Comparison of land-surface humidity between observations and CMIP5 models

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Supplementary Information
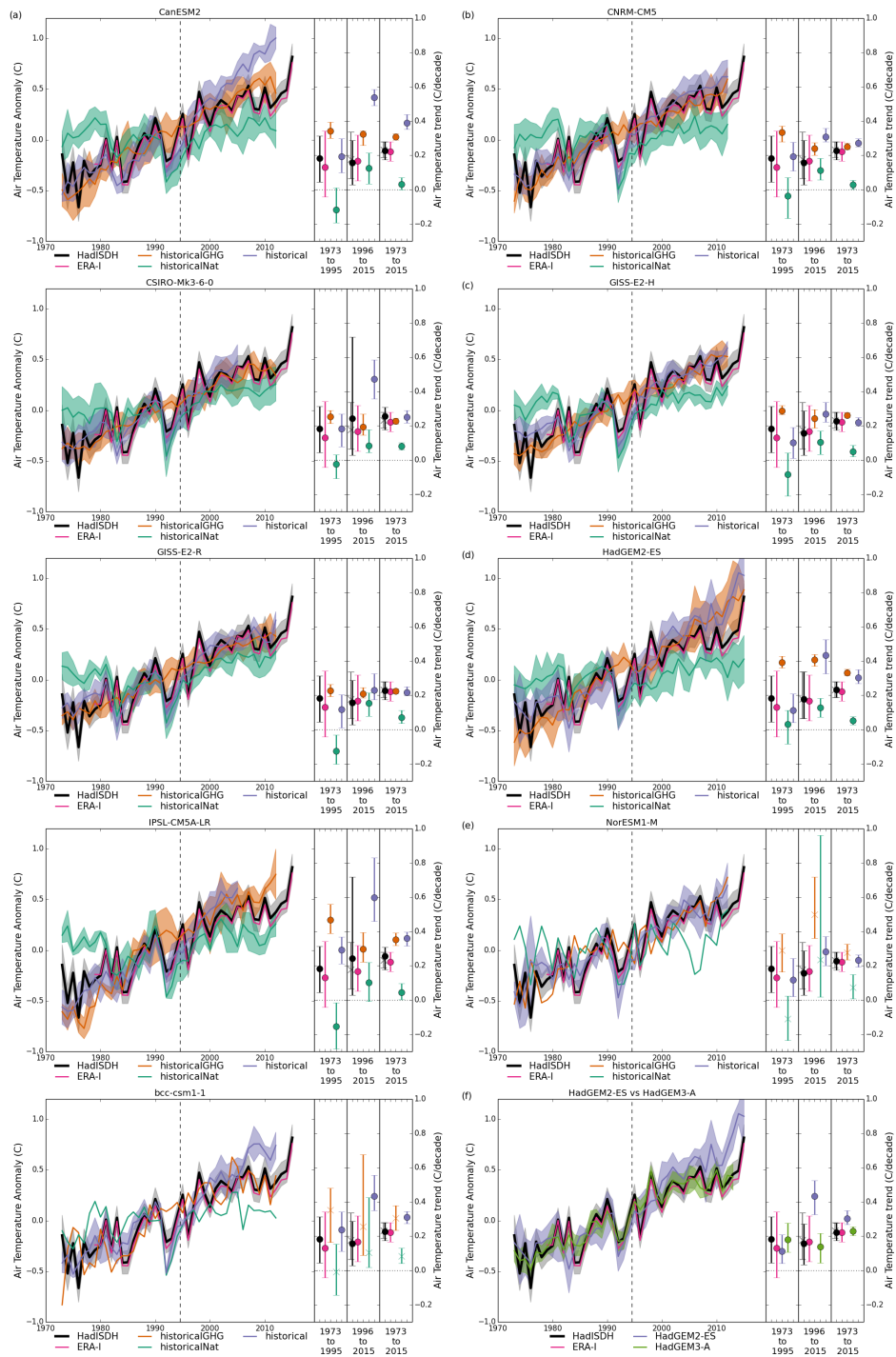
Temperature

Figure 1. Global annual timeseries for temperature for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
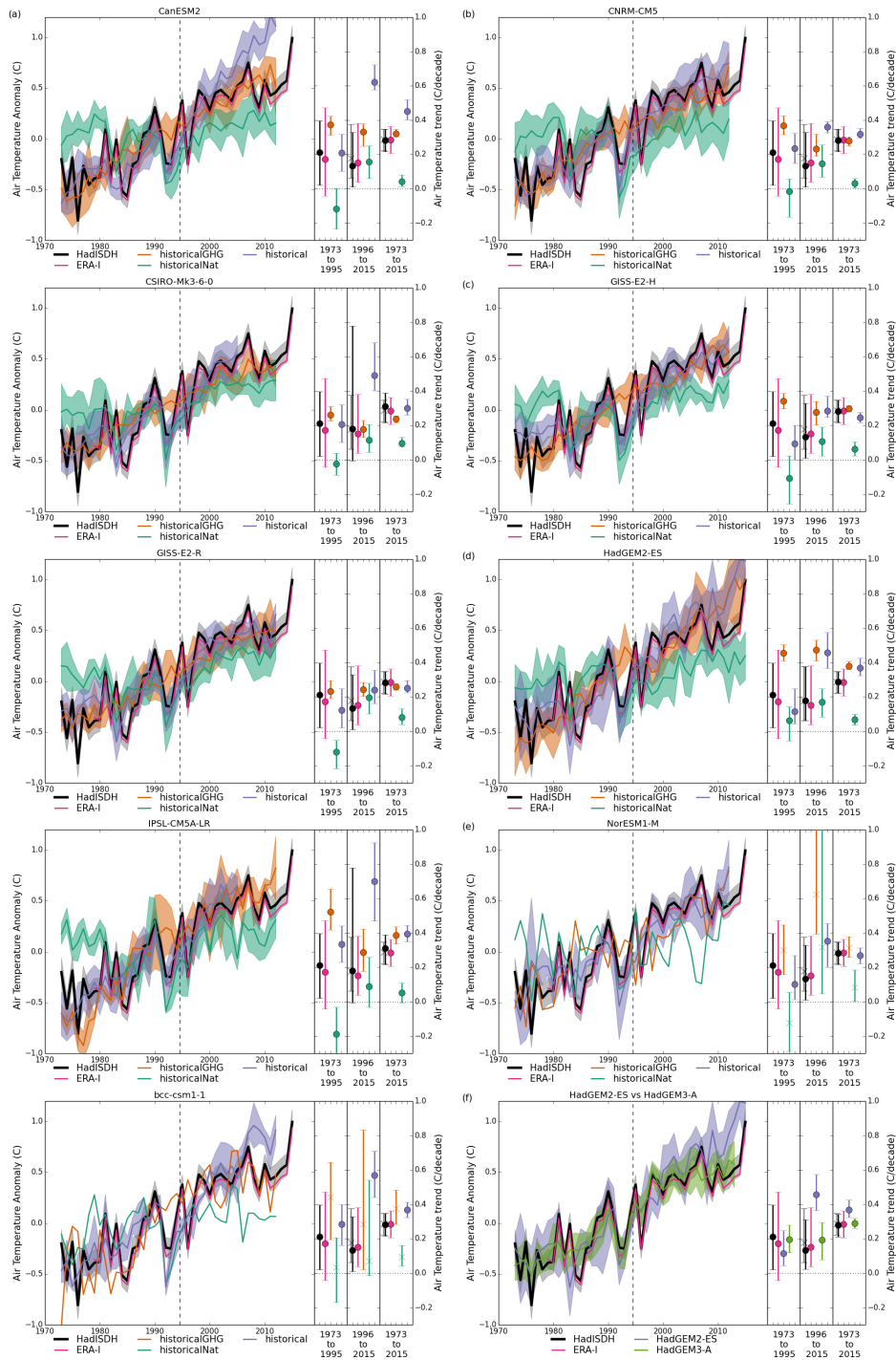
Figure 2. Northern Hemisphere annual timeseries for temperature for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
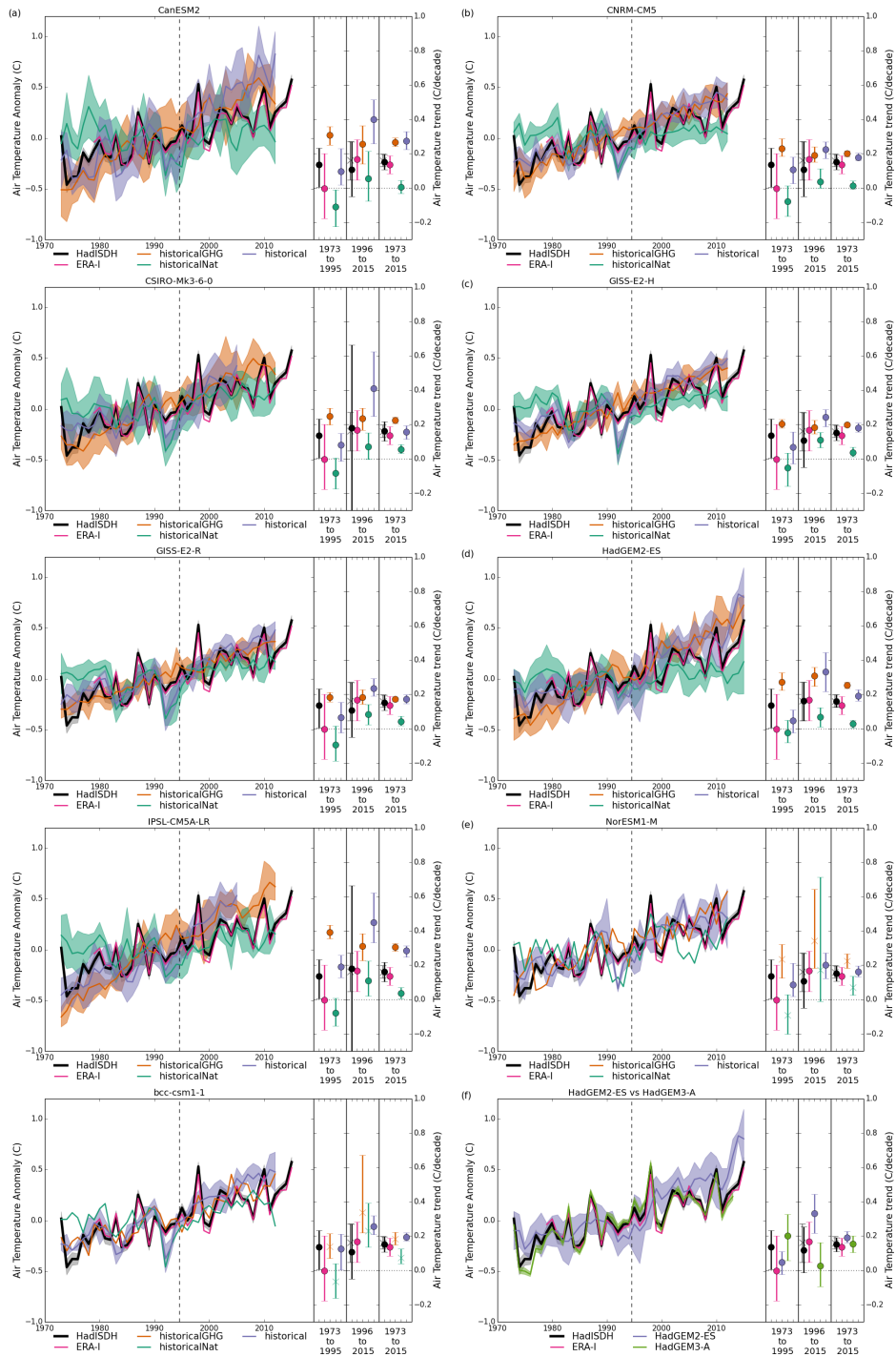
Figure 3. Tropical annual timeseries for temperature for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
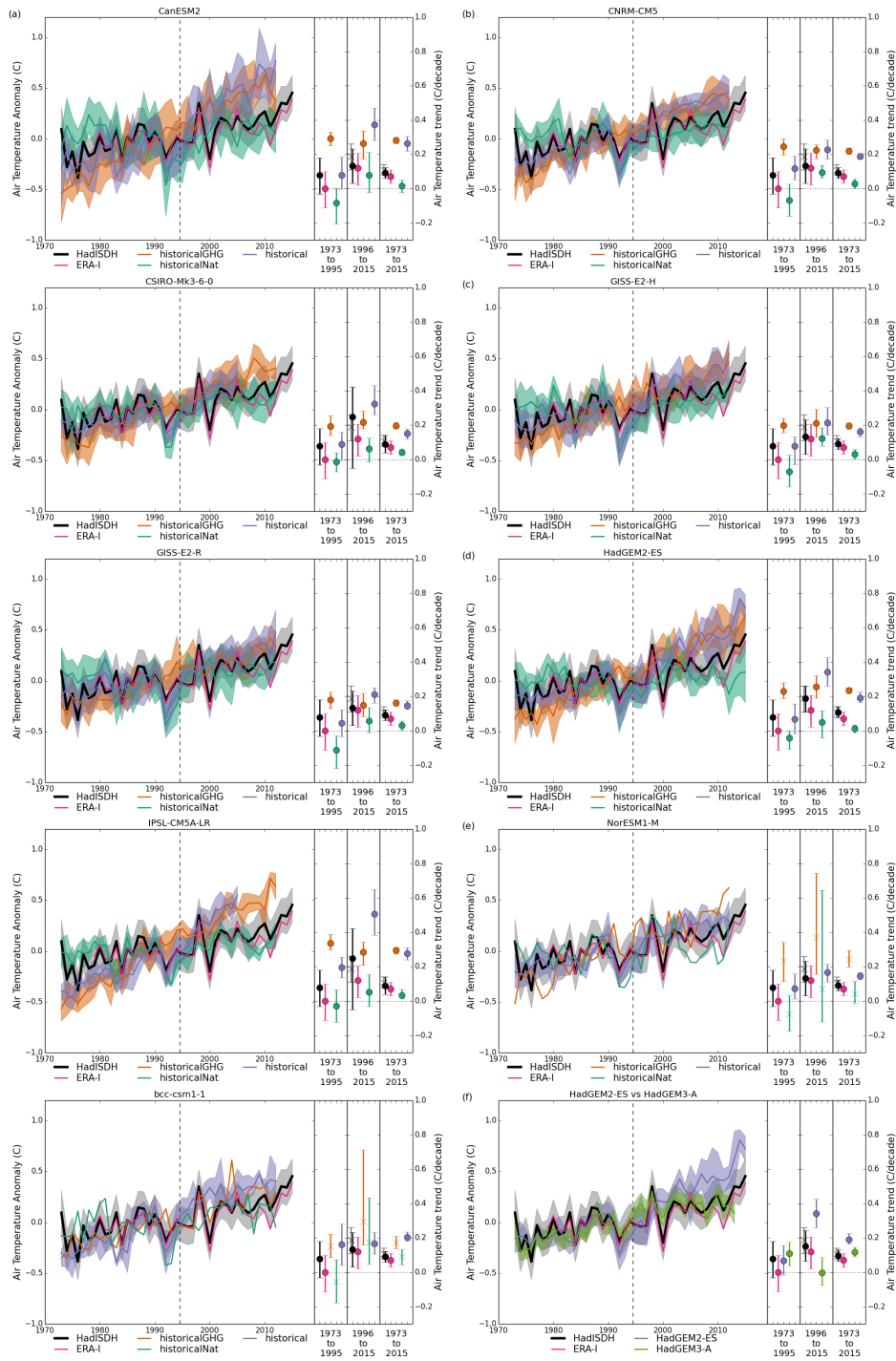
Figure 4. Southern Hemisphere annual timeseries for temperature for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
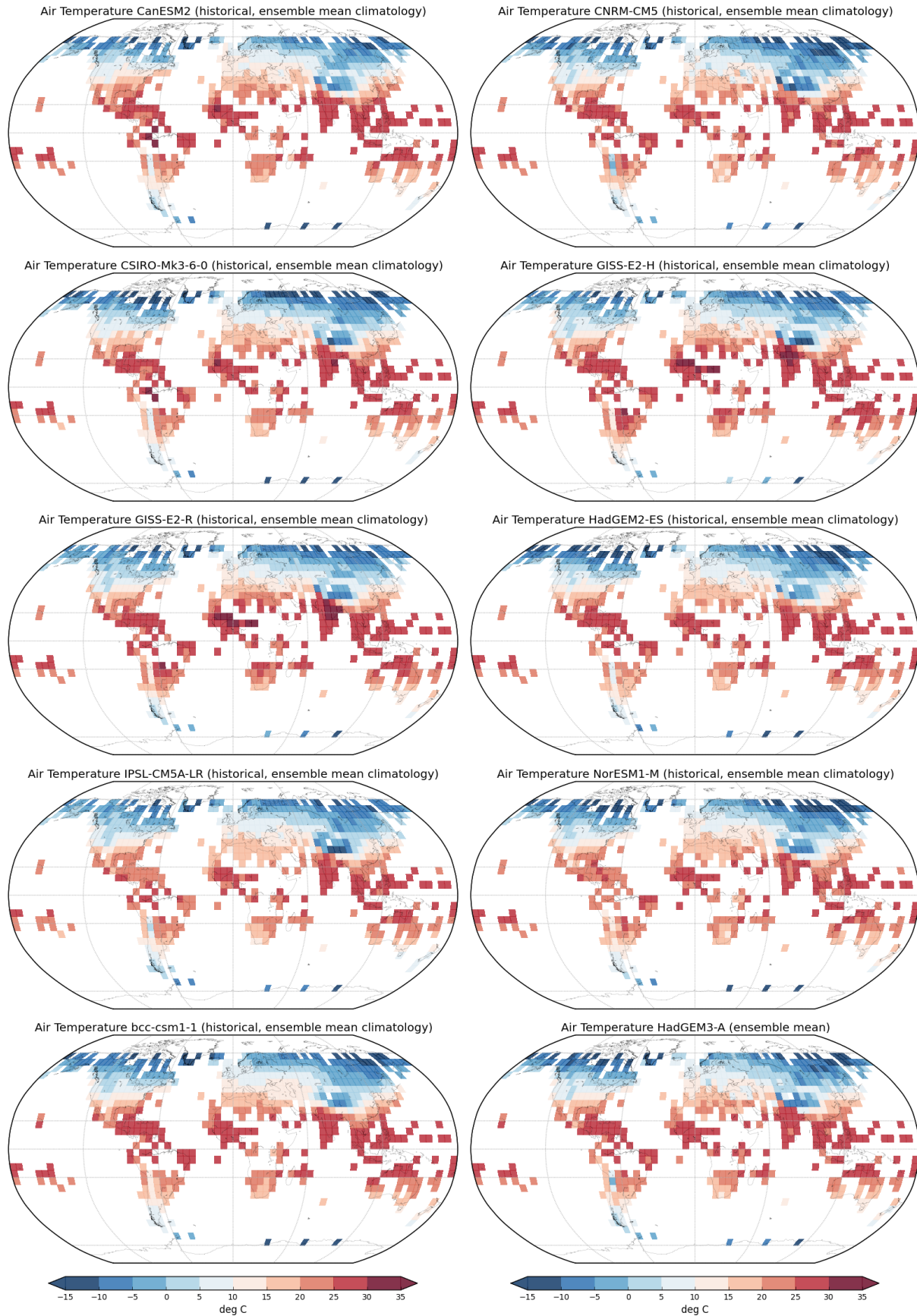
Figure 5. Temperature climatologies of the CMIP5 models at the gridbox scale. All climatologies have been calculated over the 1981 to 2010 period using identical spatio-temporal coverage to HadISDH.
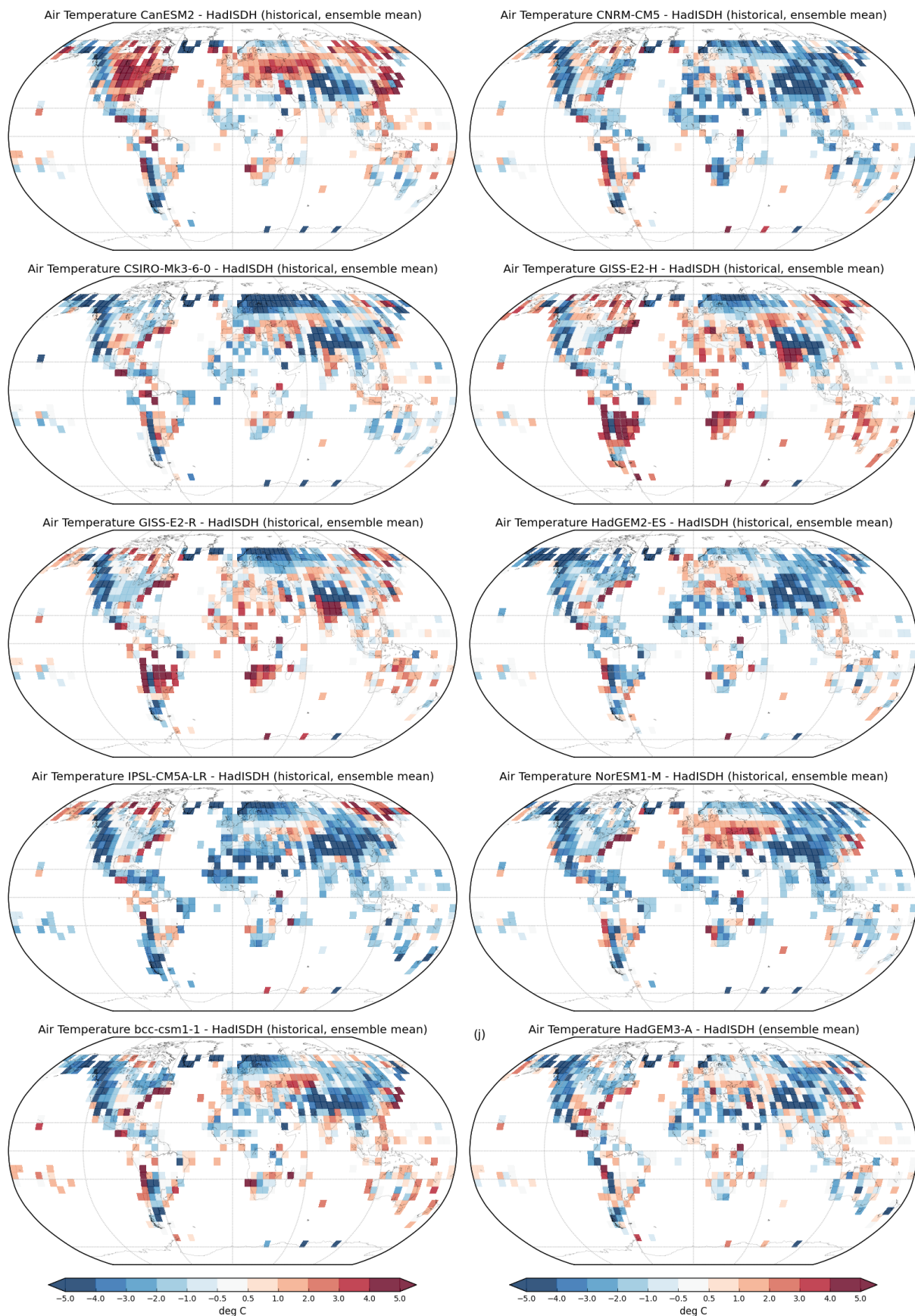
Figure 6. Climatological differences between models and observations at the gridbox scale for temperature. All climatologies have been calculated over the 1981 to 2010 period using identical spatio-temporal coverage to HadISDH.
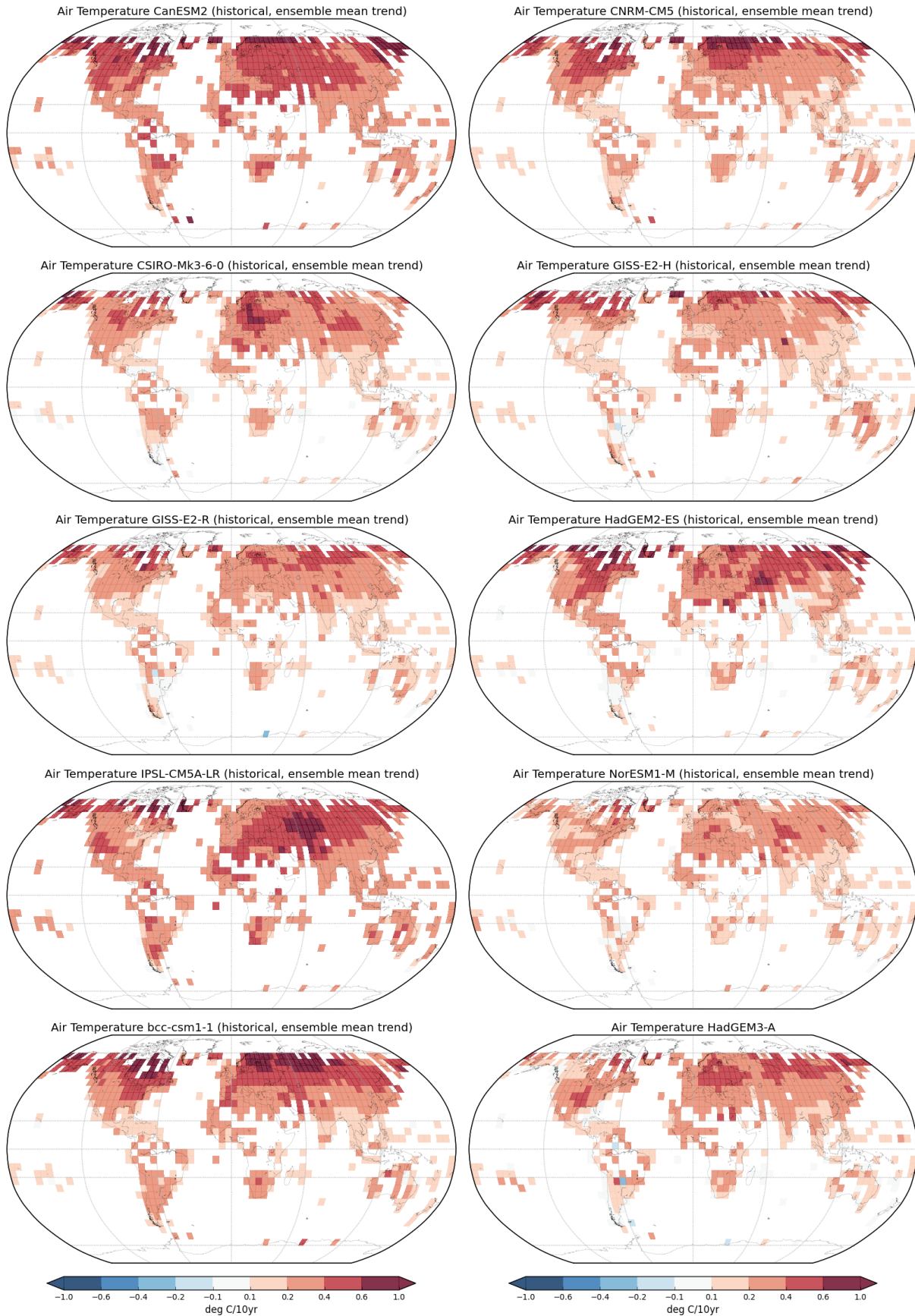
Figure 7. Linear trends of the CMIP5 models at the gridbox scale for temperature. All trends have been calculated using the median of pairwise slopes method, with identical spatio-temporal coverage to HadISDH.

