Biomass burning aerosol impact on surface winds during the 2010 Russian heatwave

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This paper elucidates the impact of biomass burning aerosols (BB) on surface winds for the Russian fires episode during 25 July to 15 August 2010. The methodology consists of three WRF-Chem simulations over Europe differing in the inclusion (or not) of aerosol-radiation and aerosol-cloud interactions. The presence of BB reduces the 10-m wind speed over Russia during this fire event by 0.2 m s^{-1} (10%). Aerosol interactions imply a decrease of the shortwave downwelling radiation at the surface leading to a reduction of the 2-m temperature. This decrease reduces the turbulence flux, developing a more stable planetary boundary layer. Moreover, cooling favours an increase of the surface pressure over Russian area and also it extends nearby northern Europe.

Keypoints:

- Biomass burning aerosols (BB) reduces the local 10-m wind speed over Russia.
- Causes should be sought on reduced surface shortwave radiation and 2-m temperature, and increase atmospheric stability.
- BB may also affect SLP, producing changes in mesoscale circulations and an increase of surface winds over distant regions.

1. Introduction

Aerosols radiative effects, which depend mainly on the aerosol optical properties, affect radiation, temperature, stability, clouds and precipitation. But, to what extent do aerosol particles affect the wind? *Jacobson and Kaufman* [2006] tried to answer this question for a case study in California during February and August, 2002–2004. These authors found a reduction of the near-surface wind speeds below them by up to 8% locally. They attributed this wind speed reduction due to the enhancement in stability caused by the aerosols directly and to aerosol-enhanced clouds. Aerosols and aerosol-enhanced clouds decreased near-surface air temperature, which increased stability and reduced turbulent kinetic energy as well as the vertical transport of horizontal properties. Moreover, wind speed reductions over China were found (average of 5.5% between February and August) where lots of biofuel burning occurred. Aside from this study, scientific literature about aerosol effects on wind is scarce. A reason of the lack of these studies could be the difficulty understanding of the physical causes of the feedbacks between aerosols and winds.

The Fifth Report of the Intergovernmental Panel on Climate Change [IPCC AR5][*Boucher et al.*, 2013; *Myhre et al.*, 2013] distinguishes between aerosol-radiation interactions (ARI) and the aerosol-cloud interactions (ACI). ARI encompass the traditional aerosol direct and semi-direct effect, and ACI mainly account for the indirect effects. Direct effects influence climate by means of absorption and scattering of solar radiation, which modify the energy balance. On the other hand, indirect effects affect the reflectance and persistence of clouds and the growth and occurrence of precipitation [*Ghan and Schwartz*, 2007; *Forkel et al.*, 2012]. The consideration of different aerosols interactions (ARI and ACI) could play a key role to understand the interplay between aerosols and winds. For instance, atmospheric aerosol affects buoyancy processes and wind shear in the atmospheric boundary layer [*Baidya and Sharp*, 2013] by modifying meteorological variables such as temperature. Consequently, turbulence characteristics and atmospheric stability change, which directly affect wind fields. Several studies have demonstrated the implications of atmospheric stability on winds [*Gualtieri and Secci*, 2011; *Sathe et al.*, 2011; *Wharton and Lundquist*, 2012; *Lorente-Plazas et al.*, 2016]. On the other hand, aerosol levels depend on winds by different processes, leading to wind-dependent emission of particles over land or ocean (for example, *Boucher et al.* [2013]; *Prijith et al.* [2014]; *Li et al.* [2015]).

An important component of aerosols are those coming from biomass burning (BB). They consist mainly in black carbon, which strongly absorbs solar radiation, having an impact on cloud processes and playing an important role in the Earth s climate system [*Bond et al.*, 2013]. The AR5 gives an estimate of +0.2 (+0.03 to +0.4) W m^{-2} as the black carbon contribution to the radiative forcing caused by ARI for the period 1750–2010, relying on *Bond et al.* [2013].

