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Exploiting the weekly cycle as observed over Europe to analyse aerosol indirect effects in two climate models

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Abstract

A weekly cycle in aerosol pollution and meteorological quantities is observed over Europe. In the present study we exploit this effect to analyse aerosol-cloud-radiation interactions. A weekly cycle is imposed on anthropogenic emissions in two general circulation models that include parameterizations of aerosol cycles and cloud microphysics. It is found that the simulated weekly cycles in sulfur dioxide, sulfate, and aerosol optical depth in both models agree reasonably well with the observed ones indicating model skill in simulating the aerosol cycle. A distinct weekly cycle in cloud droplet number concentration is demonstrated in both observations and models. For other variables, such as cloud liquid water path, cloud cover, top-of-the-atmosphere radiation fluxes, precipitation, and surface temperature, large variability and contradictory results between observations, model simulations, and model control simulations without a weekly cycle in emissions prevent us from reaching any firm conclusions about the potential aerosol impact on meteorology or the realism of the modeled second aerosol indirect effects.

1 Introduction

In its latest report, the Intergovernmental Panel on Climate Change confirmed its previous conclusion that aerosol indirect effects constitute the most uncertain anthropogenic forcing of global climate change (IPCC, 2007). Anthropogenic pollutant aerosols modify cloud optical properties by acting as cloud condensation nuclei. Specifically aerosols are thought to increase the cloud droplet number concentration (CDNC), enhancing the cloud albedo (first aerosol indirect effect; Twomey, 1974). This may also lead to a decrease in the precipitation formation rate, increasing the cloud liquid water path (LWP), cloud lifetime, and subsequently total cloud cover (second aerosol indirect effect; Albrecht, 1989). Modelling indicates that the two effects are of about the same order of magnitude (Lohmann and Feichter, 2005) but considerable uncertainties remain. In

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light of these uncertainties IPCC (2007) only quantified the cloud albedo effect, with a range of -1.8 to $-0.3\,\mathrm{W\,m^{-2}}$, and a best estimate of $-0.7\,\mathrm{W\,m^{-2}}$. Recent studies constraining the aerosol indirect effect by satellite observations (Lohmann and Lesins, 2002; Quaas and Boucher, 2005; Quaas et al., 2006), or estimating it from satellite data (Quaas et al., 2008) suggest that the indirect effect indeed may be on the upper side of this range (i.e. of a small magnitude).

Measurements of anthropogenic pollution shows a weekly cycle in many countries of Europe (Cleveland et al., 1974; Beirle et al., 2003; Shutters and Balling, 2006; Bäumer et al., 2008; Stephens et al., 2008; Xia et al., 2008; Barmet et al., 2009), in China (Gong et al., 2007), and in the United States (Murphy et al., 2008). In this latter study the weekly pattern is more pronounced for black carbon than for other aerosols. This weekly cycle in aerosol concentration is related to a weekly cycle in emissions, with reduced emissions on weekends compared to weekdays due to decreased industrial activity, less commuter traffic, and, in some European countries, a driving ban for heavy duty vehicles on Sundays.

In several studies, a weekly cycle has also been shown for some meteorological quantities, such as the surface temperature (Gordon, 1994; Bäumer and Vogel, 2007; Gong et al., 2007; Sanchez-Lorenzo et al., 2008; Laux and Kunstmann, 2008), the diurnal temperature range (Simmonds and Keay, 1997; Forster and Solomon, 2003; Shutters and Balling, 2006; Bäumer and Vogel, 2007; Gong et al., 2007; Sanchez-Lorenzo et al., 2008; Laux and Kunstmann, 2008), precipitation (Simmonds and Keay, 1997; Cerveny and Balling, 1998; Bäumer and Vogel, 2007; Gong et al., 2007; Bell et al., 2008; Sanchez-Lorenzo et al., 2008), wind speed (Cerveny and Balling, 1998; Shutters and Balling, 2006), and cloud properties (Jin et al., 2005; Bäumer and Vogel, 2007; Sanchez-Lorenzo et al., 2008). There is some debate on the statistical significance of these results in particular for precipitation (Schultz et al., 2007, and references therein; Barmet et al., 2009). However the weekly cycle appears to be a robust feature for meteorological quantities which are less variable than precipitation. It is worth noting that the amplitude and phase of the weekly cycle are different in different places.