Figure 8. Linear trend differences of the CMIP5 models from the observations at the gridbox scale for temperature. All trends have been calculated using the median of pairwise slopes method, with identical spatio-temporal coverage to HadISDH.
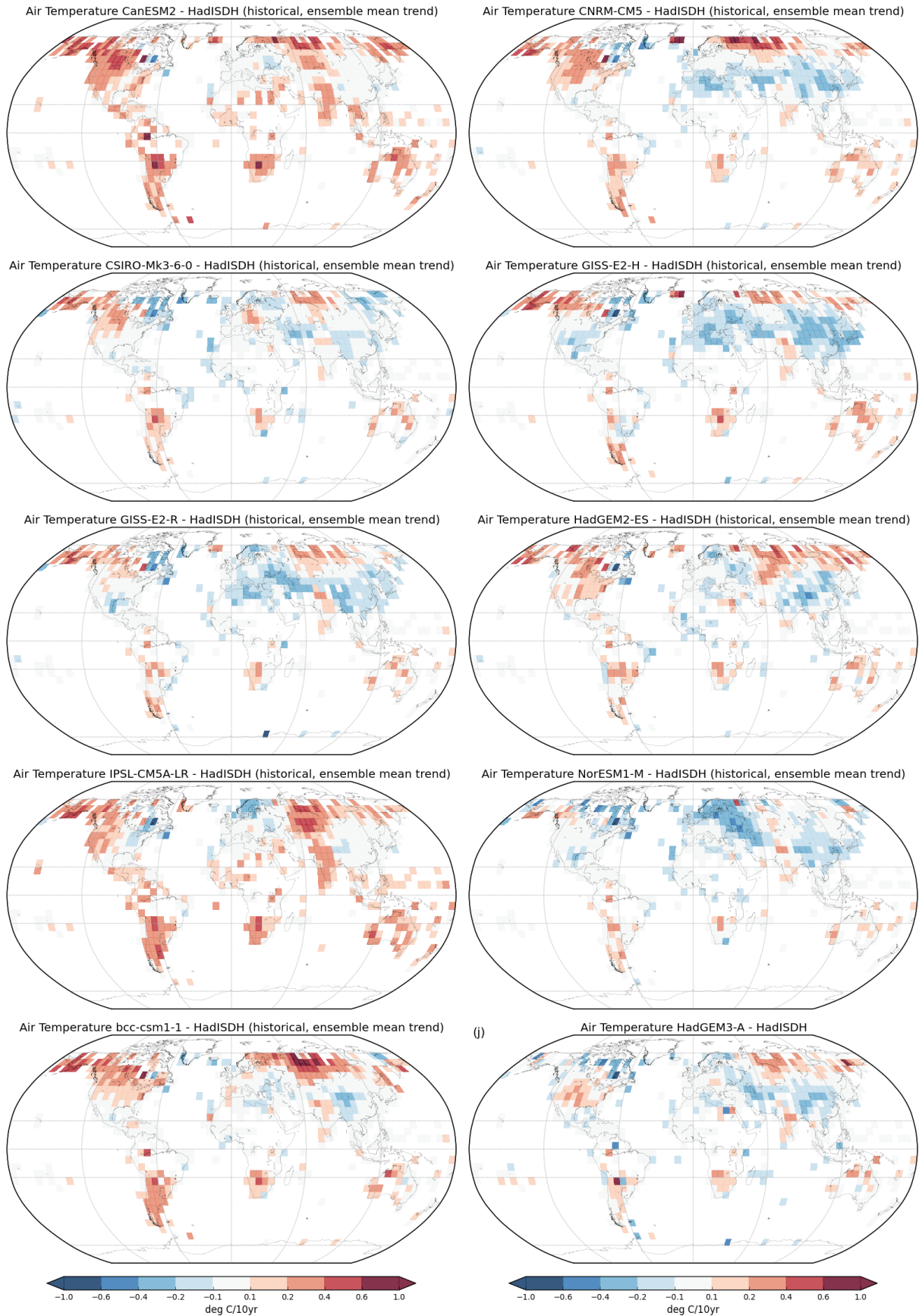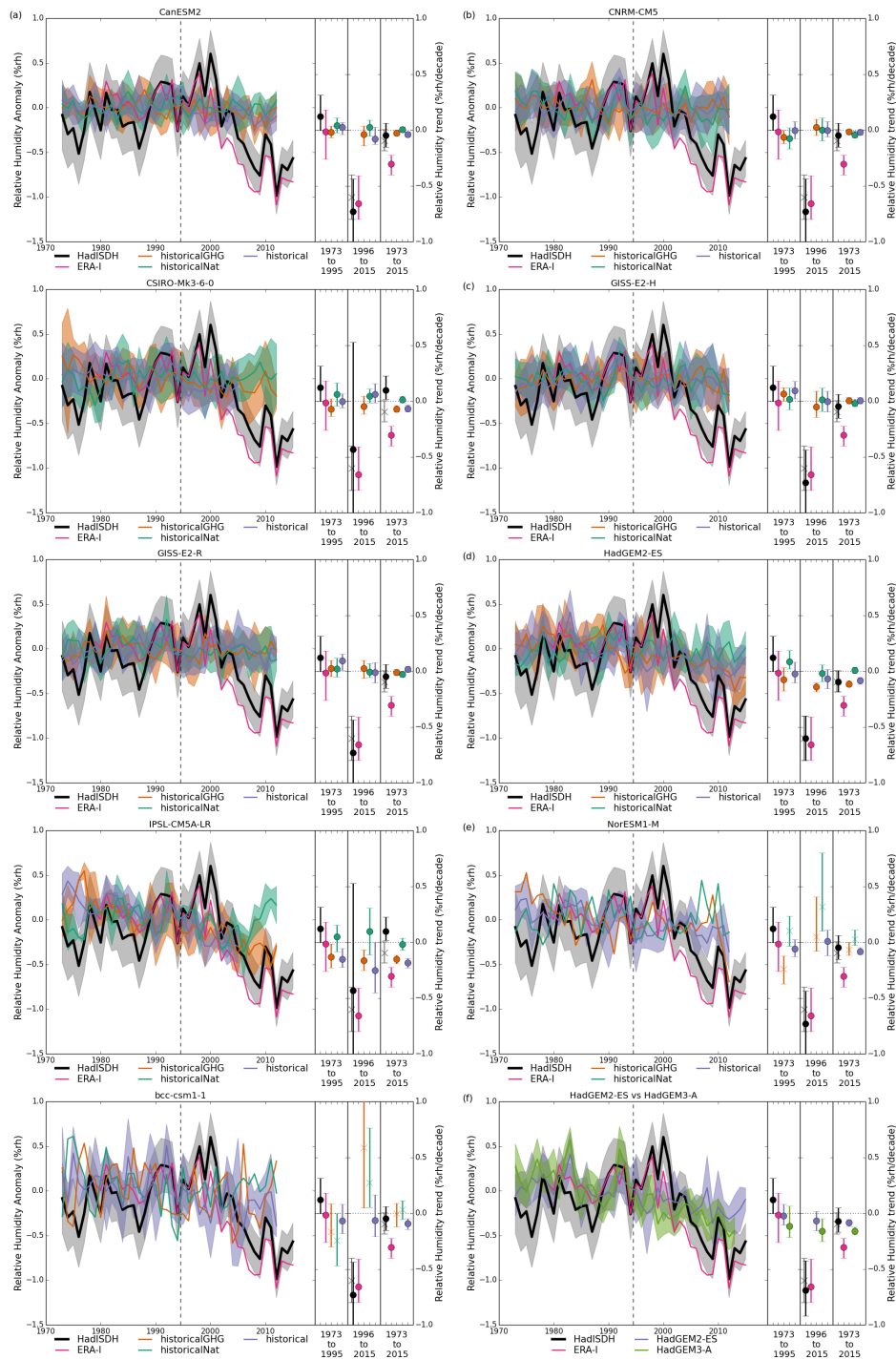
Relative Humidity

