Supporting Information for "An evaluation of the large scale atmospheric circulation and its variability in the Community Earth System Model version 2 (CESM2) and other CMIP models"

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1. Figures S1 to S15 show equivalent figures to many of those in the main text but for March-April-May (MAM) and September-October-November (SON). No equivalent figure to that of Figures 12 and 13 of the text is provided since those figures show the NAM and SAM for the full year. Two separate figures are shown for assessment of the MAM and SON Hadley circulation since the SH and NH Hadley cells are of equal importance in the equinoxial seasons, so both the NH and SH Hadley cell extent and intensity are assessed for each of these seasons.

2. Figures S16 and S17 show the biases in the mean climate and aspects of variability for CESM2-WACCM6 (i.e., the BWACCM6 simulations). These are equivalent to those for CESM2-CAM6 that were shown in the main text.

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3. Tables S1 and S2 show the jet metrics for the DJF and JJA seasons for the Atlantic and Pacific as shown in Figures 4 and 5 of the main text, respectively.

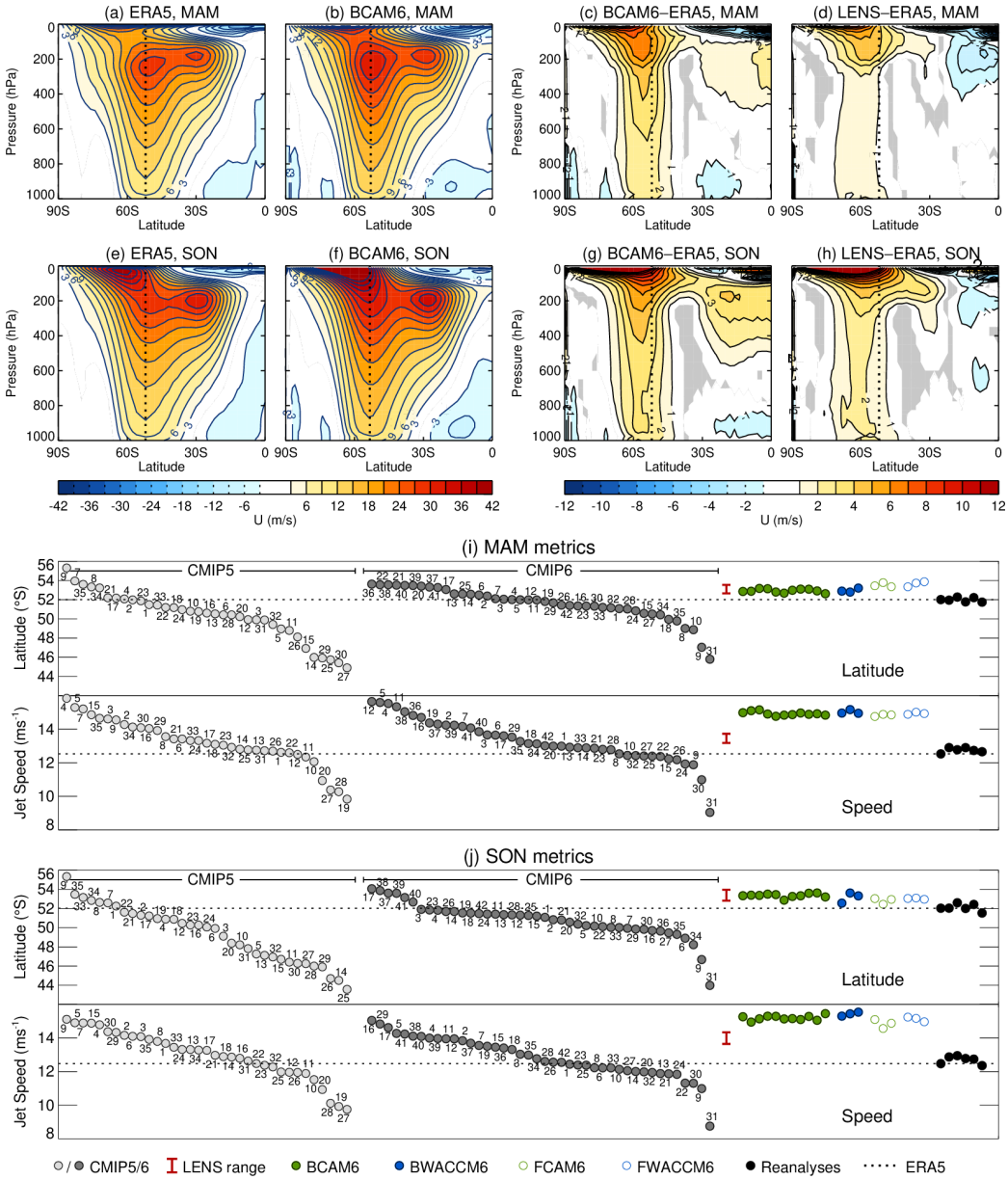

Figure S1. (a)-(d) MAM zonal mean zonal wind for (a) ERA5, (b) BCAM6, (c) BCAM6−ERA5, (d) LENS−ERA5. (e)-(h) SON zonal mean zonal wind for (e) ERA5, (f) BCAM6, (g) BCAM6−ERA5 and (h) LENS−ERA5. The black vertical dashed line in (a), (c), (d), (e), (g) and (h) depicts the ERA5 jet latitude, while that in (b) and (f) depicts the BCAM6 jet latitude. Gray shading in (c), (d), (g) and (h) shows where ERA5 lies within the spread of the model members. (i) and (j) show the SH jet latitude (top) and jet speed (bottom) in MAM and SON, respectively. In (i) and (j) light gray = CMIP5, dark gray = CMIP6, the light red range shows the range across the 40 LENS members, solid green = BCAM6, solid blue = BWACCM6, open green = FCAM6, open blue = FWACCM6 and black = reanalyses from left to right: ERA5, ERA-Interim, MERRA2, JRA55, ERA20C and 20CR. The horizontal dotted line shows the ERA5 value.

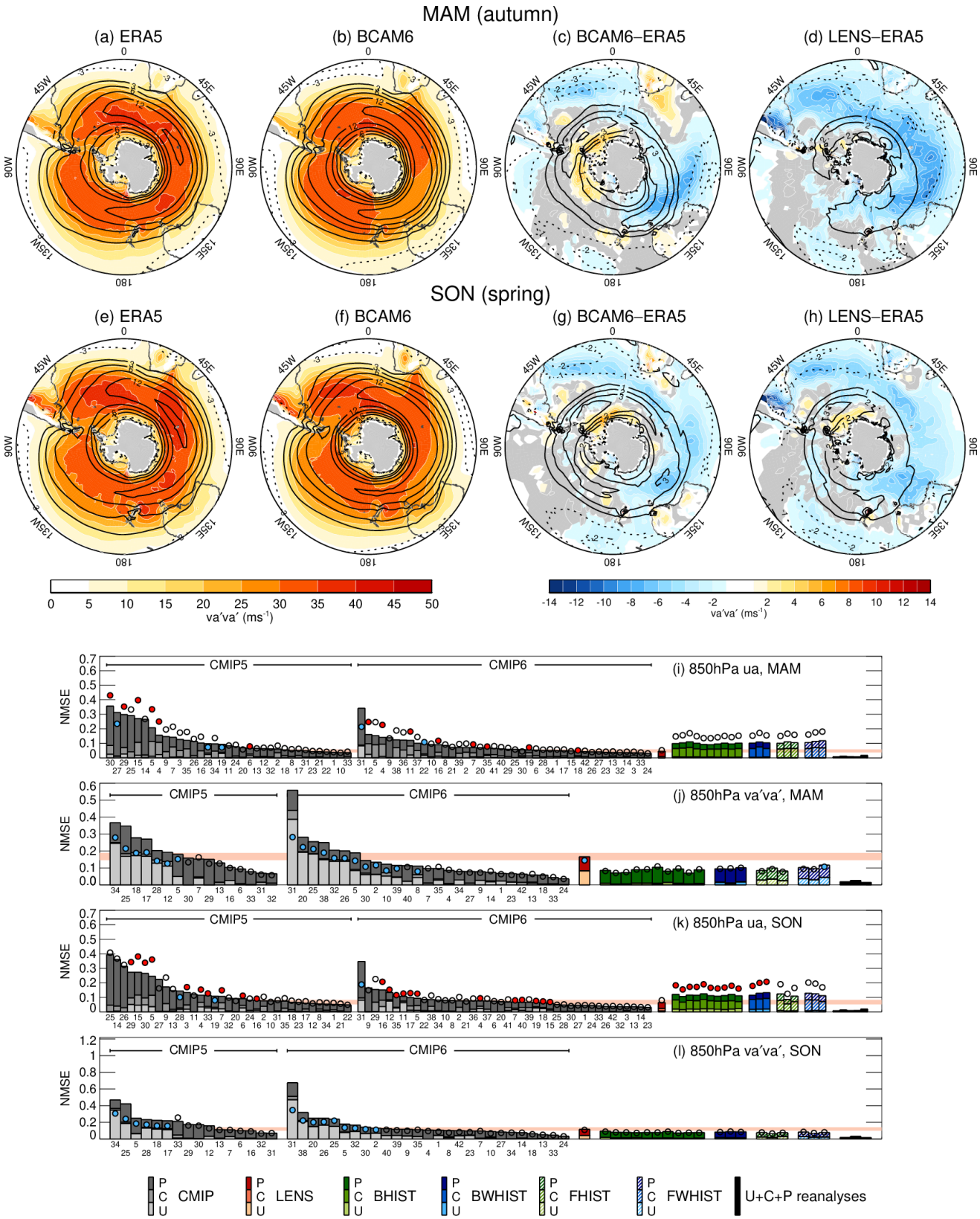

Figure S2. (a)-(h) 850hPa *ua* (contours) and 850hPa 10-day high pass filtered eddy meridional wind variance ($va'va'$) (shading). (a) ERA5, (b) BCAM6, (c) BCAM6−ERA5 and (d) LENS−ERA5 for MAM. Gray shading in (c) and (d) shows regions where ERA5 lies within the model ensemble spread. (e)-(h) are as (a)-(d) but for SON. (i) and (j) NMSE of *ua* and $va'va'$ for MAM and (k) and (l) show the same for SON.