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In the absence of a natural forcing with a seven-day period, one has to invoke a human-made cause. The weekly cycle in heat generation itself is too small to explain a weekly cycle in meteorology, so a different mechanism is required, e.g. through atmospheric chemistry. The cycle in aerosol effects has been proposed earlier as a potential cause for a weekly cycle in meteorological quantities (Cerveny and Balling, 1998; Jin et al., 2005; Bäumer and Vogel, 2007; Gong et al., 2007; Bell et al., 2008; Sanchez-Lorenzo et al., 2008), but according to the literature, cycles in greenhouse-gases (Cerveny and Coakley, 2002) and large-scale dynamics (Sanchez-Lorenzo et al., 2008; Laux and Kunstmann, 2008) might also play a role.

2 Method

We use here a combination of various kinds of observations and global climate modelling to analyse the aerosol indirect effects by exploiting the observed weekly cycle. The region chosen is Europe (approx. 35° N–70° N, 10° W–30° E) and we restrict the analysis to land areas.

Data from 177 ground-based stations from the European Monitoring and Evaluation Program (EMEP; Hjellbrekke, 2008) are analysed to investigate the weekly cycle of aerosols and aerosol precursors using measurements of near-surface sulfur dioxide (SO_2) and sulfate (SO_4) concentrations. A list of the stations, their locations, and time periods covering the observations can be found on http://tarantula.nilu.no/projects/ccc/onlinedata/main/stations_main.html.

Ground-based observations of various meteorological quantities from 41 stations of the German Meteorological Service (Deutscher Wetterdienst, DWD) are also analysed. Daily data for time periods of up to 130 years are used. Locations of the data and time periods are detailed on http://www.dwd.de/bvbw/appmanager/bvbw/dwdwwwDesktop?_nfpb=true\&T82002gsbDocumentPath=Navigation%2FOeffentlichkeit%2FKlima__Umwelt%2FKlimadaten%2Fkldaten__kostenfrei%2Fstations_C3_BCbersicht__tabelle__node.html__nnn%3Dtrue. A subset of these data has also been analysed by Bäumer and Vogel (2007).

Satellite data from the MODerate Resolution Imaging Spectroradiometer (MODIS; Remer et al., 2005; Platnick et al., 2003) and the Clouds and the Earth's Radiant Energy System (CERES; Wielicki et al., 1996) are also used. The data from the Terra satellite with a sun-synchronous orbit overpassing a point at the Earth's surface at about 10:30 a.m. local time cover the March 2000–December 2006 period for CERES and March 2000–March 2008 for MODIS, and data from the Aqua satellite overpassing at about 01:30 p.m., the July 2002–December 2006 period for CERES and July 2002–July 2007 for MODIS. We use the AOD and cloud properties from the MOD08_D3 (Terra) and MYD08_D3 (Aqua) collection 5 datasets, and broadband short-wave planetary albedo and outgoing long-wave radiation form the CERES Single Scanner Footprint (SSF) Edition 2 dataset applying the User Applied Revisions Rev1 (FM1 for Terra and FM3 for Aqua). We compute for each day of the time period an area average for the European continental area for each of the datasets, from which we then analyse the weekly cycle.

The global climate models we use are a developmental version of HadGEM2-AML (Jones et al., 2007) and the ECHAM5 (Roeckner et al., 2003). HadGEM2-AML (Atmosphere/Mixed-Layer ocean) includes interactive aerosol models (Jones et al., 2007; Bellouin et al., 2007; Rae et al., 2007) and a representation of aerosol indirect effects (Jones et al., 2001). The ECHAM5 model includes a comprehensive aerosol module (Feichter et al., 1997; Stier et al., 2005) and a detailed cloud microphysical scheme (Lohmann et al., 2007).