During the end of July and mid August extensive heatwave/fires occurred over Russia and specifically over the Moscow area. According to *Konovalov et al.* [2011], high levels of particles were caused by the mix of smoke particles plus accumulated urban and industrial atmospheric pollution, with values of daily particulate matter with diameter smaller than 10 micrometer (PM_{10}) up to 700 μg m^{-3}. Moreover, there was an important influence of the aerosol solar extinction on the photochemistry. Simulation results from *Péré et al.*

[2015] showed reductions of the photolysis rate of NO_2 and O_3 (especially over the entire boundary layer). Several studies (e.g. *Chubarova et al.* [2012]; *Péré et al.* [2014]) analysed the properties of particles from an optical and radiative point of view during this heatwave. These latter authors found a solar radiation reduction at the ground up to 80-150 W m^{-2}. However, these results were found by using off-line coupled models and only included direct effects (ARI). Despite *Péré et al.* [2014] find a wind reduction over the target domain, their methodology neglects the importance of on-line chemistry-climate coupling. Wind changes may be conditioned by aerosol optical depth (AOD), who is strongly influence by the aerosol feedbacks affecting aerosol vertical distribution [*Mishra et al.*, 2015] and vertical profiles of meteorological variables by absorbing and scattering solar radiation [*Zhang et al.*, 2015]. These feedbacks cannot be characterize by off-line coupling.

Therefore, the contribution presented here goes one step beyond previous studies by including on-line feedbacks between aerosols and meteorology in a regional climate-chemistry coupled model, and by solving online ARI in addition to ACI (and hence considering aerosol feedbacks with meteorology). Those effects are not considered in off-line simulations. Moreover, the novelty of this work is related to the target area covered: our aim is to assess the influence of BB aerosols on spatially-distributed winds over Europe and, specially over the Russian area. This study also contributes to verify the results found with global-to-urban models in other areas as California or China [*Jacobson and Kaufman*, 2006].

2. Simulations and methods

2.1. Model configuration

The version 3.4.1 of the WRF-Chem online-coupled meteorology and chemistry model [*Grell et al.*, 2005; *Skamarock et al.*, 2008] was used in order to perform the simulations. The experiments are focused over Europe to study Russian wildfires during 25 of July to 15 of August 2010. The simulations presented here have been run in the context of the EuMetChem COST ES1004 Action (http://www.cost.eu/COST_Actions/essem/ES1004). For a detailed description of the simulations, the reader is referred to *Forkel et al.* [2015] and *Baró et al.* [2015]. Nevertheless, Table 1 depicts a short description of the modelling parameterizations. Meteorological variables and particles have been extensively evaluated in *Brunner et al.* [2015] and *Im et al.* [2015] and are therefore not included in this work for the sake of brevity.

The simulation domain uses a horizontal resolution of 0.22^o (approximately 23 km) with a Lambert Conformal projection and complains with Euro-CORDEX requirements. 33 vertical sigma levels are used for vertical resolution (lowest layer at 24 m). The model top has been set at 50 hPa. Data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses (with data at 00 and 12 UTC) and with respective forecasts have been used as initial (IC) and boundary conditions (BC) (time interval of 3 hours used as BC). Chemical IC were provided by ECMWF IFS-MOZART (Model for OZone and Related chemical Tracers) [*Brasseur et al.*, 1998]. Wildfires emission data come from the IS4FIRE Project [*Sofiev et al.*, 2009], where emissions are estimated by re-analysis of fire radiative power data obtained by MODIS instrument (onboard Aqua and Terra satellites).

2.2. Experimental design

Three different simulations are constructed differing only in the inclusion (or not) of ARI and ACI: (1) No aerosol feedbacks (Base, NRF), (2) only ARI (simulation includes only the direct radiative forcing, DRF) and (3) ARI+ACI feedbacks (all radiative feedbacks, RF). It is important to clarify that although the Base case does not include any aerosol radiation interactions, there is a standard aerosol assumption for aerosol-radiation and aerosol-cloud interactions of some continental aerosol. No heat released is considered in the simulations of this study.

With the purpose of studying the effects of BB aerosols on surface winds, a sensitivity analysis were conducted by taking the Base case as reference. Differences between DRF and RF with respect to the Base case have been assessed. Positive (negative) values means that DRF and RF have higher (lower) values than the Base case. These spatial differences are inspected for the 10-m wind speed (WS10), shortwave downwelling radiation at the surface (SWDNB), 2-m temperature (T2), planetary boundary layer height (PBLH), AOD at 550 nm, relative humidity (RH) and sea level pressure (SLP). The impact of the BB aerosols on WS10 is assessed by computing spatial correlation between the variation in WS10 and the rest of meteorological variables found for DRF-Base and RF-Base simulations. Correlations are 95% significant according to a correlation significance test [*Wilks*, 2011].

