Derivation of RCM-driven potential evapotranspiration for hydrological climate change impact analysis in Great Britain: a comparison of methods and associated uncertainty in future projections

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Supplementary material

Sect. 1: PET methods and associated equations (for daily estimates)

PET method	Equation
FAO56 (Allen et al., 1998)	$\mathrm{PE[mm\ day^{-1}]} = \dfrac{\lambda^{-1}\Delta(R_n - G) + \gamma \dfrac{900}{T+273} U_2(e_s - e_d)}{\Delta + \gamma(1 + 0.34U_2)}$
Penman-Monteith (modified) (Kay et al., 2003)	$\mathrm{PE[mm\ day^{-1}]} = \dfrac{1}{\lambda}\dfrac{\Delta(R_n - G) + \rho C_p(e_s - e)/r_a}{\Delta + \gamma(1 + r_s/r_a)}$
Priestley-Taylor (Priestley and Taylor, 1972)	$\mathrm{PE[mm\ day^{-1}]} = \propto \dfrac{1}{\lambda}\dfrac{\Delta}{\Delta + \gamma}(R_n - G)$
Turc (Turc, 1961)	$\mathrm{PE[mm\ day^{-1}]} = 0.31\ \dfrac{T}{T+15}(R_{sn} + 2.09)\left(1 + \dfrac{50 - RH}{70}\right)$ for $RH < 50\%$ $\mathrm{PE[mm\ day^{-1}]} = 0.31\ \dfrac{T}{T+15}(R_{sn} + 2.09)$ for $RH > 50\%$
Jensen-Haise (Jensen et al., 1990)	$\mathrm{PE[mm\ day^{-1}]} = \dfrac{1}{\lambda}0.025(T+3)R_s$
Makkink (Jacobs et al., 2009)	$\mathrm{PE[mm\ day^{-1}]} = \dfrac{1}{\lambda}\dfrac{R_n}{R_s}\dfrac{\Delta}{\Delta + \gamma}R_s$
Priestley-Taylor Idso-Jackson (Shuttleworth, 1993)	$\mathrm{PE[mm\ day^{-1}]} = \propto \dfrac{1}{\lambda}\dfrac{\Delta}{\Delta + \gamma}(1 - \alpha)\left(0.25 + 0.5\dfrac{n}{N}\right)S_0 - \left(0.9\dfrac{n}{N} + 0.1\right)\left(-0.02 + 0.261\exp\left(-7.7 \times 10^{-4}T^2\right)\right)\sigma T^4$

Hamon (Oudin et al., 2005)	$\mathrm{PE}[\mathrm{mm\ day}^{-1}] = \left(\frac{N}{12}\right)^2 \exp\left(\frac{T}{16}\right)$
McGuinness-Bordne (Oudin et al., 2005)	$\mathrm{PE}[\mathrm{mm\ day}^{-1}] = \frac{1}{\lambda} S_0 \left(\frac{T+5}{68}\right)$
Oudin (Oudin et al., 2005)	$\begin{cases} \mathrm{PE}[\mathrm{mm\ day}^{-1}] = \frac{1}{\lambda} S_0 \left(\frac{T+5}{100}\right) & \text{if } T > -5°\mathrm{C} \\ \mathrm{PE}[\mathrm{mm\ day}^{-1}] = 0 & \text{if } T \leq -5°\mathrm{C} \end{cases}$
Blaney-Criddle (Blaney and Criddle, 1950)	$\mathrm{PE}[\mathrm{mm\ day}^{-1}] = kTp_d$ with $p_d = 100 \frac{N_d}{\sum_{i=1}^{365} N_i}$
Thornthwaite (Xu and Singh, 2001)	$\mathrm{PE}' = 16 \left(\frac{10T}{I}\right)^a$ $a = 0.49239 + 0.01792\, I - 7.71\, 10^{-5} I^2 + 6.75\, 10^{-7} I^3$ $\mathrm{PE}[\mathrm{mm\ month}^{-1}] = \mathrm{PE}' \frac{N_m}{12} \frac{D_m}{30}$

Sect. 2: Notations and used values of meteorological variables

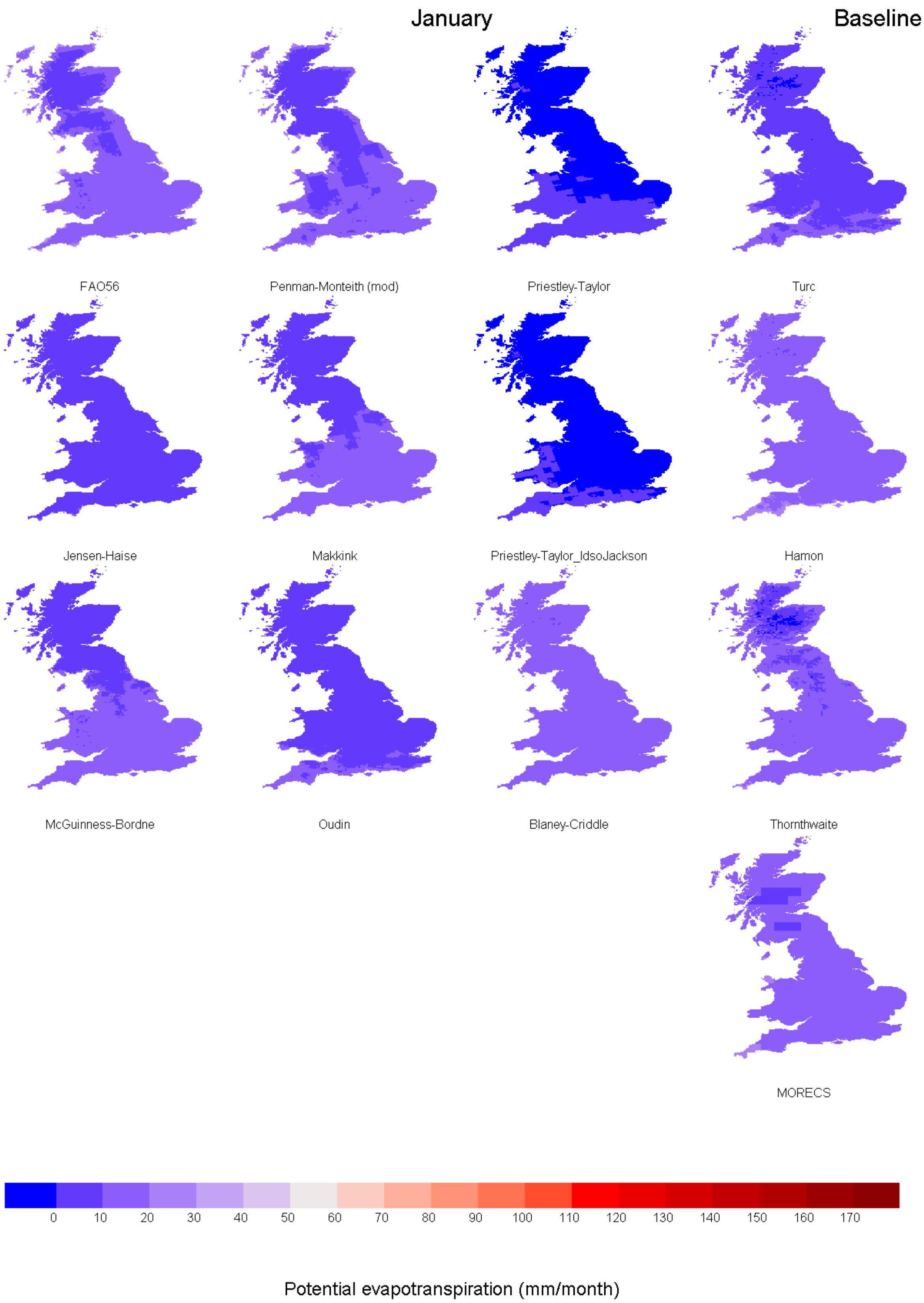
Values used in the PET calculations calculated from meteorological inputs and the equations used to calculate them

Symbol	Variable name	Units	Description	Formula
δ	Solar declination	radians	Angle between rays of the sun and the plane of the earth's equator.	$\delta = 0.4093\sin\,(\frac{2\pi}{365}J - 1.405)$ *With J Julian day number* *Note that MORECS uses a different equation:* $\delta = 0.41\cos\left(\frac{2\pi(J-172)}{365}\right)$
C_p	Specific heat at constant pressure (for water)	$MJkg^{-1}°C^{-1}$	Amount of heat required to change a unit mass of a substance by one degree in temperature Note this is a re-arrangement of the equation of the Psychrometric constant	$C_p = \frac{\gamma\varepsilon\lambda}{P}$ *With* γ *in* $KPaC^{-1}$ λ *in* $MJkg^{-1}$ *P in KPa*
d_r	Relative earth-sun distance		Distance between earth and sun varies through the year due to the ellipse orbit of the earth around the sun.	$d_r = 1 + 0.033\cos\,(\frac{2\pi}{365}J)$
ω_s	Sunset hour angle	radians	Angle by which the ray of the sun reaches the earth's surface.	$\omega_s = \arccos\,(-\tan\Phi\tan\delta)$ *With* Φ *latitude (+ is north, - is south)*
N	Maximum possible daylight length	hours	Length of the period when the rays of the sun reach the earth's surface.	$N = \frac{24}{\pi}\omega_s$ *Note that MORECS uses a different equation:* $N = 24 - 2(\frac{12}{\pi}\arccos(\tan\delta\tan\phi +$ $0.0145\cos\delta\cos\phi$
e_s	Saturated water vapour pressure	kPa	Equilibrium of rates of vaporisation and condensation for a given temperature that occurs at particular vapour pressure, the saturated vapour pressure.	$e_s = 0.6108e^{(\frac{17.27T}{237.3+T})}$ *With T temperature in °C*
e_a	Actual water vapour pressure	kPa	Actual water vapour pressure at dew point.	$e_a = 0.6108e^{(\frac{17.27T_d}{237.3+T_d})}$ *With* T_d *temperature at dew point, °C*
Δ	Gradient of vapour pressure curve	$kPa°C^{-1}$	Gradient of vapour pressure curve is the slope of the non linear relationship between pressure and temperature.	$\Delta = \frac{4098e_s}{(237.3+T)^2}$
λ	Latent heat of	$MJkg^{-1}$	Amount of energy needed for water to be	$\lambda = 2.501 - 0.002361T$

Symbol	Variable name	Units	Description	Formula
	vaporisation		transformed from a liquid to a gas, approximated as λ=2.45 $MJkg^{-1}$.	*With T as 20°C*
P	Atmospheric pressure	kPa	The change of pressure due to altitude	$P = 101.3(\frac{293 - 0.0065z}{293})^{5.26}$ *With z elevation above sea level*
ρ_a	Mean air density	Kgm^{-3}	The mass of air per unit volume. It depends on the atmospheric pressure P and temperature T	$\rho_a = \frac{P}{T_{Kv}R}$ *With TKv the virtual temperature:* $T_{Kv} = 1.01(T + 273)$ *°K (T in °C)* *and R specific gas constant for dry air (=0.287kJkg-1°K-1)*
RH	Relative humidity	%	Amount of water the air can hold at a certain temperature. In other words the percentage ratio of actual vapour pressure to saturated vapour pressure.	$RH = 100\frac{e_a}{e_s}$
f	Cloudiness factor or fraction	[-]	Amount of cloud cover in the atmosphere, related to number of bright sunshine hours in a day. Different coefficients can be used for humid and arid areas. Using the longwave coefficients for arid areas a simplified version of the formula can be derived. A second expression is given by Jensen 1990. In this formula the cloudiness factor is expressed as the effect of clouds on short-wave global radiation The simplified version is the one used in this paper	Shuttleworth, 1993 $f = \left(a_c \frac{b_s}{a_s + b_s}\right)\frac{n}{N} + (b_c + \frac{a_s}{a_s + b_s} a_s)$ *With: n as bright sunshine hours (h),* *a_s is fraction of extraterrestrial radiation (S_0) for n=0,* *a_s+ b_s is fraction of extraterrestrial radiation for n>0,* *a_c and b_c are long wave coefficients for clear skies.* *N is the maximum possible daylight hours* Simplified version (Allen et al., 1998) $f = 0.9\frac{n}{N} + 0.1$ Jensen, 1990 $f = a_c\frac{R_s}{S_0} + b_c$ *With R_s solar (short-wave) radiation (MJ m^2/day)*
G	Soil heat flux	$MJm^{-2}month^{-1}$	Energy that moves from the surface to subsurface soil by conduction, depends on	Monthly formulation (Shuttleworth, 1993)