In HadGEM2, A 10-year perturbed simulation has been performed where climatological emissions of anthropogenic aerosols and aerosol precursors have been increased by 10.5% during weekdays and decreased by 26.3% on Saturdays and Sundays (peak-to-peak amplitude in emissions of 38%). This follows the suggestion by Bäumer et al. (2008) that week-end emissions are one third lower than weekday emissions. The changes in emissions are such that the weekly average in emissions remains unchanged. The 10-year perturbed simulation is analysed as two 5-year simulations.

A 5-year control simulation has also been performed but only a few model variables have been saved with a daily resolution. Although the weekly cycle in anthropogenic emissions may be different in different parts of the world, the same weekly pattern – mostly representative of Europe and North America – has been applied everywhere but results are only considered over Europe.

With ECHAM5, two 5-year simulations with a 3-month spin-up have been carried out using the AeroCOM year 2000 emissions (Dentener et al., 2005) for natural and anthropogenic aerosols and observed monthly-mean prescribed sea-surface temperature and sea-ice cover distributions as boundary conditions. In the control simulation, monthly- or annual-mean emissions, have been used depending on the aerosol type. In the experiment investigating the influence of a weekly cycle, anthropogenic emissions over European land areas are reduced by 33% on Saturdays and Sundays, and increased during the weekdays accordingly (peak-to-peak amplitude in emissions of 46%).

Note that there is no diurnal cycle in emissions in either model. This may perhaps shorten the week-end effect in the models as compared to the real world. Also no weekly cycle is applied to biofuel and biomass burning emissions.

3 Results

The weekly cycles found in the observations are compared against those diagnosed in the model experiments with a weekly cycle of emissions and also against the control simulations in Fig. 1. Table 1 further summarizes for each analysed quantity the mean weekly amplitude (weekly maximum – weekly minimum) and the weekday occurrence of the extreme values. All the amplitudes quoted in this section are peak-to-peak amplitudes; percentage changes are relative to the weekly mean.

In the surface concentrations measured by the EMEP network, a significant weekly cycle in aerosol precursor gas (SO_2) and aerosol (SO_4) is found. The amplitude of the weekly cycle in SO_2 is about 0.34 $\mu g\,m^{-3}$ (13%), and 0.055 $\mu g\,m^{-3}$ (5%) for SO_4. The

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weekly cycle imposed on the climate models (38% and 46% amplitude in HadGEM2 and ECHAM5, respectively) results in a weekly cycle in SO_2 which is too strong (overestimated by about a factor of 2.5) compared with the EMEP observations. The weekly cycle observed for the sulfate aerosol (SO_4) concentration is much smaller than the one in SO_2. Both models show a reduction of the same order of magnitude as in the observations. This shows that the processes in the sulfate aerosol cycles in both models are qualitatively well simulated. The observations show the SO_2 and SO_4 minimum both occur on Monday compared with the marked Sunday minimum in the models.

In satellite-retrieved aerosol optical depth (AOD), the amplitude is 0.010 (5.6%) and 0.0080 (4.6%) for MODIS on Terra and Aqua, respectively. This value is similar to the 4.0% amplitude found by Xia et al. (2008) from the ground-based sunphotometer network Aeronet. Bäumer et al. (2008), however, report much larger amplitudes with 10–20% changes in AOD for selected stations. The timing of the AOD minimum (Mondays for both satellites and HadGEM2, Sundays for ECHAM5) is relatively well captured by the models. The amplitude in the AOD weekly cycle is overestimated by both models, though to a lesser extent than that in the weekly cycle in SO_4. This could indicate that natural aerosols – which should not exhibit any weekly cycle – are underestimated in the model or that the lifetime of anthropogenic aerosols is too short in the models.

For SO_2, SO_4, and AOD, the control simulations do show a weak weekly cycle. However, the weekly cycle simulated in the experiment simulation is clearly distinguished from this noise. HadGEM2 captures better than the ECHAM5 the gradual increase in SO_4 and AOD from the Sunday/Monday minimum to the Friday/Saturday maximum as shown in the observations. In ECHAM5, the increase in aerosols at the beginning of the week, and the decrease at the end, are clearly too sharp indicating that the chemical processing from aerosol precursors to aerosols might be too fast in this model.