3. Results

3.1. Base case meteorological situation

As stated by several works (e.g. *Im et al.* [2015] or *Forkel et al.* [2015]), the BB aerosols generated by the Russian wildfires had a very important impact on PM10 ground levels, with concentrations largely exceeding 700 μg m^{-3}. This increase was evidenced by satellite observations like Terra-MODIS (not shown), Results from WRF-Chem simulation are in agreement with these previous findings. Figure 1 shows the time aggregation of PM10 emissions averaged during the fires period, where largest values are gathered over the region where wildfires took place.

First row of Figure 2 shows the mean values of the Base case (no aerosol interactions) for SWDNB, T2, PBLH, AOD, and RH (vertically averaged). The SLP mean spatial pattern (first row in Figure 2(b)) shows a high pressure system over the northeast of the target area with a strong positive SLP anomaly for this period. This leaded to a strong positive surface temperature anomaly and weak winds from the southeast. Regarding the AOD, values between 1 to 1.8 are found over Russian area and RH values are around 50

The highest WS10 average (over 7 m s^{-1}) is found offshore, over the Baltic sea, Sweden and Finland coastline. Also large WS10 values are found in south Russia, south Ukraine and over Azov Sea (around 6–7 m s^{-1}) while in the center of the subdomain winds are around 3 m s^{-1}.

3.2. Effects on wind speed

The analysis of the BB aerosols impacts on WS10 with respect to the Base case (Figure 3 second and third row) shows a strong heterogeneity in the spatial patterns of differences for both DRF and RF simulations. However, there is a clear WS10 reduction up to 10% (mean reduction of 0.2 m s^{-1} with respect to average WS10 of 2 m s^{-1}) over the target area. Some areas present a WS10 reduction up to 0.35 m s^{-1} for both DRF and RF simulation. In *Péré et al.* [2014], horizontal wind speed over Moscow during 8 August was reduced between 0.05–0.86 m s^{-1}. Our mean values for the whole period are included in that range.

3.3. Causes of wind variation

In order to explore the physical causes of the WS10 changes, we have examined several meteorological variables (as SWDNB, T2, PBLH, AOD, RH and SLP), some of them also covered on previous studies [*Jacobson and Kaufman*, 2006]. Second and third rows in Figure 2 represent the differences found for DRF and RF cases, respectively. Variables SWDNB, T2, PBLH, AOD and RH are represented over the Russian area whereas SLP is represented over the whole Europe for a better understanding of this variable and since its effects extend beyond the Russian area.

The impact of considering aerosols feedbacks in the on-line simulations is analyzed by comparing with the Base simulation. Differences between DRF and RF are similar over the Russian wildfires area because the processes are mainly related to the ARI, occurred during this event. In both cases (DRF and RF) the aerosol effects imply a decrease of SWDNB. The maximum differences are around 80 W m^{-2} over Russia as the period mean. This difference involves a T2 reduction up to 0.9 K over Russia (consistent with *Péré et al.* [2014], who found reductions of 0.2 to 2.5 K). The temperature decrease diminishes the convective processes and the turbulence, resulting in a lower PBLH with lower values up to 300 m with respect to Base case over the target area. Changes in AOD are found when considering aerosol feedbacks, resulting in an increase up to 0.25 over the Russian area. This could be related to the increase of the RH (with values around 3.5%) which is directly related to the hygroscopic growth, which in turn is related to the effective radius and hence to the particle extinction [*Curci et al.*, 2015]. This increased RH may explain the increase of AOD during the fires. Positive differences are also found for SLP, because the decrease of the temperature enhances the SLP not only over the Russian area but also extended over the North of Europe. Hence, the reduction is directly related to an increase of the atmospheric stability where lower PBLH is found and there was an increase of the SLP. *Jacobson and Kaufman* [2006] also explored the effects of clouds on winds; however clear skies are found over the entire target period.

3.3.1. Wind correlation

To assess whether changes in the WS10 may be attributed to changes in meteorological variables (SWDNB, T2, PBLH, AOD, RH and SLP) correlations are computed between the meteorological variables (Figure 2) and WS10 (Figure 3) for the spatial differences of Base case minus RF or DRF. Estimations cover the Russian area. In general, correlations are lower than +0.6 and higher than -0.6. The correlations of ΔWS10 with ΔSWDNB, ΔT2 and ΔPBLH are in the order of +0.45 to +0.55. ΔWS10 is anticorrelated with ΔSLP, ΔAOD and ΔRH, and anticorrelation is higher for DRF than for RF (-0.4 versus -0.35). In general, slight differences are found between DRF and RF case since this fire episode is mainly explained by ARI. ARI only increase or decrease the radiation which is directly related with the meteorological variables assessed. Including ACI implies more complex physical hampering to attribute the causes of the changes.