Symbol	Variable name	Units	Description	Formula
			soil temperature fluctuations	$G = 0.14(T_{month2} - T_{month1})$
γ	Psychrometric constant (for water)	$KPa°C^{-1}$	Describes the thermodynamic properties of moist air at a constant pressure. Relates the partial pressure of water in the air to the air temperature	Shuttleworth, 1993 $\gamma = \frac{c_p P}{\varepsilon\lambda}$ *With c_p specific heat of moist air* $c_p = 1.013 \times 10^{-3} MJkg^{-1}°C^{-1}$ *P atmospheric pressure* *ε ratio of molecular weight of water vapour to that of dry air:* $\varepsilon = 0.622$
S_0	Extraterrestrial radiation	$MJmm^{-2}day^{-1}$	The amount of solar energy that reaches the top of the atmosphere. Depends on angle of sun radiation and length of day.	Shuttleworth, 1993 $S_0 = 37.62 d_r(\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s)$
R_s	Solar radiation	MJm^2day^{-1}	Amount of energy measured at the earth's surface including direct and diffuse short-wave radiation	Generalised form (Jensen et al., 1990) $R_s = S_0(a_s + b_s \frac{n}{N})$ Here $a_s = 0.25$ and $b_s = 0.50$
R_{ns}	Net solar radiation	MJm^2day^{-1}	That part of the incident short wave radiation that is captured at the ground (reflection losses are taken into account), in other words, the absorbed incoming solar radiation.	Shuttleworth, 1993 $R_{ns} = (1 - \alpha)R_s$ *With α albedo*
R_{nl}	Net long-wave radiation	MJm^2day^{-1}	Incoming (atmosphere to ground) minus outgoing (ground to atmosphere) long-wave radiation	$R_{nl} = f\varepsilon'\sigma T^4$ *With ε' net emissivity between atmosphere and ground (given for average conditions):* $\varepsilon' = 0.34 - 0.139\sqrt{e_a}$ *σ Stefan-Boltzmann constant:* $\sigma = 4.903 \times 10^{-9}$ $MJK^{-4}m^{-2}day^{-1}$ *T mean air temperature in °K*
R_n	Net radiation	MJm^2/day	Difference between the net solar radiation and the long-wave radiation	$R_n = R_{ns} - R_{nl}$

1 Maps of mean MORECS PET and PET derived from HadRM3-Q0 for the 1961-1990 period



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February
Baseline
FAO56
Penman-Monteith (mod)
Priestley-Taylor
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McGuinness-Bordne
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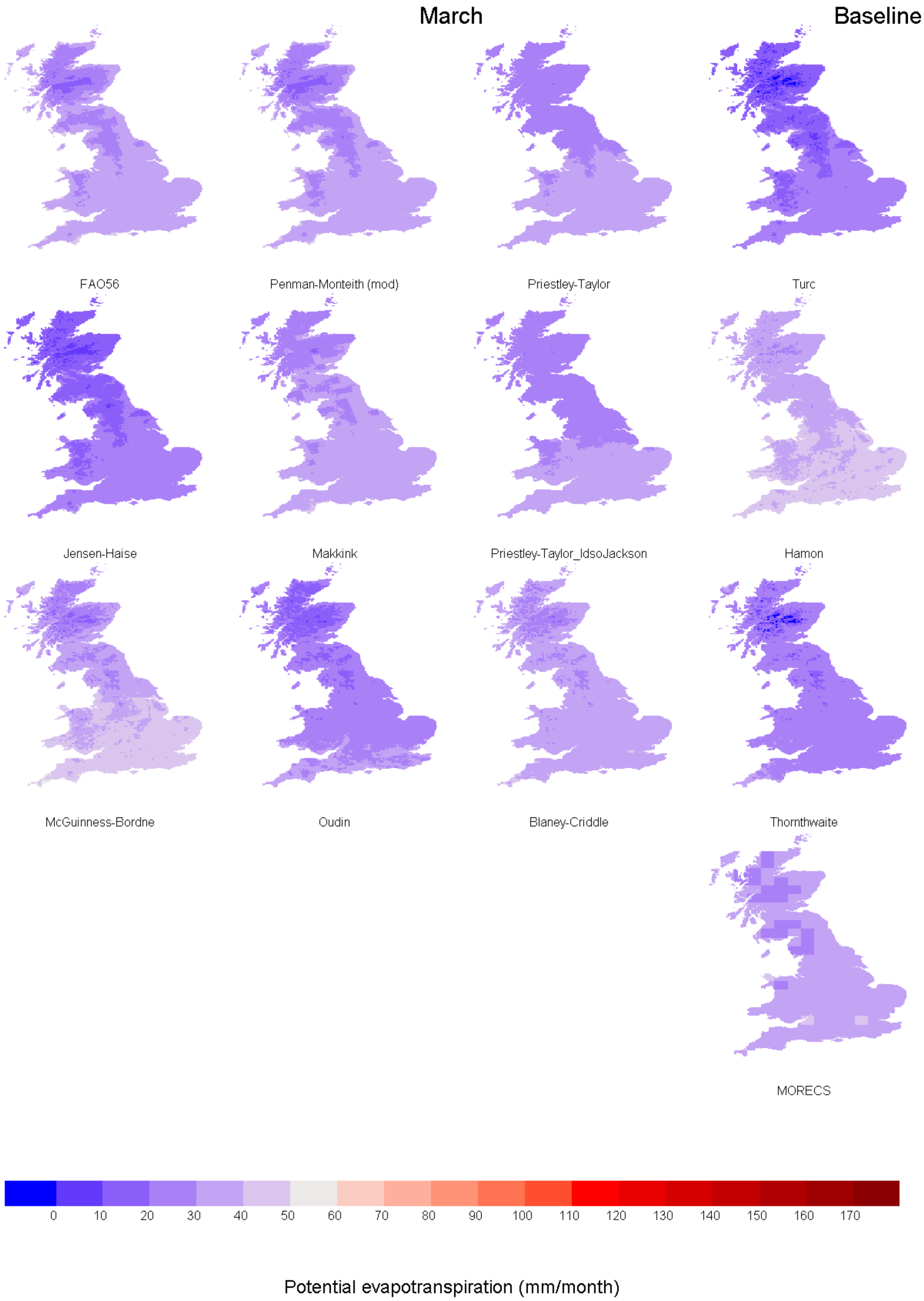
Potential evapotranspiration (mm/month)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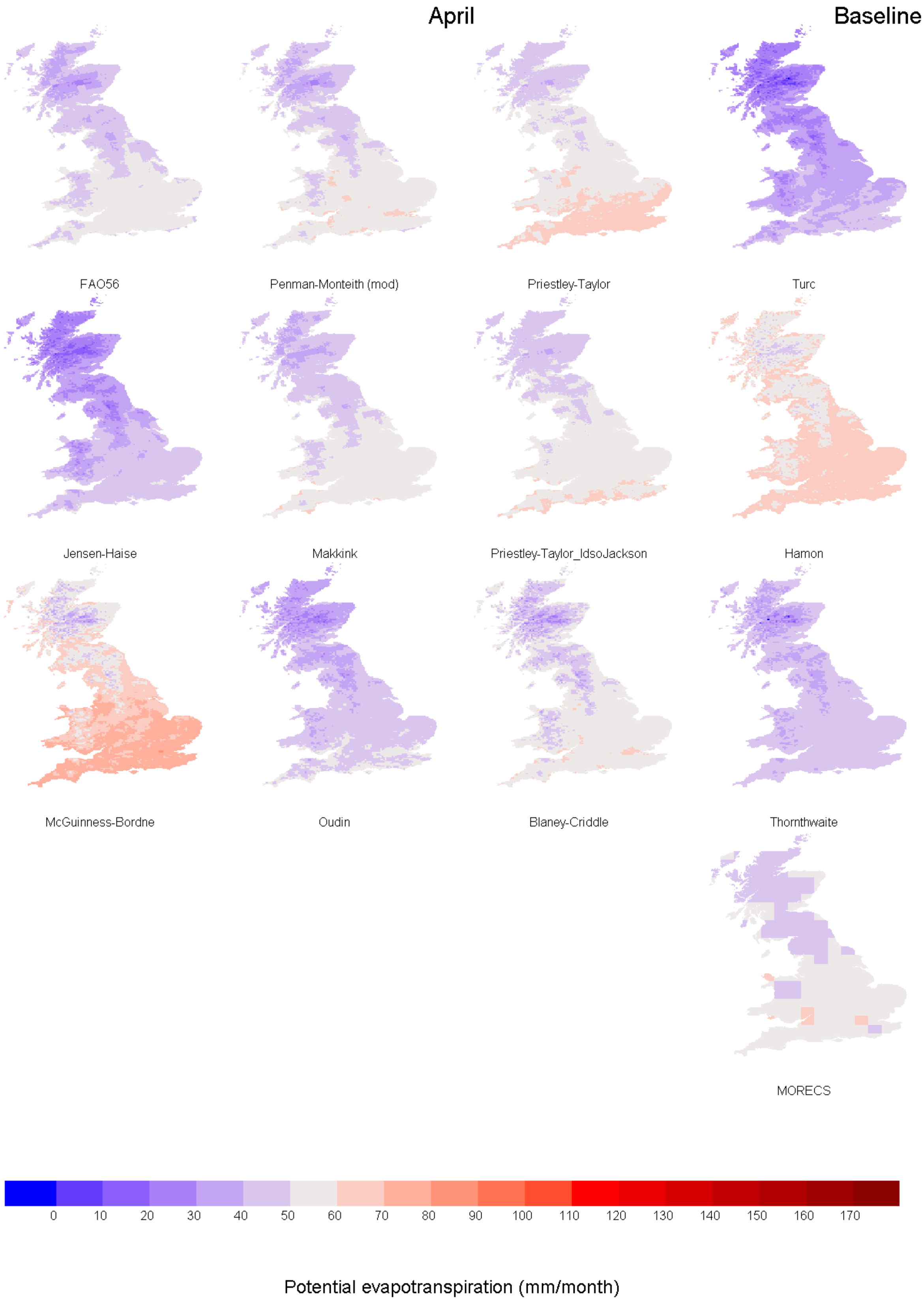