Aerosols serving as cloud condensation nuclei may lead to an increase in cloud droplet number concentration. Figure 1d shows indeed a clear weekly cycle in the satellite-retrieved adiabatic cloud droplet number concentration (derived as in Quaas

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et al., 2006) for both datasets with a minimum on Monday (Sunday for Aqua) and an amplitude of 5 cm^{-3} (Terra) and 10 cm^{-3} (Aqua). Both models show a weekly cycle in CDNC similar in minimum (Sunday) and amplitude (though overestimated) to the observations. This weekly cycle is clearly a feature of the experiment simulations compared with the control runs. The overestimation is comparable to the one found for AOD. This may be interpreted as a suggestion that the parameterization of aerosol activation in the models, or the link between aerosol and cloud droplet concentrations, is reasonably well simulated.

The satellite retrievals show a consistent weekly cycle in the cloud liquid water path, with a clear minimum on Saturdays/Sundays, and larger values during weekdays (Fig. 1e). The ECHAM5 model shows a similarly large variability. However, the modelled variability in the experiment and control simulations is equally large, so that no conclusion about an aerosol effect can be drawn (HadGEM2 data are not available for LWP). For cloud fraction, the observations from Terra and Aqua disagree on a weekly cycle. Both models show variability of the same order of magnitude, for both the experiment and control simulations. This appears to indicate that no distinguishable signal of a second aerosol indirect effect can be found in cloud fraction, and perhaps not even in LWP.

Both direct and indirect aerosol effects influence the planetary albedo. Variability in planetary albedo for a given location is dominated by variability in cloud cover, cloud water path, CDNC, and aerosol concentration. As can be seen in Fig. 1g, the observations from CERES on Terra show a weekly cycle in albedo which would be consistent with an influence of anthropogenic aerosols on albedo. However, a low value on Wednesdays, and the less clear cycle in the Aqua data indicate that this finding is not very robust. The ECHAM5 model shows a weekly cycle in albedo which is consistent with that found in the Terra observations, although the timing of the minimum (Monday vs. Saturday) is different. On the other hand, HadGEM2 shows a weekly cycle of the opposite sign. The likely reason is that in the simulation, the cloud cover happens to show a weekly cycle with a minimum during weekdays and a maximum during weekends, which is reflected in the albedo cycle.

The direct aerosol effect can be best seen in clear-sky conditions. For this, CERES footprints labeled as cloud-free have been selected to compute the weekly cycle in the clear-sky albedo (Fig. 1h). The weekly cycle found is not very robust (particularly in the Aqua observations), and the ECHAM5 model shows a cycle opposite to the expectation. Thus, the short available timescale is not sufficient to distinguish direct aerosol effects in the weekly cycle.

There have been speculations whether aerosols might invigorate convection, increasing cloud top height, which would lead to an enhanced cloud greenhouse effect (reduced outgoing longwave radiation; Devasthale et al., 2005; Koren et al., 2005). As shown in Fig. 1i, such an effect cannot be confirmed by any discernible weekly cycle in the OLR data available for this study.

The DWD station data we analysed show a weekly cycle consistent with the expectation in the daily maximum (daytime) temperature, which, in contrast to the minimum (nighttime) temperature, is directly influenced by cooling aerosol effects in the shortwave spectrum. A very similar weekly cycle is found in the model simulation – however, the control experiment with no weekly cycle in the aerosol emissions also happens to show a very similar cycle. While this is an uncanny coincidence, there is no reason why the control simulation could show a weekly cycle, and a fortuitous instance of natural variability is the only explanation. Similarly, variability of the same order of magnitude is found in the weekly cycle of the near-surface daily mean temperature in the observations and in both the experiment and control simulations from both models. The conclusion is that the available time series do not show a discernible aerosol-influenced weekly cycle in near-surface temperatures.

A clear weekly cycle is also found for the ground-based precipitation measurements. However, neither do the models allow to attribute this cycle to an aerosol effect, nor is the weekly cycle in precipitation consistent with the one found for LWP or cloud cover.