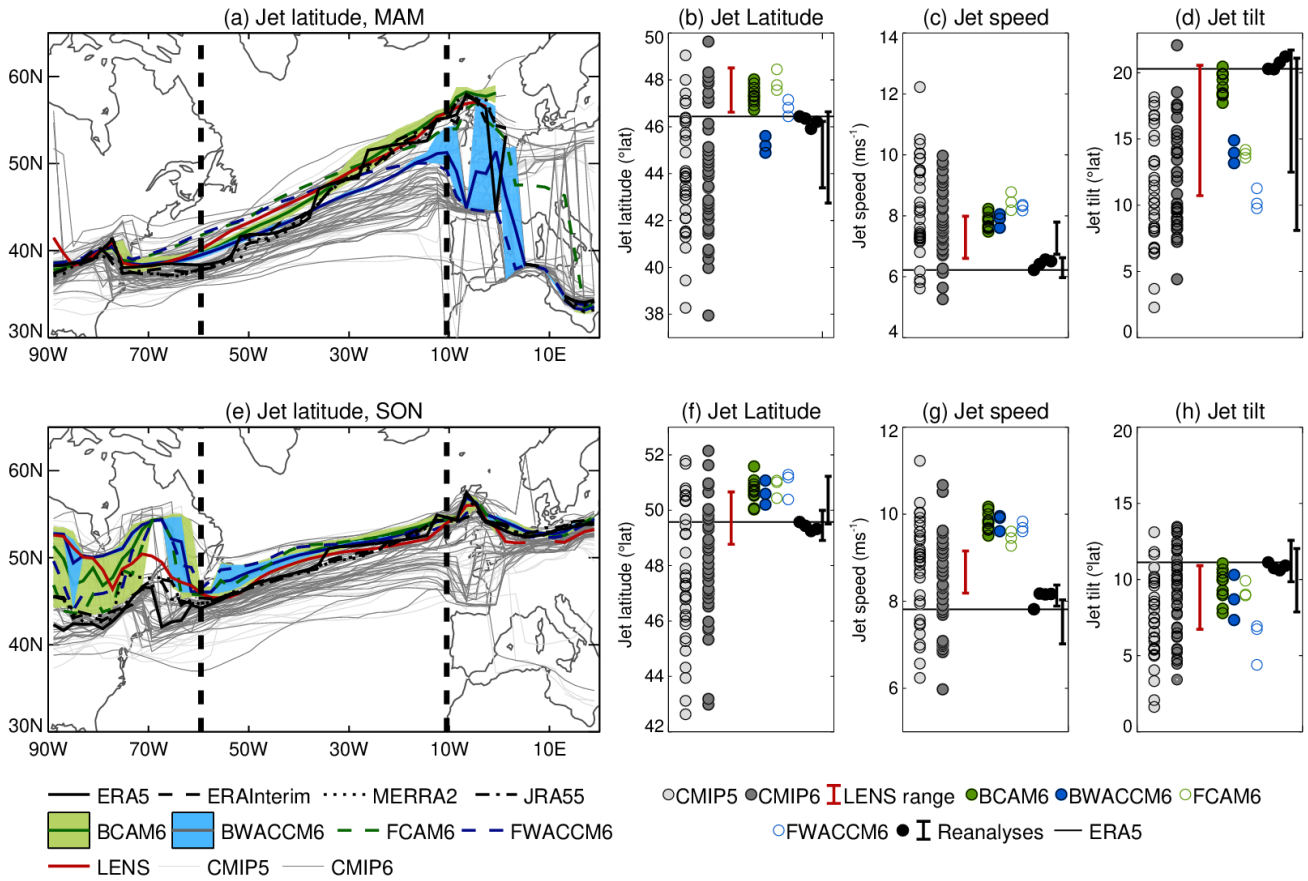

Figure S3. Metrics of the North Atlantic jet. (a) Local jet latitude, (b) Atlantic averaged jet latitude, (c) Atlantic averaged jet speed and (d) jet tilt across the Atlantic, during MAM. Metrics are calculated between 60°W and 10°W (black dashed lines in (a)). (e)-(h) are as (a)-(d) but for SON.

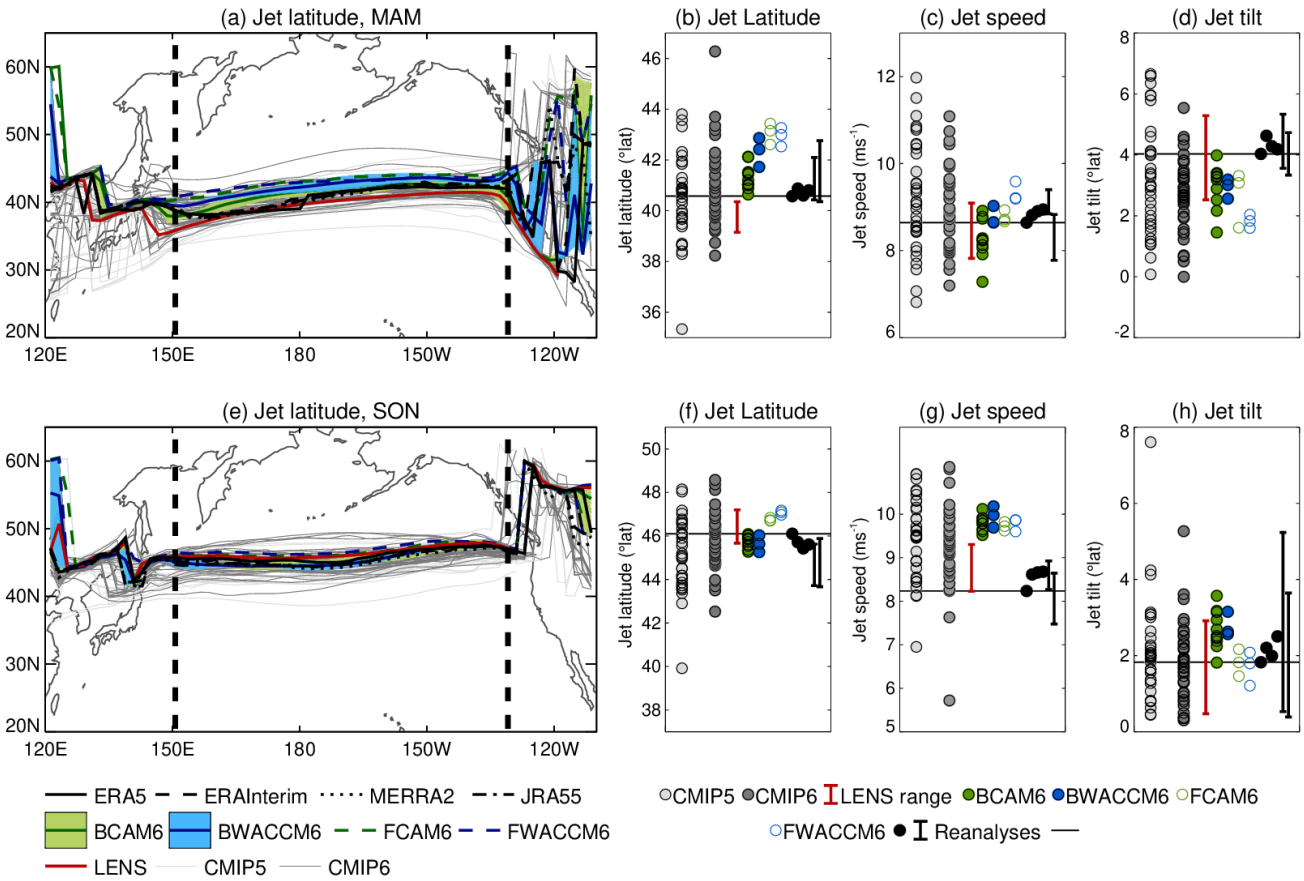

Figure S4. Metrics of the North Pacific jet. (a) Local jet latitude, (b) Atlantic averaged jet latitude, (c) Atlantic averaged jet speed and (d) jet tilt across the Atlantic, during MAM. Metrics are calculated between 150°E and 130°W (black dashed lines in (a)). (e)-(h) are as (a)-(d) but for SON.