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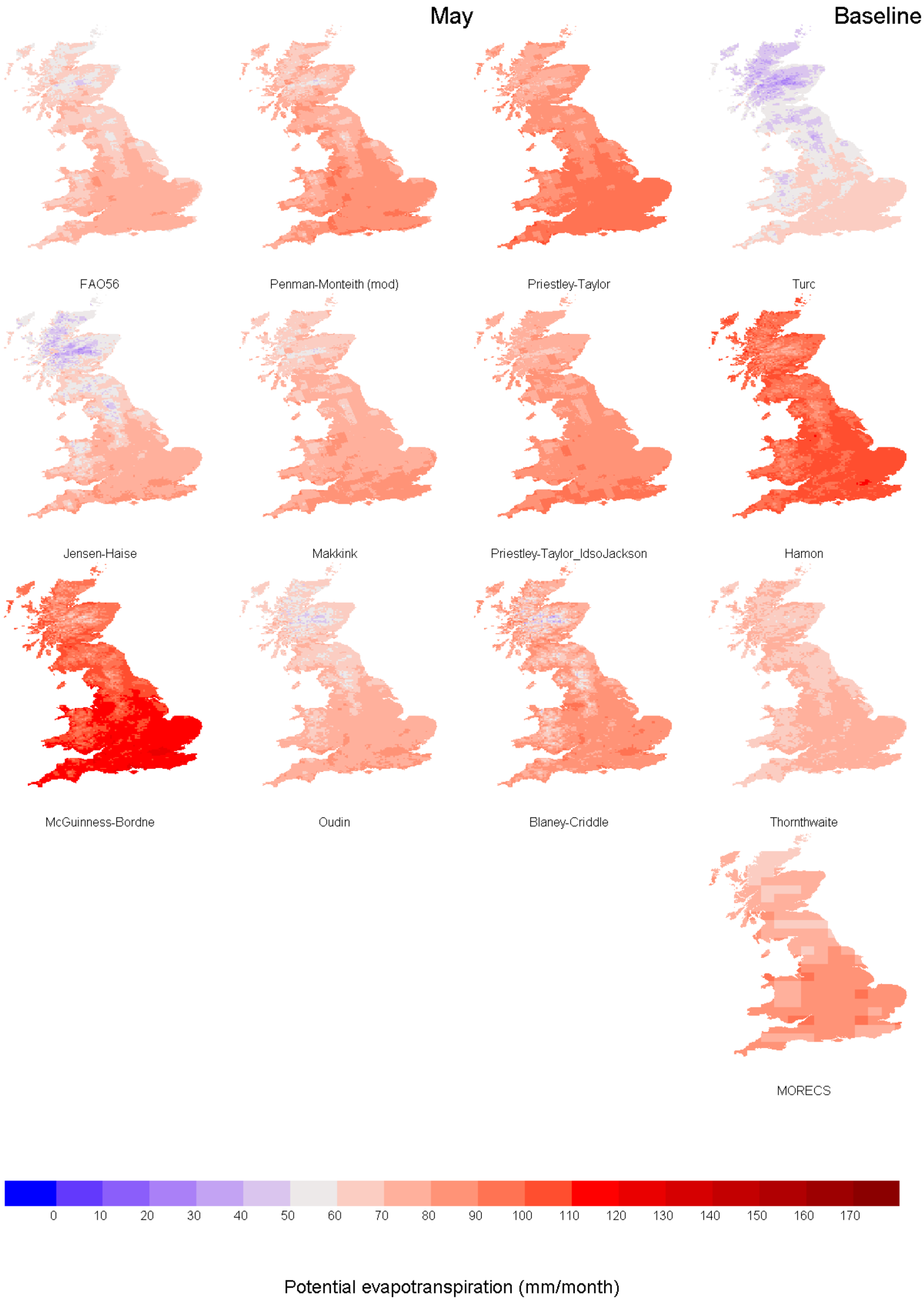
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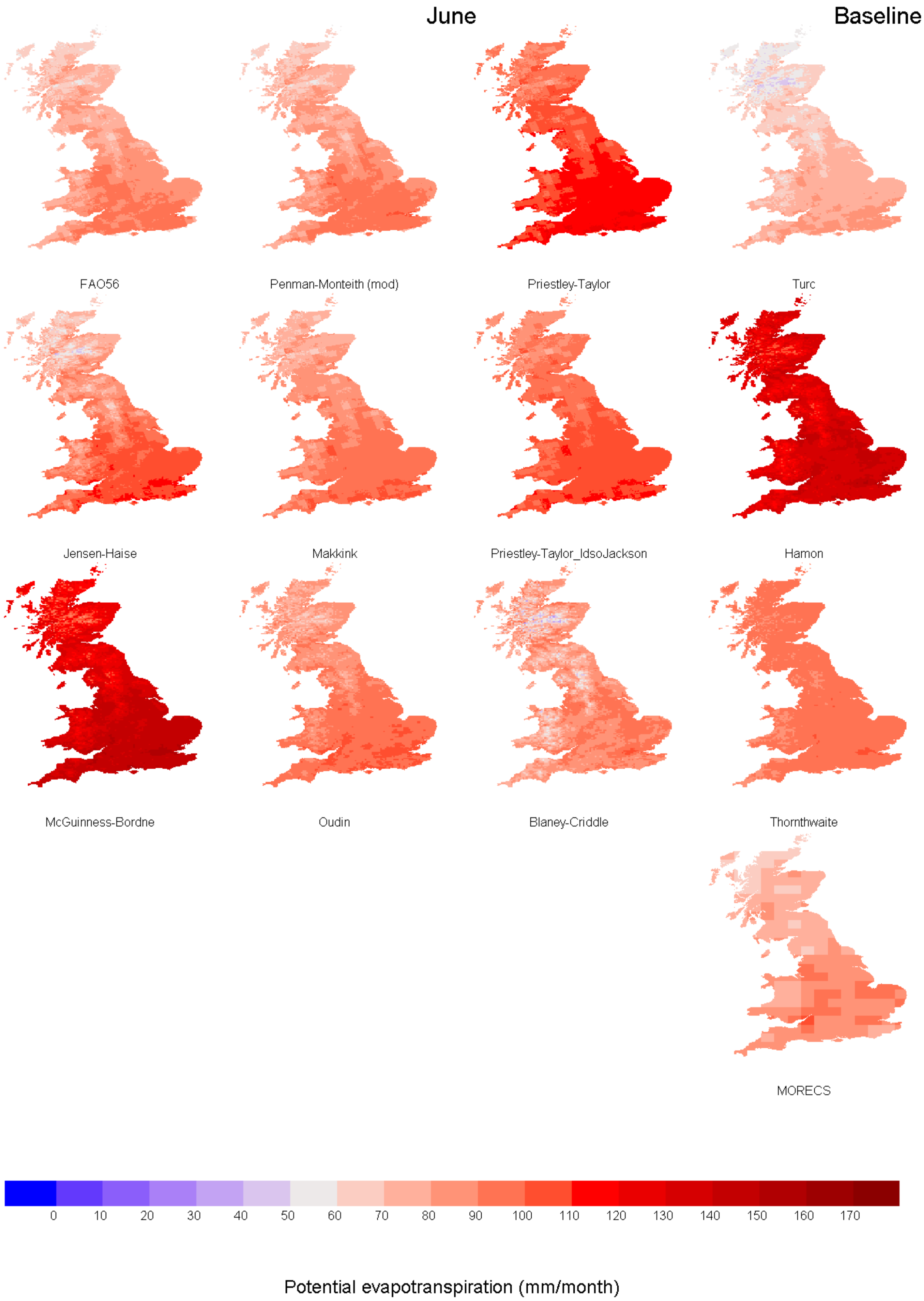

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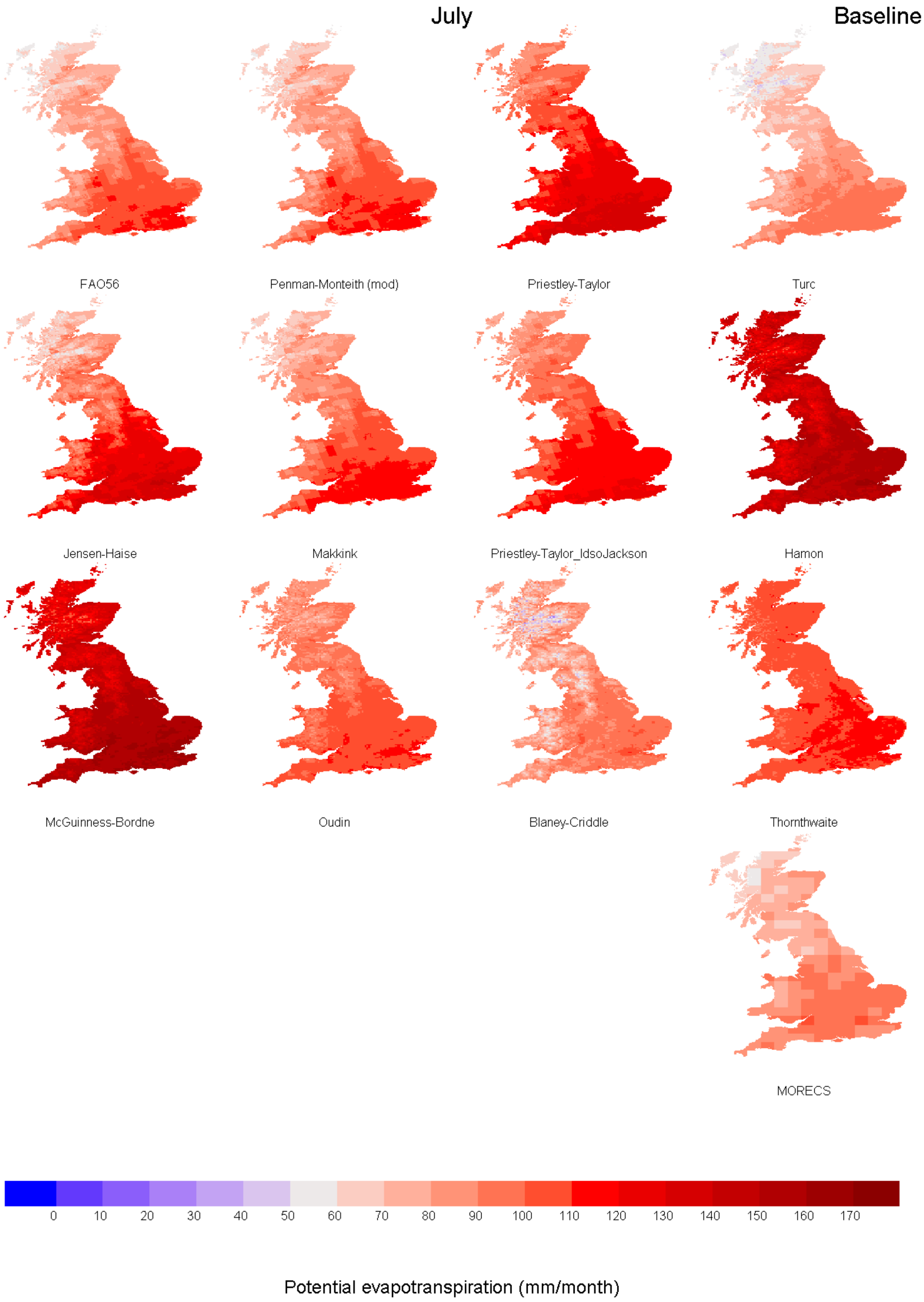
Potential evapotranspiration (mm/month)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Potential evapotranspiration (mm/month)

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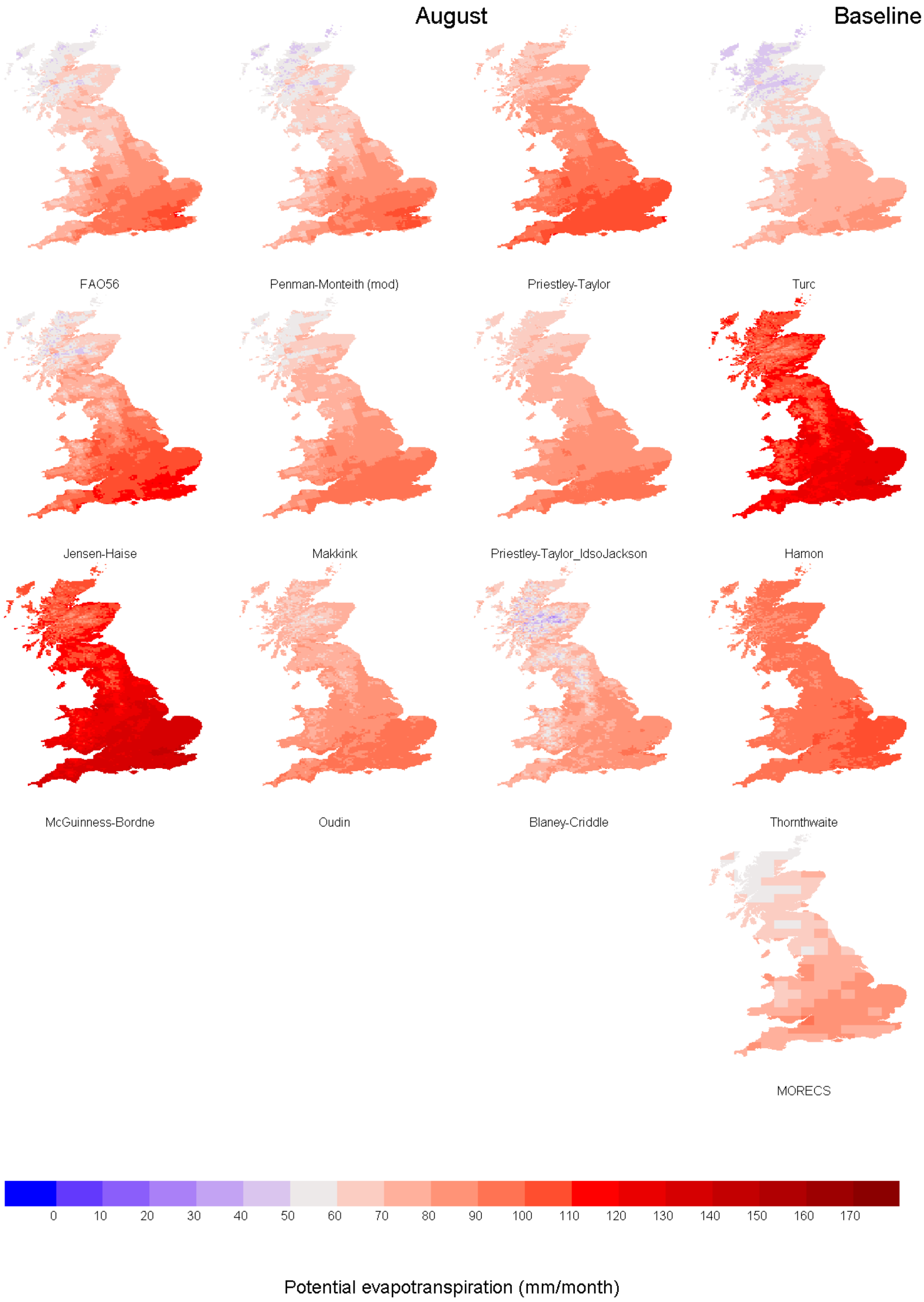