4. Conclusions

Focusing on the heatwave/wildfires episode that took place during summer 2010 over Russia, this study demonstrates that considering BB aerosols feedbacks could play a key role when simulating surface winds. Results show that these aerosols can affect surface winds not only where emission sources are located, but also further from the release areas. Local winds decrease due to a reduction of SWDNB which leads to decreases in T2. In addition, atmospheric stability increases when considering aerosol feedbacks, inducing a lower PBLH. Meanwhile, the presence of BB aerosols in the atmosphere can change the SLP, producing changes in mesoscale circulations and an increase of surface winds over distant regions.

With the present analysis, we highlight the relevance of including aerosols feedbacks when simulating surface winds, which could contribute both to the skill of weather prediction and improve climatological studies. For instance, better understanding of feedbacks between aerosols and winds could help the decision making on fires management and could condition the planning on wind energy. Albeit this promising conclusion, this work only analyzes a particular episode and more case studies will be needed to support these conclusions.

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Table 1. WRF-Chem parameterizations included in this study.

Parameterizations	**Name**	**References**
Microphysic option	Lin	*Lin et al.* [1983]
Photolysis option	Fast J	*Fast et al.* [2006]
Shortwave radiation	Goddard	*Chou and Suarez* [1994]
Longwave radiation	RRTMG	*Morcrette et al.* [2008]
Planetary Boundary Layer	YSU	*Hsu et al.* [2011]
Cummulus option	Grell 3D	*Grell and Dévényi* [2002]
Dust model	MOSAIC MADE/SORGAM	*Schell et al.* [2001] *Zaveri et al.* [2008]
Gas phase mechanism	RADM2	*Stockwell et al.* [1990]
Aerosol mechanism	MADE/SORGAM	*Schell et al.* [2001]
Organic module	SORGAM	*Schell et al.* [2001]
Wet deposition	Grid scale	*Easter et al.* [2004]
Dry deposition	Wesley resistance	*Wesely* [1989]
Aerosol size	Aitken, accumulation and coarse	
Anthropogenic emissions	TNO-MACC	*Pouliot et al.* [2012]
Biogenic emissions	MEGAN	*Guenther et al.* [2006]
Fire emissions	IS4FIRE	http://is4fires.fmi.fi

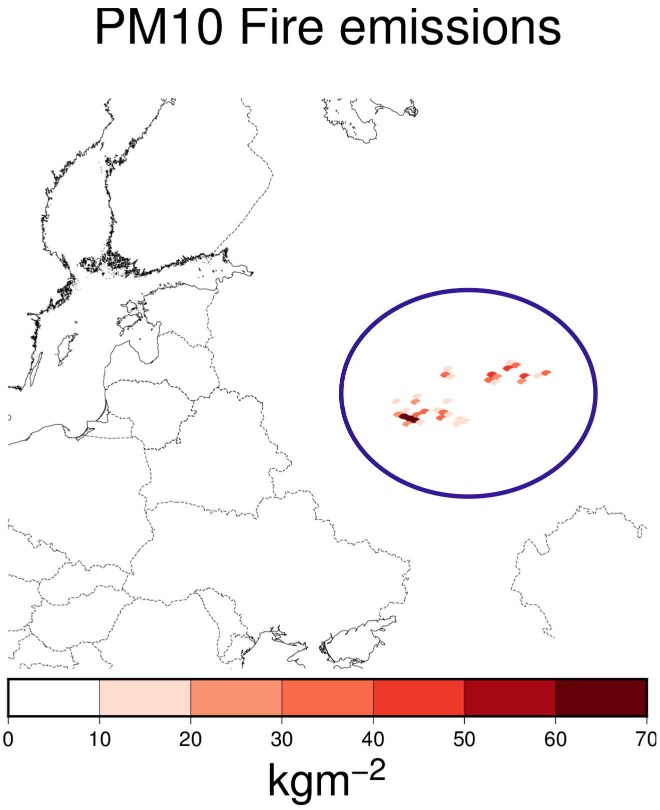

Figure 1. Total PM10 fire emissions during the fire episode (25 July-15 August 2010). The region affected by the wildfires is highlighted with a circle.