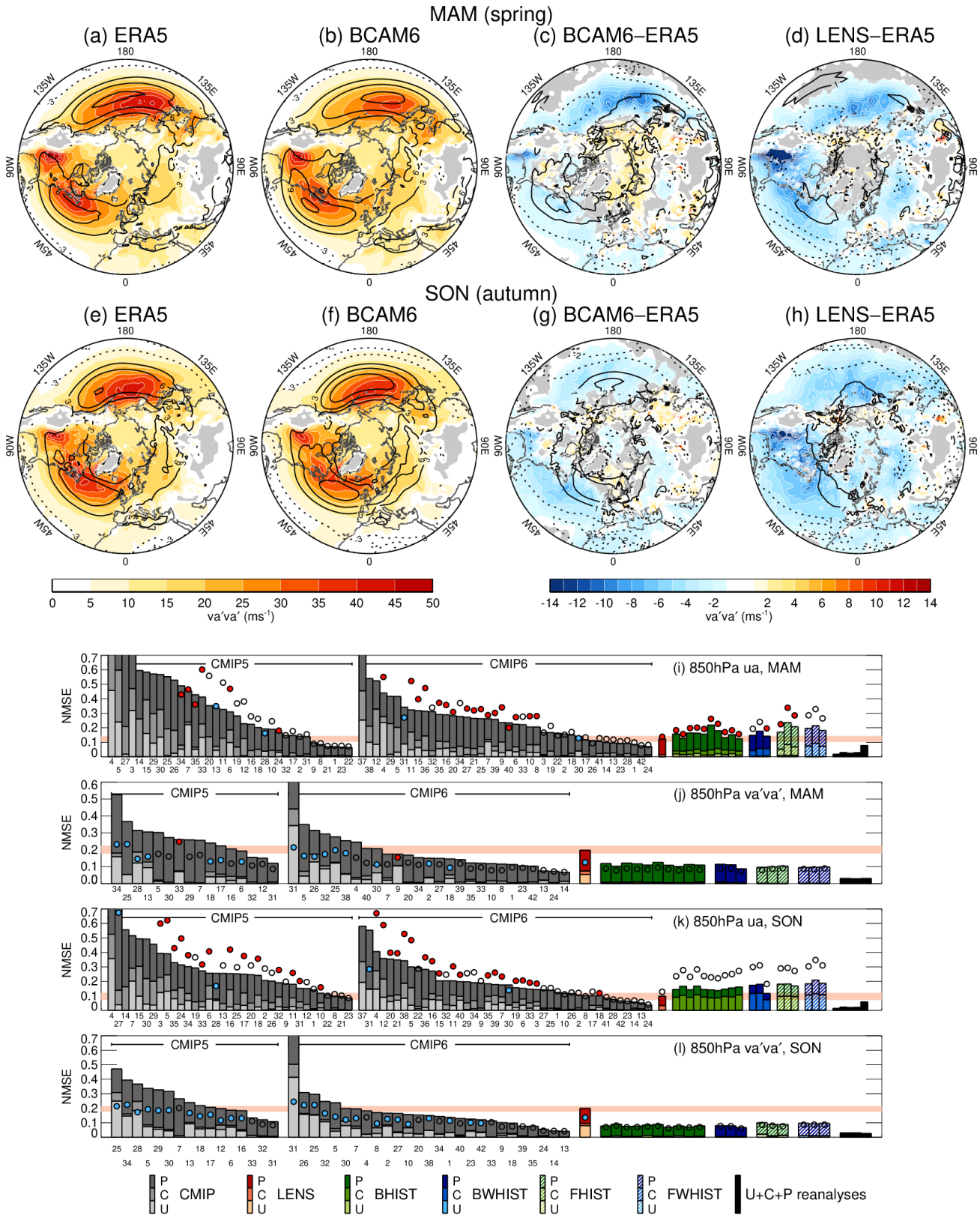

Figure S5. (a)-(h) 850hPa ua (contours) and 850hPa 10-day high pass filtered eddy meridional wind variance ($va'va'$) (shading). (a) ERA5, (b) BCAM6, (c) BCAM6−ERA5 and (d) LENS−ERA5 for MAM. Gray shading in (c) and (d) shows regions where ERA5 lies within the model ensemble spread. (e)-(h) are as (a)-(d) but for SON. (i) and (j) NMSE of ua and $va'va'$ for MAM and (k) and (l) show the same for SON.

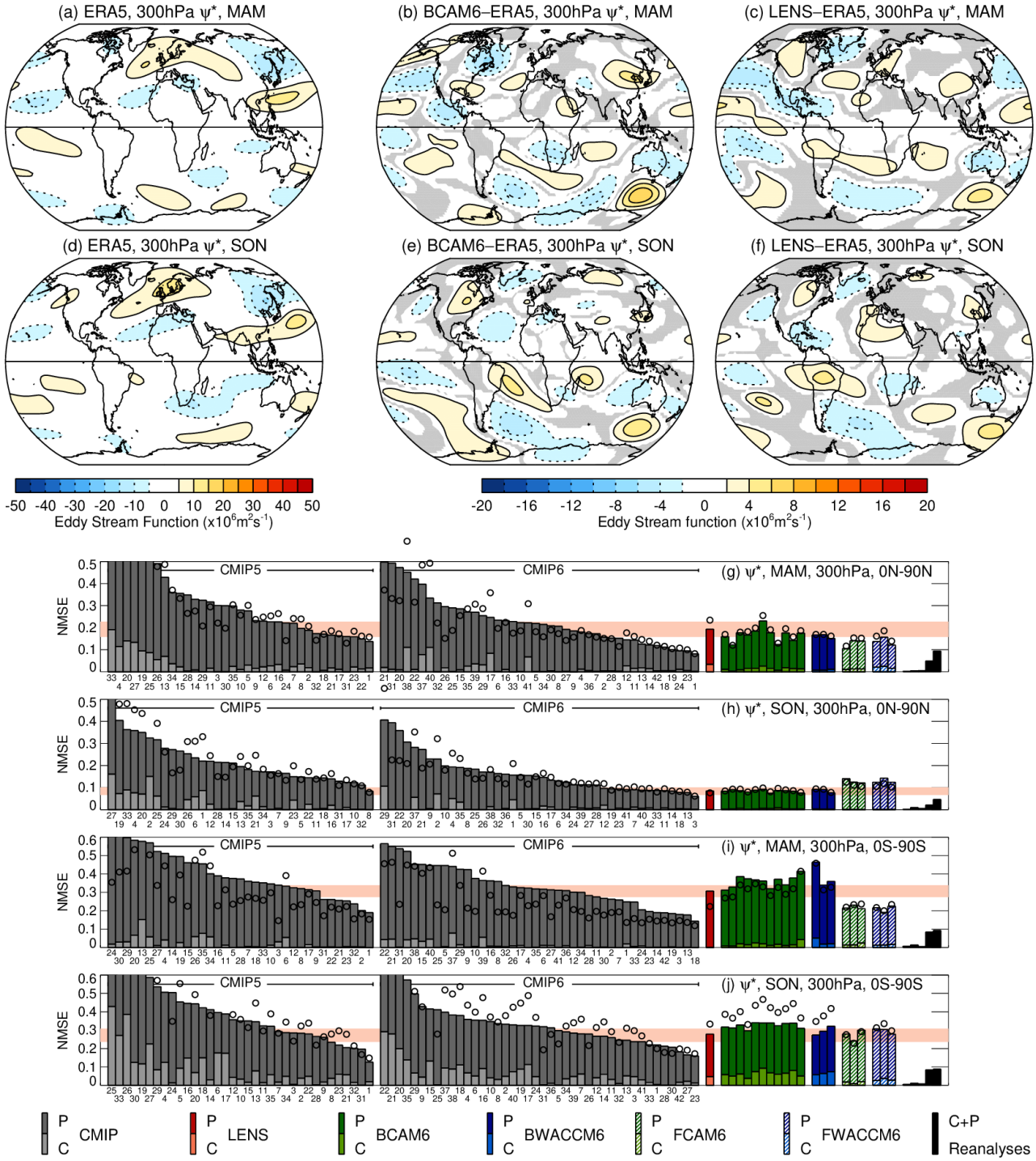

Figure S6. 300hPa eddy stream function during MAM for (a) ERA5, (b) BCAM6−ERA5 and (c) LENS−ERA5. Gray shading in (b) and (c) shows regions where ERA5 lies within the model ensemble spread. (d)-(f) are as (a)-(c) but for SON. (g)-(j) NMSE for NH during MAM, NH during SON, SH during MAM and SH during SON, respectively.