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Potential evapotranspiration (mm/month)

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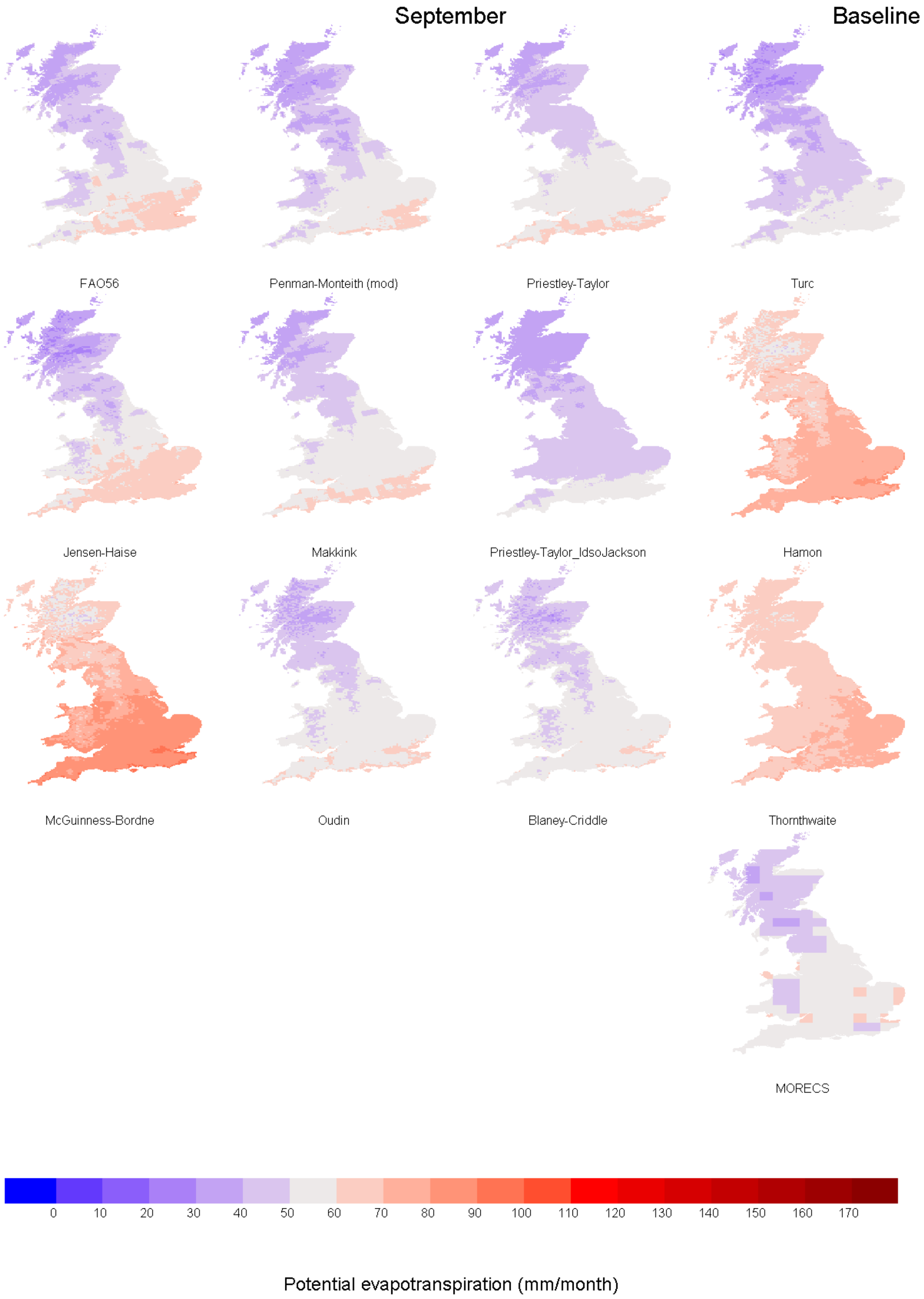
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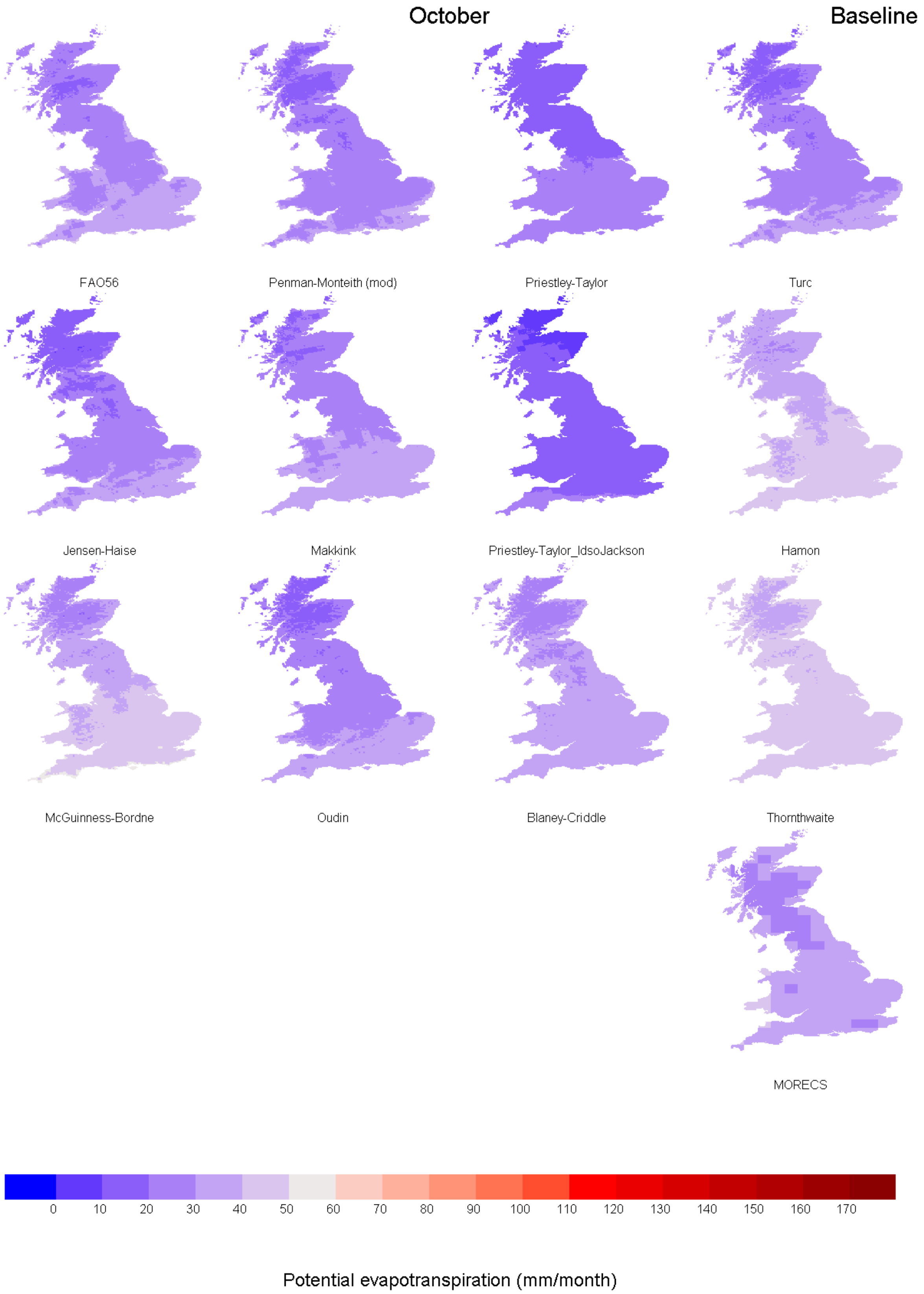
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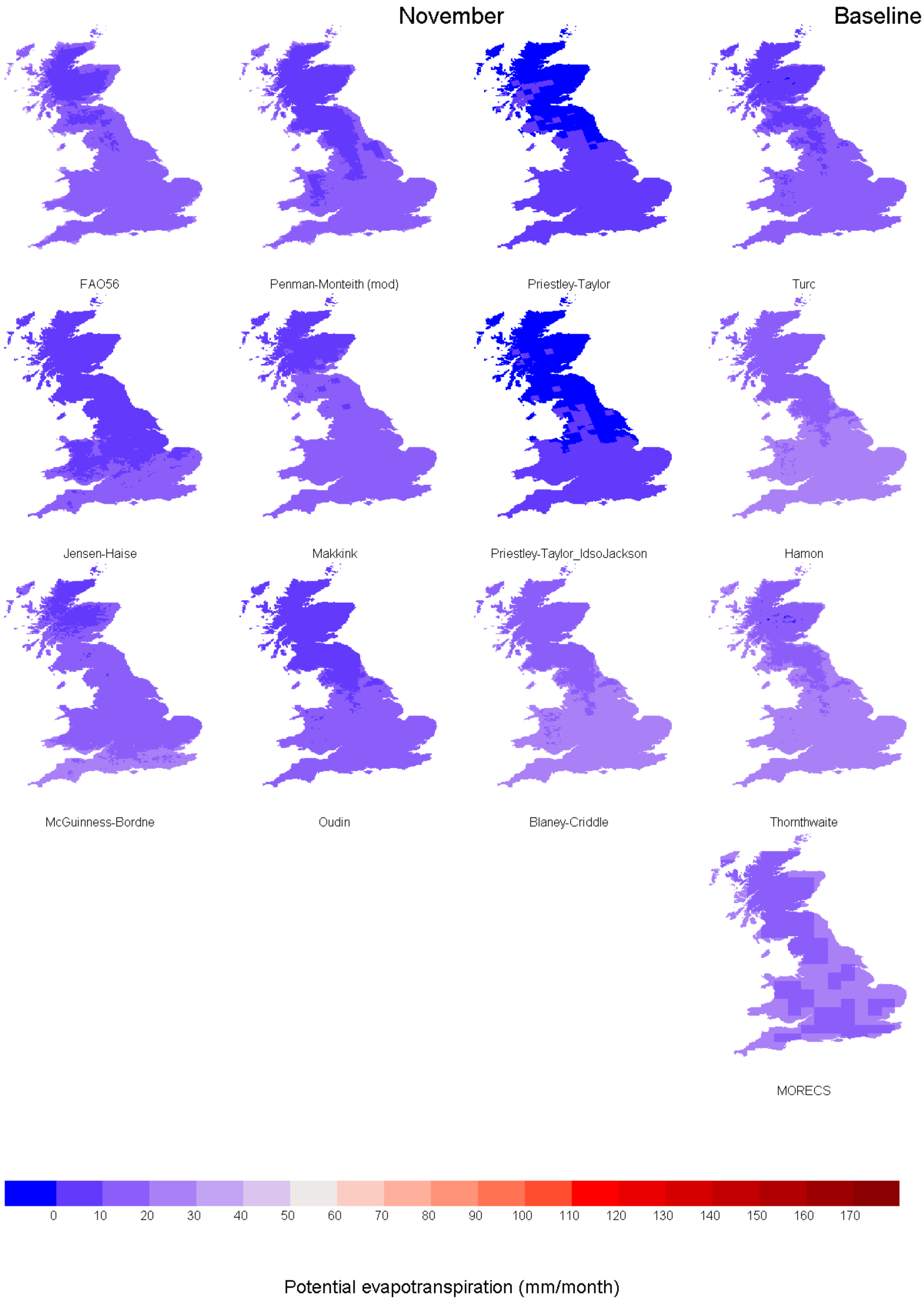
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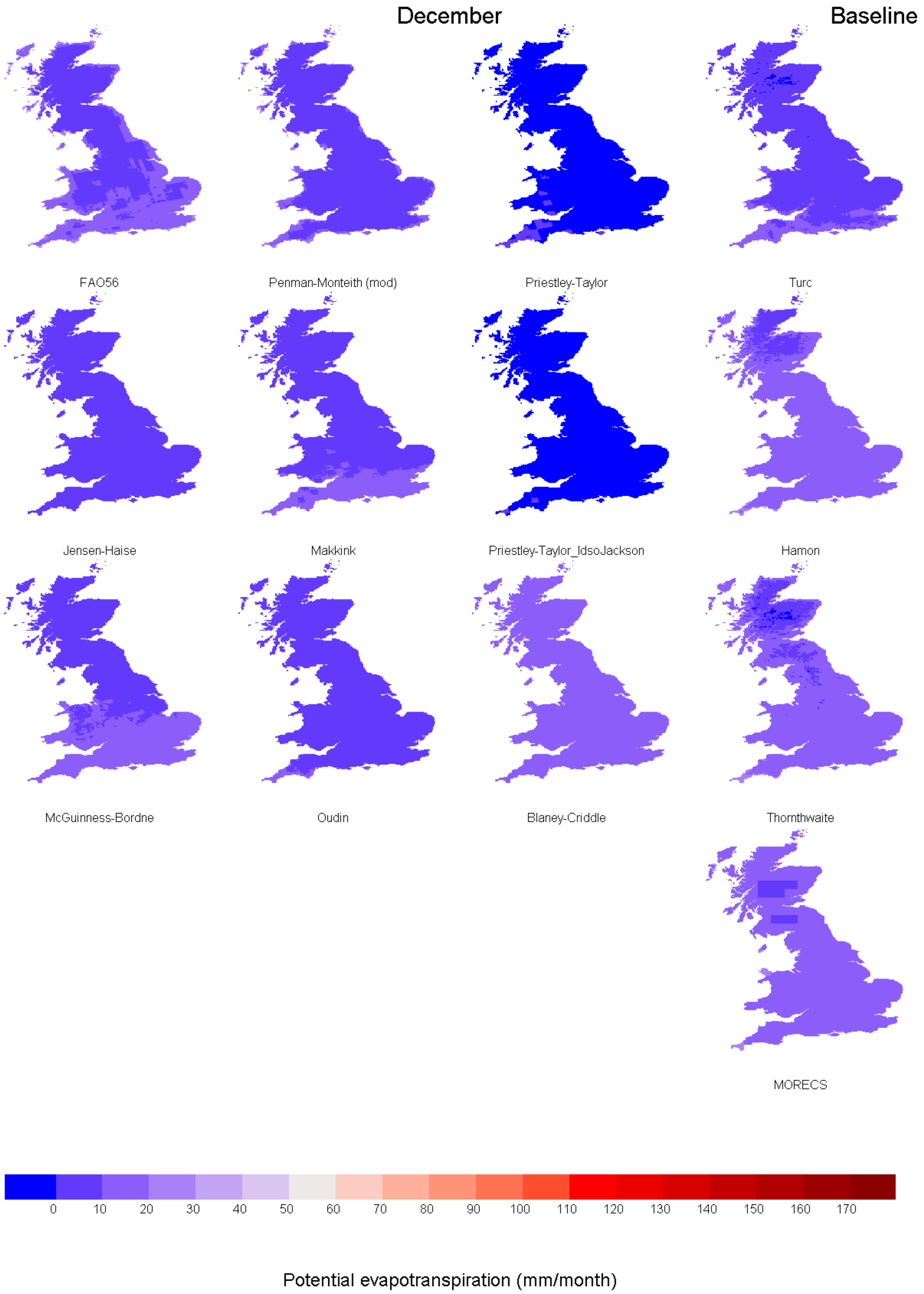
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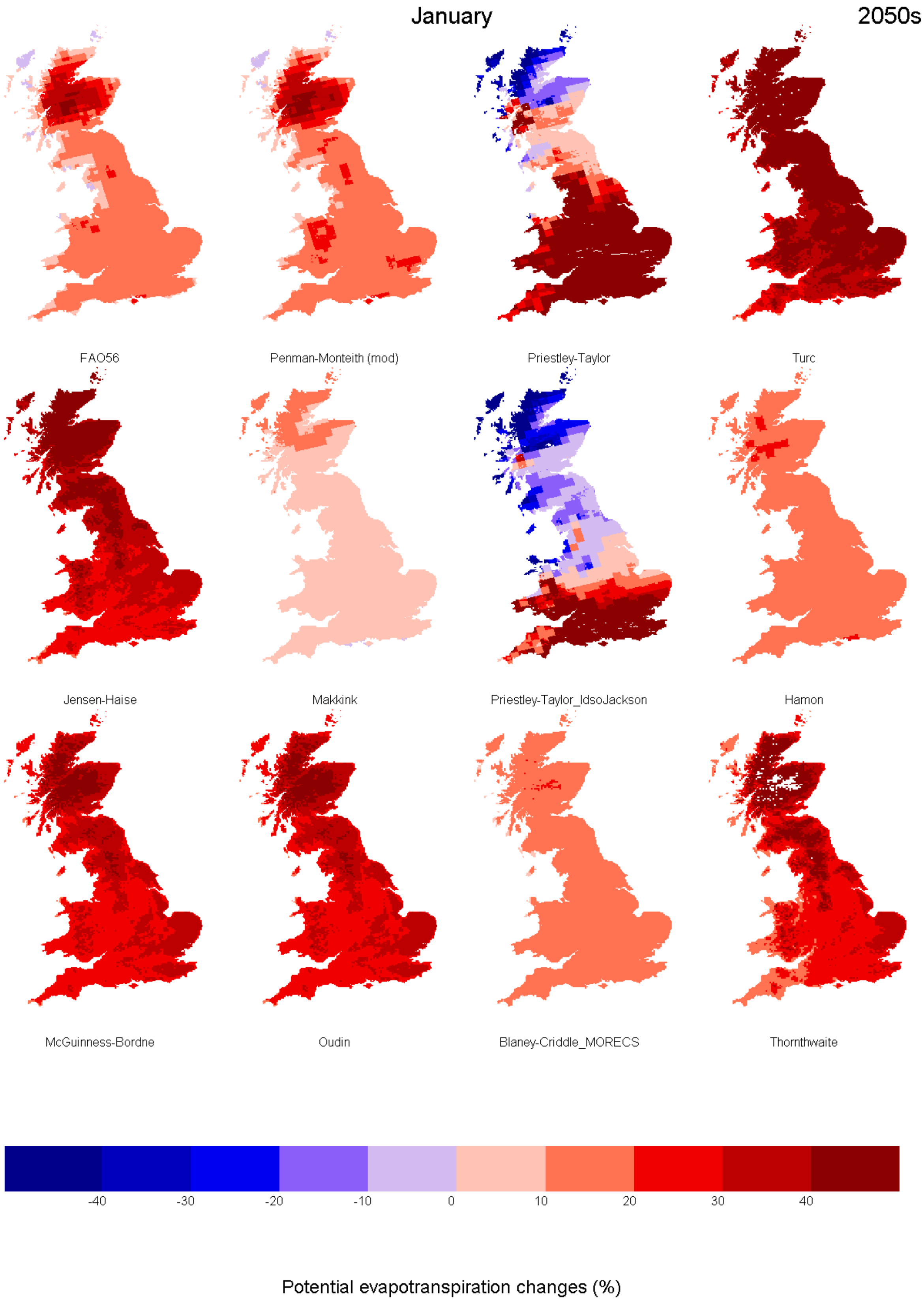
Potential evapotranspiration (mm/month)