Figure 9. Global annual timeseries for relative humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
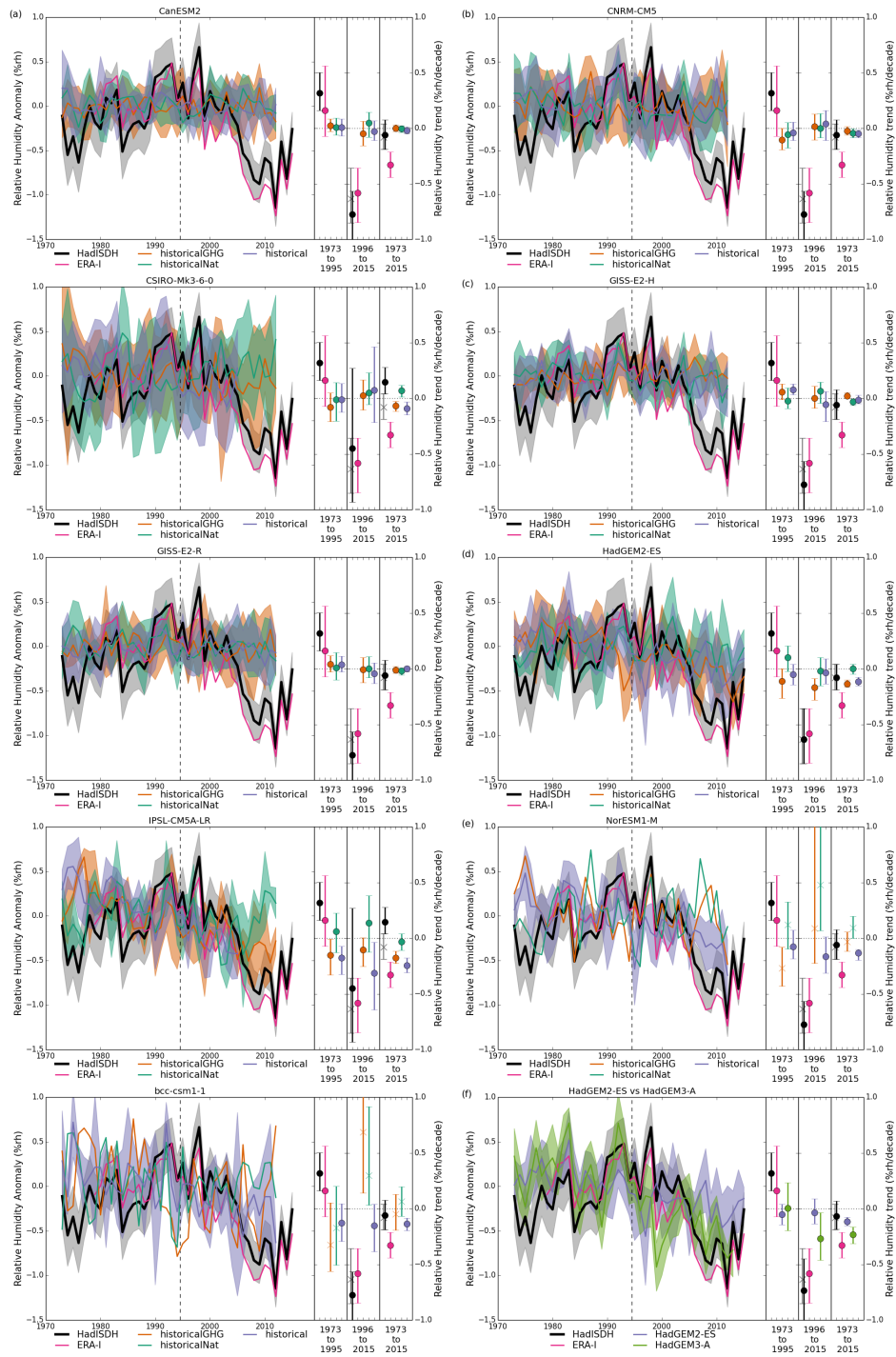
Figure 10. Northern Hemisphere annual timeseries for relative humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
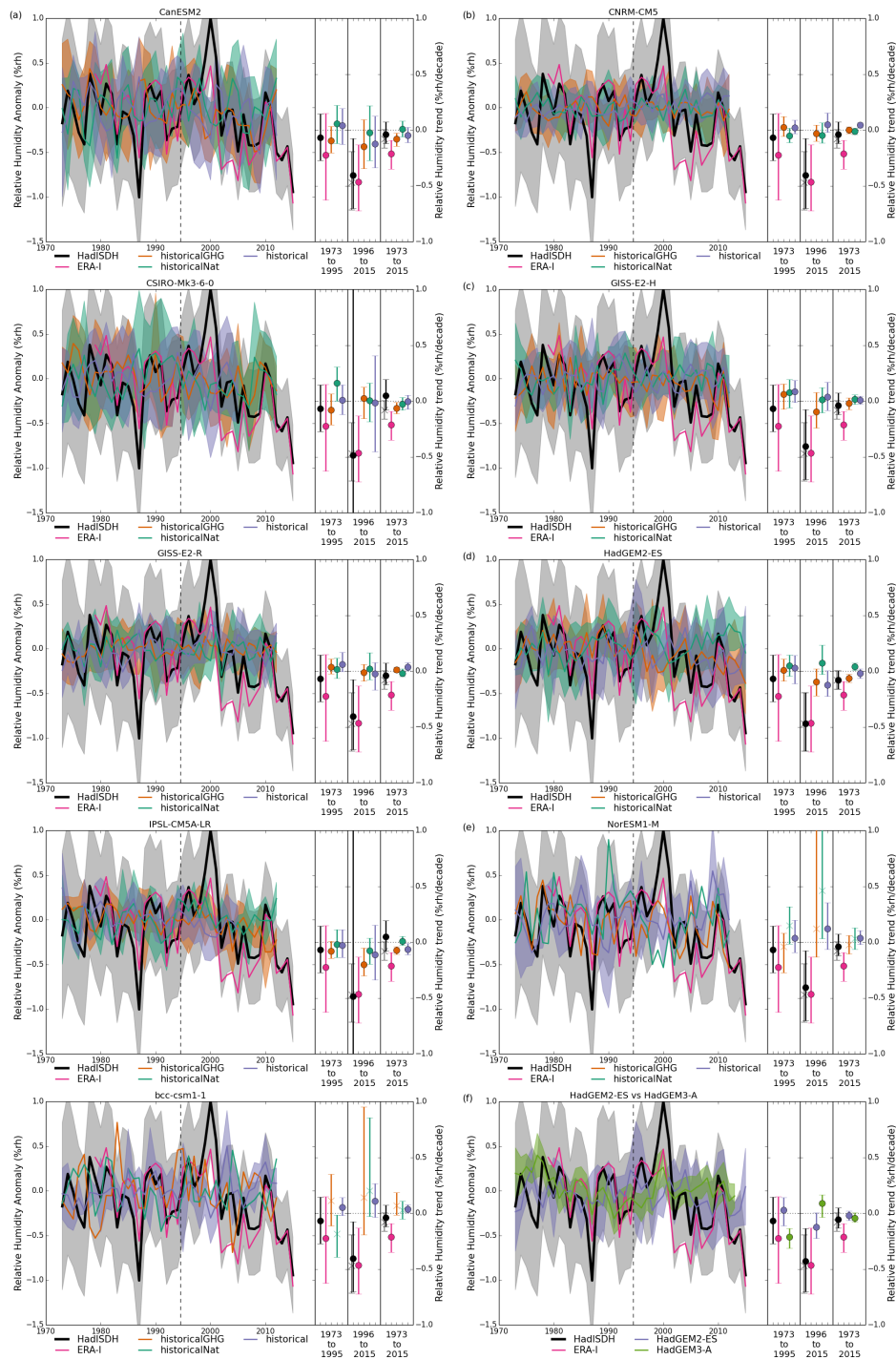
Figure 11. Tropical annual timeseries for relative humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
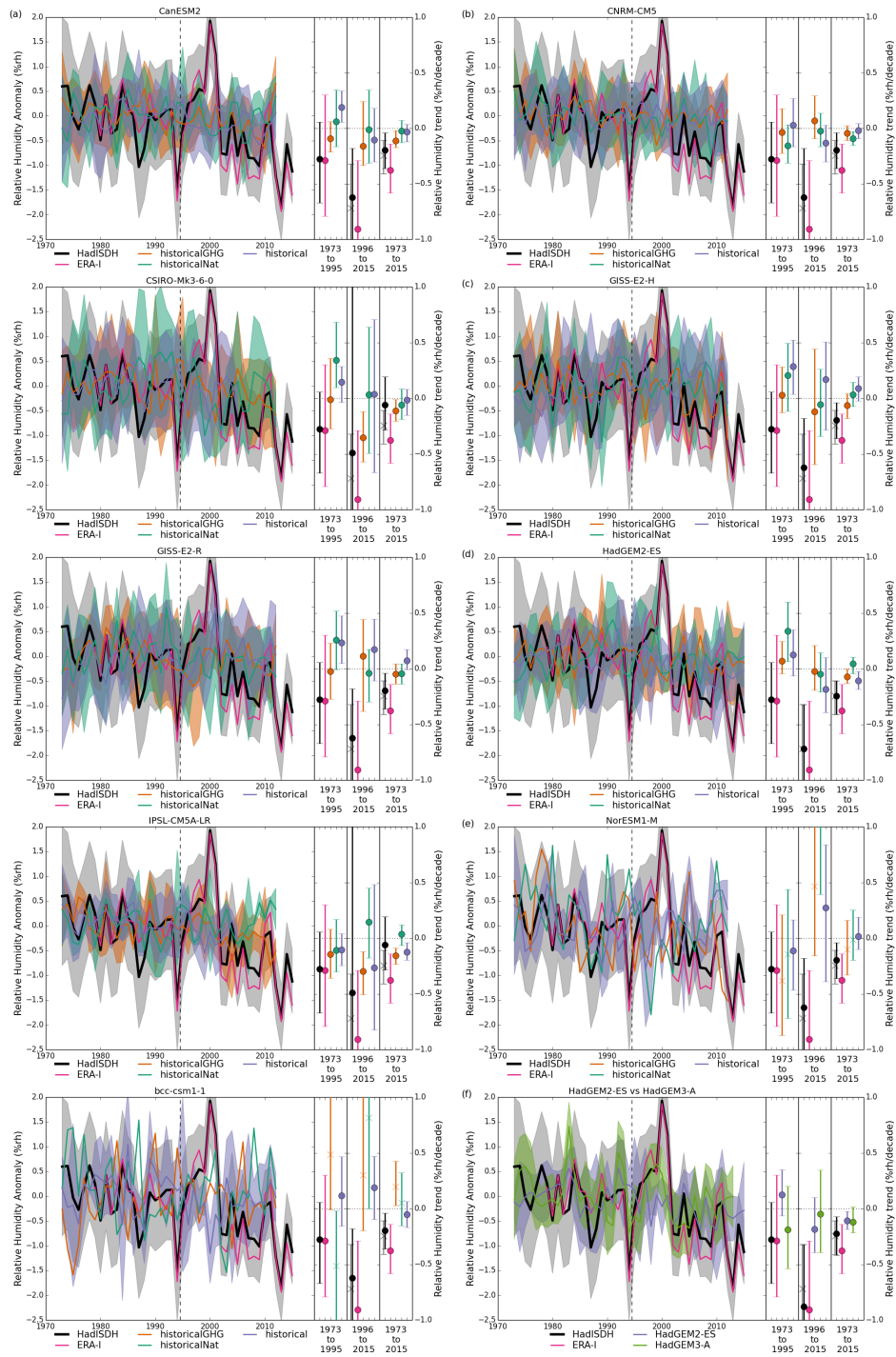
Figure 12. Southern Hemisphere annual timeseries for relative humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
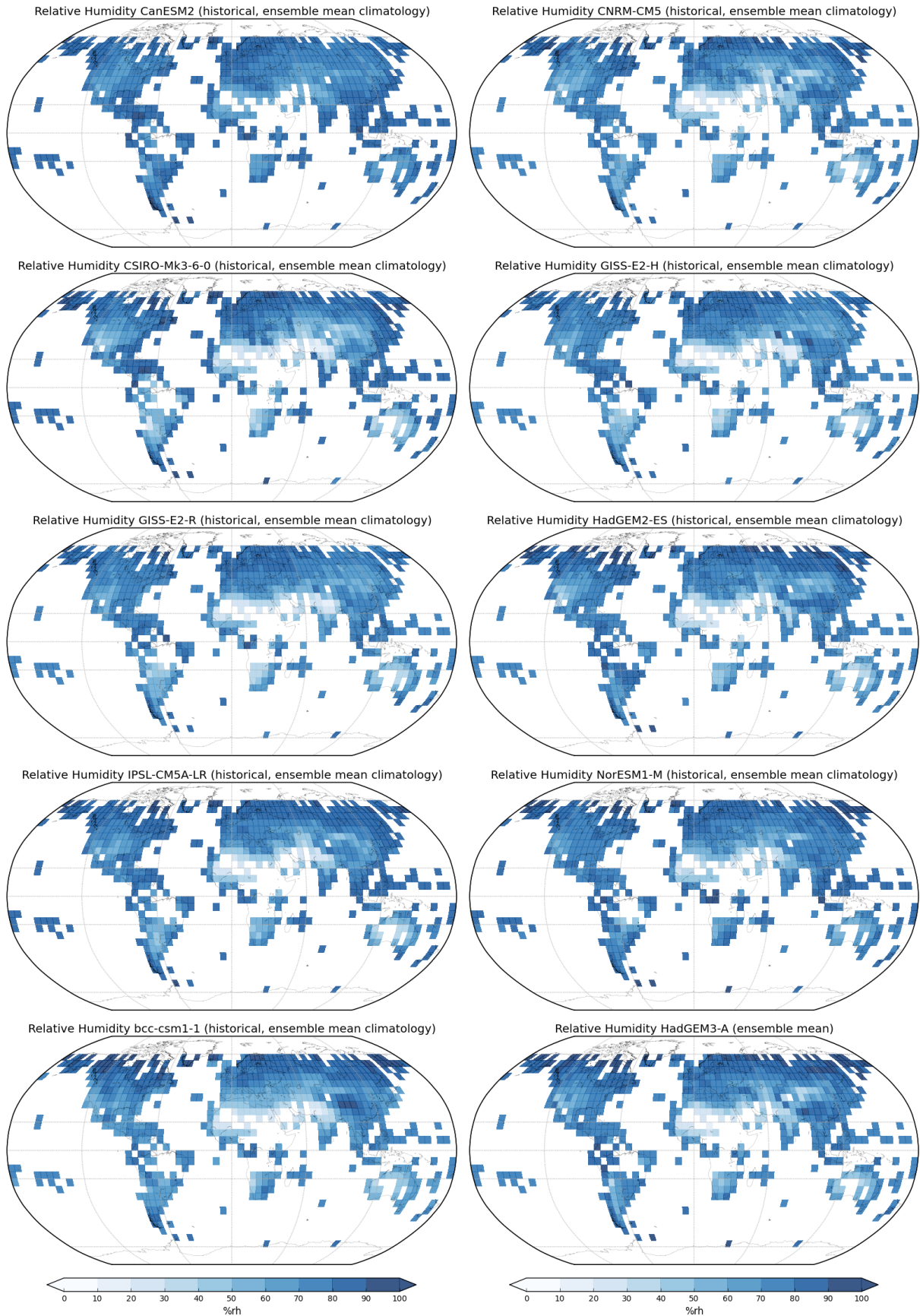
Figure 13. Relative humidity climatologies of the CMIP5 models at the gridbox scale. All climatologies have been calculated over the 1981 to 2010 period using identical spatio-temporal coverage to HadISDH.
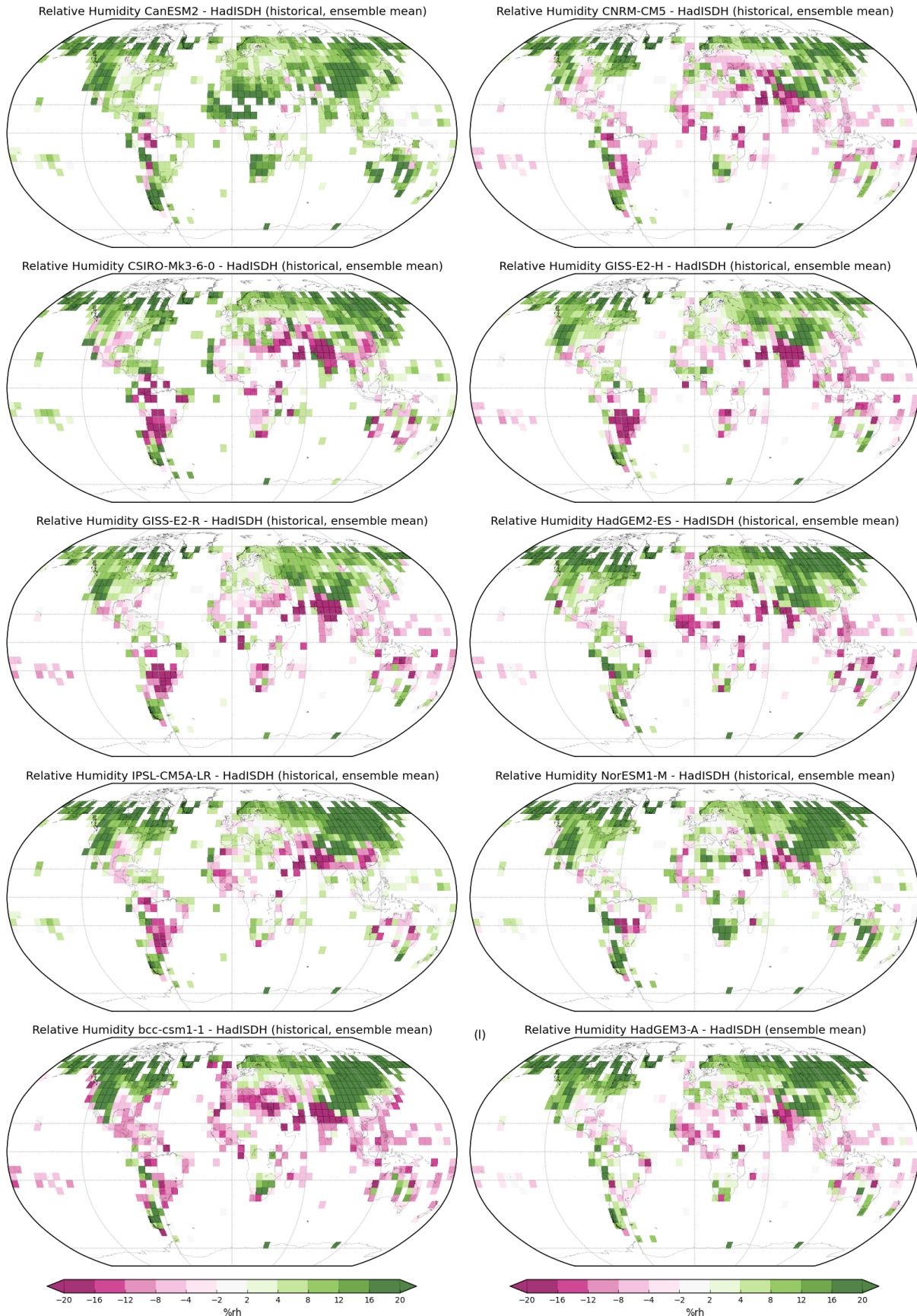
Figure 14. Climatological differences between models and observations at the gridbox scale for relative humidity. All climatologies have been calculated over the 1981 to 2010 period using identical spatio-temporal coverage to HadISDH.
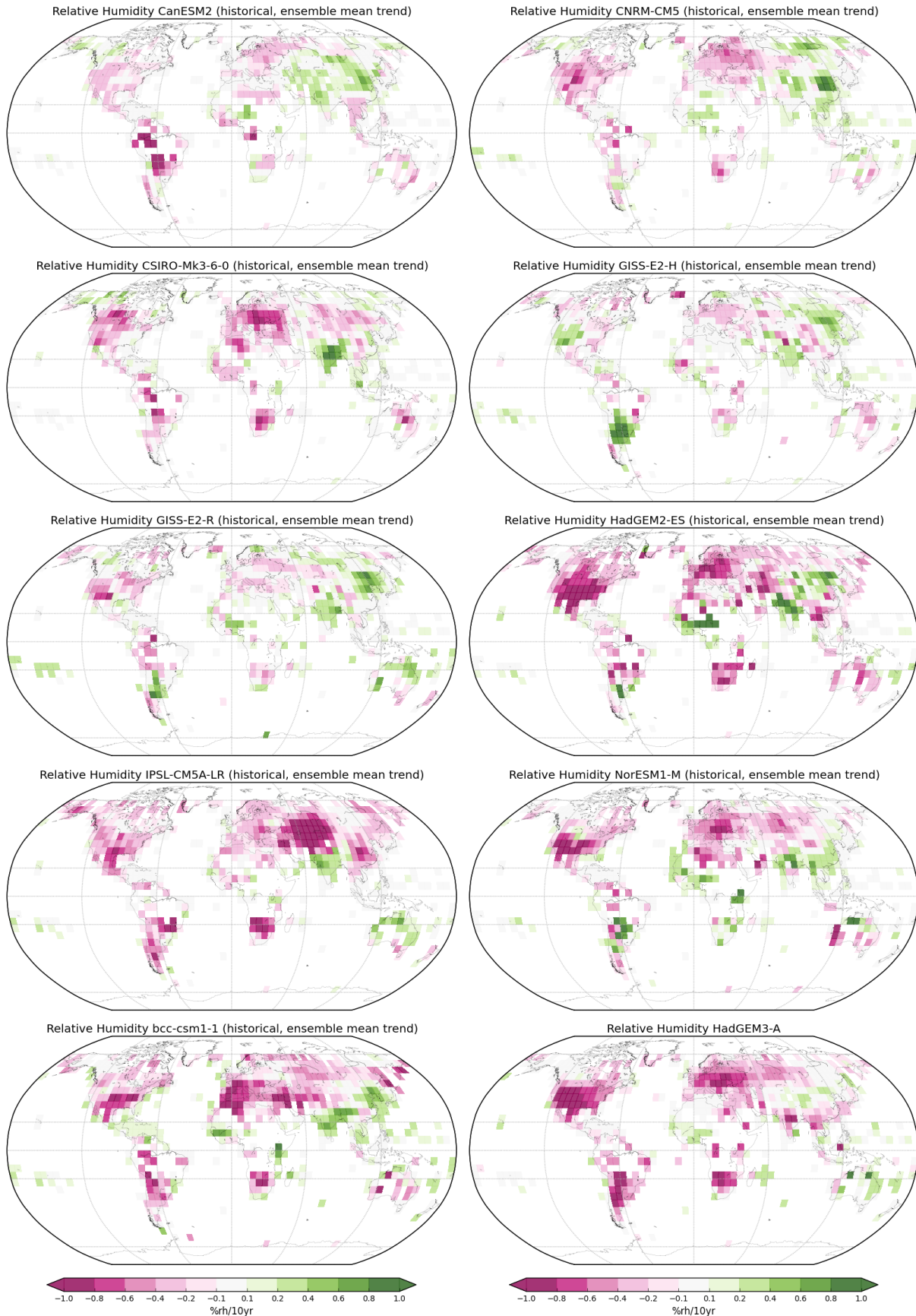
Figure 15. Linear trends of the CMIP5 models at the gridbox scale for relative humidity. All trends have been calculated using the median of pairwise slopes method, with identical spatio-temporal coverage to HadISDH.

