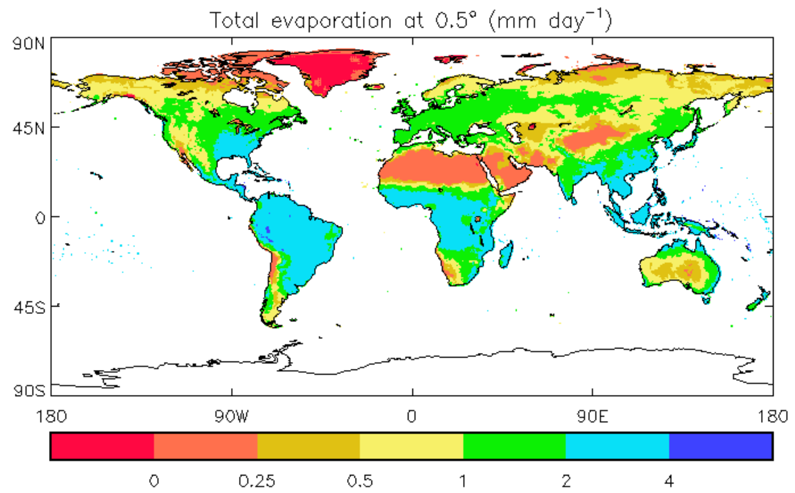
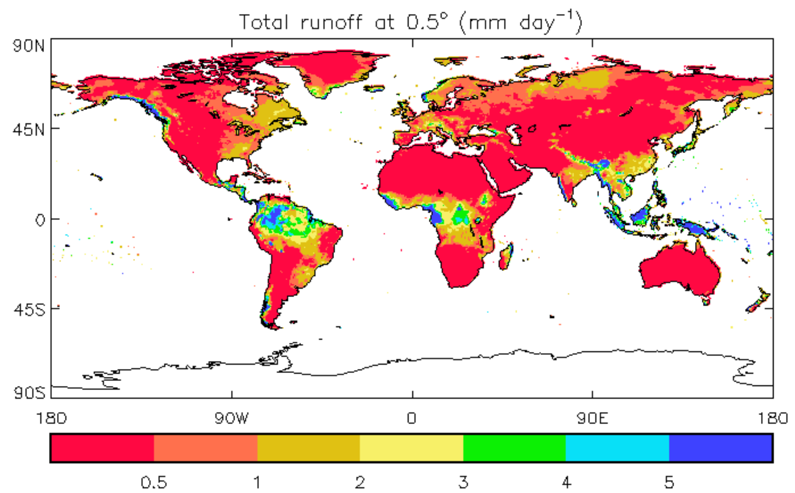
Technical Report No. 44

IMPACT OF SPATIAL AND TEMPORAL RESOLUTION ON MODELLED TERRESTRIAL HYDROLOGICAL CYCLE COMPONENTS





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Abstract

The impact of both spatial and temporal resolution on the components of the terrestrial hydrological cycle are investigated using the WATCH forcing dataset (WFD) and the JULES (Joint UK Land Environment Simulator) land surface model. The various spatial resolutions are achieved by degrading the native half degree latitude/longitude resolution WATCH dataset to both one degree and two degrees. The temporal resolutions are created by degrading the native three hourly WATCH forcing dataset to six hourly and using the WATCH interpolator to derive a one hour forcing dataset.

There is little difference in the moisture stores of soil water and canopy water in the long term mean from the various resolutions, so the analysis presented is for the changes in evaporation and runoff. The evaporation is further analysed into its various components for the spatial resolution. Results suggest that there is little impact from spatial resolution, but the interpolation method for temporal resolution can have a significant effect on the total mean evaporation/runoff balance.

Introduction

Observing the terrestrial components of the water cycle are difficult due to the nature of the land surface. The heterogeneity of the soil means that point measurements of soil moisture are not representative of an area average soil moisture content. Alternative techniques for observing soil moisture, such as satellite observations using microwave channels, can only be used to obtain the soil moisture in the top few centimetres of the soil. As such, creating a global climatology of soil moisture from observations is extremely challenging.

The alternative approach for creating a climatology for the components of the terrestrial water cycle is to use a land surface model driven by observational atmospheric climate data. This approach was used in the Global Soil Wetness Project (GSWP2, Dirmeyer et al., 2006), which used a number of land surface models to derive these components. The GSWP2 dataset covered a period from 1980 to 1995 and as such only a 10 year period was analysed, allowing for a 5 year spin-up period. Whilst this proved to be an extremely useful dataset, the limitation in length has lead to some alternative atmospheric datasets that can be used to drive such land surface models, but for longer periods (e.g., Ngo-Duc et al., 2005, Sheffield et al. 2006)

The WATCH forcing dataset (WFD, Weedon et al., 2010, 2011) is another alternative for atmospheric data, but unlike the other datasets which have a spatial resolution of one degree, the WATCH dataset has a native resolution of half a degree. This gives the potential for more detail in the terrestrial water components, but at a substantial increase in the computation time required to complete the simulations. However, this raises the question of whether the increased resolution and computational time gives only an increased detail, or if the impact of resolution changes the overall accuracy of the terrestrial water cycle. For instance, when averaged back to the coarser resolution grid, does the increased resolution change the distribution of water amongst the various components of the terrestrial water cycle?

In addition to the spatial resolution of the forcing datasets, the temporal resolution may also be important. Many land surface models have been developed to exchange fluxes of heat, moisture and momentum with the atmosphere over short timescales, as these fluxes are required as a boundary conditions to the atmospheric evolution. However, global climatological forcing datasets are often available with only a coarse temporal resolution due to issues resulting from the storage of such data volumes. These data are often at a temporal resolution of three or six hours, but can also be held as only daily data. Whilst some hydrological models are designed to run with such daily data, it is unclear what the impact would be on the land surface models that expect a higher temporal resolution for their forcing.

To address these issues, the WATCH forcing dataset has been used as various spatial resolutions to force the JULES (Joint UK Land Environment Simulator, Best et al., 2011, Clark et al., 2011) land surface model. These forcing data have also been interpolated and averaged to produce datasets at alternative temporal resolutions of one, three and six hours. Results from these simulations have been compared to assess the impact of spatial and temporal resolution on the terrestrial water cycle components.

Method

The JULES model was run with forcing data at spatial resolutions of half degree latitude by longitude, one degree and two degree, with temporal resolution of one hour. Additional simulations have also been undertaken at a spatial resolution of half degree with temporal resolution of both three hours and six hours.

The original data set used to provide the half degree control run is the WATCH forcing data at half degree resolution, with the following variables: near surface air temperature at 2m (Tair), near surface wind speed at 10m (Wind), surface pressure (PSurf), near surface specific humidity at 2m (Qair), surface incident longwave radiation (LWdown), surface incident shortwave radiation (SWdown), rainfall rate (Rainf) and snowfall rate (Snowf). All variables are available at 3 hourly temporal resolution, except shortwave radiation, rainfall and snowfall which are available at 6 hour. These variables have been interpolated to 3 hourly resolution to provide consistent temporal resolution for all input data. This was achieved by using a weather generator also provided by the WATCH project. These 3 hourly data are then interpolated within the JULES model to provide forcing data at a 1 hour timestep.

The half degree data set was used to create one degree and two degree datasets using a simple downscaling technique of area averaging over grid boxes. A one degree land mask was generated from the half degree land mask by analysing each gridpoint from the four higher resolution gridpoints that occupy the same location on the globe. The one degree gridpoint was determined to be a land point if two or more gridpoints from the half degree land mask were defined as land. The newly created forcing data at the new one degree land point was then generated by taking the average of the values of the half degree land points within that box. This process was then repeated to create the two degree land mask and data from the one degree datasets.