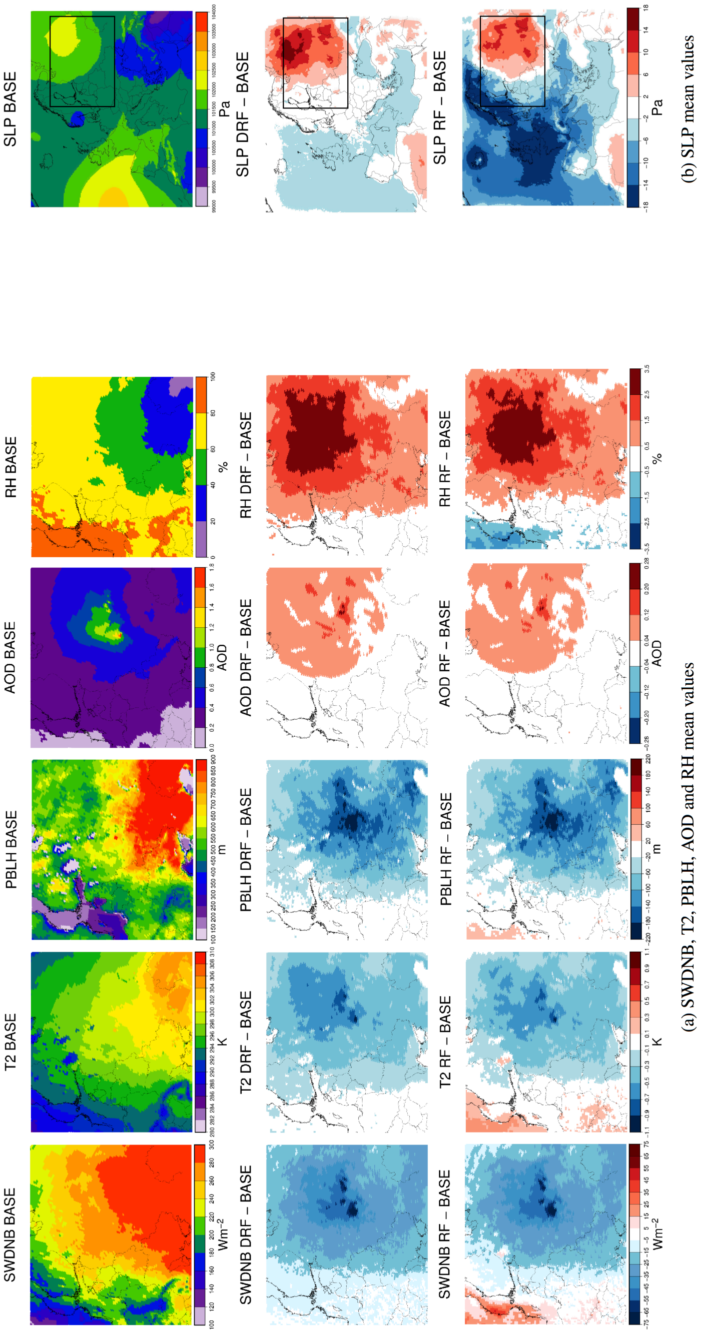

Figure 2. Mean values during Russian forest fires. First row represents the Base case; second row DRF-Base differences, third row RF-Base differences. Note: SLP values are shown for all Europe, for a better assessment and the area shown in (a) is marked with a square.