Figure 16. Linear trend differences of the CMIP5 models from the observations at the gridbox scale for relative humidity. All trends have been calculated using the median of pairwise slopes method, with identical spatio-temporal coverage to HadISDH.
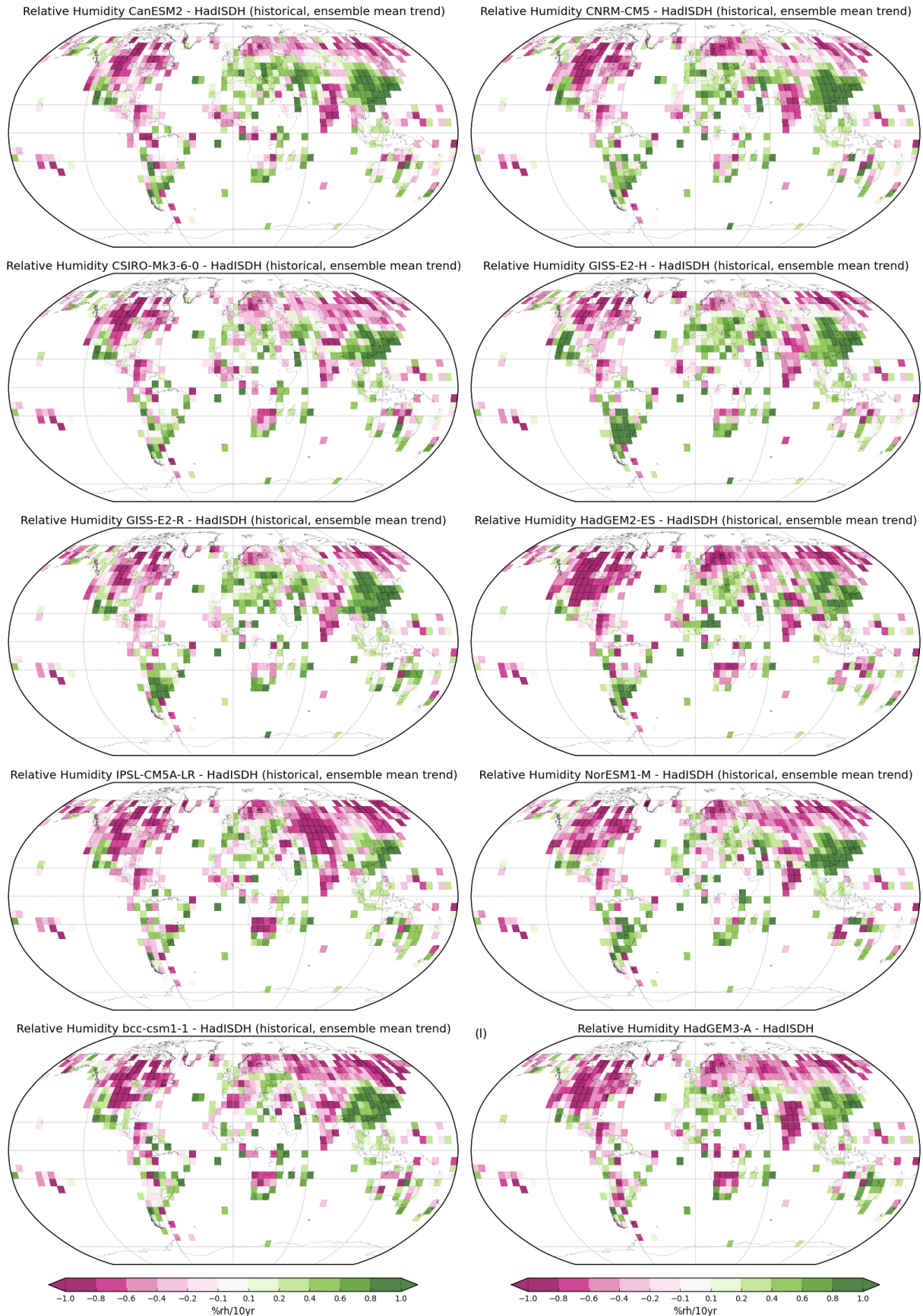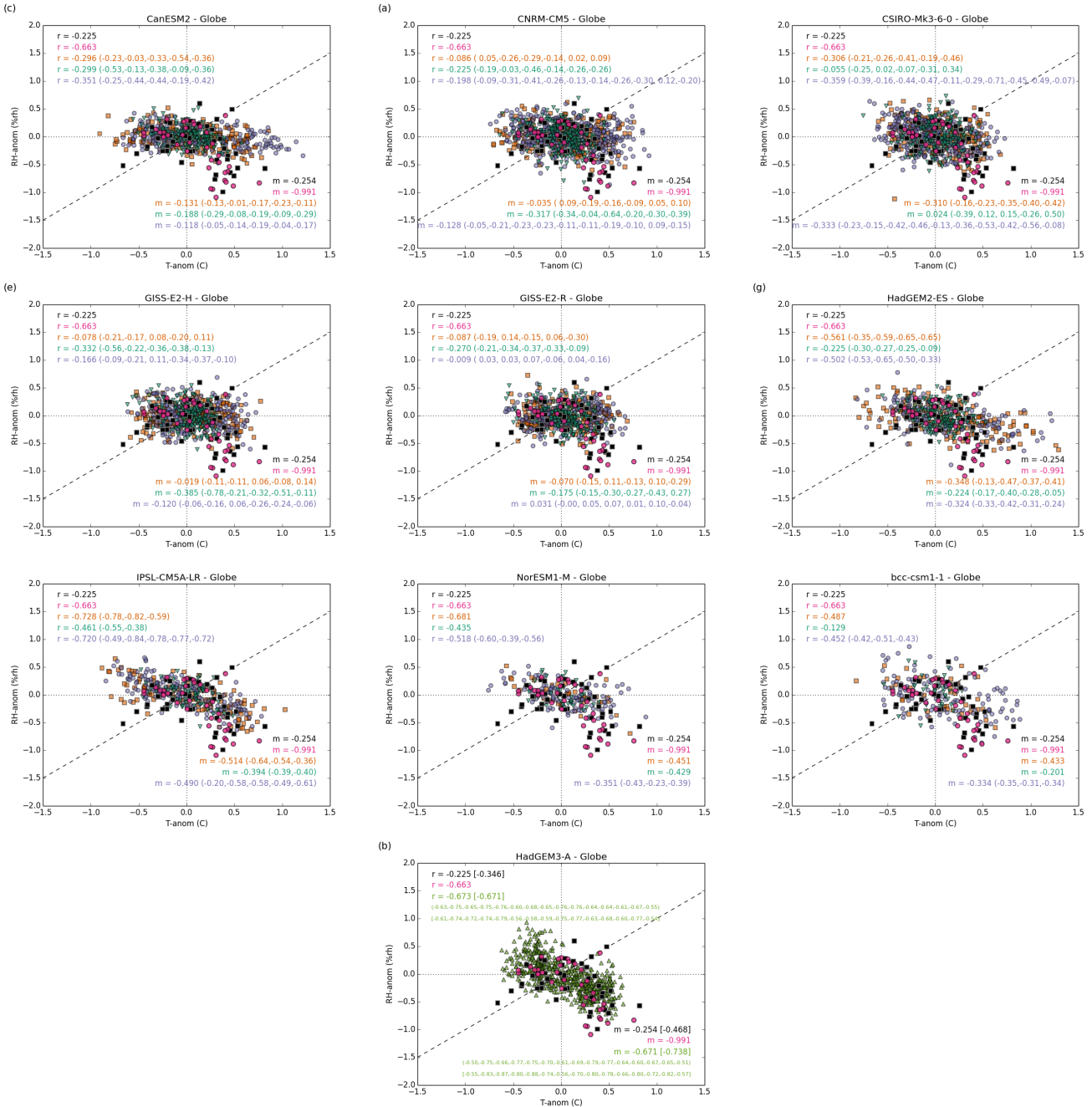
Figure 17. Relationships in global average temperature and relative humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.