To create the 6 hour temporal resolution forcing dataset, each of the variables within the standard 3 hour forcing dataset was averaged. To create the forcing dataset with a one hour temporal resolution, the WATCH weather generator was used to downscale the standard 3 hourly WATCH fording dataset.

Results for the spatial resolution

Figure 1 shows the global mean total evaporation and total runoff from the higher resolution, half degree simulation. Whilst the total evaporation shows a globally varying pattern which follows the expected climatological pattern of global precipitation, the runoff has relatively small values everywhere apart from the tropics. These global patters are consistent amongst the simulations with degrading resolutions.

Looking at the difference plots for the total evaporation for the half degree and one degree resolutions (Fig. 2a) and the one degree and two degree resolutions (Fig. 2b), we can see that although there are differences between the simulations with various resolutions, these differences are patchy and of opposite sign. The differences in the total runoff (Fig. 3), again show a patchy signal with values of opposite sign. The differences are mainly largest in the tropics, however this is consistent with the areas of greatest actual total runoff.

These differences may well occur from the way in which the soil properties are defined at the various resolutions. The non-linearity of the soil properties means that the dominant soil is used for a gridbox, hence as the resolution changes, so can the dominant soil type. This is confirmed by looking at the differences in the soil properties. For example, figure 4 shows the differences in soil moisture saturation between the half degree and one degree resolutions (Fig 4a), and the one degree and two degree resolutions (Fig 4b). These plots show a similar patchy behaviour to that of the total evaporation.

The nature of the differences in the total evaporation and the total runoff show that although there are some differences due to the way in which the soil parameters are defined by the dominant soil type, the impact of spatial resolution on the overall distribution of precipitation into evaporation and runoff on the global basis is small.

Looking in more details at the various components that make up the total evaporation, it is possible to see some consistent differences that are cased by the changing resolution. Whilst still patchy in nature, the evaporation which removes soil moisture (i.e. transpiration and bare soil evaporation) shows a consistent reduction in the evaporation across the tropics as the resolution is degraded (Fig 5). This reduction is evaporation is offset by an increased evaporation from the water held within vegetation canopies as the resolution is degraded (Fig. 6). Note that the canopy evaporation is not influenced by the patchy nature of the changes to the soil properties as the resolution changes; hence there is a smoother signal to the changes in this component of the terrestrial water cycle, than seen in the other evaporation components.

The changes in canopy evaporation can be explained by considering the physical processes of intercepted rainfall by vegetation. An intense convective precipitation shower of short duration will lead to more water falling through the vegetation canopy compared to light intermittent precipitation with a longer duration. This is partly due to the nature of the intensity of the precipitation, but mainly caused by evaporation that can occur during the longer time period of the light intermittent precipitation, leading to a reduction in the canopy water held on the canopy which can then be replaced by further precipitation. The net result is canopy evaporation over the period that can exceed the water holding capacity of the vegetation.

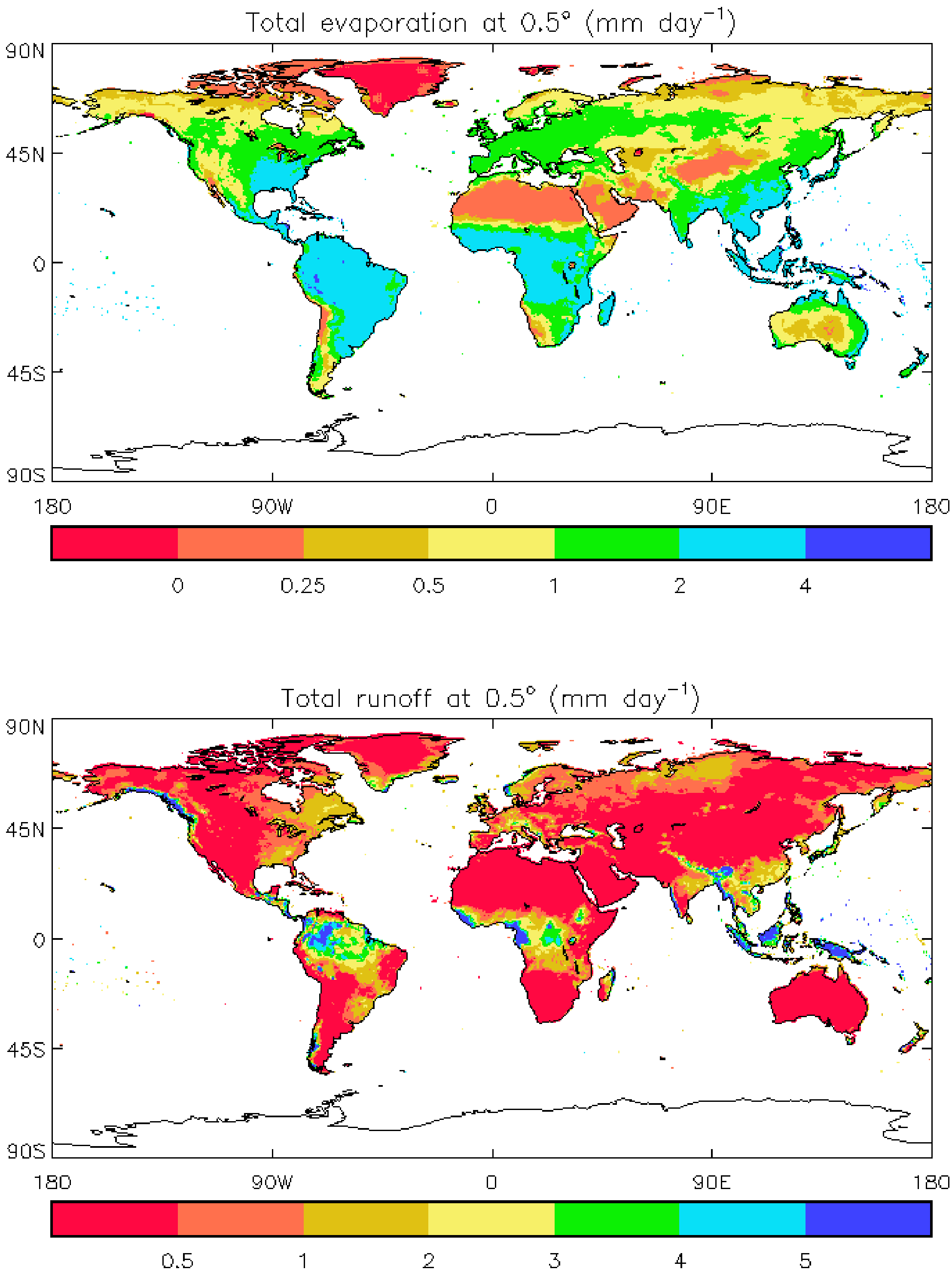


Figure 1: Mean global total (a) evaporation and (b) runoff, from the JULES simulation with the native resolution WATCH forcing data.