PET percentage change between averages values calculated for the 1961-1990 and 2040-2069 time slices from HadRM3-Q0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Potential evapotranspiration changes (%)

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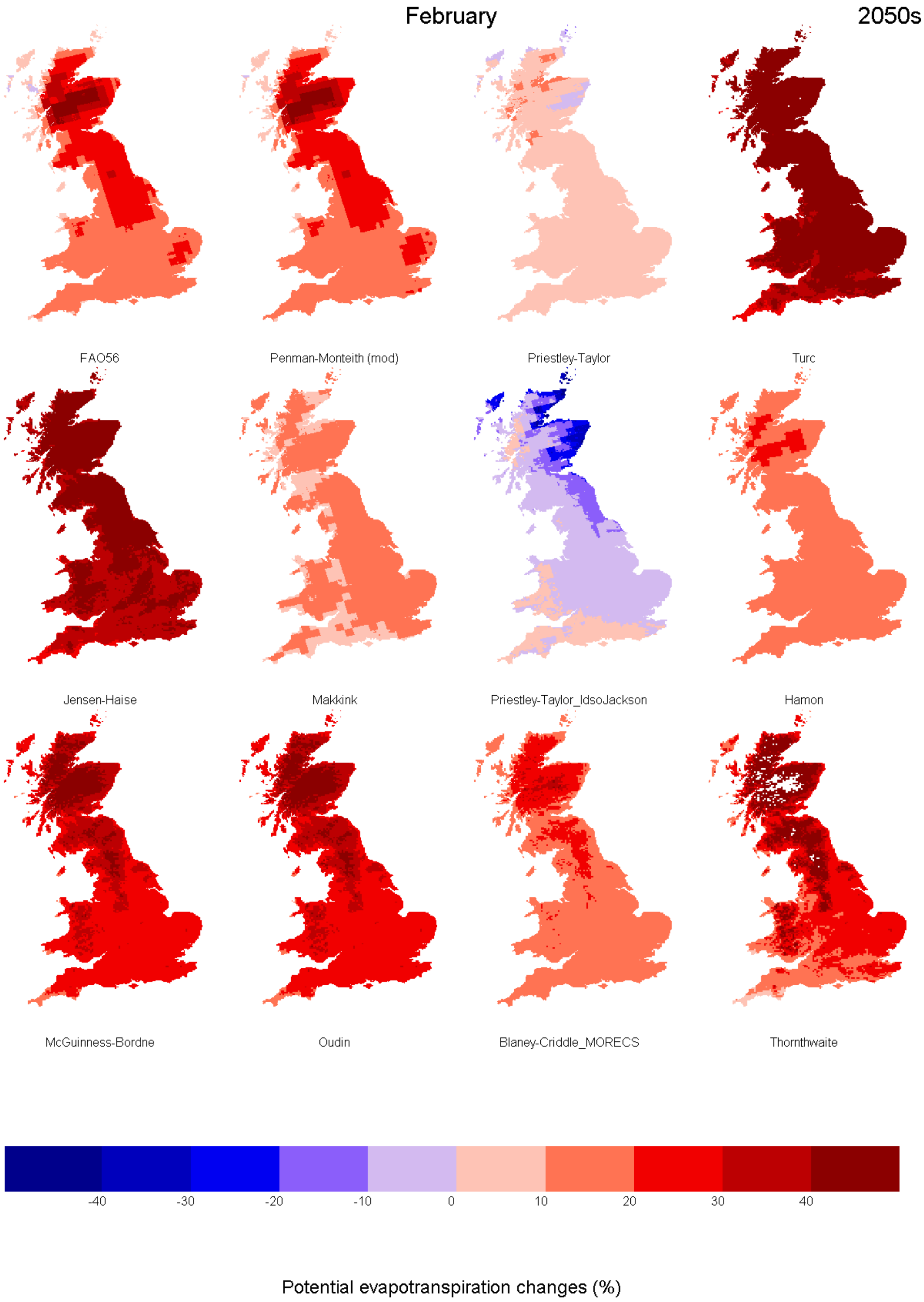
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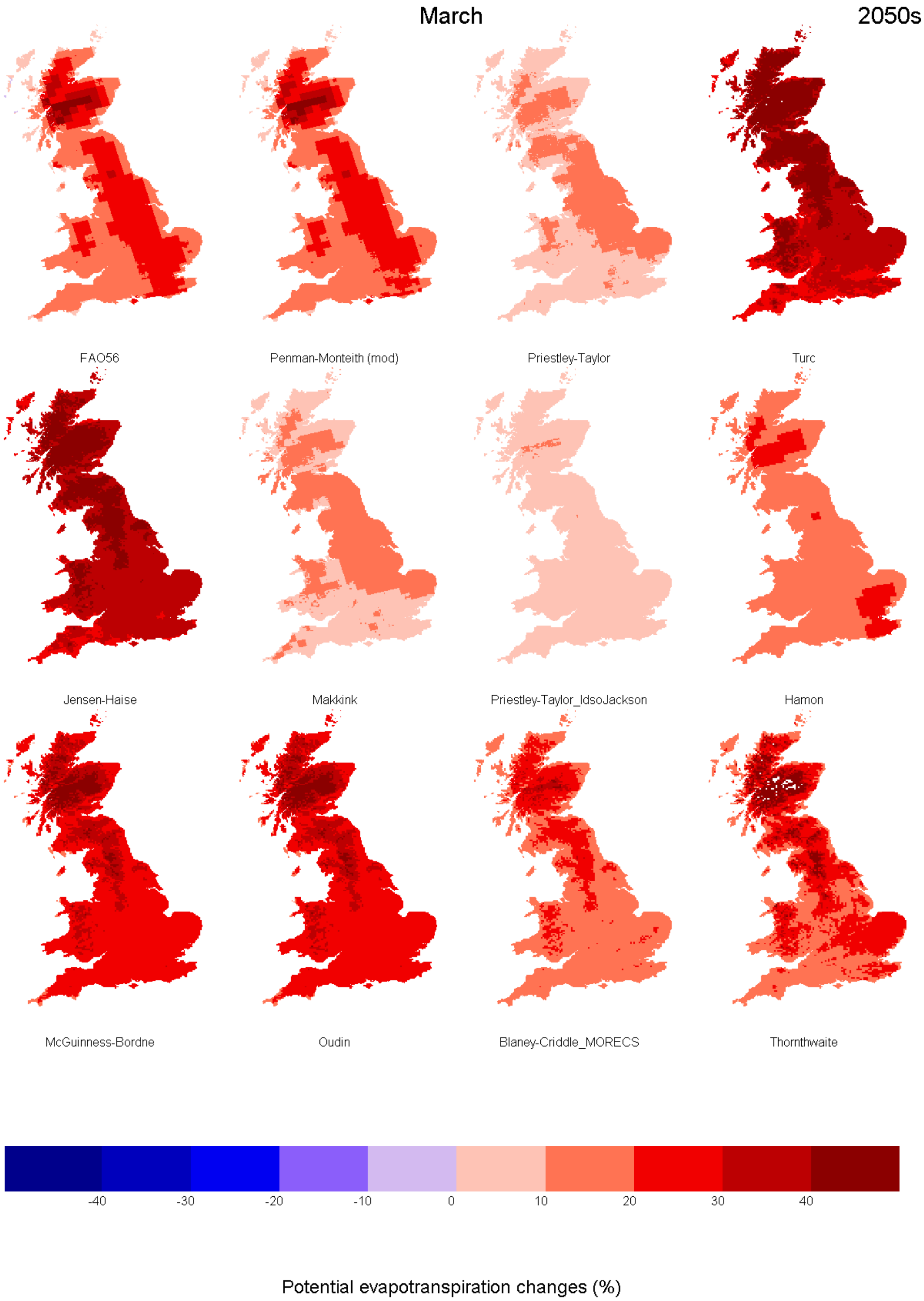
Potential evapotranspiration changes (%)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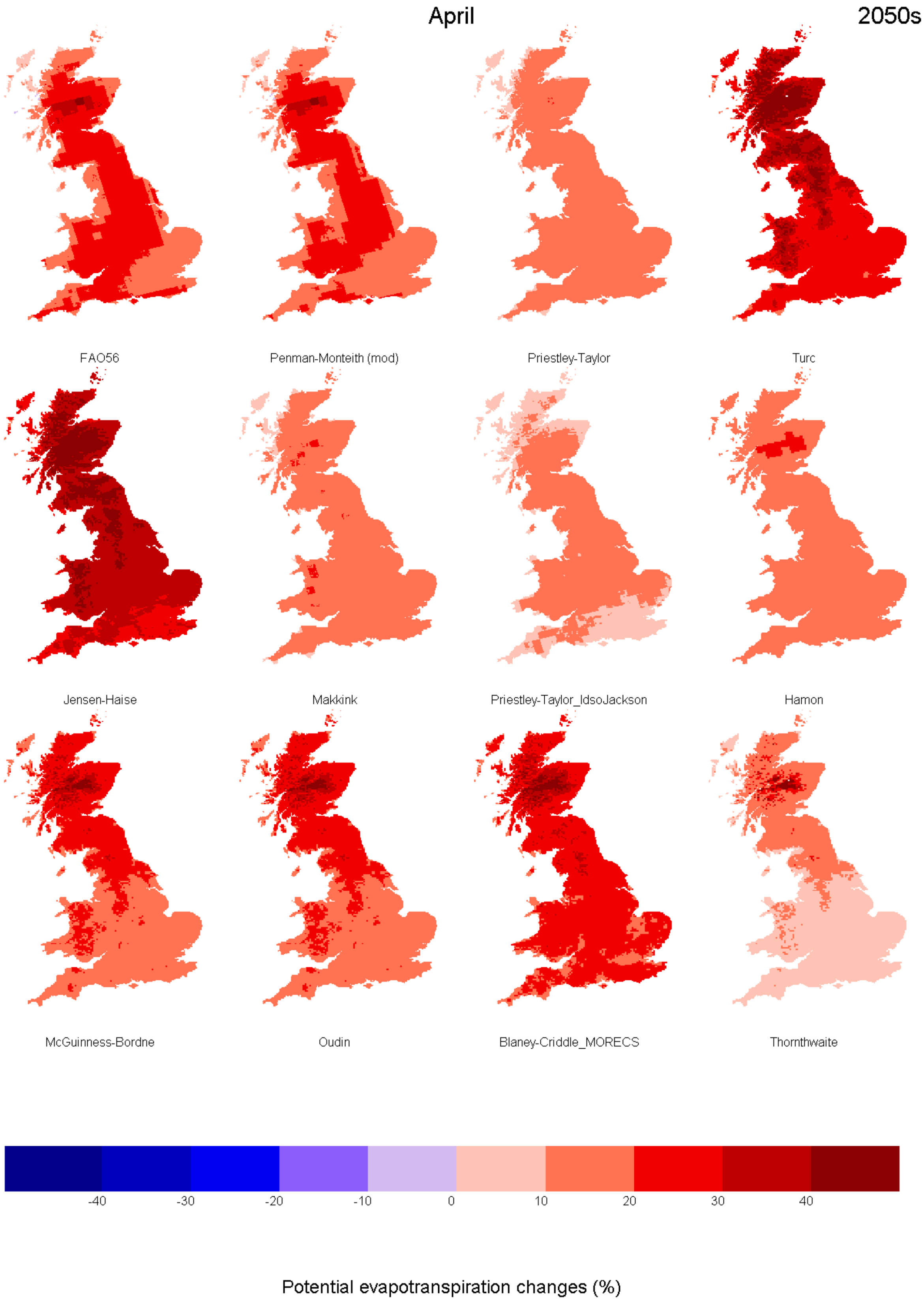