Figure 18. Relationships in Northern Hemisphere average temperature and relative humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.
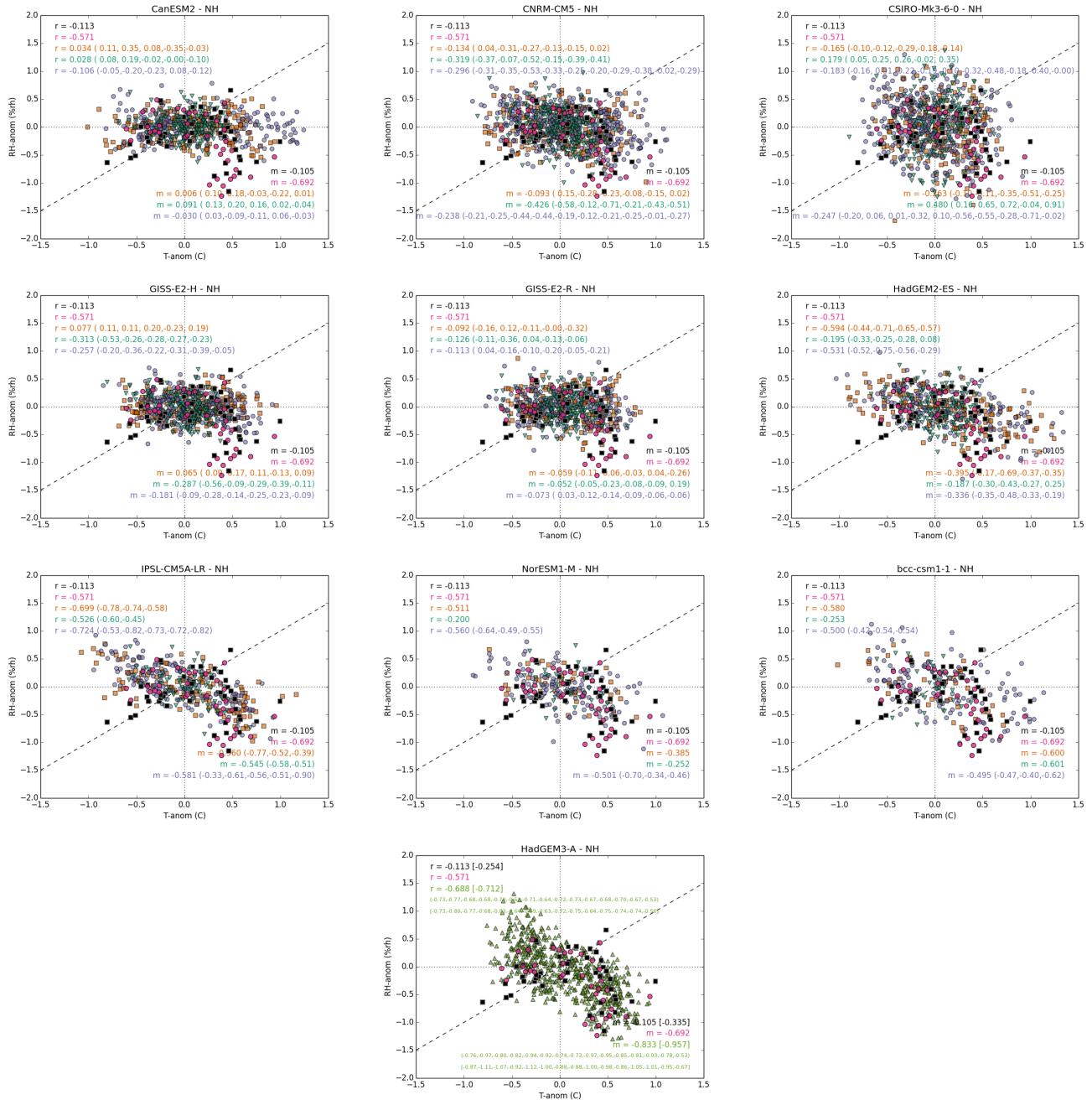
Figure 19. Relationships in tropical average temperature and relative humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.
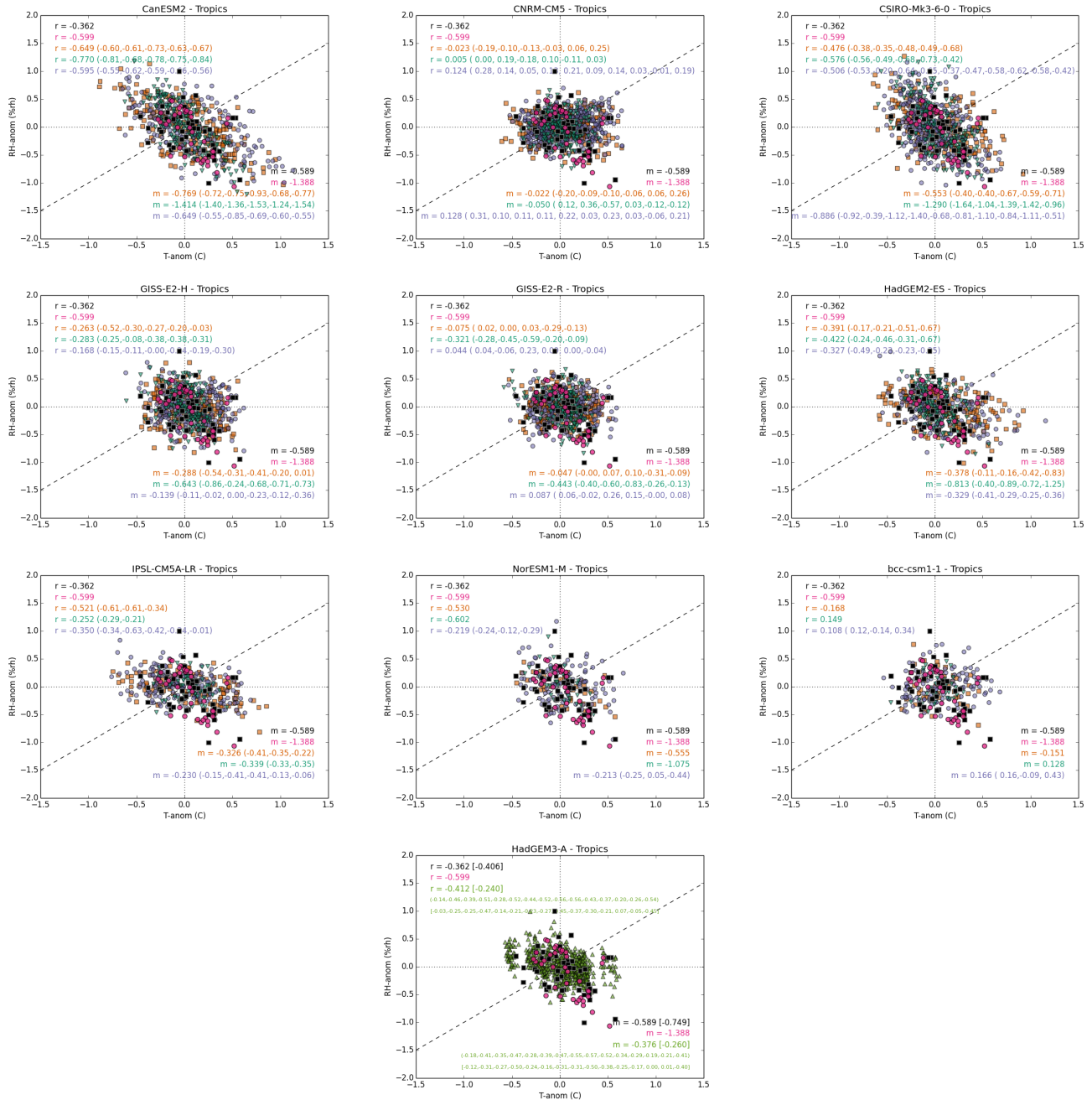
Figure 20. Relationships in Southern Hemisphere average temperature and relative humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.
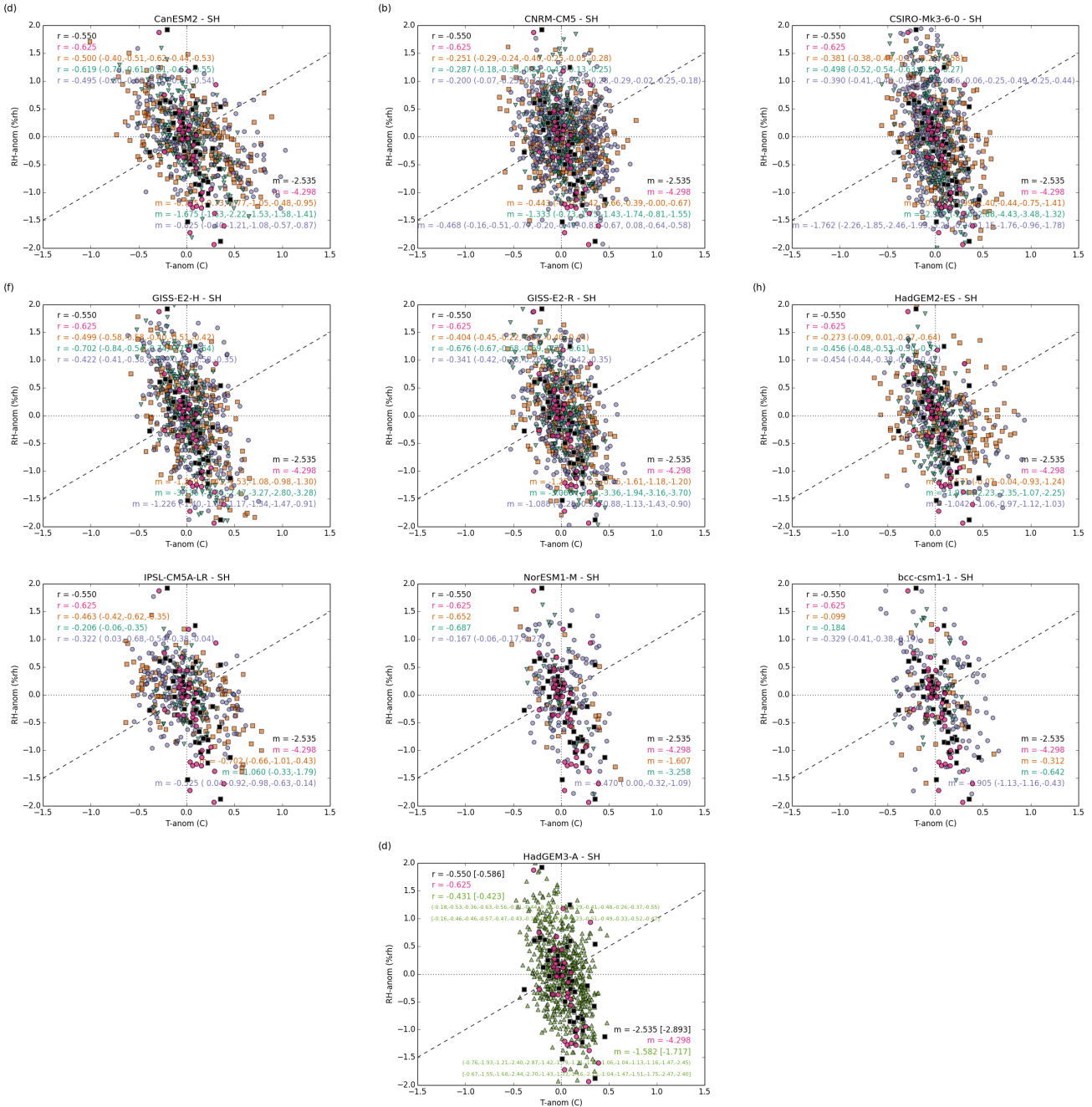
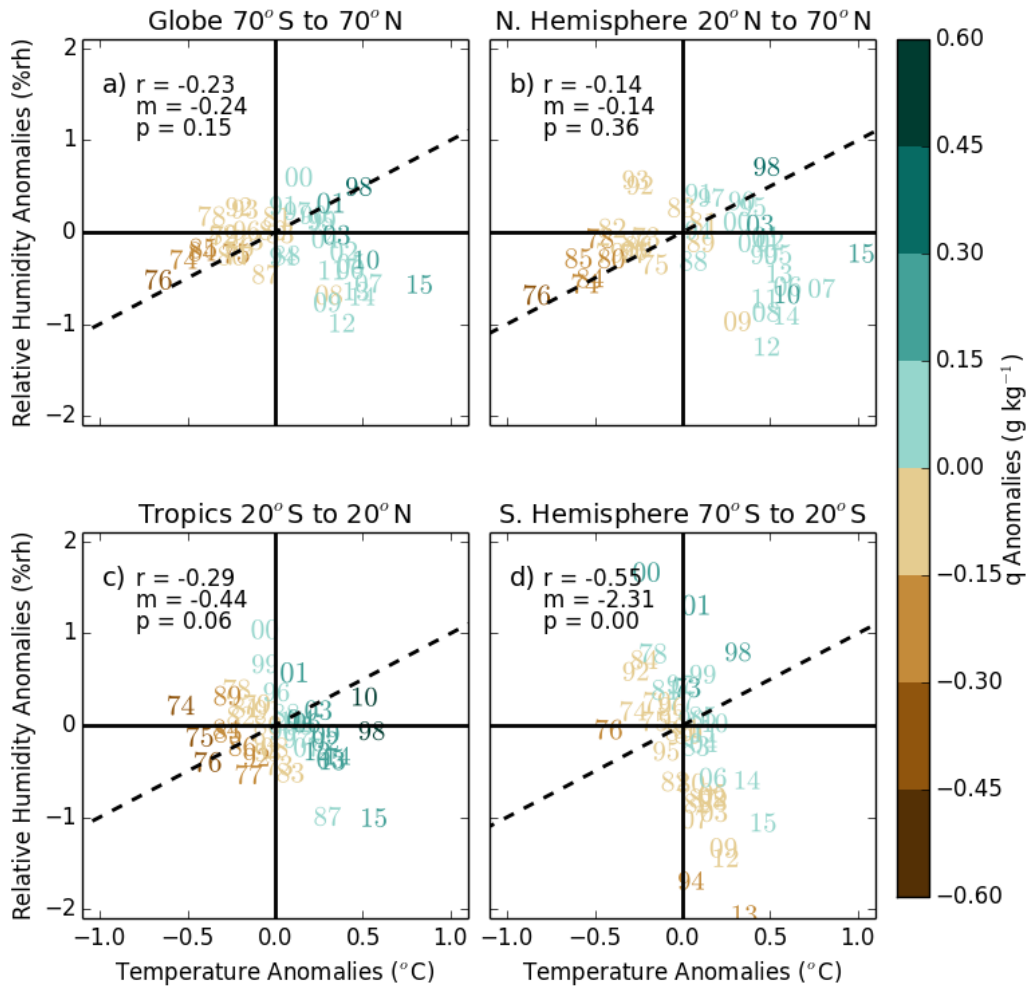**Figure 21.** Temperature-relative humidity relationship, with the relative humidity anomaly as the colour scale, with the years as the points. The four zonal regions used in this analysis are shown in the four panels.
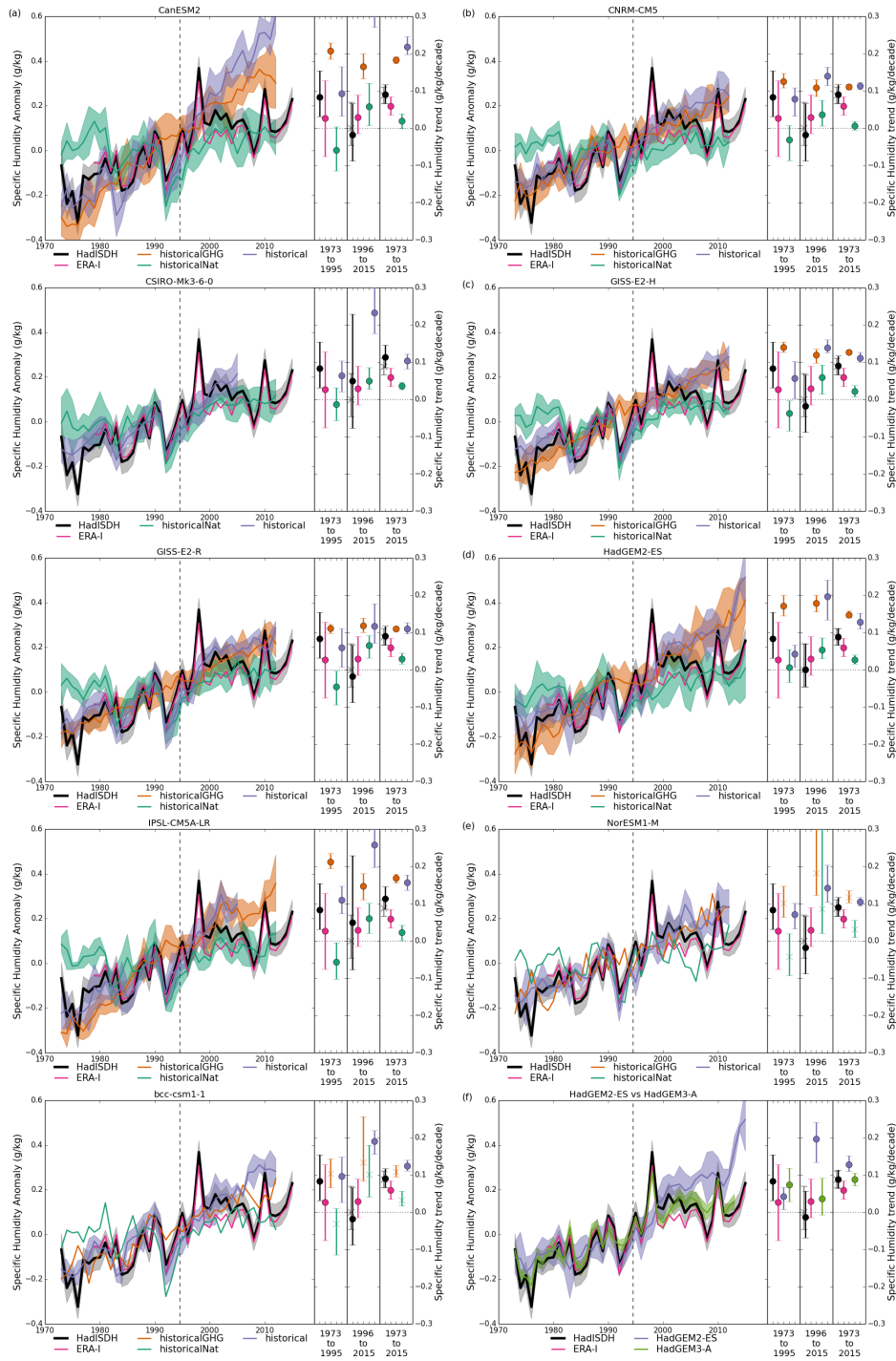
Specific Humidity

Figure 22. Global annual timeseries for specific humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.