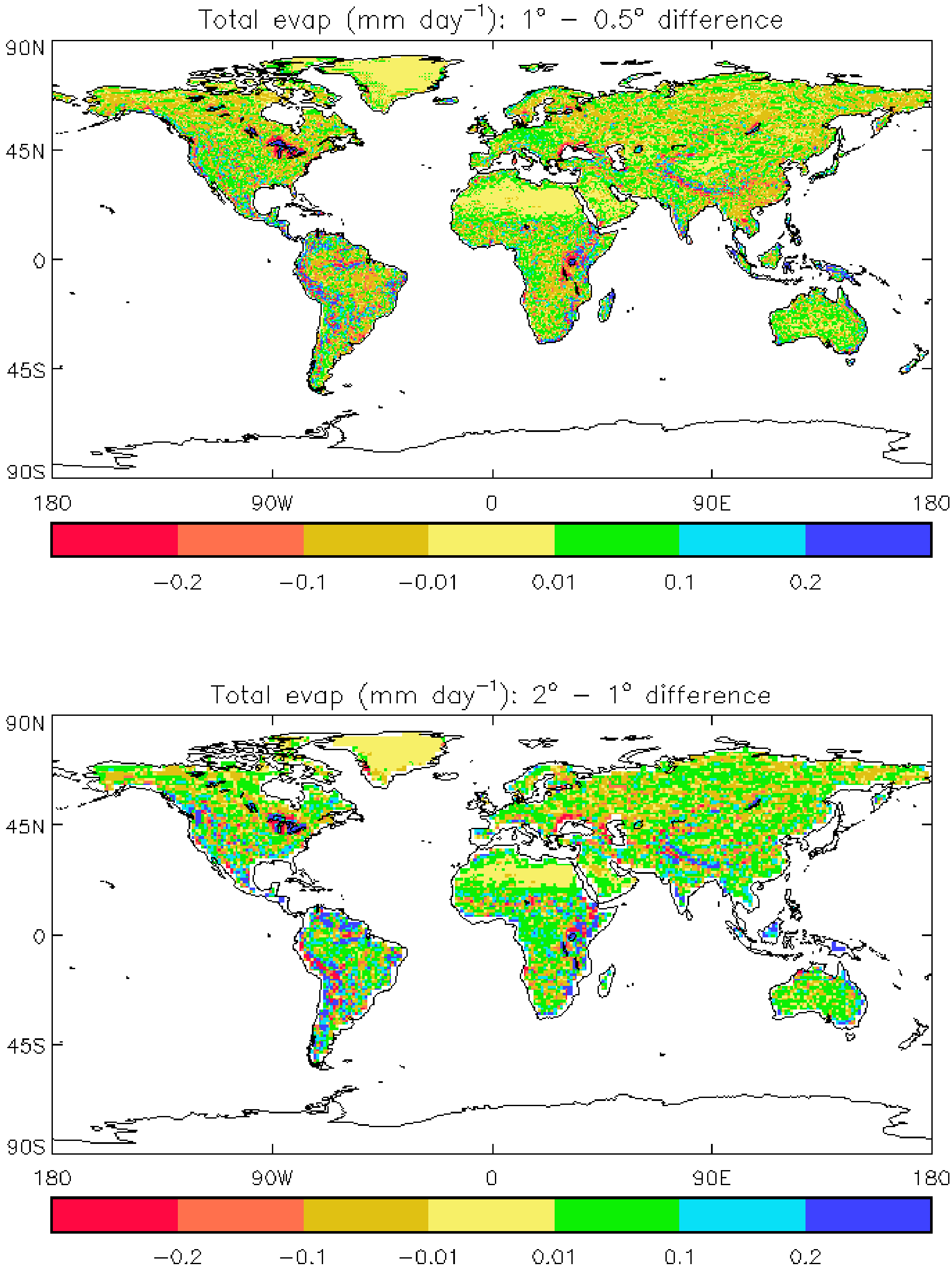


Figure 2: Differences in global mean total evaporation from (a) one degree – half degree spatial resolutions, and (b) two degree – one degree spatial resolutions

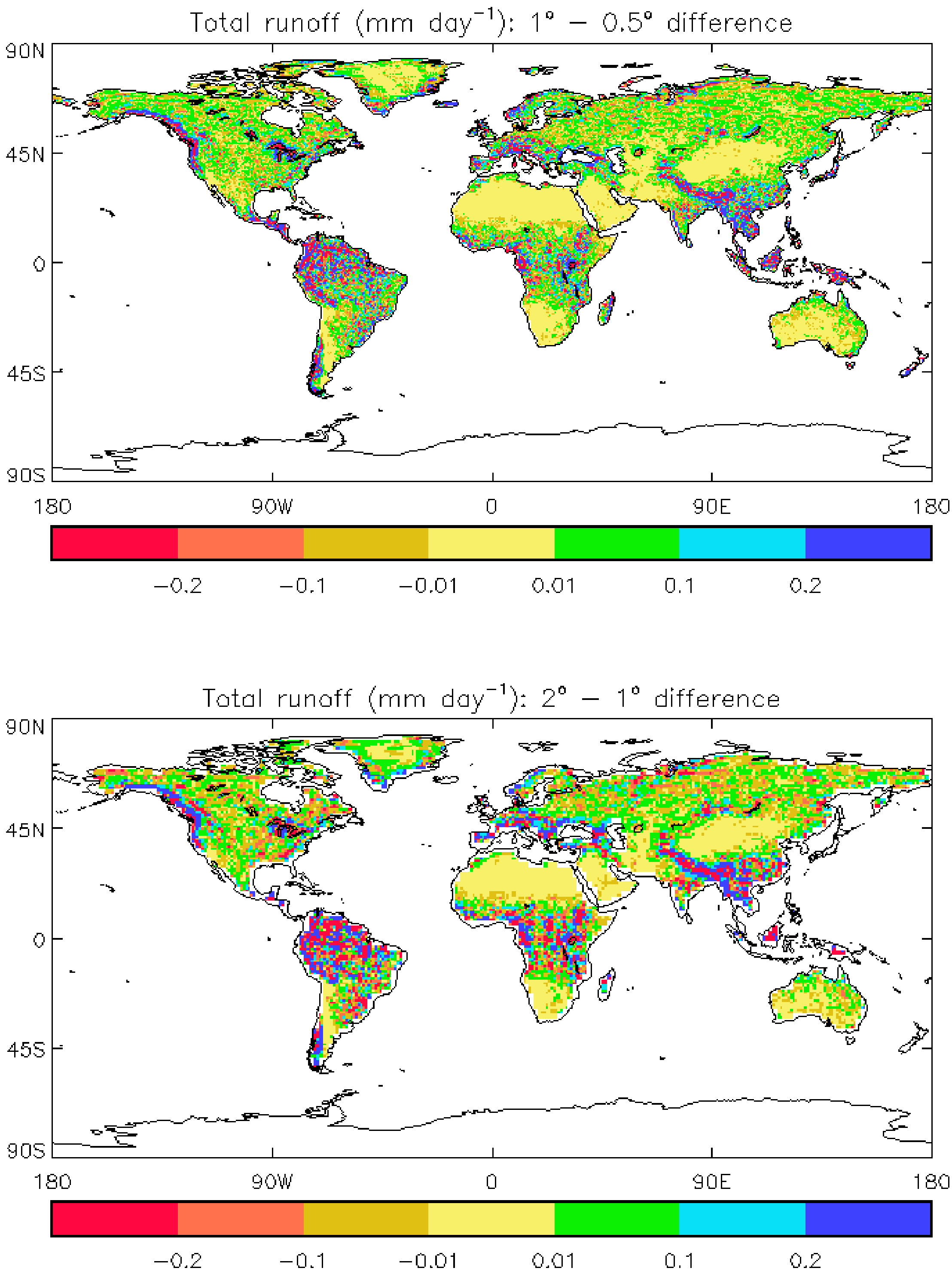


Figure 3: Differences in global mean total runoff from (a) one degree – half degree spatial resolutions, and (b) two degree – one degree spatial resolutions