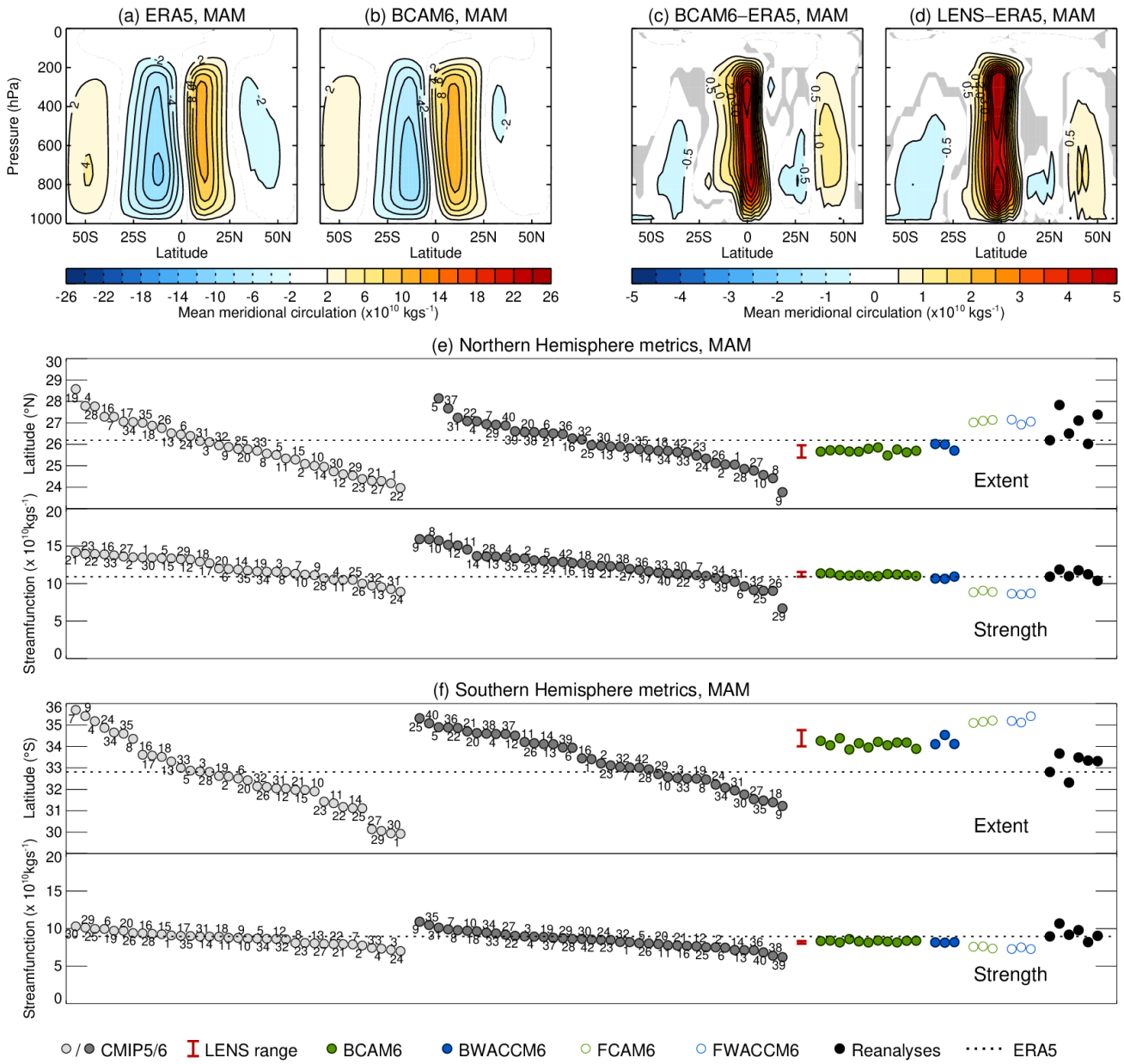

Figure S7. (a)-(d) The MAM zonal mean meridional stream function for (a) ERA5, (b) BCAM6, (c) BCAM6−ERA5 and (d) LENS−ERA5. Gray shading in (c) and (d) shows regions where ERA5 lies within the distribution of the model ensemble members. (e) Hadley cell extent (top) and strength (bottom) in the NH during MAM, (f) is as (e) but for the SH during MAM.

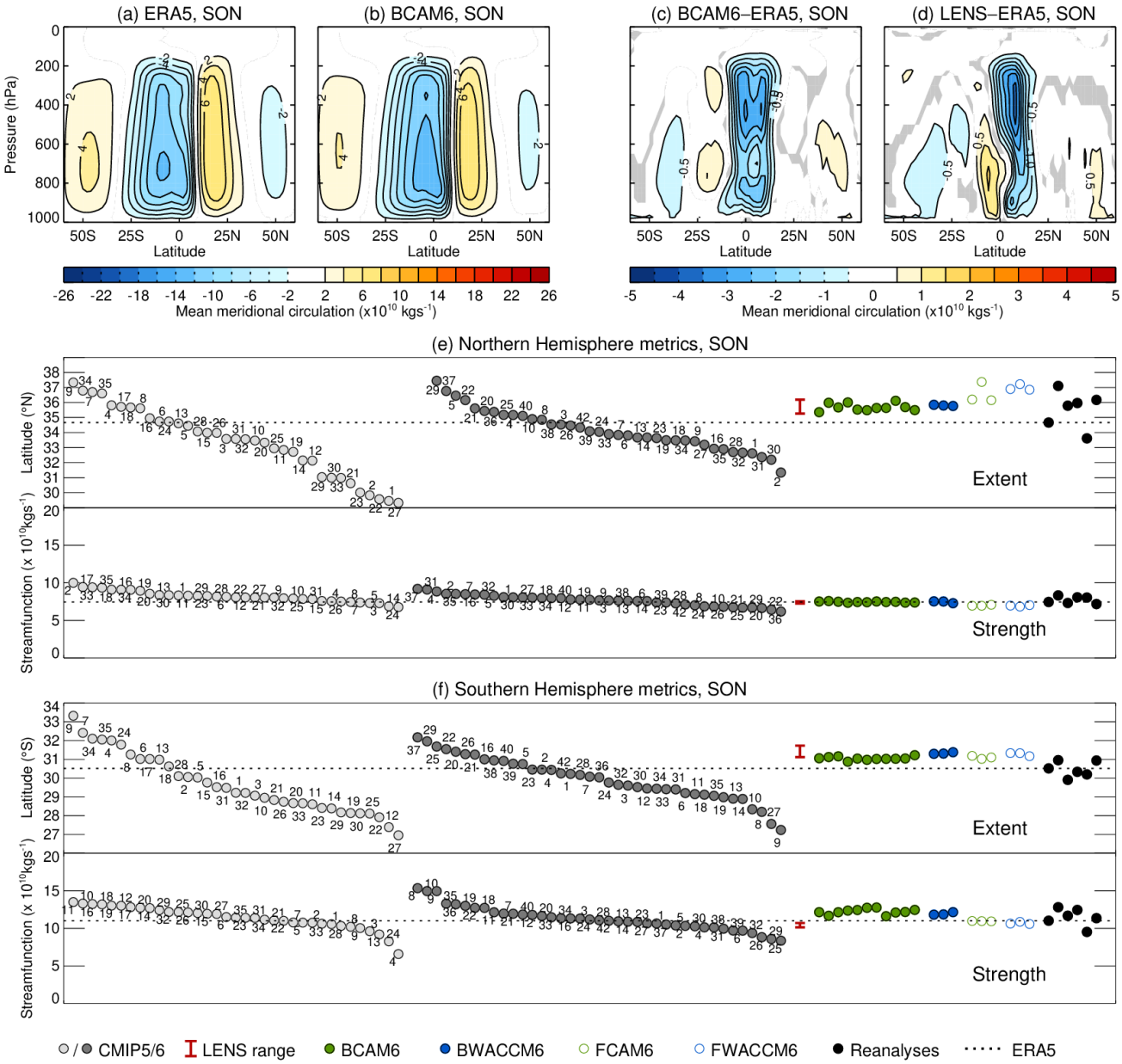

Figure S8. As Fig. S7 but for SON.

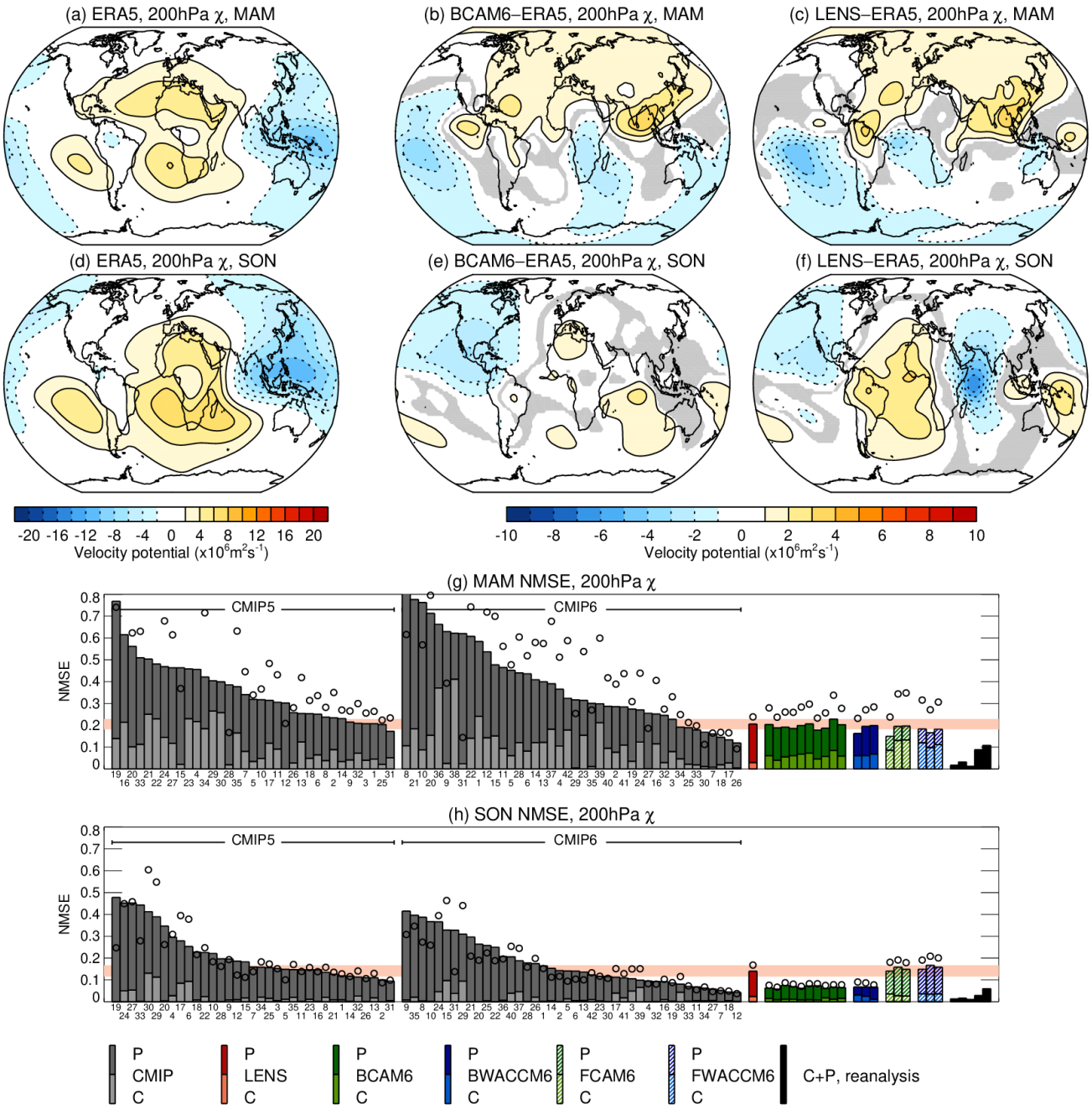

Figure S9. 200hPa velocity potential. (a) ERA5, (b) BCAM6−ERA5 and (c) LENS−ERA5 during MAM. Gray shading in (b) and (c) depicts where ERA5 lies within the spread of the model ensemble. (d)-(f) are as (a)-(c) but for SON. (g) and (h) show the NMSE and its components (see legend) along with the SVR (circles) for MAM and SON, respectively. The light red range that spans (g) and (h) indicates the minimum to maximum range of the LENS ensemble members and the ordering of the reanalyses from left to right is ERA-Interim, MERRA2, JRA55, ERA20C and 20CR. Note there is no unconditional bias for velocity potential since its global average is zero.