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4 Summary and conclusions

Weekly cycles have been analysed in surface observations of sulfur dioxide and sulfate concentrations, satellite observations of aerosol optical depth, cloud properties (cloud droplet number concentration, cloud liquid water path, total cloud cover), radiation (albedo, clear-sky albedo, and outgoing long-wave radiation), and surface observations of meteorological quantities (daily maximum and mean temperatures, and precipitation). The same quantities have been simulated in two different general circulation models (HadGEM2 and ECHAM5), where in an experiment simulation the aerosol emissions have been reduced during weekends (Saturday/Sunday) and increased during weekdays accordingly, yielding an amplitude in emissions of about 40%. Control experiments without a weekly cycle in aerosol emissions have been performed for comparison.

A clear weekly cycle is observed in aerosol quantities (surface concentrations of SO_2 and SO_4, and satellite-retrieved AOD). The imposed weekly cycle in aerosol emissions in the models leads to an overestimation in the amplitude of the weekly cycle of surface concentrations of SO_2, SO_4, and AOD. Both models and observations show a stronger cycle in SO_2 than in SO_4 and AOD, indicating that the models simulate the sulfate aerosol cycle qualitatively well.

The aerosol indirect effect is reflected in a clearly distinguishable weekly cycle in CDNC, which both models rather skillfully simulate. A weekly cycle consistent with a second indirect effect is found for LWP in the satellite observations, but not in total cloud cover. The variability in both quantities in both the experiment and control simulations suggests that no conclusion about a second indirect effect can be drawn from the data analysed here.

For the planetary albedo, the observed weekly cycle is uncertain. On the one hand ECHAM5 captures the cycle in the experiment simulation, with much less variability in the control simulation. On the other hand, the HadGEM2 shows a weekly cycle inconsistent with the observations, likely due to the variability in total cloud cover. The amplitude in planetary albedo found in ECHAM5 is similar to the one found in the Terra observations despite the fact that the amplitude in CDNC and AOD is overestimated. For the clear-sky planetary albedo, OLR, temperature (both daily maximum and mean), and precipitation, no clear weekly cycle was found. In the cases where the observations seem to show a weekly cycle, the models show variability of equal magnitude in both the experiment and control simulations.

In summary, clear weekly cycles have been found in aerosols and cloud droplet number concentration, and the models confirm that the contrast in emissions between weekdays and weekends leads to such a cycle. Cycles related to second aerosol indirect effects (LWP, cloud cover) or thermodynamic effects of aerosols on clouds (OLR) are not distinguishable in the datasets. Similarly, our results do not support the attribution of observed weekly cycles in temperatures (either maximum or daily-mean) and precipitation to aerosol effects. It could be that such observed weekly cycles are accidental. A mixed result has been found for planetary albedo, where one model does show a weekly cycle consistent with the observations, while the other one does not.

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Table 1. Amplitudes of the weekly cycles in observations/satellite retrievals and as simulated by the imposed emission cycle with an amplitude of 46% in ECHAM5 and of 38% in HadGEM2, respectively. Please note that most of the EMEP stations are located in Central Europe, and that the models apply the same amplitude in anthropogenic emissions throughout the entire area.