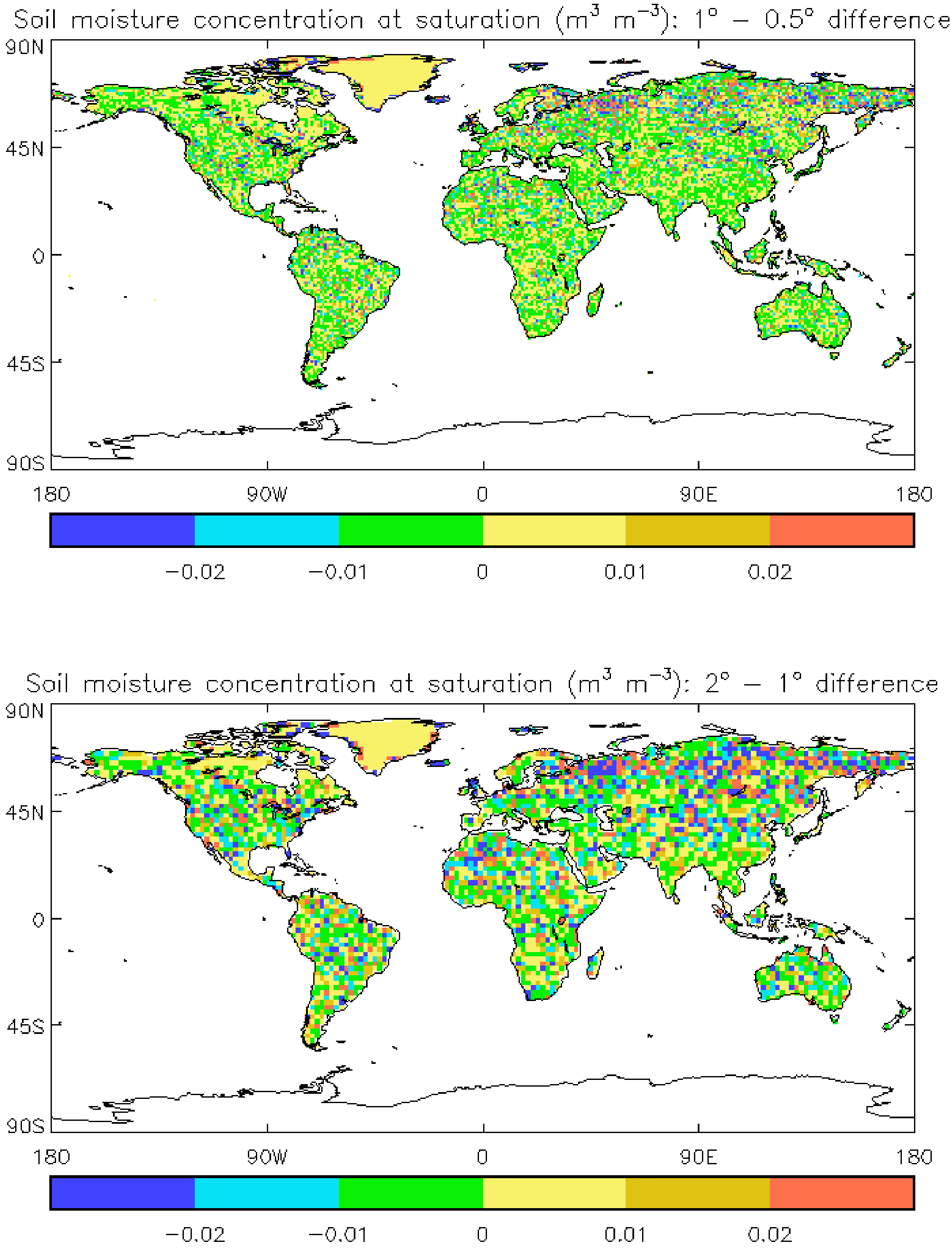


Figure 4: Differences in global soil moisture concentration at saturation for (a) one degree – half degree spatial resolutions, and (b) two degree – one degree spatial resolutions

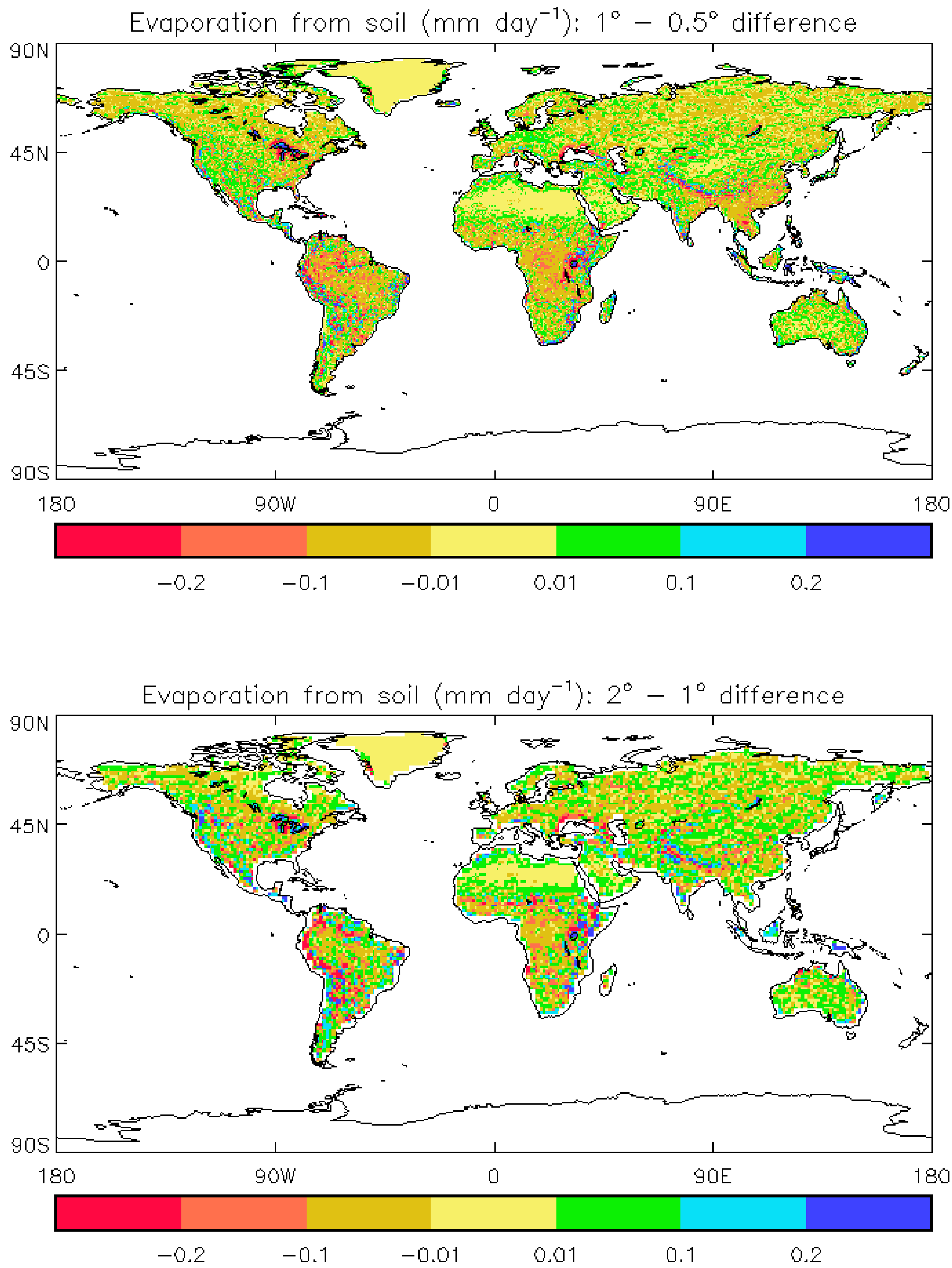


Figure 5: Differences in global mean soil evaporation (i.e., transpiration and bare soil evaporation) from (a) one degree – half degree spatial resolutions, and (b) two degree – one degree spatial resolutions