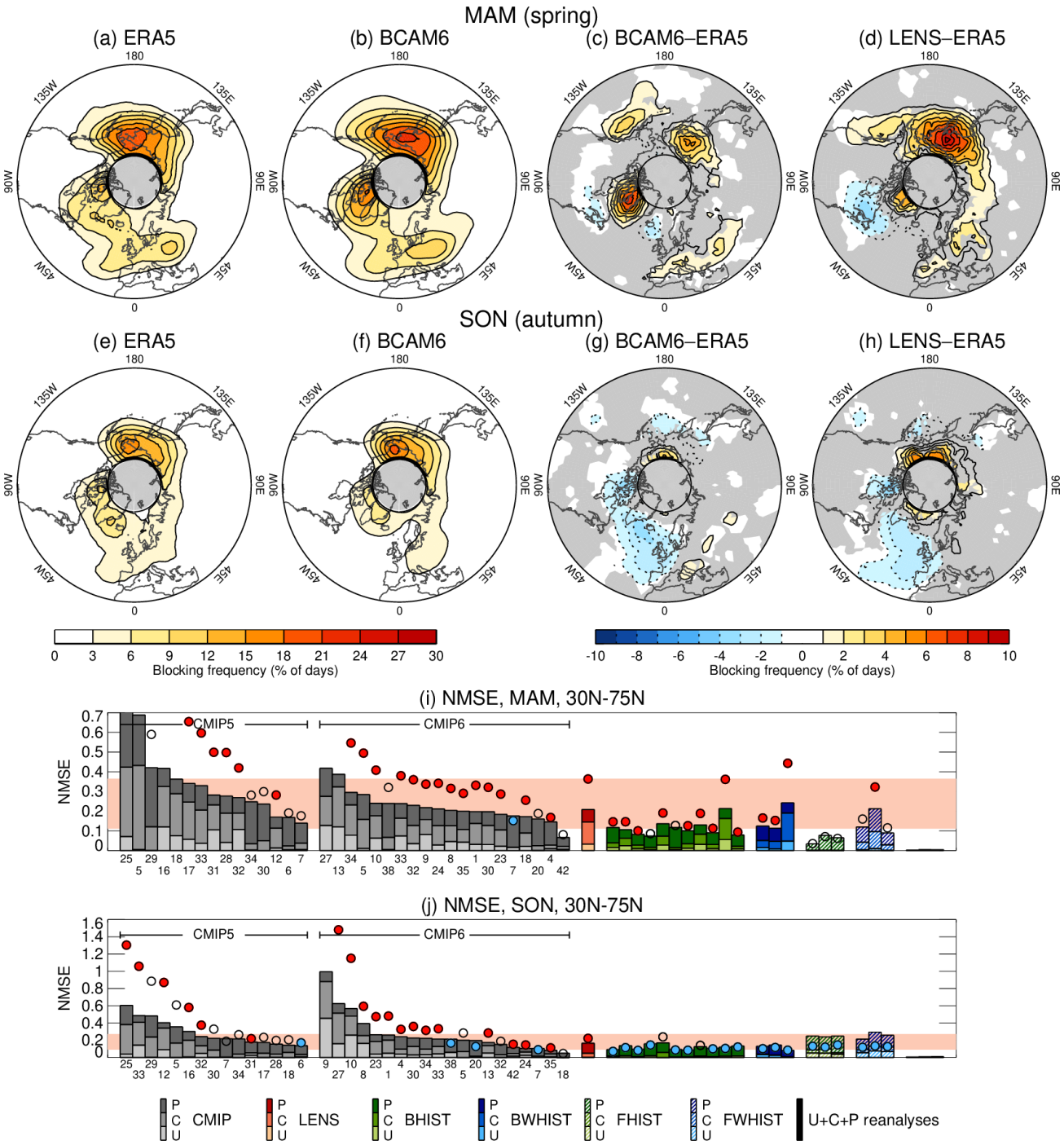

Figure S10. Blocking frequency (% of days) for the NH between 30°N and 75°N. (a)-(d) show MAM ERA5 climatology, BCAM6 climatology, BCAM6−ERA5 and LENS−ERA5, respectively. Gray shading in (c) and (d) indicate where ERA5 lies within the model ensemble member distribution. (e)-(h) are as (a)-(d) but for SON. (i) and (j) NMSE (see legend) and SVR (circles) for MAM and SON, respectively. The light red range that spans (i) and (j) indicates the minimum to maximum ranges for LENS and the reanalyses are ordered from left to right: ERAInterim, MERRA2 and JRA55. For CMIP, when the unconditional bias corresponds to a magnitude of the spatial mean bias that is greater than 10% of the ERA5 spatial mean the SVR circle is shaded red/blue for positive/netgative biases.

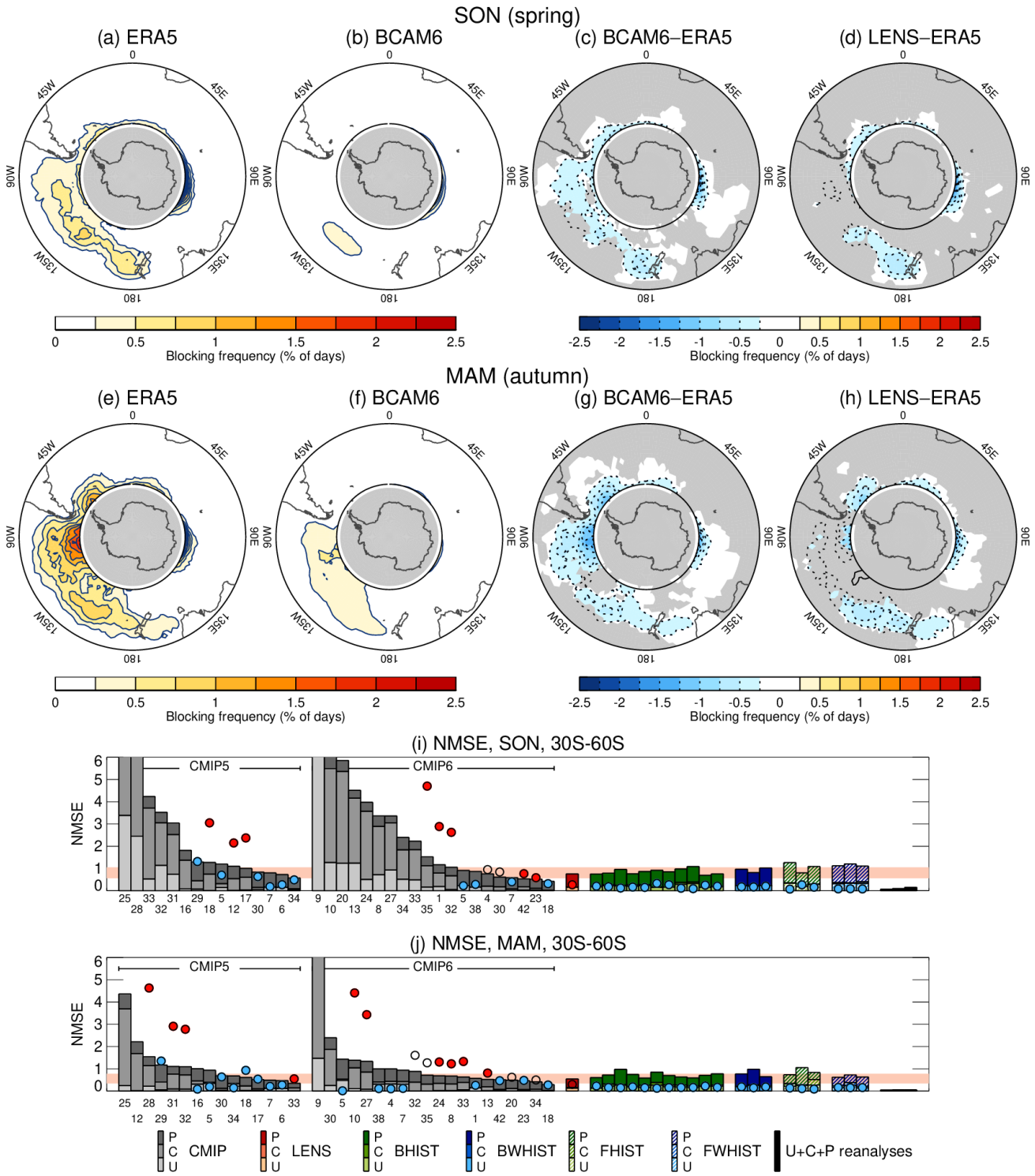

Figure S11. Blocking frequency (% of days) for the SH between 30°S and 60°S. (a)-(d) show the SON ERA5 climatology, BCAM6 climatology, BCAM6−ERA5 and LENS−ERA5, respectively. Gray shading in (c) and (d) indicate where ERA5 lies within the model ensemble member distribution. (e)-(h) are as (a)-(d) but for MAM. (i) and (j) NMSE (see legend) and SVR (circles) for SON and MAM, respectively. The light red range that spans (i) and (j) indicates the minimum to maximum ranges for LENS and the reanalyses are ordered from left to right: ERA-Interim, MERRA2 and JRA55. For CMIP, when the unconditional bias corresponds to a spatial mean bias that has a magnitude greater than 10% of the ERA5 spatial mean, the SVR symbols is colored red/blue for positive/negative biases.