Figure 23. Northern Hemisphere annual timeseries for specific humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
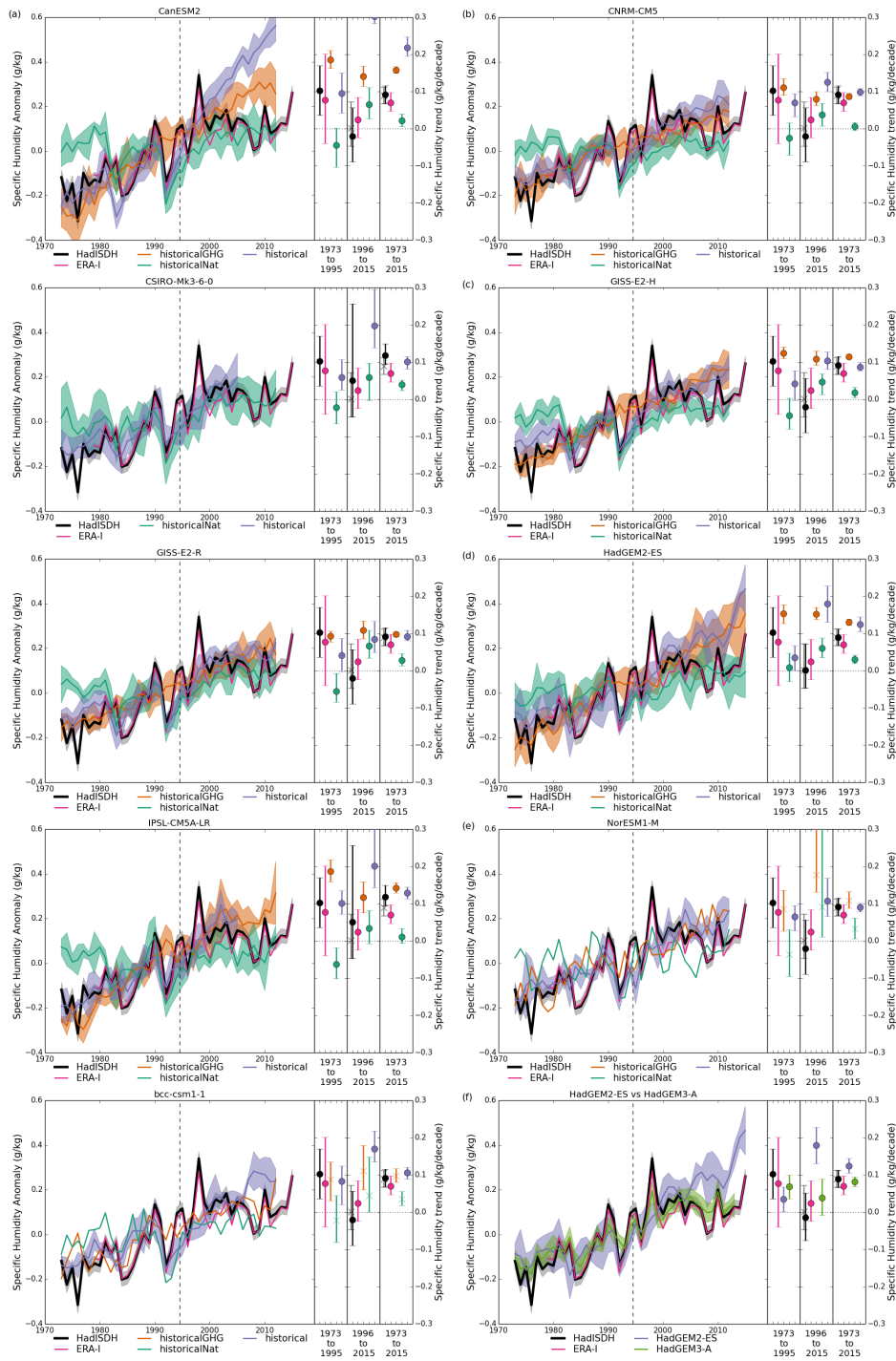
Figure 24. Tropical annual timeseries for specific humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
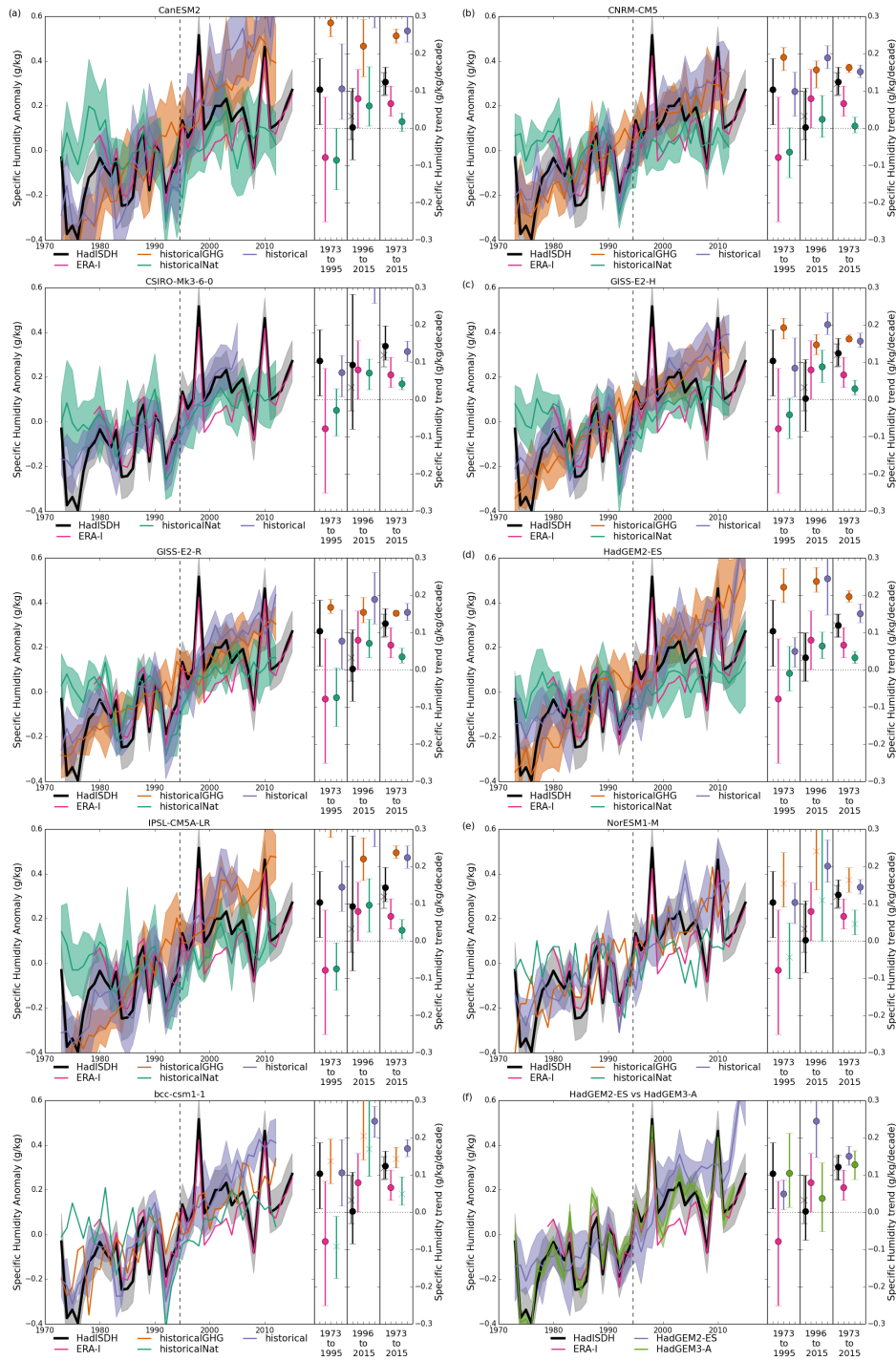
Figure 25. Southern Hemisphere annual timeseries for specific humidity for the nine CMIP5 models and HadGEM3-A, using a climatology period of 1976-2005. HadISDH is shown by the thick black line, ERA-Interim by the magenta line and the historical, historicalNat and historicalGHG ensemble averages by the purple, green and orange lines respectively. The uncertainty ranges are shown using the coloured shading. The right-hand panels show the values of the linear trends for HadISDH, ERA-Interim and the ensemble averages of all three experiments for the early (1973-1994), late (1995-2015) and full periods. For the late and full period panels, the HadISDH trend is shown matching the temporal coverage of the *historical* model (circle) and its full coverage (cross). If there is only one ensemble member for the model, then the trend is marked with a cross rather than circle.
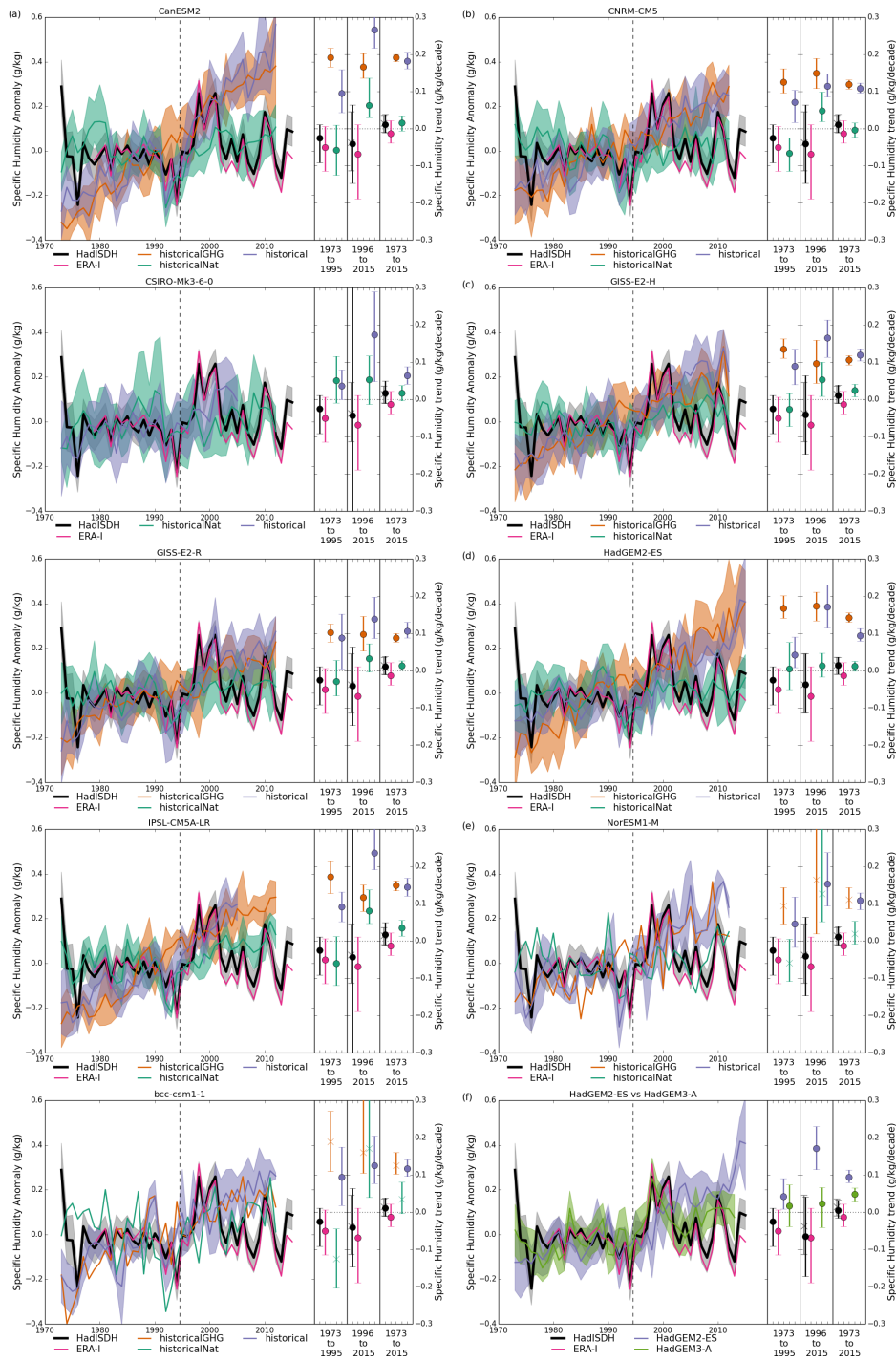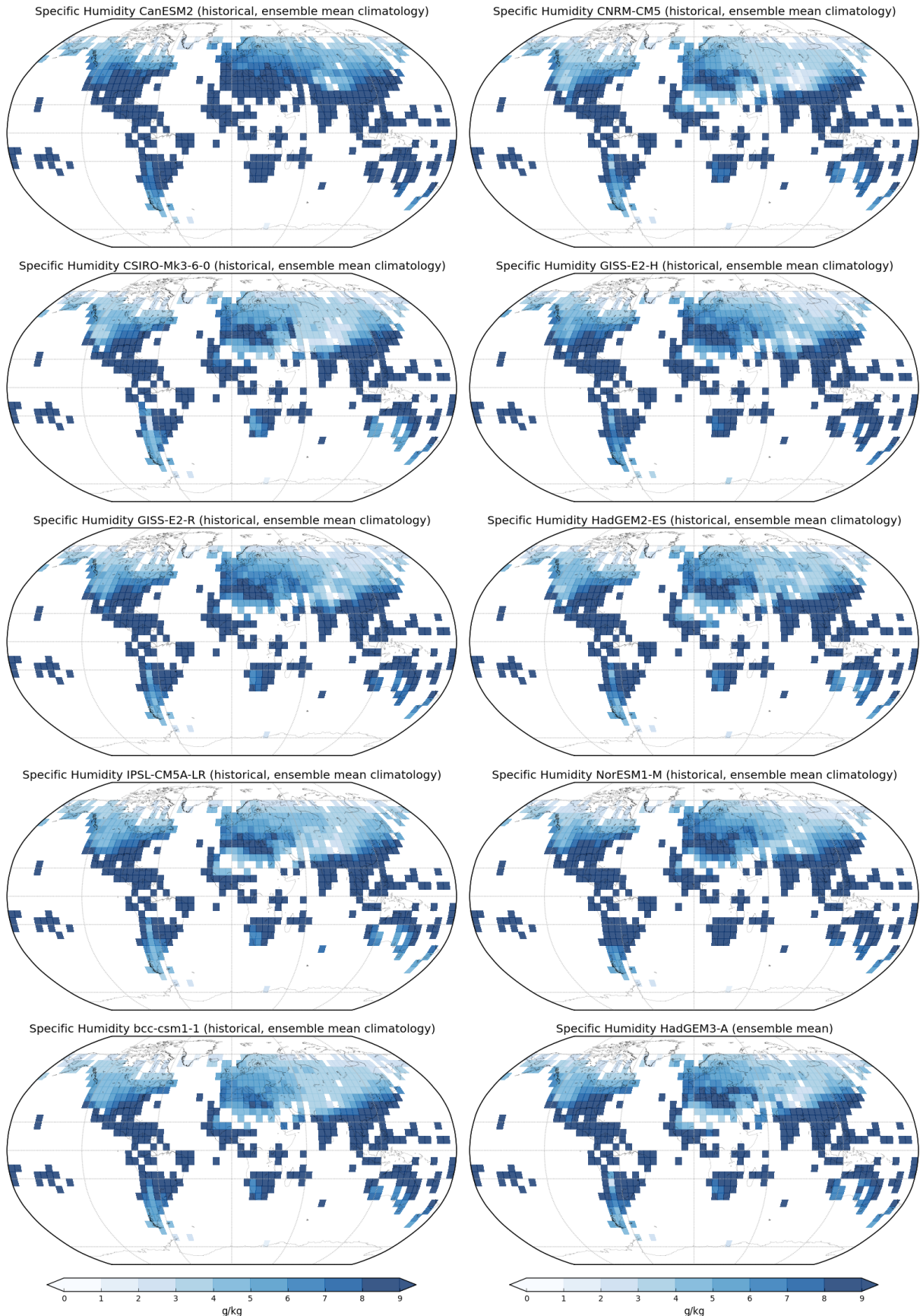
Specific Humidity CanESM2 (historical, ensemble mean climatology)