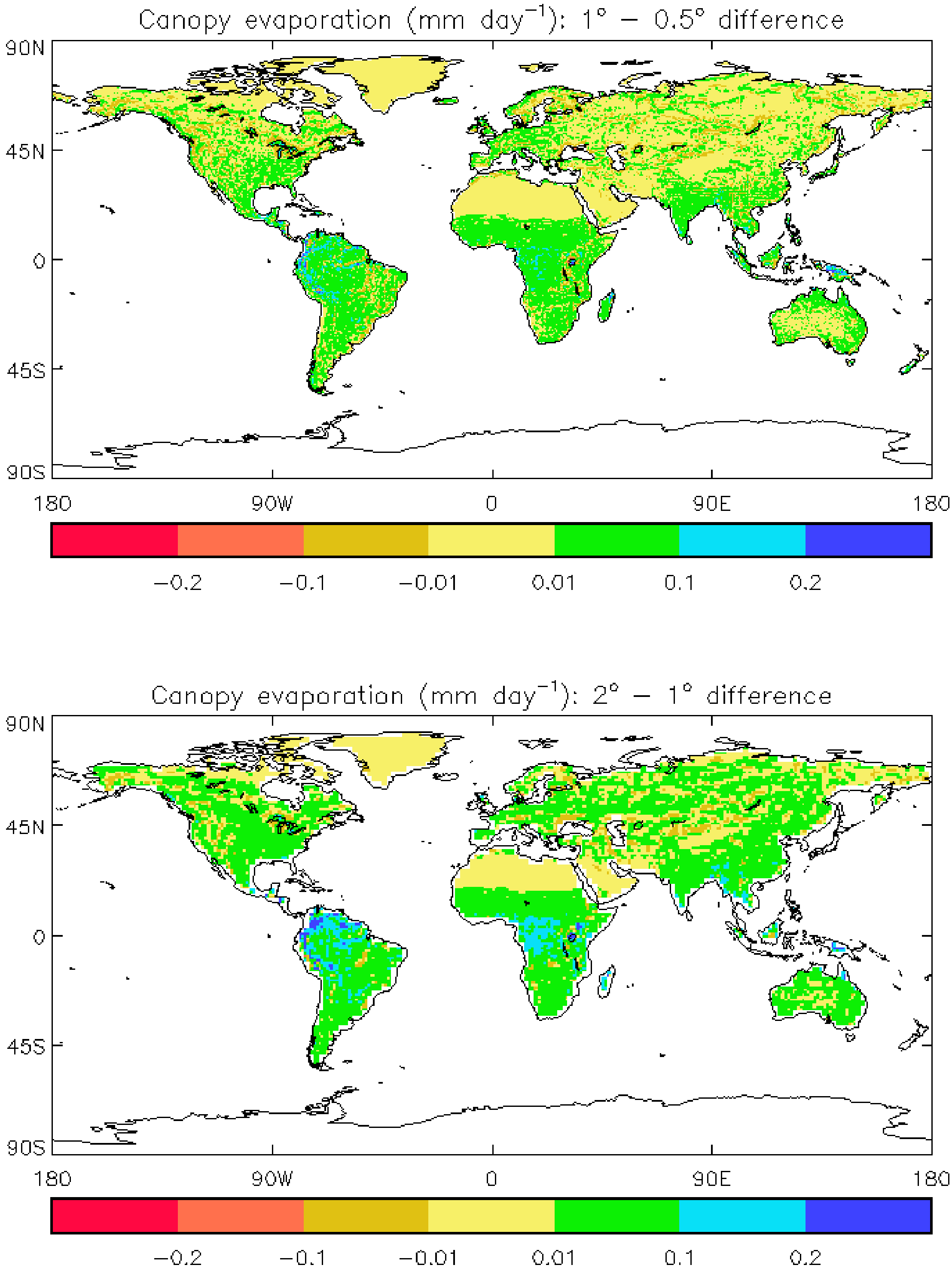


Figure 6: Differences in global mean canopy evaporation from (a) one degree – half degree spatial resolutions, and (b) two degree – one degree spatial resolutions

Higher spatial resolution is likely to lead to precipitation with increased intensity, especially for convective storms and especially in the tropics. This is consistent with the greatest differences in the model simulations with degraded resolution also occurring in the tropics.

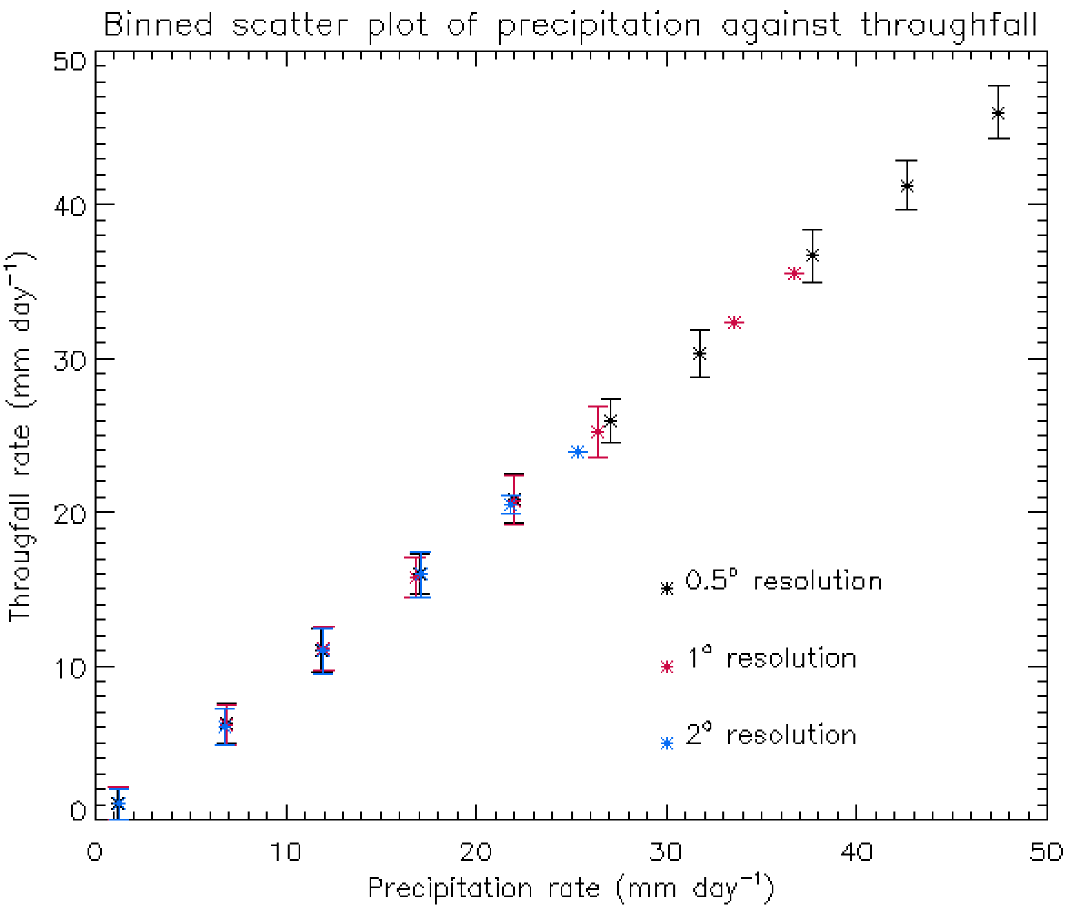


Figure 7: Modelled relationship between precipitation and canopy throughfall for the various spatial resolutions.