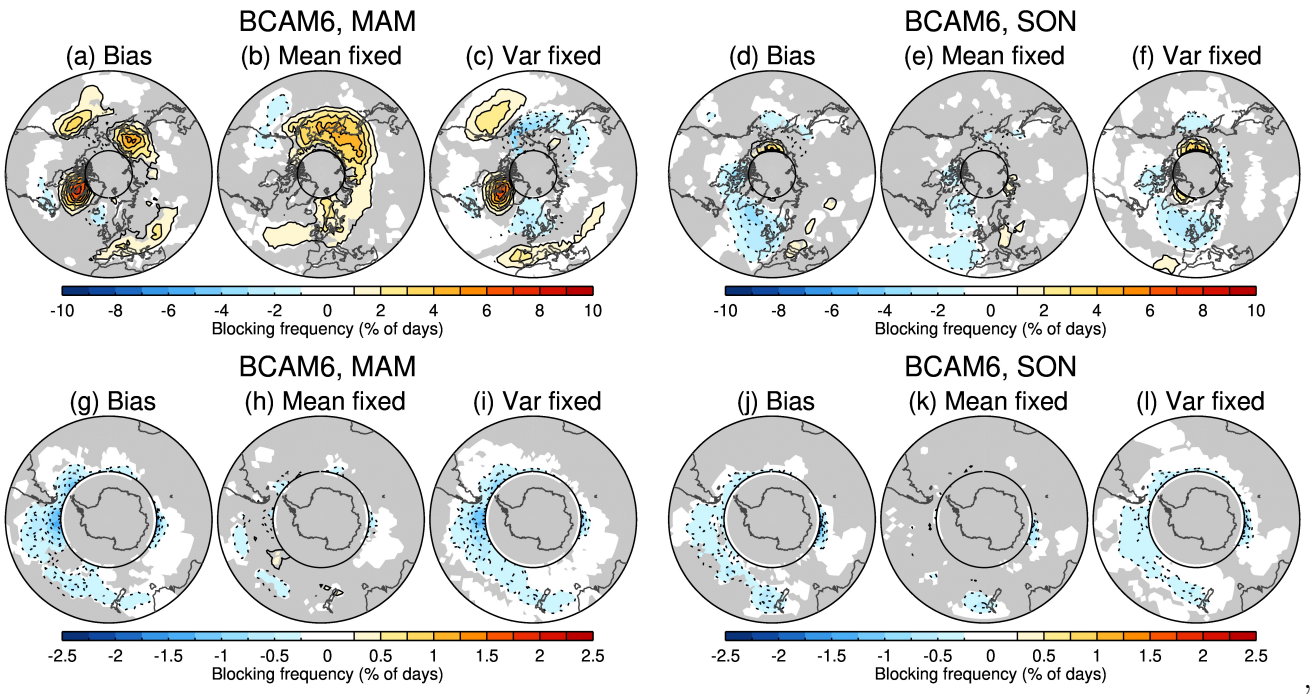

Figure S12. (a)-(c) shows a decomposition of the NH MAM blocking bias in BCAM6 (a) into a contribution that is present when the seasonal mean climatology of zg is replaced by that of ERA5 (b) and a contribution that is present when the deviations from the seasonal mean climatology of zg are replaced by those of ERA5 (c) i.e., (b) shows the bias that would be present if the mean state were improved but the variability left unchanged and (c) shows the bias that would be present if the variability were improved but the mean state left unchanged. (d)-(f), (g)-(i) and (j)-(k) are as (a)-(c) but for the NH during SON, the SH during MAM and the SH during SON, respectively.

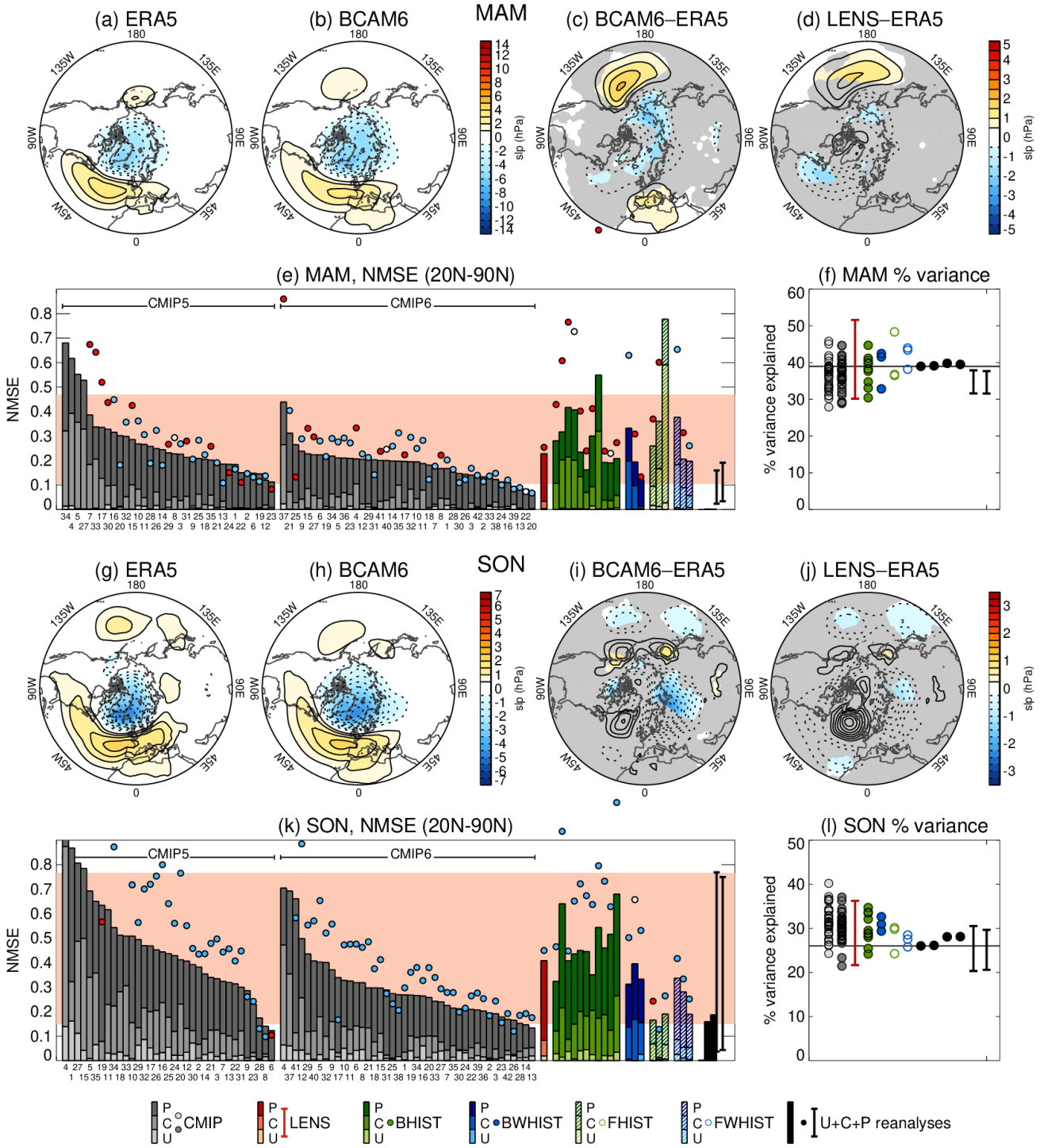

Figure S13. (a)-(d) The MAM NAO for (a) ERA5, (b) BCAM6, (c) BCAM6−ERA5 and (d) LENS−ERA5. (e) the NMSE of the spatial structure of the MAM NAO from 20N-90N: gray = CMIP5 and 6; red = LENS with the light red range that spans the panel indicating the minimum and maximum for the 40 members; green = BCAM6; blue = BWACCM6; green hatched = FCAM6; blue hatched = FWACCM6; black from left to right = ERA5, ERA-Interim, MERRA2, JRA55 and the range of 36 years segments of ERA20C and 20CR. (f) The percentage of variance explained by the NAO with the same ordering as (e). (g)-(l) are as (a)-(f) but for the SON NAO.