		Amplitude (relative)	Day of min/max (*where max rather than min)
SO_2 surface concentration	EMEP	0.34 $\mu g\,m^{-3}$ (13%)	Mo
	HadGEM2	1.00 $\mu g\,m^{-3}$ (35%)	Su
	ECHAM5	1.25 $\mu g\,m^{-3}$ (31%)	Su
SO_4 surface concentration	EMEP	0.055 $\mu g\,m^{-3}$ (5%)	Mo
	HadGEM2	0.14 $\mu g\,m^{-3}$ (15%)	Su
	ECHAM5	0.17 $\mu g\,m^{-3}$ (13%)	Su
AOD	MODIS Terra	0.010 (5.6%)	Mo
	MODIS Aqua	0.0080 (4.6%)	Mo
	HadGEM2	0.0091 (8.5%)	Mo
	ECHAM5	0.0168 (7.6%)	Su
CDNC	MODIS Terra	5.3 cm^{-3} (2.6%)	Mo
	MODIS Aqua	10.4 cm^{-3} (5.2%)	Su
	HadGEM2	10.0 cm^{-3} (6.7%)	Su
	ECHAM5	14.5 cm^{-3} (7.2%)	Su
LWP	MODIS Terra	2.49 $g\,m^{-2}$ (2.0%)	Su
	MODIS Aqua	3.00 $g\,m^{-2}$ (2.1%)	Su
	ECHAM5	2.39 $g\,m^{-2}$ (2.6%)	Mo
TCC	MODIS Terra	0.0035 (0.55%)	Th
	MODIS Aqua	0.0043 (0.66%)	Mo
	HadGEM2	0.010 (1.8%)	Th
	ECHAM5	0.010 (1.5%)	Mo
Albedo	CERES Terra	0.0053 (1.49%)	Sa
	CERES Aqua	0.0099 (2.67%)	Tu
	HadGEM2	0.0035 (0.92%)	Tu
	ECHAM5	0.0050 (1.20%)	Mo
Clear-sky albedo	CERES Terra	0.0064 (2.30%)	Mo
	CERES Aqua	0.0321 (11.25%)	We
	ECHAM5	0.0042 (1.98%)	Tu
OLR	CERES Terra	1.03 Wm^{-2} (0.44%)	We*
	CERES Aqua	1.44 Wm^{-2} (0.62%)	We*
	ECHAM5	0.37 Wm^{-2} (0.15%)	Mo*
Maximum Temperature	DWD	0.134 K	Mo*
	ECHAM5	0.200 K	Mo*
Temperature	DWD	0.069 K	We*
	HadGEM2	0.076 K	Fr*
	ECHAM5	0.151 K	Su*
Precipitation	DWD	1.15 $mm\,day^{-1}$ (6.7%)	Fr*
	HadGEM2	0.048 $mm\,day^{-1}$ (2.0%)	Su*
	ECHAM5	0.28 $mm\,day^{-1}$ (10.8%)	Th*

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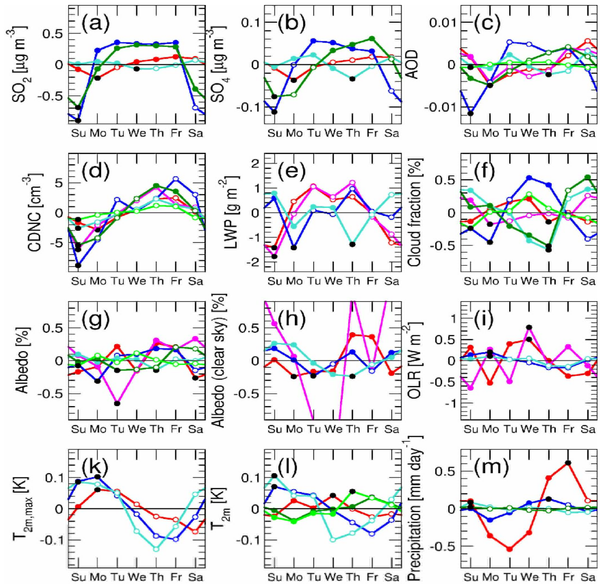

Fig. 1. Weekly cycle (deviation from mean value) of **(a)** surface SO_2 concentration [μg m^{-3}], **(b)** surface SO_4 concentration [μg m^{-3}], **(c)** aerosol optical depth, **(d)** cloud droplet number concentration [cm^{-3}], **(e)** liquid water path [g m^{-2}], **(f)** total cloud cover [%], **(g)** planetary albedo [%], **(h)** clear-sky planetary albedo [%], **(i)** outgoing long-wave radiation [W m^{-2}], **(k)** daily maximum near-surface temperature [K], **(l)** daily-mean near-surface temperature [K], **(m)** precipitation [mm day^{-1}]. In red, primary observational dataset; pink, secondary dataset, when available; green, HadGEM2 simulation including a weekly aerosol emissions cycle; light green, HadGEM2 control simulation, when available; blue, ECHAM5 simulation including a weekly aerosol emissions cycle; turquoise, ECHAM5 control simulation. Please see Table 1 for the list of observations of the various quantities. The black circle in each line indicates the day of the minimum (or maximum in the case of OLR, temperatures, and precipitation), and filled circles indicate days that are statistically significantly different from this extreme (at the 10% level in Student's t-test).

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