This is highlighted by considering the fraction of throughfall which occurs for given precipitation amounts (Fig. 7). For lower daily precipitation totals, the fraction which results in throughfall is similar for all of the spatial resolutions. However, as the daily totals in precipitation increase, the higher resolution simulations tend to lead to larger throughfall. This is emphasised at the high end of the daily precipitation totals, where only the high resolution simulation has such precipitation events, which give the largest throughfall. Hence the higher resolution simulations will tend to have more throughfall in general and thus less canopy water, which is subsequently evaporated.

The reduced throughfall from the degraded resolution simulations results in a lower soil moisture, hence giving the compensating lower values of evaporation from the soil (by either transpiration or bare soil evaporation). However, these differences in both the canopy evaporation and the soil evaporation are relatively small compared to the overall total evaporation. So they are unlikely to impact largely on the overall terrestrial water cycle.

Results for temporal resolution

The global mean differences in total evaporation between using a three hour timestep and a one hour timestep are shown in figure 8a, whilst the differences between a six hour timetep and a three hour timestep is shown in figure 8b. It is clear from this figure that there are large differences in the total evaporation, especially in the tropics. There is a general reduction in the total evaporation as the timestep of the model is increased, with a consistent signal between the one hour, three hour and six hour simulations. However, the differences between the six hour and three hour timesteps are larger than for those between the three hour and one hour timesteps.

The reduction in global mean total evaporation is compensated by a global mean increase in total runoff (figure 9). The patterns shown in these differences are the same as those for the evaporation, but with increasing runoff as the timestep is increased. This demonstrates that the excess water at the surface which is not being evaporated has to result in additional surface runoff as the net storage of soil water is limited. So the net impact of increasing timestep is to change the water balance at the surface.

The cause of these differences is apparent from studying a time series for various components of the surface energy balance. Figure 10 shows such a time series for some of these components. We can see from this figure that although the shortwave radiation has the same integrated flux over a diurnal cycle, the longer timestep simulations do not receive the peak values for forcing the model that are obtained with the shorter timesteps. The impact of this can be seen in the latent heat flux, where the increased timestep reduces the flux of moisture into the atmosphere, with a subsequent increase in the sensible heat flux. The resultant increase in surface temperature leads to a reduction in the net radiation through the outgoing longwave radiation, which feeds back on the energy available for evaporation.

These differences can be explained by looking at the equations used for the surface energy balance (e.g. see Best et al., 2011), which in its simplest form can be written as:

$$Q = H + LE + G$$

$$H = \frac{\rho c_p}{r_a}\left(T_* - T_1\right)$$

$$E = \frac{\rho}{r_a + r_s}\left(Q_{sat}\left(T_*\right) = Q_1\right)$$

$$G = A_s\left(T_* - T_{s1}\right)$$

where Q is the net radiation, H is the sensible heat flux, E is the turbulent moisture flux, L is the latent heat of condensation at 0 ^oC, G is the surface soil heat flux, ρ is the density of air, c_p is the specific heat capacity of air, r_a is the aerodynamic resistance, r_s is the surface resistance, T_* is the surface temperature, T_1 and Q_1 are the temperature and specific humidity at a reference height in the atmosphere, $Q_{sat}(T)$ is the saturated specific humidity at temperature T, A_s is the thermal conductivity of the soil and T_{s1} is the soil temperature near the surface.

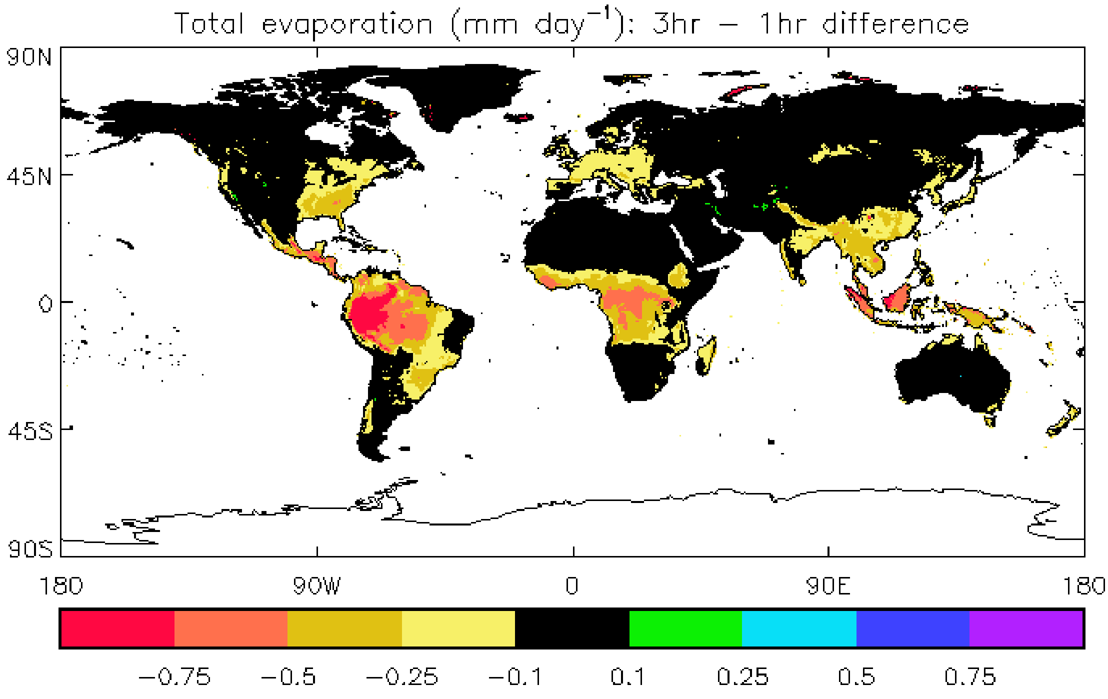
These equations are generally linearised around the surface temperature in order to obtain a consistent solution for the surface fluxes that conserves energy, as this temperature drives each of the flux gradients. In order to linearise the evaporation equation, the rate of change of saturated specific humidity with temperature has to be determined, and this term has a very non-linear behaviour for a given change in temperature. The term increases more rapidly at higher temperatures.

The net result is that evaporation becomes more efficient as the surface temperature increases, but surface temperature increases are largely driven by the net incoming shortwave radiation. Hence the higher peak values of the shortwave radiation obtained with the shorter timestep simulations will lead to more efficient evaporation on average. Hence the shorter timestep simulations have greater evaporation at the expense of the sensible heat.

It is not just the timestep of the simulations that influence the resulting water balance components, but also the temporal resolution of the forcing data itself. Figure 11 shows the same energy balance components as figure 10, but here each simulation uses the same timestep, whilst the differences are caused by the temporal resolution of the forcing data. In order to obtain timestep information that is of a higher temporal resolution than the forcing data, some interpolation is required. Whilst for many of the forcing data linear interpolation is likely to be adequate, this is not the case for the shortwave radiation, due to the non-linear temporal behaviour of the sun's path across the sky (e.g. at sunset and sunrise).

A simple way to ensure that energy is conserved is to hold the solar radiation constant over the temporal timescale of the forcing data, as is seen in figure 11a. However, this method also prevents the peak values in the shortwave radiation from being obtained for forcing on the timestep (compared to a temporal resoluition of the forcing data that is the same as the timestep), leading to the same general behaviour as is seen from lengthening the timestep itself. The resultant behaviour on the other terns of the energy balance are then also the saem as for lengthening the timetep, with increased evaporation and the expense of the sensible heat and surface soil heat fluxes (Fig 11), although the impact is smaller than for increasing timesteps.