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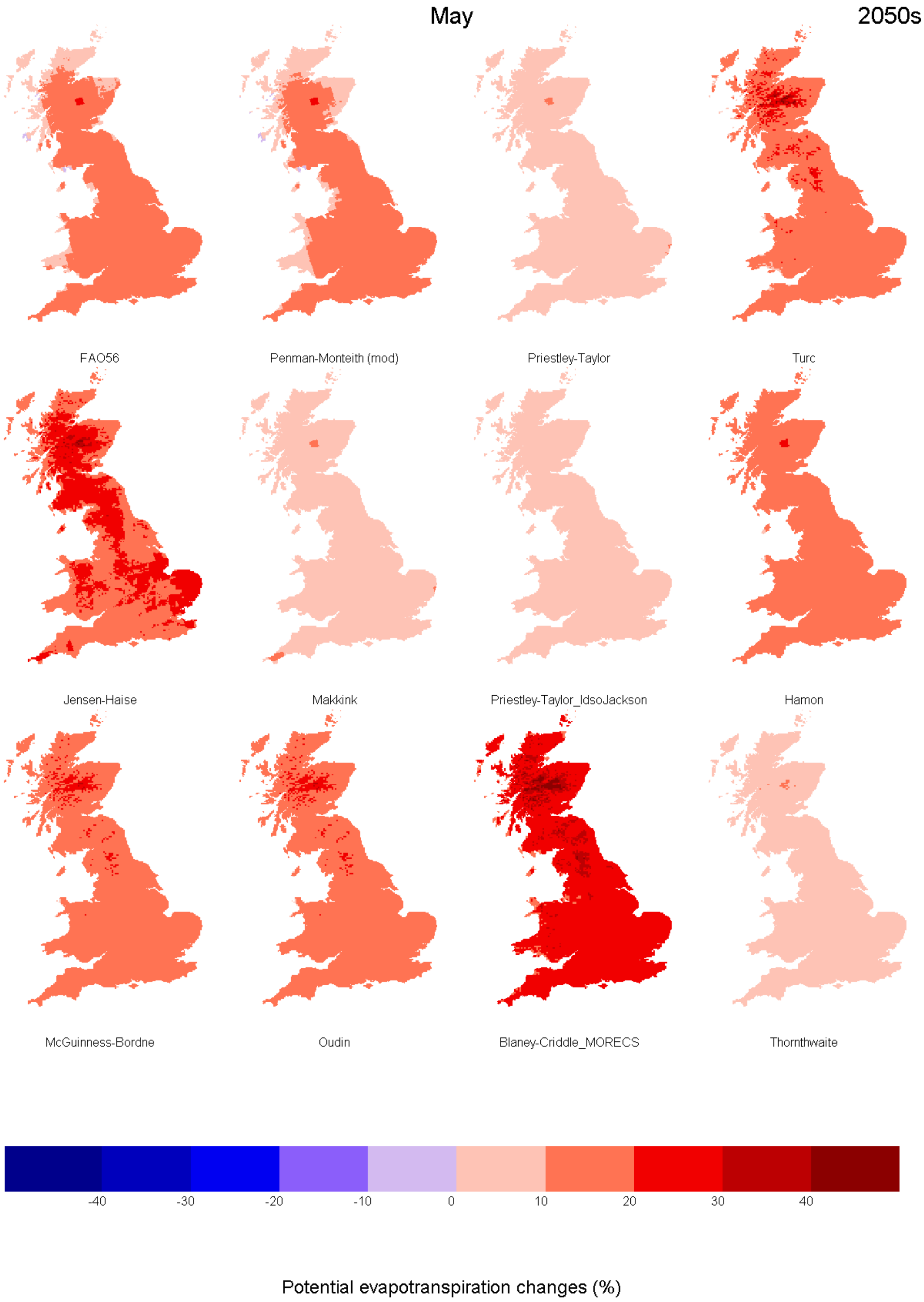
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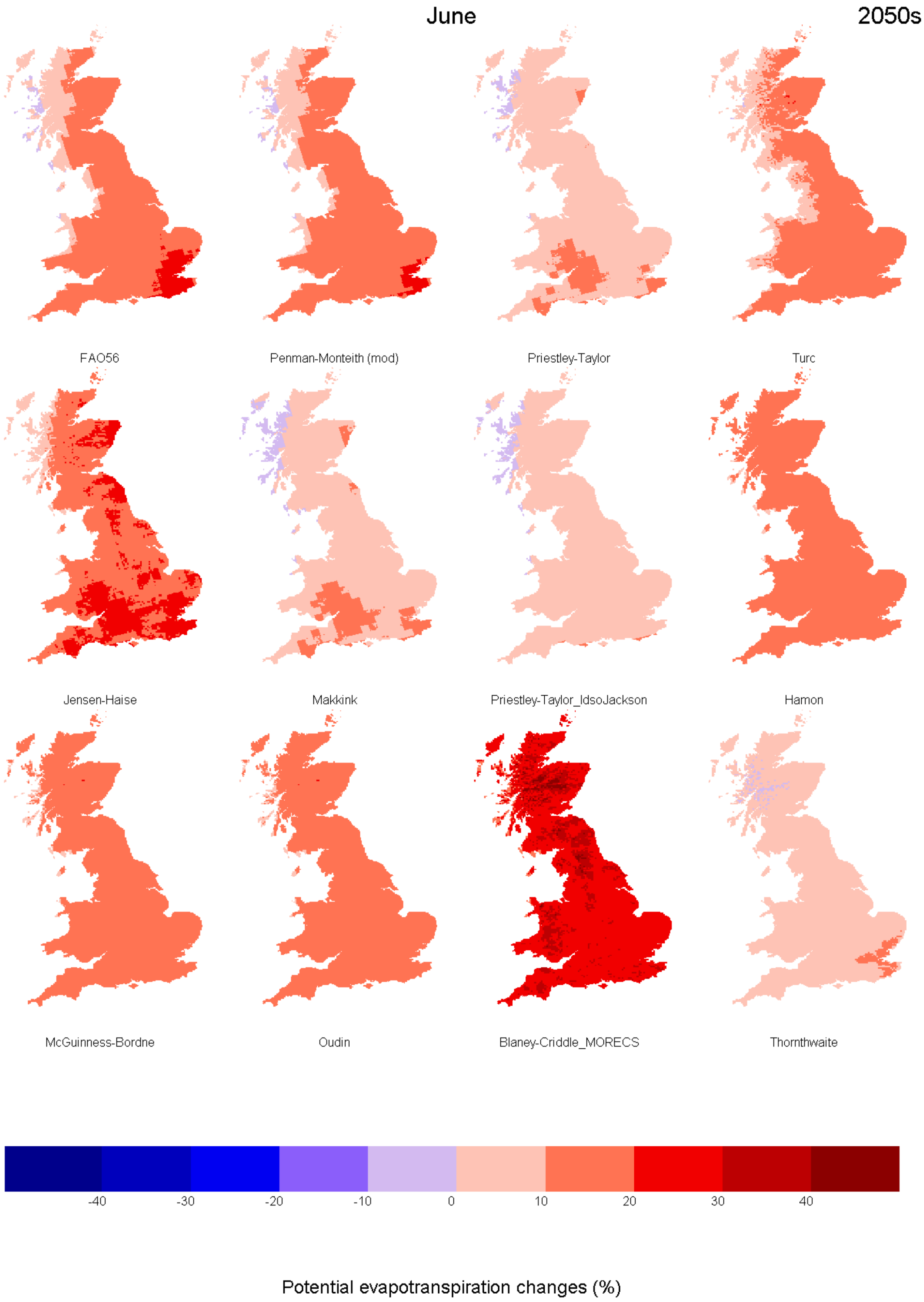
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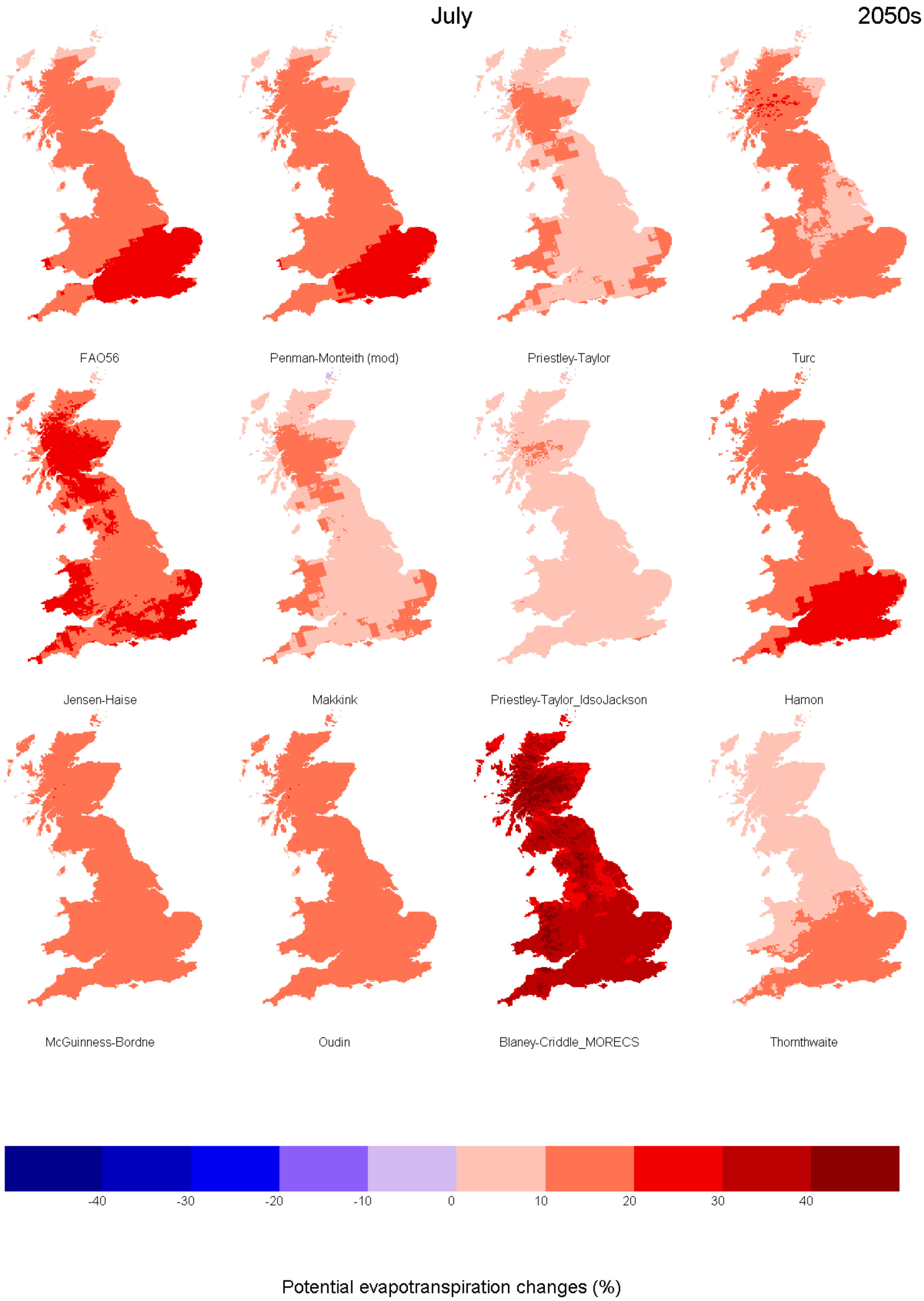
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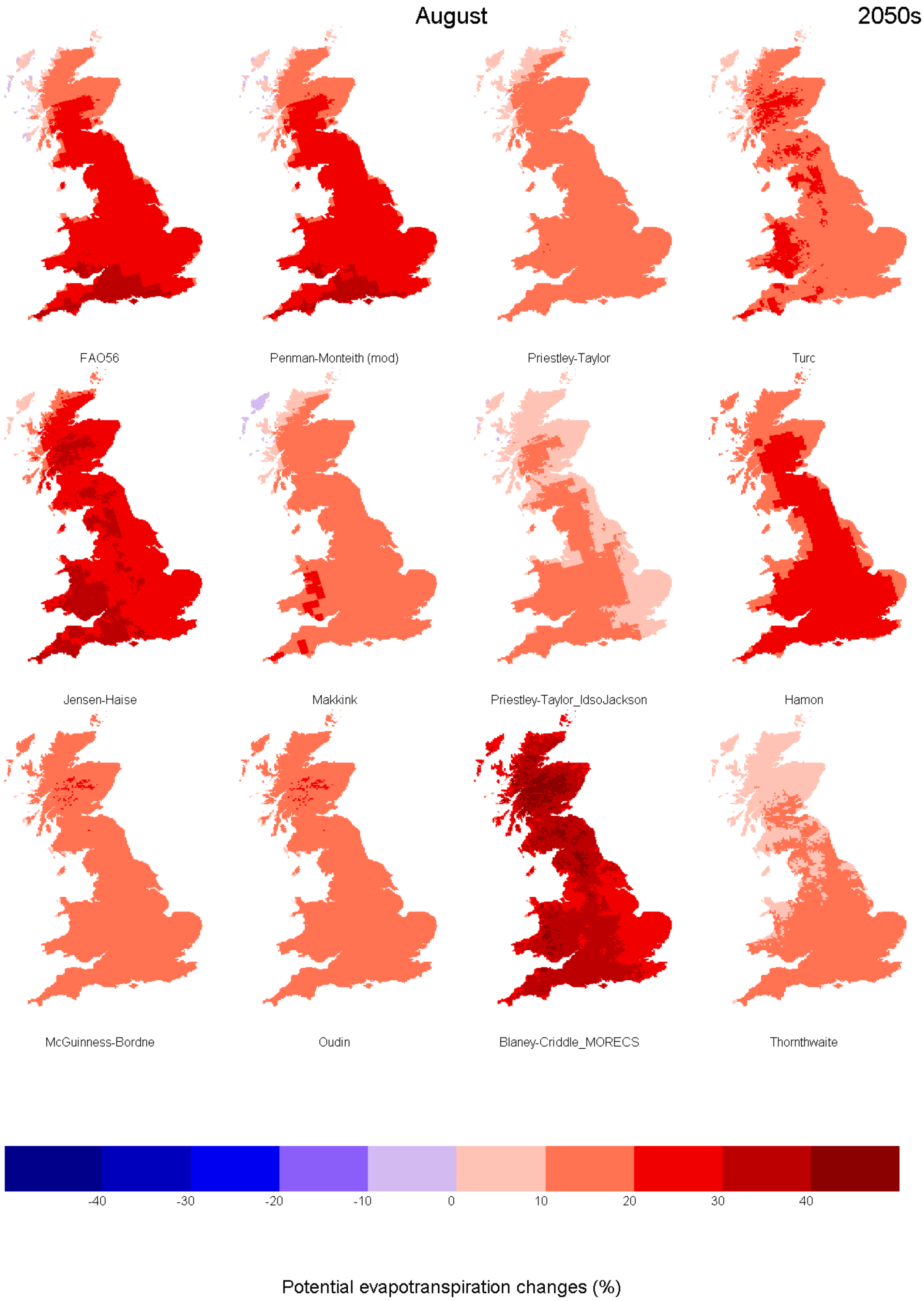
Potential evapotranspiration changes (%)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Potential evapotranspiration changes (%)