Specific Humidity CNRM-CM5 (historical, ensemble mean climatology)

Specific Humidity CSIRO-Mk3-6-0 (historical, ensemble mean climatology)

Specific Humidity GISS-E2-H (historical, ensemble mean climatology)

Specific Humidity GISS-E2-R (historical, ensemble mean climatology)

Specific Humidity HadGEM2-ES (historical, ensemble mean climatology)

Specific Humidity IPSL-CM5A-LR (historical, ensemble mean climatology)

Specific Humidity NorESM1-M (historical, ensemble mean climatology)

Specific Humidity bcc-csm1-1 (historical, ensemble mean climatology)

Specific Humidity HadGEM3-A (ensemble mean)

g/kg

g/kg

Figure 26. Specific humidity climatologies of the CMIP5 models at the gridbox scale. All climatologies have been calculated over the 1981 to 2010 period using identical spatio-temporal coverage to HadISDH.
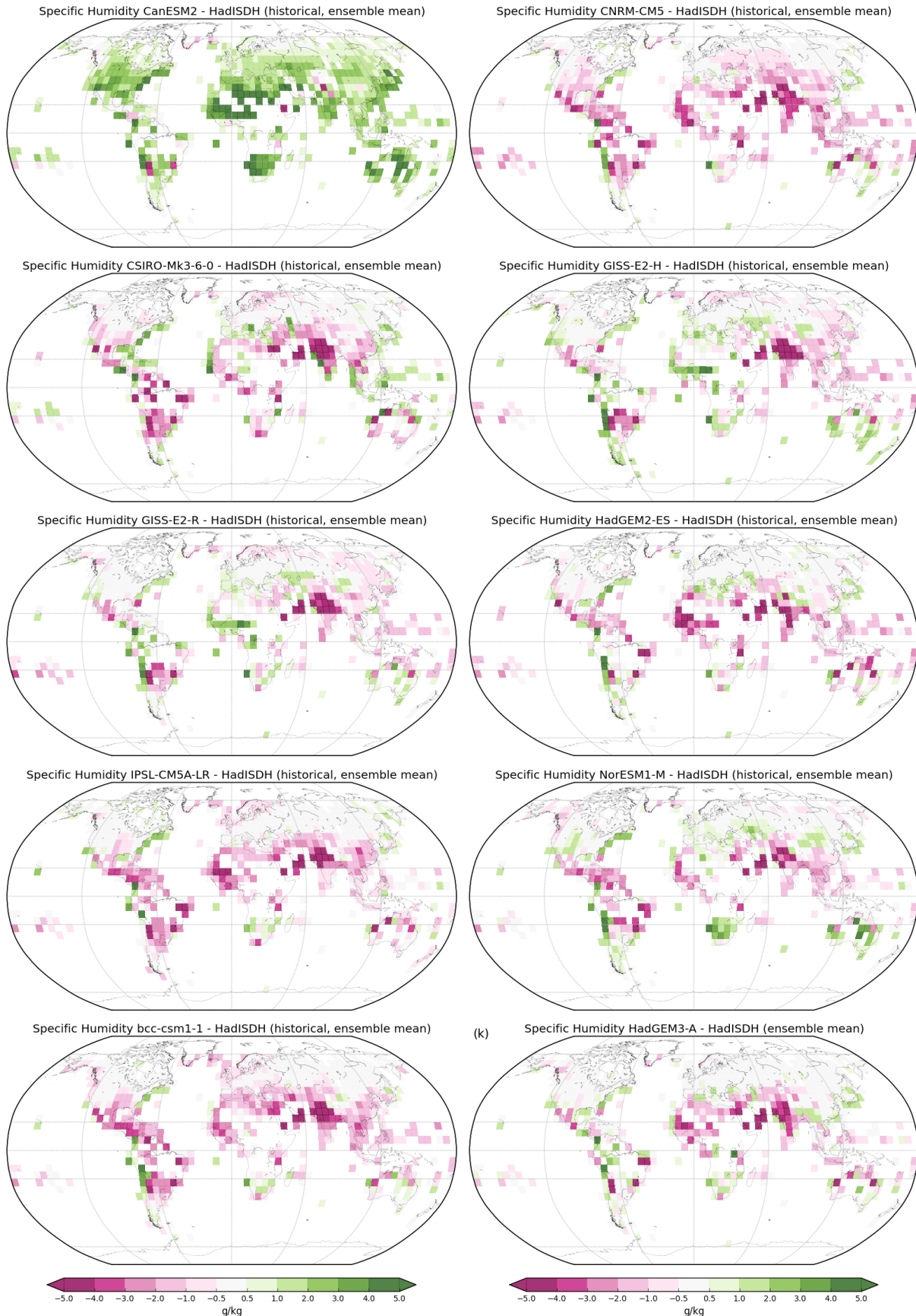
Figure 27. Climatological differences between models and observations at the gridbox scale for specific humidity. All climatologies have been calculated over the 1981 to 2010 period using identical spatio-temporal coverage to HadISDH.
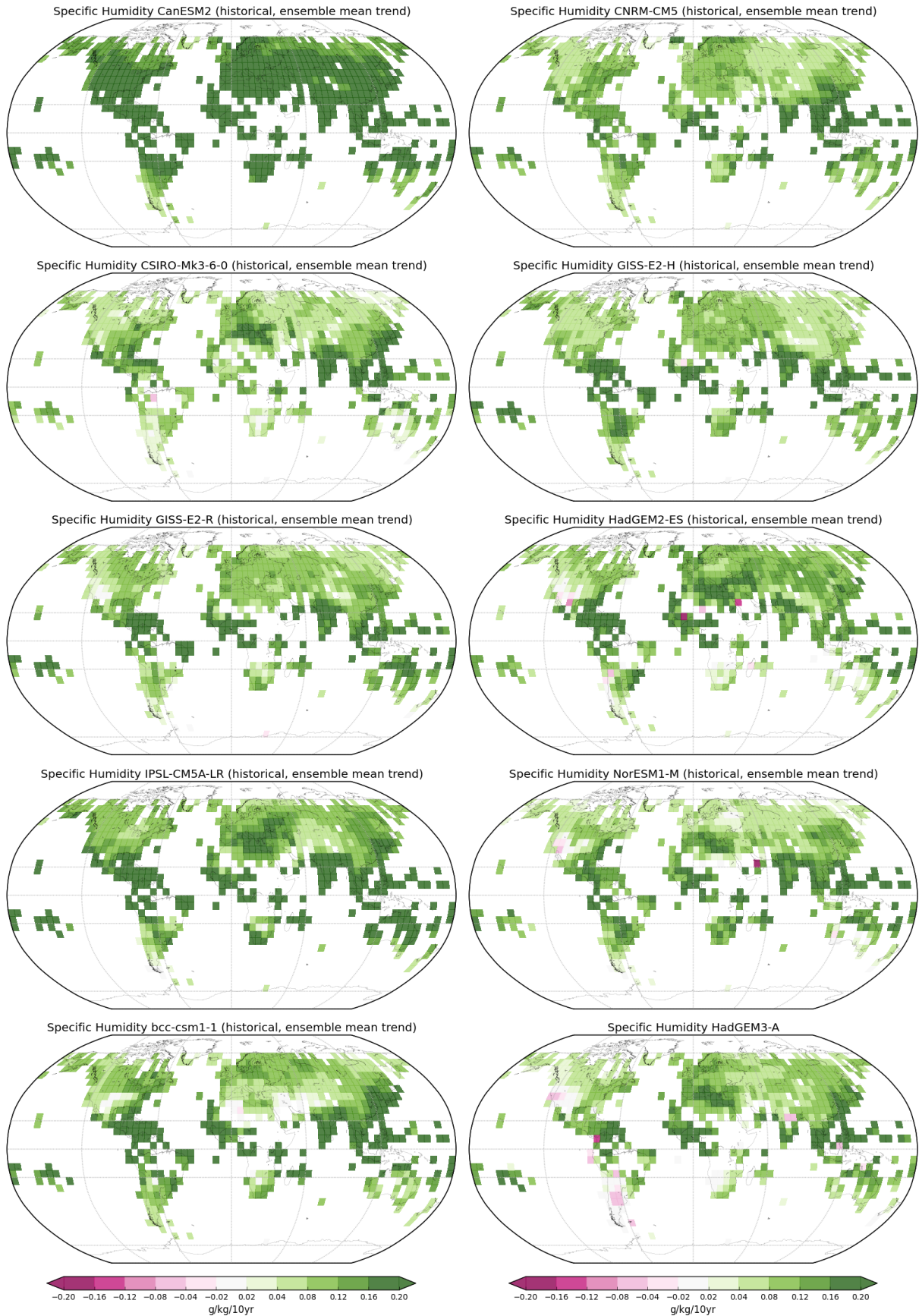
Figure 28. Linear trends of the CMIP5 models at the gridbox scale for specific humidity. All trends have been calculated using the median of pairwise slopes method, with identical spatio-temporal coverage to HadISDH.
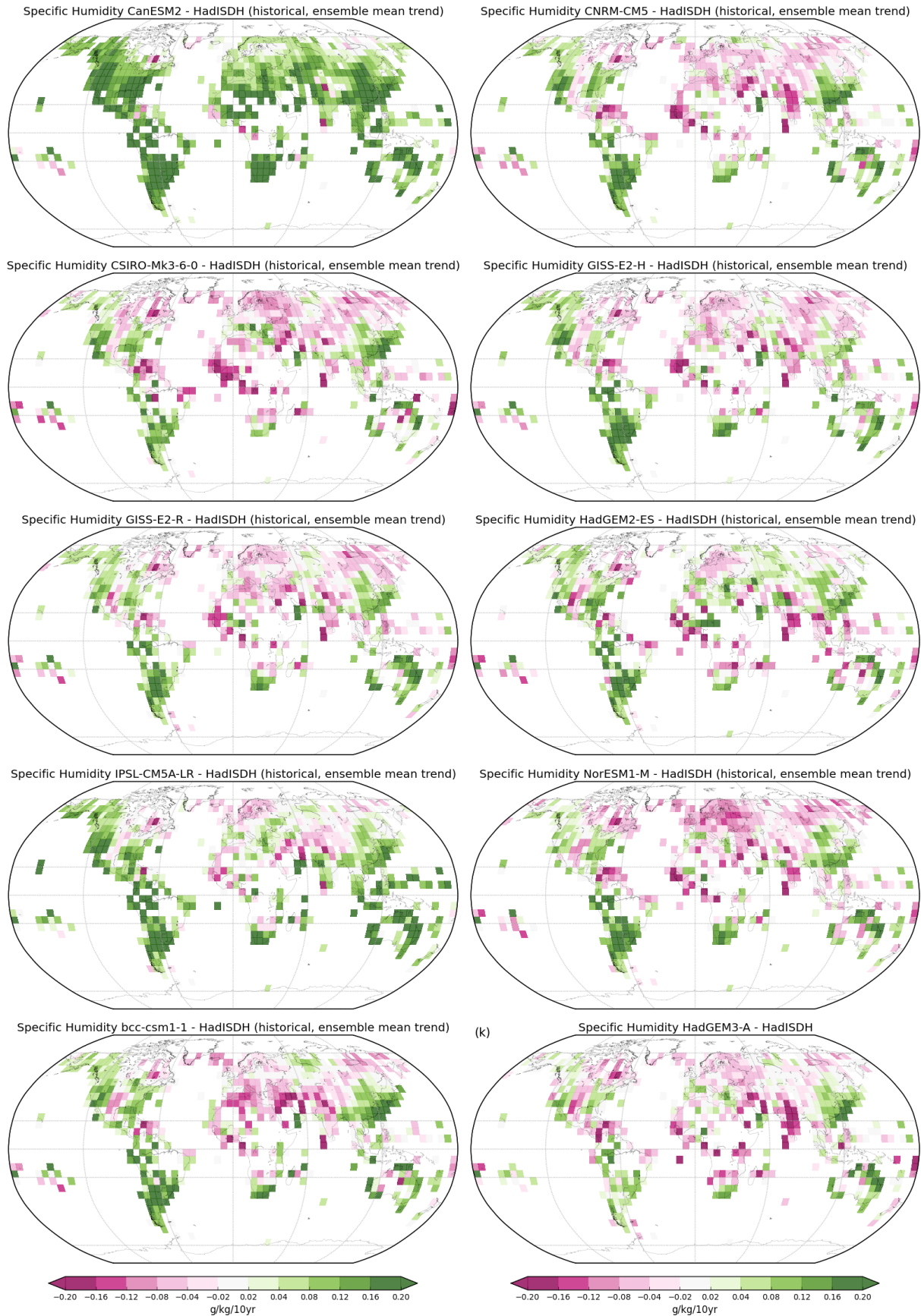
Figure 29. Linear trend differences of the CMIP5 models from the observations at the gridbox scale for specific humidity. All trends have been calculated using the median of pairwise slopes method, with identical spatio-temporal coverage to HadISDH.