Hence care needs to be taken in the chosen interpolation techniques used in order to run the simulations with a timestep that is shorter than the temporal resolution of the forcing data. This is especially true for the shortwave radiation that will need to include the sun's zenith angle, whist also conserving energy.



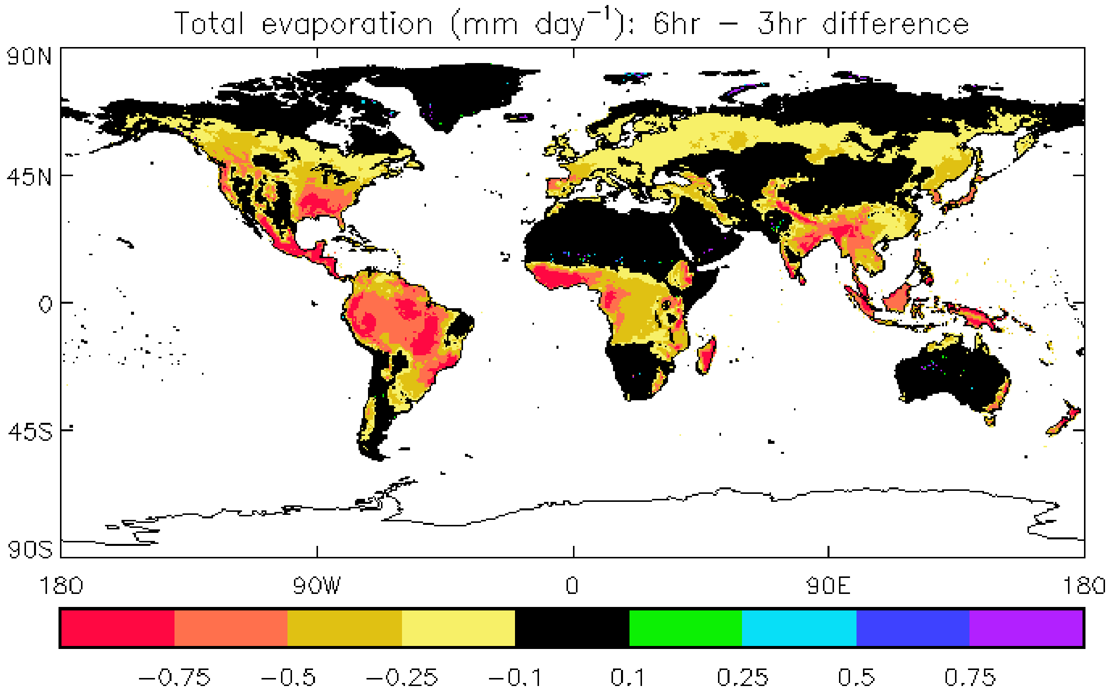
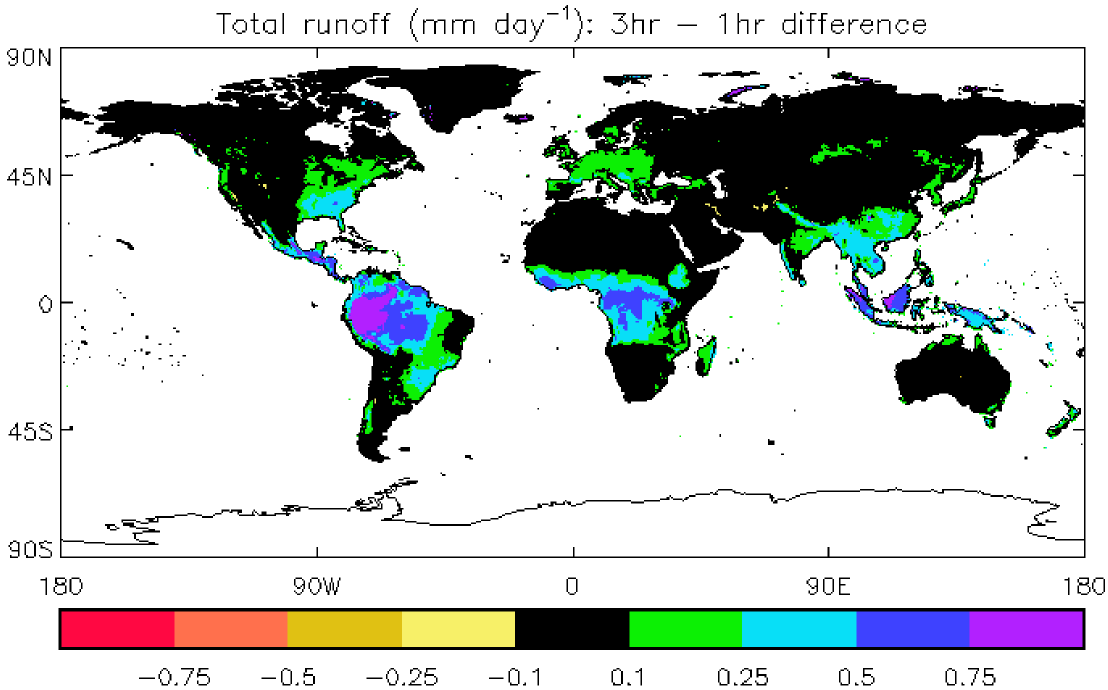


Figure 8: Differences in global mean total evaporation from (a) three hour – one hour model timsetep, and (b) six hour – three hour model timestep



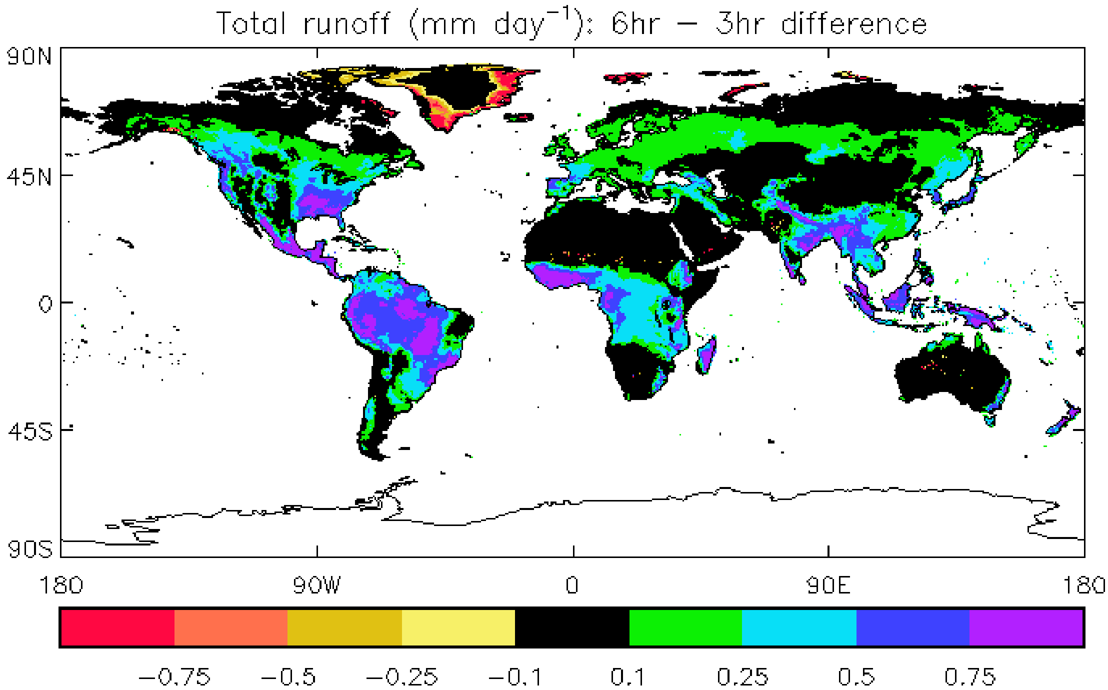


Figure 9: Differences in global mean total runoff from (a) three hour – one hour model timsetep, and (b) six hour – three hour model timestep

