25 September 2017; Received in revised form 24 January 2018; Accepted 3 February 2018
Available online 08 February 2018
0169-8095/ 

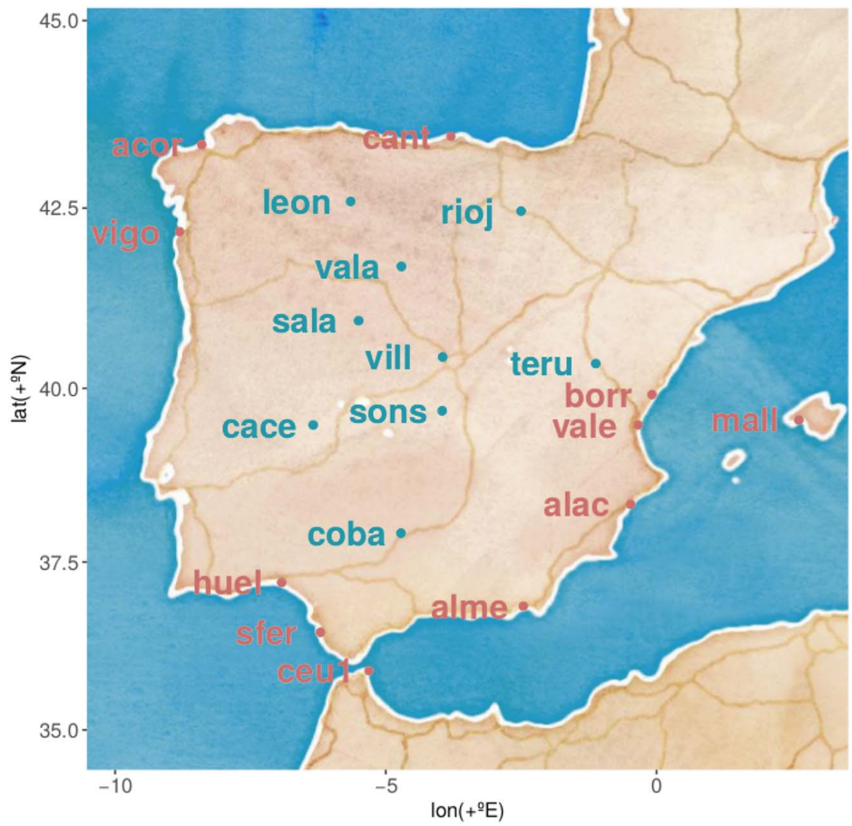


**Fig. 1.** Location of the twenty stations selected. Coastal stations are written in red and inland stations in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

have studied the change in surface radiation due to water vapor (Soden et al., 2002; Di Biagio et al., 2012; Román et al., 2014), none quantifies nor analyzes the WVEFF or WVRE and its dependences on IWV and SZA, as it has already been done for clouds (Mateos et al., 2013b, 2014b), aerosols (Mateos et al., 2013a, 2014a) and ozone (Antón and Mateos, 2013; Antón et al., 2016). This paper aims to be useful for a better understanding of the individual contributions of water vapor to the radiation budget in the Iberian Peninsula, and evaluate the WVEFF under different conditions of SZA and IWV in this context. Knowledge about surface energy balance sensitivity to variations of IWV is important to assess the system's response to future climate changes.

## 2. Integrated water vapor data

IWV data used in this work were recorded from 20 GPS Spanish stations located mostly in the Iberian Peninsula (see Fig. 1 and Table 1). For a full description of the method to derive IWV data from GPS, refer to Bevis et al. (1992). In the process of positioning a GPS ground-based station, the fundamental idea is to determine the distance to several GPS satellites in order to triangulate the receiver position. The distance is obtained by measuring the time that the microwave signals take from GPS satellites to GPS receivers. The signals, however, suffer some delays along their way. One of those delays is called the slant tropospheric delay (STD), which is caused by the tropospheric gases. STD is due to two contributions, one related to water molecule's dipolar momentum, slant wet delay (SWD), and a non-dipolar contribution, due to all gases (including water vapor), which is known as slant hydrostatic delay (SHD)

$$\mathrm{STD} = \mathrm{SWD} + \mathrm{SHD} \tag{1}$$

Such delay can be converted to zenith tropospheric delay (ZTD) by applying mapping functions. Mapping functions are different for SHD and SWD, but they are similar, so an approximation can be made

**Table 1**
Location of GPS stations considered.

| Station | Acronym | Latitude | Longitude | Altitude |
|---|---|---|---|---|
| | | (°N) | (°E) | (m) |
| A Coruña | acor | 43.36 | −8.40 | 12 |
| Alicante | alac | 38.34 | −0.48 | 10 |
| Almería | alme | 36.85 | −2.46 | 77 |
| Burriana | borr | 39.91 | −0.08 | 22 |
| Cáceres | cace | 39.48 | −6.34 | 384 |
| Ceuta | ceu1 | 35.89 | −5.31 | 53 |
| Córdoba | coba | 37.92 | −4.72 | 162 |
| Huelva | huel | 37.20 | −6.92 | 29 |
| León | leon | 42.59 | −5.65 | 915 |
| Logroño | rioj | 42.46 | −2.50 | 452 |
| Mallorca | mall | 39.55 | +2.63 | 62 |
| Salamanca | sala | 40.95 | −5.50 | 800 |
| San Fernando | sfer | 36.46 | −6.21 | 4 |
| Santander | cant | 43.47 | −3.80 | 48 |
| Sonseca | sons | 39.68 | −3.96 | 755 |
| Teruel | teru | 40.35 | −1.12 | 956 |
| Valencia | vale | 39.48 | −0.34 | 28 |
| Valladolid | vala | 41.70 | −4.71 | 766 |
| Vigo | vigo | 42.18 | −8.81 | 33 |
| Villafranca | vill | 40.44 | −3.95 | 596 |

$$\mathrm{STD} = m_{\mathrm{wet}}(E)\mathrm{ZWD} + m_{\mathrm{hydrostatic}}(E)\mathrm{ZHD} = m(E)\mathrm{ZTD} \tag{2}$$

$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD} \tag{3}$$

If pressure at surface is known, ZHD can be modeled, and ZWD obtained from subtracting ZTD minus ZHD. ZWD is proportional to IWV

$$\mathrm{ZWD} = \kappa \mathrm{IWV} \tag{4}$$

The constant $\kappa$ can be determined from the mean temperature of the atmosphere weighted by the water vapor content. This mean