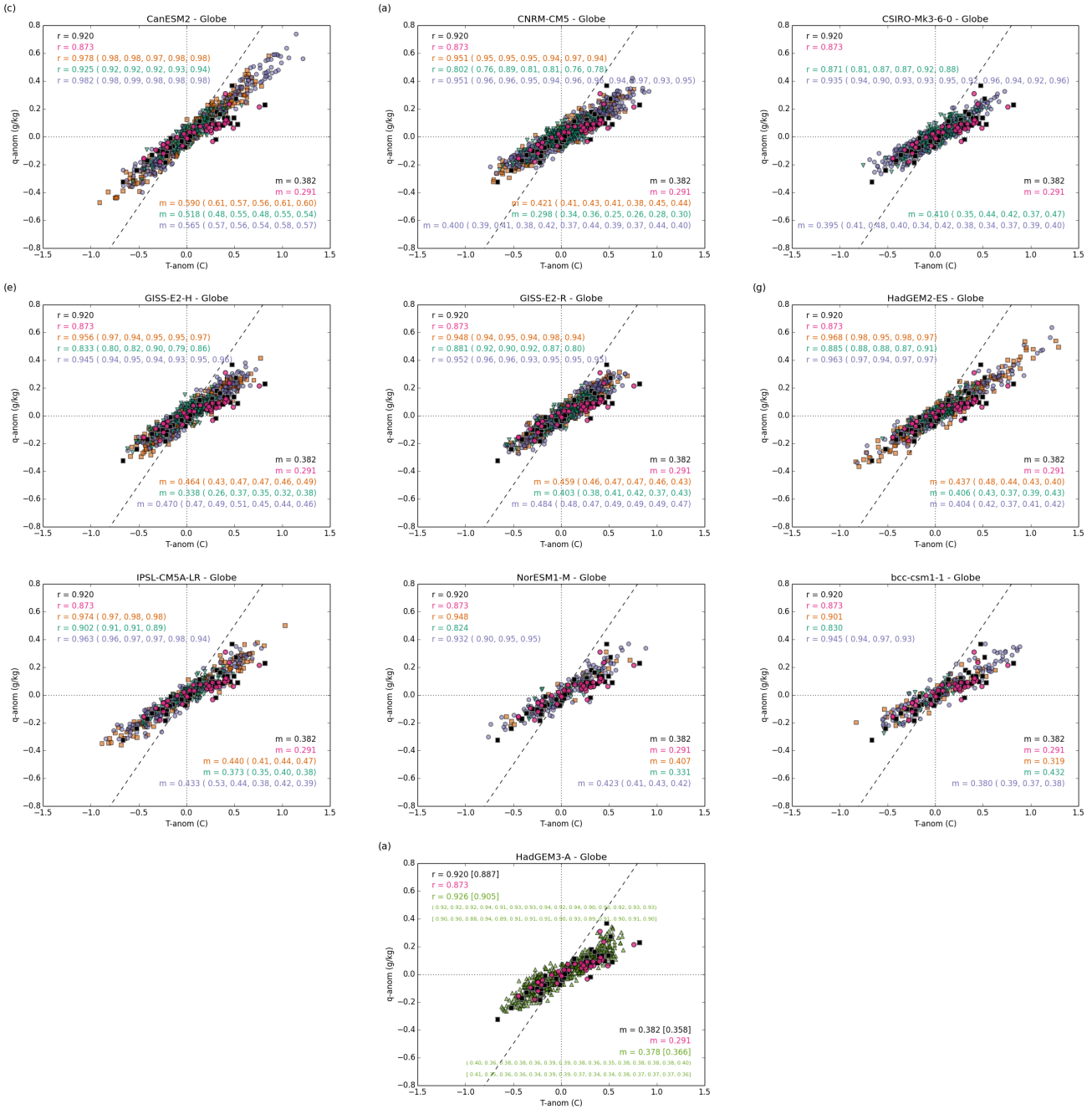
Figure 30. Relationships in global average temperature and specific humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.
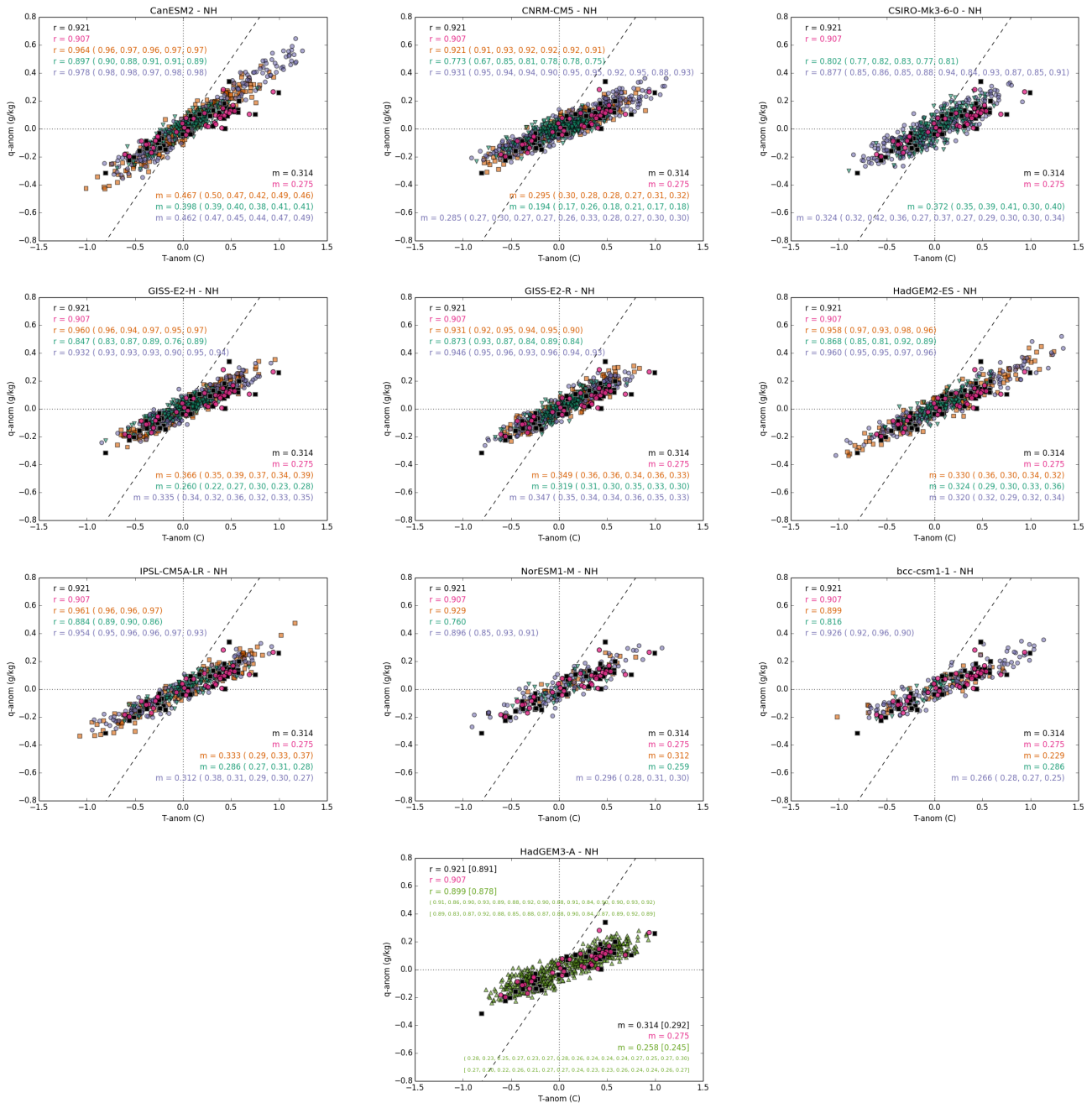
Figure 31. Relationships in Northern Hemisphere average temperature and specific humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.
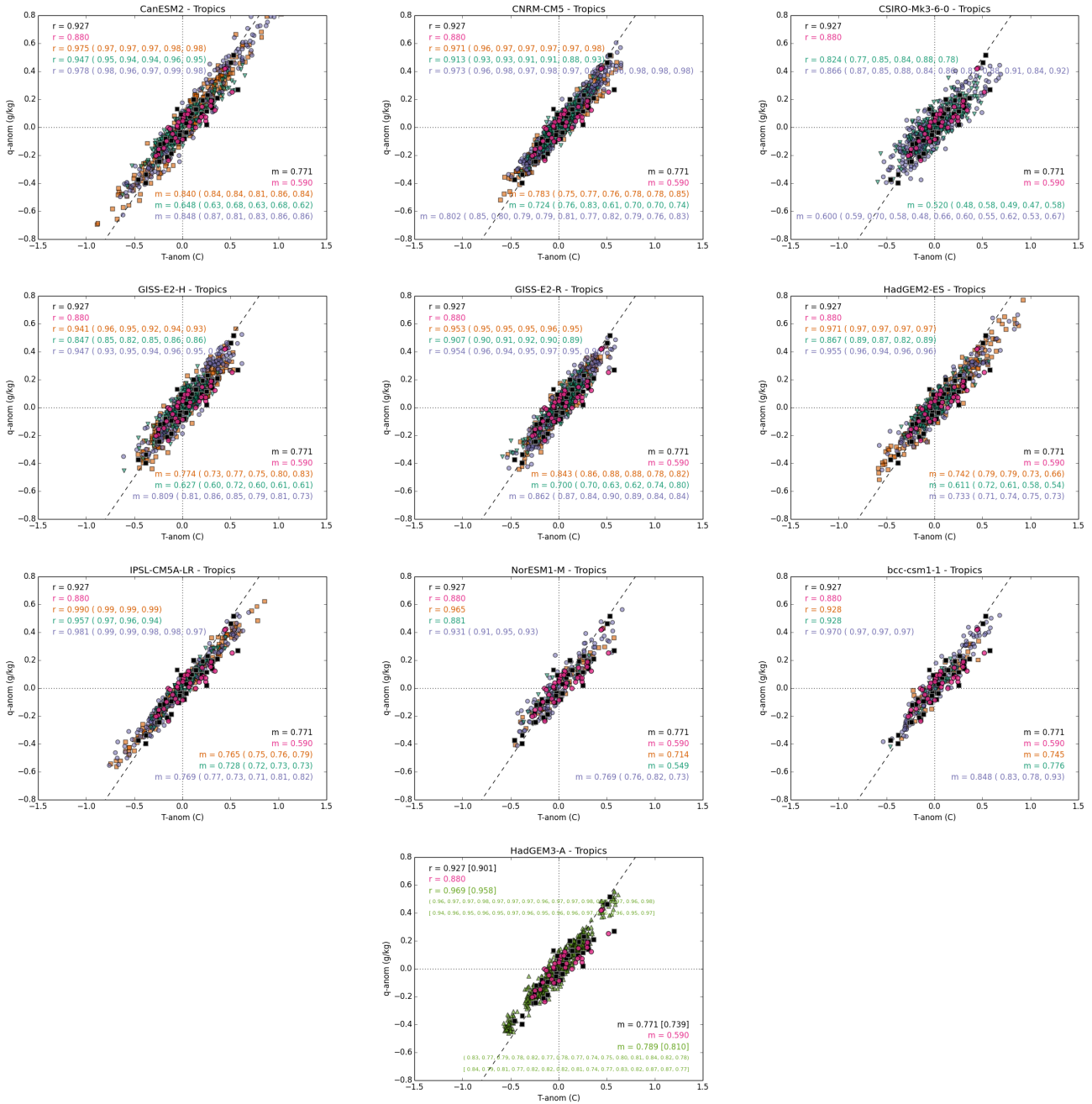
Figure 32. Relationships in tropical average temperature and specific humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.
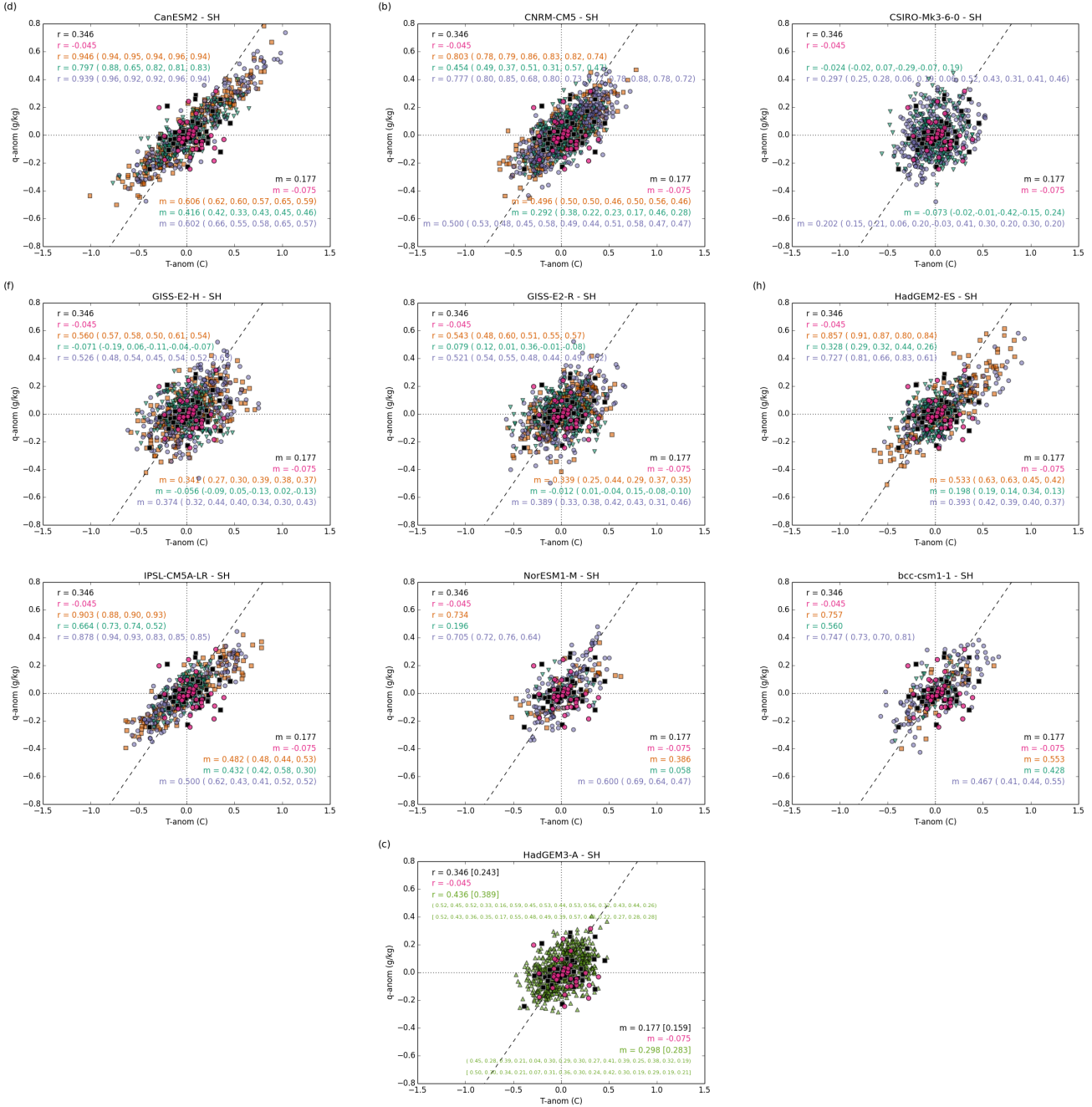
Figure 33. Relationships in Southern Hemisphere average temperature and specific humidity for CMIP5 models compared to HadISDH and ERA-Interim. Correlations (r) are shown in the top left hand corner. The gradient of the line of best fit is given in the bottom right hand corner. HadISDH is shown in black. ERA-Interim is shown in magenta. *Historical*, *historicalNAT* and *historicalGHG* are shown in purple, green and orange respectively. The ensemble mean value is given for each model with individual member values in parentheses. Values in square brackets are calculated using data matched to the coverage of ERA-Interim, for both HadISDH and HadGEM3-A.
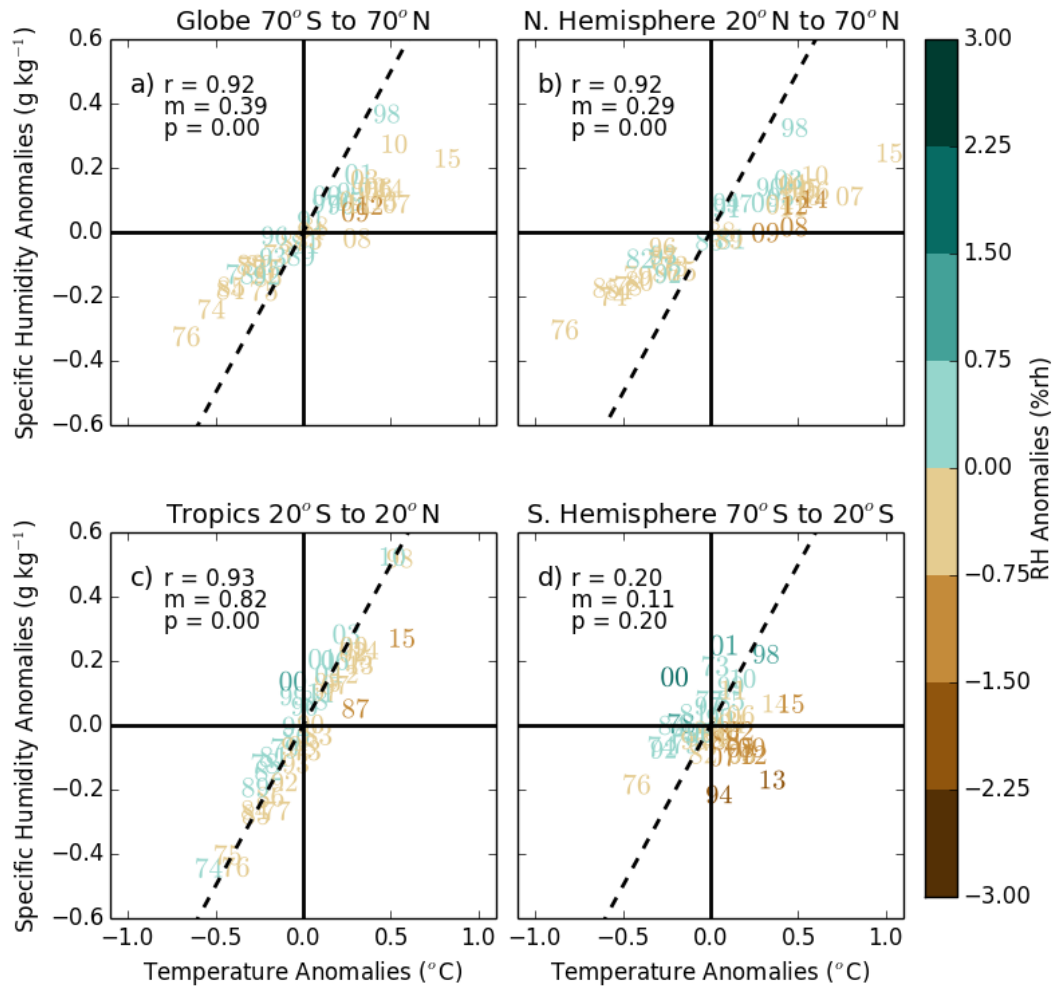
Figure 34. Temperature-specific humidity relationship, with the relative humidity anomaly as the colour scale, with the years as the points. The four zonal regions used in this analysis are shown in the four panels.