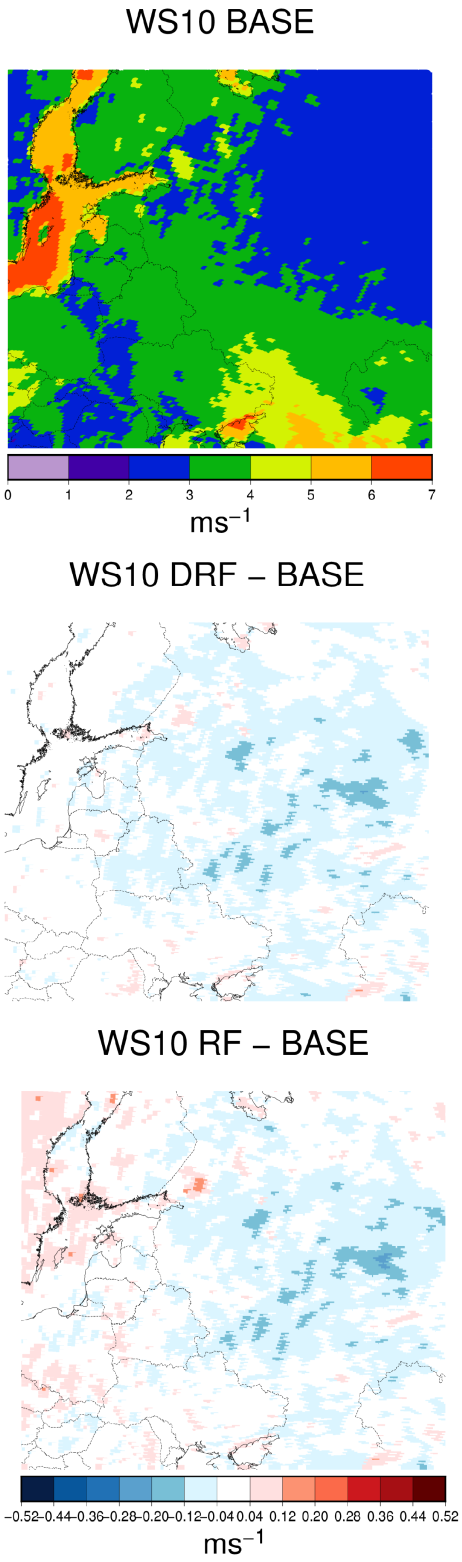

Figure 3. Aerosol effects on WS10. First row represents the Base case; second row DRF-Base differences and third row RF-Base differences.

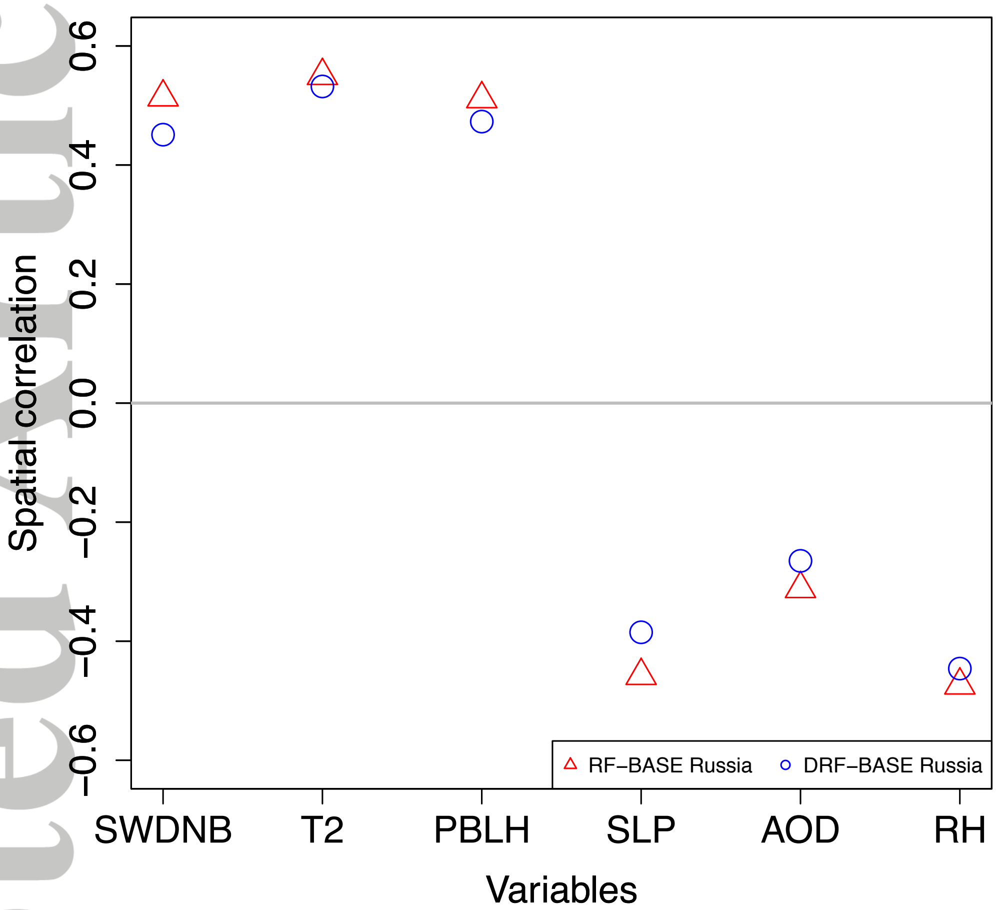

Figure 4. Spatial correlation over Russian area of WS10 differences and differences in several meteorological variables: SWDNB, T2, PBLH, SLP, AOD and RH. Correlations are computed for the spatial differences between experiments RF (triangles) and DRF (circles) and Base case, i.e., Figure 3 versus Figure 2.