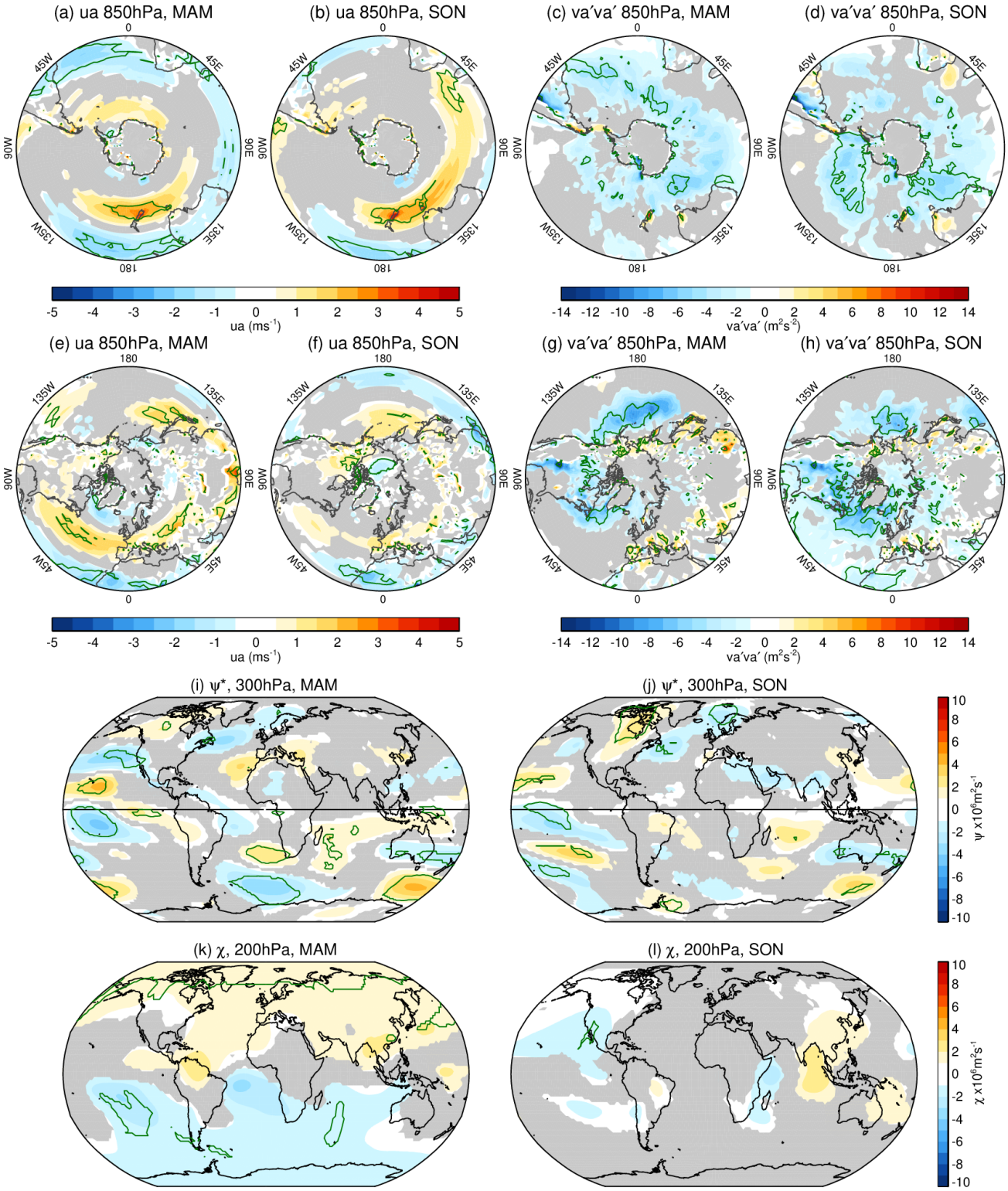

Figure S14. CMIP6 ensemble mean bias relative to ERA5. Gray shading depicts regions where less than 75% of the models agree on the sign of the change and green contour shows where mode than 95% of models agree on the sign of the change. (a), (b), (e) and (f) show 850hPa *ua*. (c) (d), (g) and (h) show 850hPa 10-day high pass eddy meridional wind variance. (i) and (j) show 300hPa eddy stream function and (k) and (l) show 200hPa velocity potential.

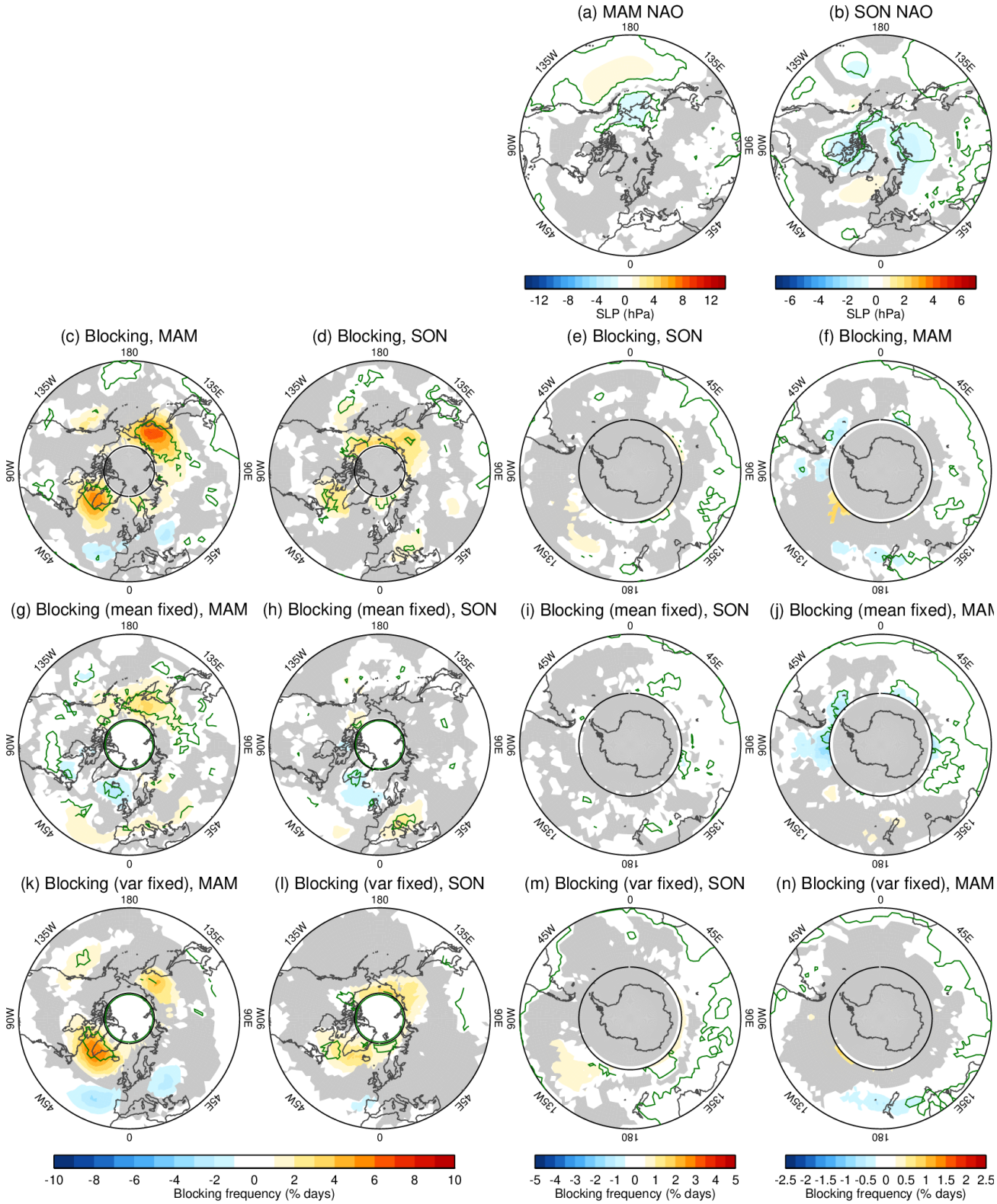

Figure S15. CMIP6 ensemble mean biases relative to ERA5 for variability metrics. Gray shading depicts regions where less than 75% of the models agree on the sign of the change and green contour shows where more than 95% of models agree on the sign of the change. (a) and (b) show the spring and autumn NAO. (c)-(f) show the representation of blocking. (g)-(j) are as (c)-(f) but replacing each models climatology with that of ERA5 before calculating the blocking statistics. (k)-(n) are as (c)-(f) but replacing each models transient variability (deviations from climatology) with that of ERA5 before calculating the blocking statistics.