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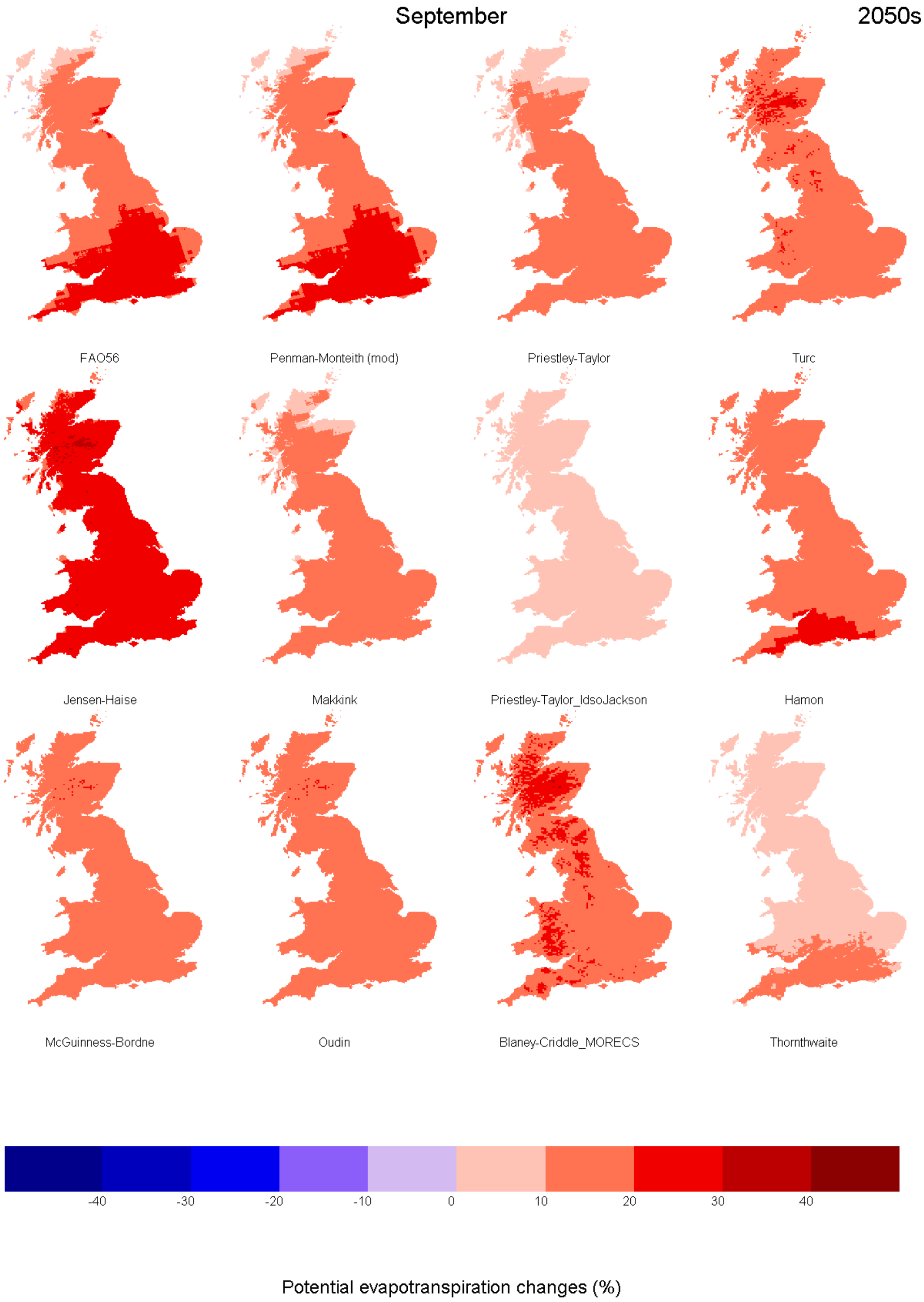