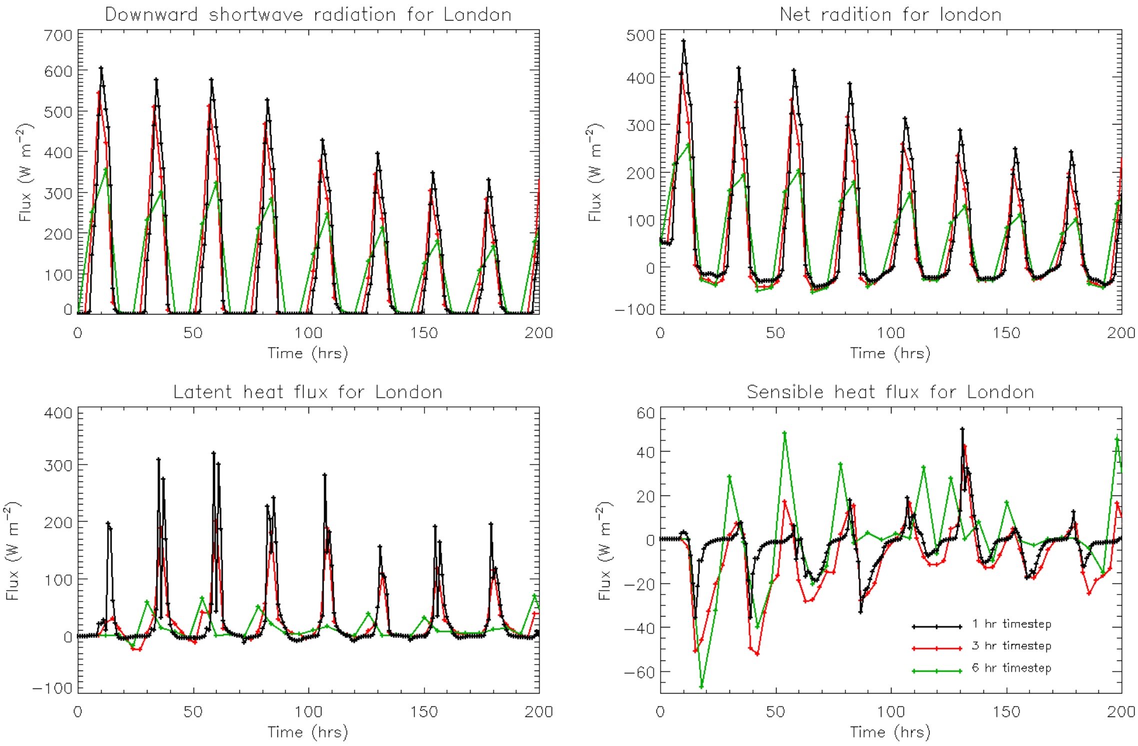


Figure 10: Example time-series for gridpoint containing London, U.K., with varying timestep, for (a) downward component of shortwave radiation, (b) net radiation, (c) latent heat flux and (d) sensible heat flux.

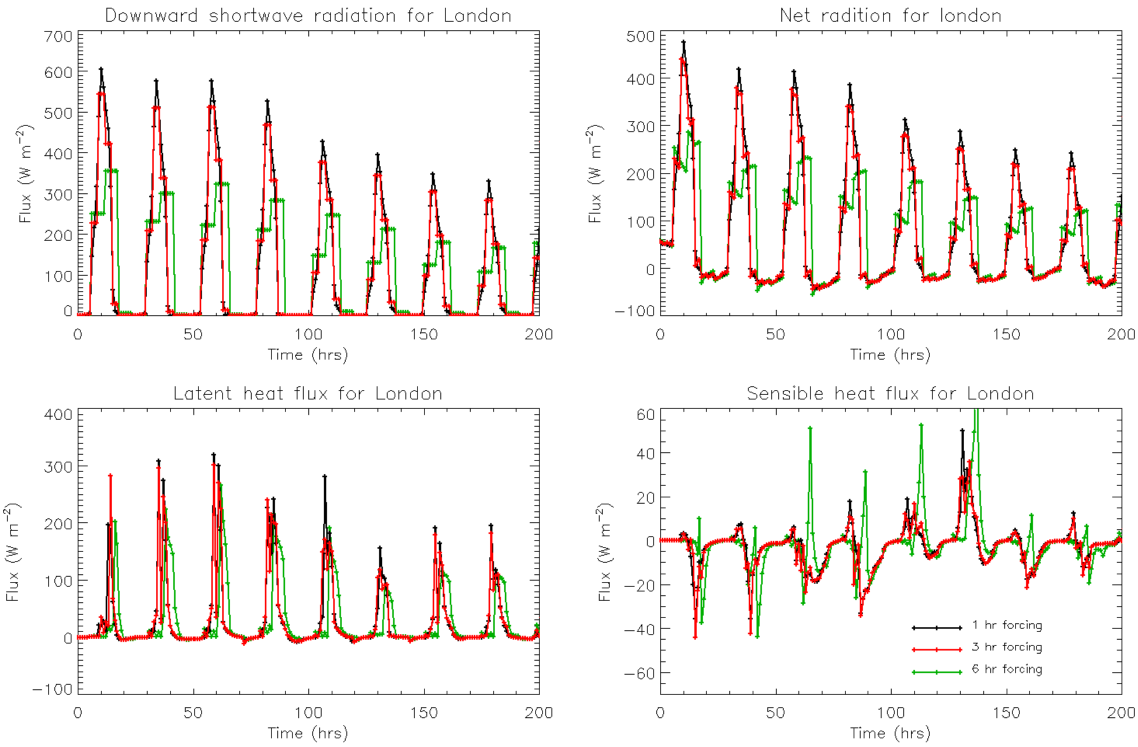


Figure 11: Example time-series for gridpoint containing London, U.K., with varying temporal resolution forcing data, for (a) downward component of shortwave radiation, (b) net radiation, (c) latent heat flux and (d) sensible heat flux.

Conclusions

The results from the spatial resolution tests suggest that there is little overall impact on the components of the terrestrial water balance from degrading the spatial resolutions. The impacts in the total evaporation and runoff have a patch behaviour that is of opposite sign, due mainly to the soil properties and how these are defined. However, the magnitude of these differences is small.

When looking at the elements that make up the terrestrial water cycle components, we find that there are some differences in evaporation due to the spatial resolution. Higher resolution forcing tends to have larger peak precipitation rates, leading to less water being held within vegetation canopies. The result is for the model runs with higher resolution forcing to have less canopy evaporation, but a compensating larger evaporation from the soil (i.e. combined transpiration and bare soil evaporation).

The differences in the components of the terrestrial water cycle are larger when considering temporal resolution. The averaging of the available energy over the longer timescales leads to less evaporation in general, due to non-linearities in the relationship between the saturated specific humidity and temperature, which drives the moisture gradient between the surface and the atmosphere. The net result is for the lower temporal resolution forcing runs to have less total evaporation, but with a compensating larger total runoff. Hence the temporal resolution impacts on the overall distribution, of the available water that lands at the surface, between that returned to the atmosphere (through evaporation) or returned to the ocean (via runoff and river flow).

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