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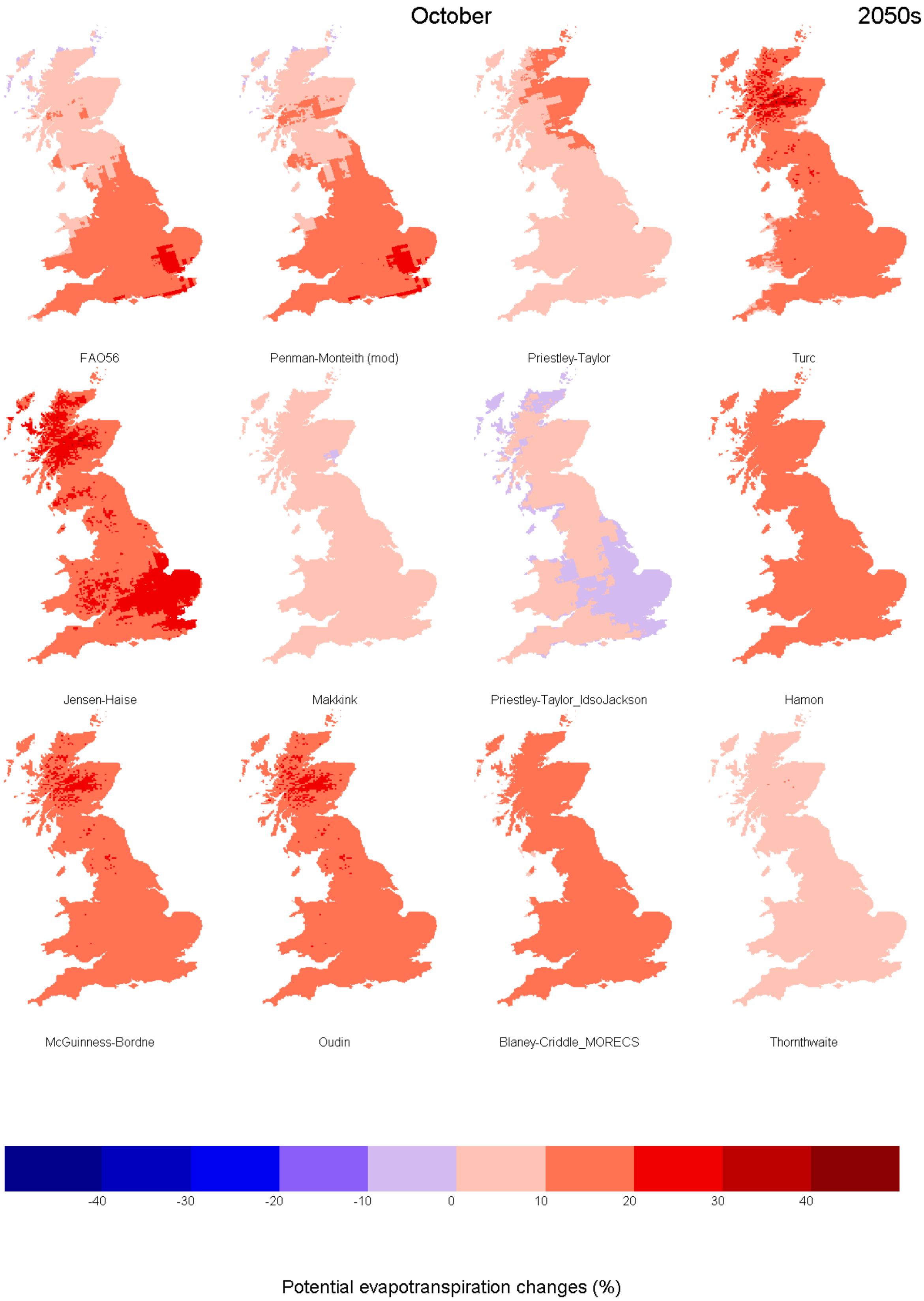
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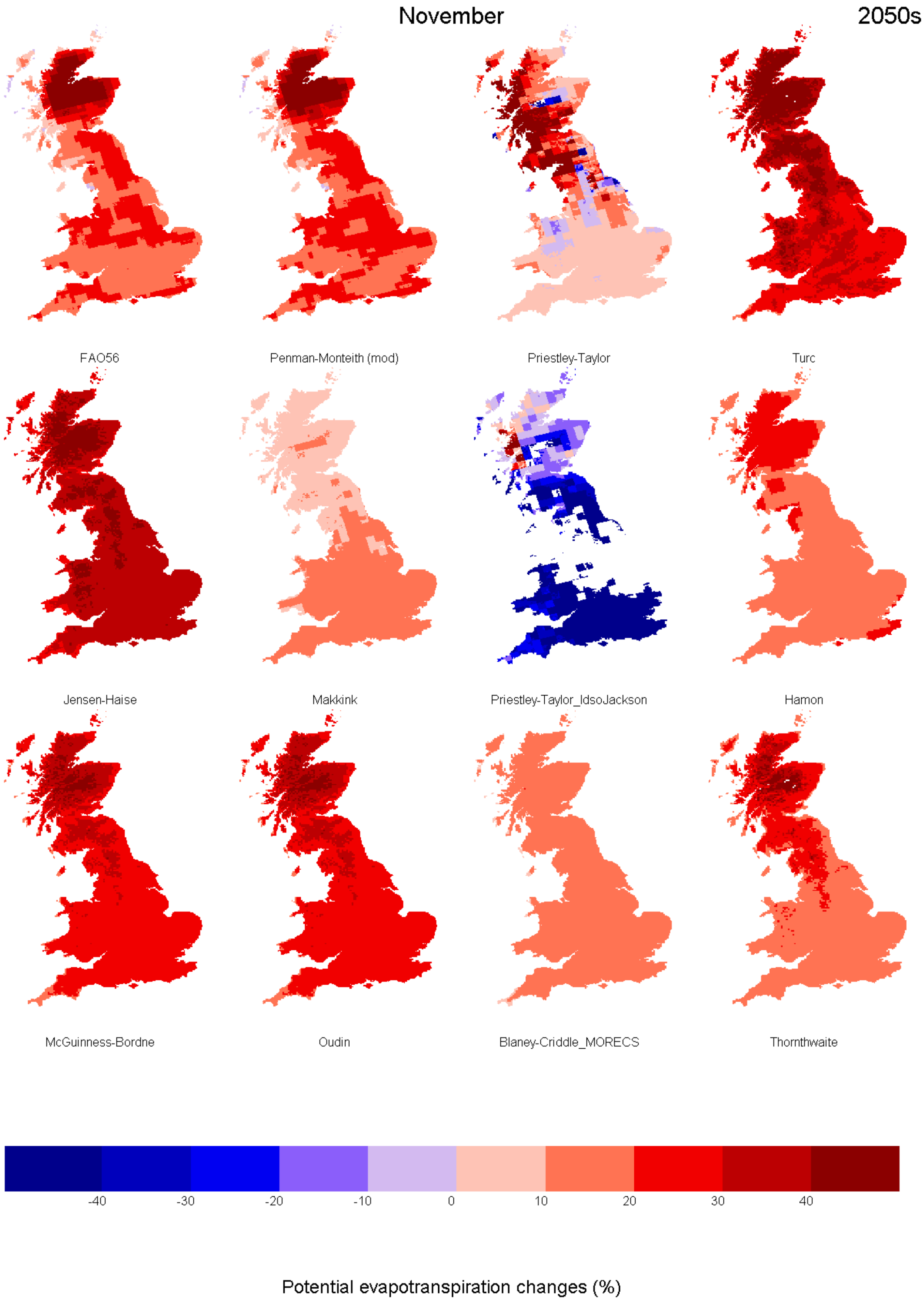
Jensen-Haise
Makkink
Priestley-Taylor_IdsoJackson
Hamon
McGuinness-Bordne
Oudin
Blaney-Criddle_MORECS
Thornthwaite
-40
-30
-20
-10
0
10
20
30
40
Potential evapotranspiration changes (%)

1


November
2050s
FAO56
Penman-Monteith (mod)
Priestley-Taylor
Turc
Jensen-Haise
Makkink
Priestley-Taylor_IdsoJackson
Hamon
McGuinness-Bordne
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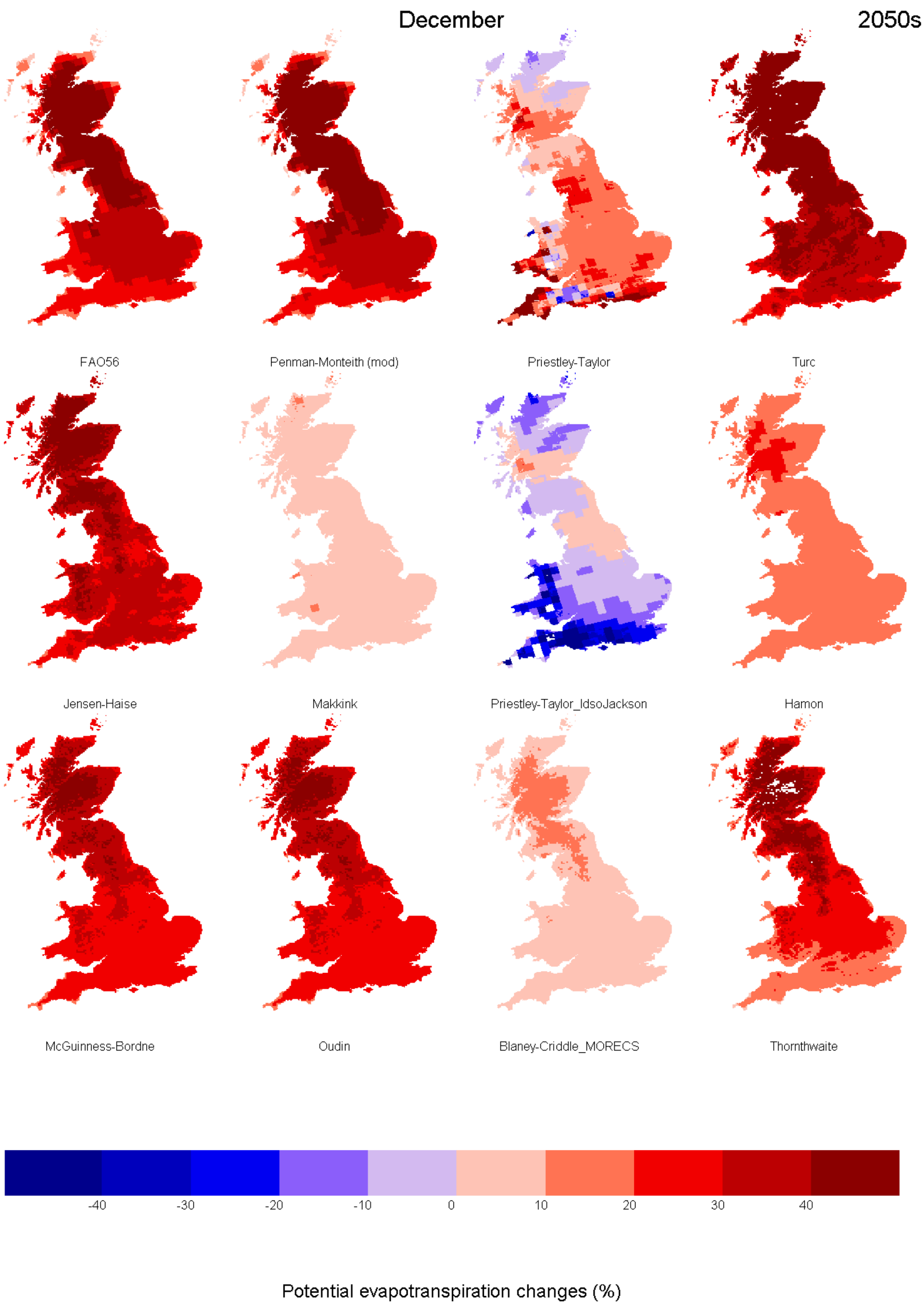
Blaney-Criddle_MORECS
Thornthwaite
-40
-30
-20
-10
0
10
20
30
40
Potential evapotranspiration changes (%)


December
2050s
FAO56
Penman-Monteith (mod)
Priestley-Taylor
Turc
Jensen-Haise
Makkink
Priestley-Taylor_IdsoJackson
Hamon
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Potential evapotranspiration changes (%)