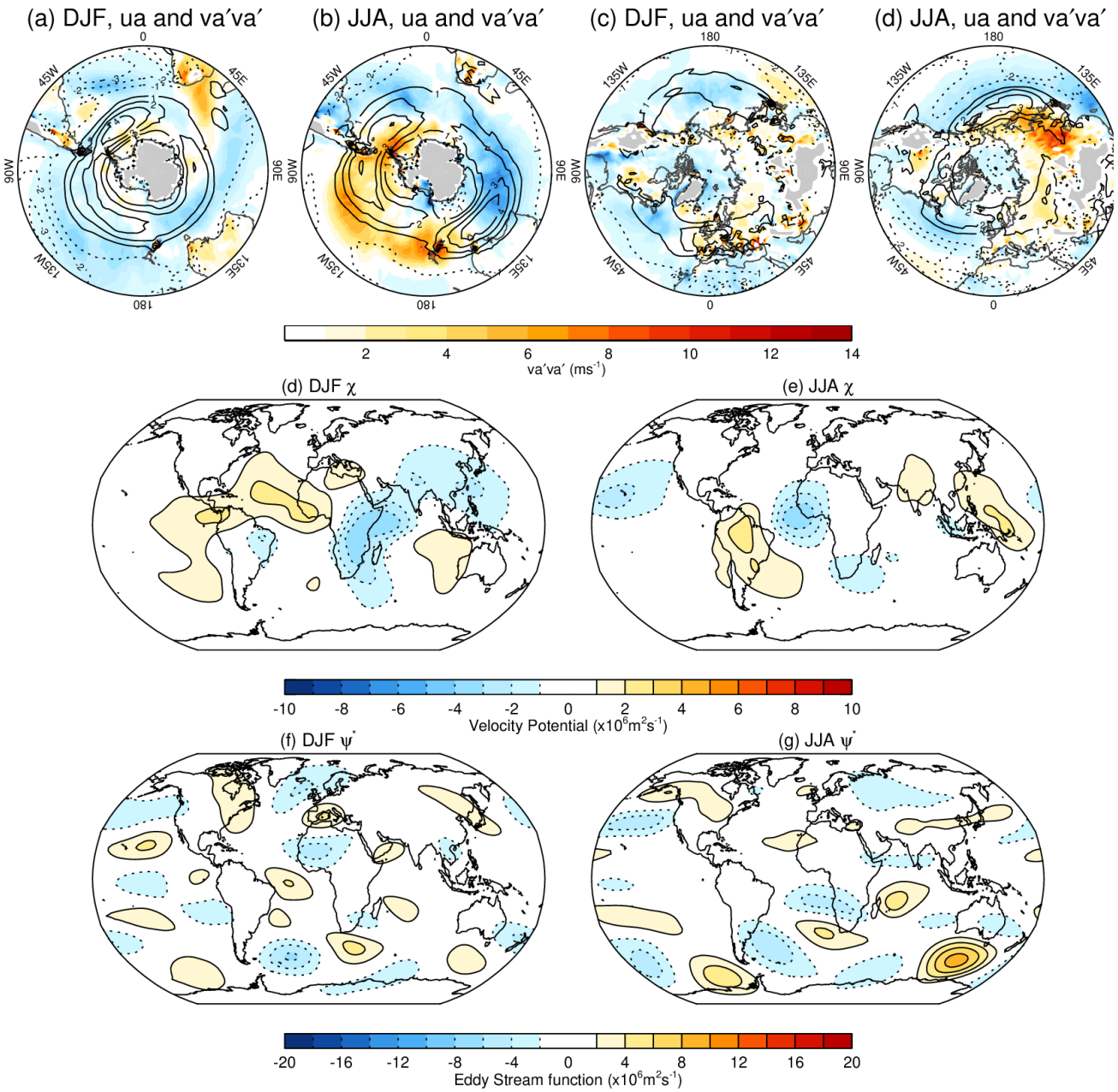

Figure S16. Mean field biases relative to ERA5 for CESM2-WACCM (the BWACCM6 simulations). (a),(b),(c) and (d) 850hPa zonal wind and 10-day high pass filtered eddy meridional wind variance for SH DJF, SH JJA, NH DJF and NH JJA, respectively. (d) and (e) 200hPa velocity potential for DJF and JJA, respectively and (f) and (g) 300hPa eddy stream function for DJF and JJA, respectively.

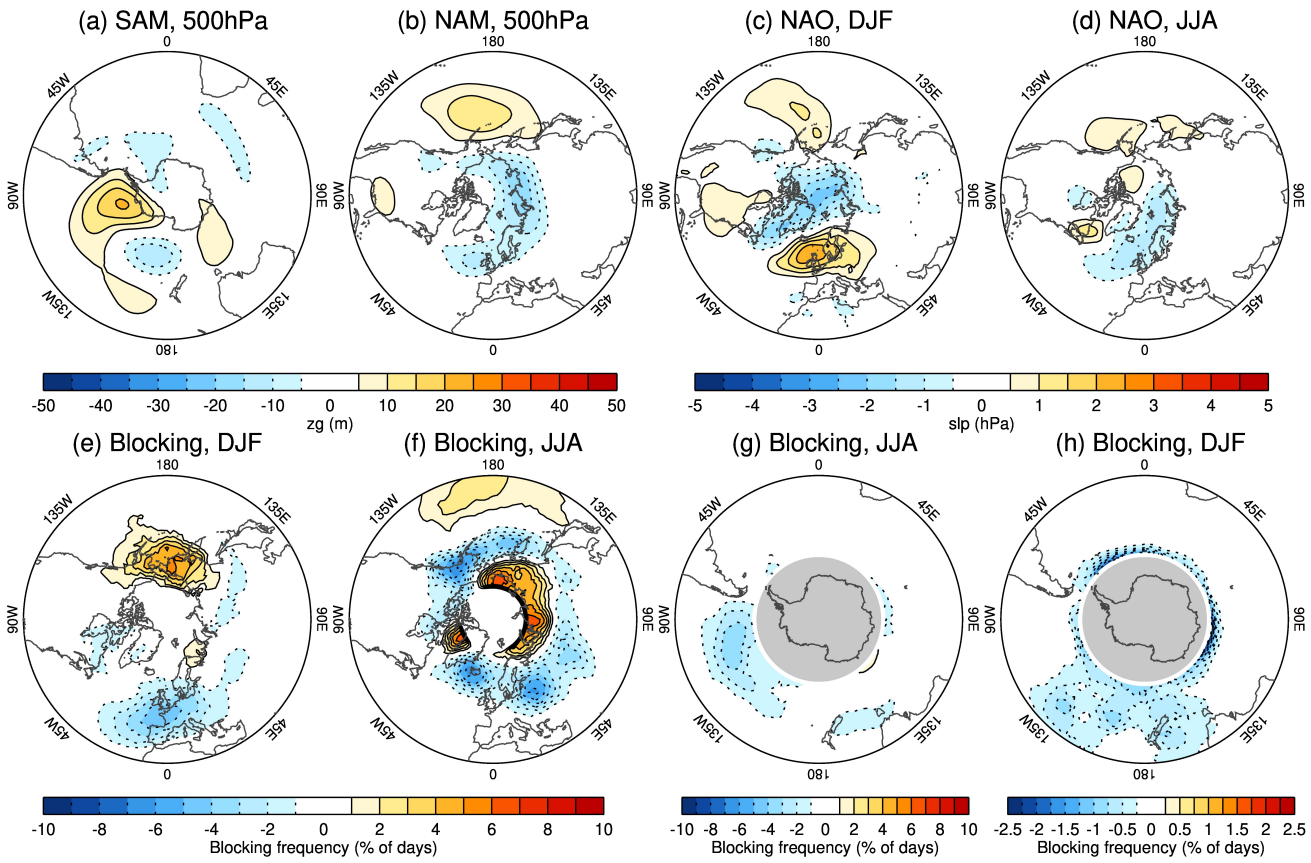

Figure S17. Variability biases relative to ERA5 for CESM2-WACCM (the BWACCM6 simulations). (a) structure of 500hPa zg anomalies associated with the SAM. (b) as (a) but for the NAM. (c) the DJF NAO. (d) the JJA NAO. (e)-(h) are Blocking frequencies for NH DJF, NH JJA, SH JJA and SH DJF, respectively.

Table S1. North Atlantic jet metrics as shown in Figure 4 of the main text

CMIP5							CMIP6						
Name	Jet latitude		Jet Speed		Jet Tilt		Name	Jet Latitude		Jet Speed		Jet Tilt	
	DJF	JJA	DJF	JJA	DJF	JJA		DJF	JJA	DJF	JJA	DJF	JJA
ACCESS1-0	47.10	49.51	10.47	6.27	13.21	14.60	ACCESS-CM2	42.18	49.49	8.91	5.91	17.08	15.12
ACCESS1-3	49.41	50.80	10.99	7.02	12.55	14.14	ACCESS-ESM1-5	49.39	50.74	11.18	7.91	12.64	16.09
bcc-csm1-1	44.57	48.26	13.06	8.78	7.86	13.66	AWI-CM-1-1-MR	44.71	47.89	9.99	7.41	6.72	11.64
bcc-csm1-1-m	45.66	49.56	14.88	9.56	5.15	11.57	BCC-CSM2-MR	45.14	48.46	11.78	8.94	8.56	11.86
BNU-ESM	44.77	49.87	13.08	7.86	6.94	11.56	BCC-ESM1	42.59	46.93	9.75	8.28	10.79	12.72
CanESM2	45.34	49.34	12.71	8.92	7.77	12.60	CAMS-CSM1-0	44.19	47.50	10.24	8.47	8.21	12.89
CCSM4	47.62	48.06	14.00	7.63	8.04	13.96	CanESM5	46.18	49.35	13.06	7.52	12.56	13.25
CESM1-CAM5	48.10	47.09	11.62	7.65	12.19	10.59	CNRM-CM6-1	43.93	44.47	10.10	5.23	12.15	8.28
CESM1-WACCM	46.58	47.92	10.53	7.22	11.53	16.82	CNRM-CM6-1-HR	42.13	45.78	9.16	5.37	13.55	12.82
CMCC-CM	42.29	46.45	9.69	7.65	11.98	11.92	CNRM-ESM2-1	43.70	44.94	10.39	4.94	12.44	9.83
CMCC-CMS	41.50	45.73	10.49	8.63	11.45	11.31	E3SM-1-0	43.41	47.20	11.44	8.75	12.66	9.59
CNRM-CM5	43.26	45.76	10.53	7.37	10.28	5.83	E3SM-1-1	44.52	47.95	11.57	8.71	13.90	10.06
CSIRO-Mk3-6-0	39.95	47.22	9.00	8.64	9.45	14.43	EC-Earth3	46.96	49.05	10.95	6.94	11.22	14.43
FGOALS-g2	38.93	43.35	9.06	6.87	3.60	6.25	EC-Earth3-Veg	46.63	49.07	10.84	6.84	10.80	13.79
FIO-ESM	43.89	47.56	12.61	7.06	8.12	9.75	FGOALS-f3-L	46.60	47.26	12.41	6.78	7.30	9.70
GFDL-CM3	46.01	46.72	10.67	7.79	17.06	8.76	FGOALS-g3	45.92	49.55	11.47	6.68	5.64	8.57
GFDL-ESM2G	44.32	46.77	10.89	8.24	10.02	9.36	FIO-ESM-2-0	48.48	47.93	11.68	8.15	14.48	12.77
GFDL-ESM2M	42.51	47.37	10.56	8.14	9.32	9.40	GFDL-CM4	42.85	46.12	9.98	7.79	15.10	9.60
GISS-E2-H	40.29	47.18	9.06	4.44	15.80	10.47	GFDL-ESM4	42.82	45.77	11.30	8.14	12.93	9.90
GISS-E2-R	41.01	47.58	10.31	4.91	12.77	16.01	GISS-E2-1-G	43.63	47.49	10.28	6.20	11.64	14.84
HadGEM2-AO	47.39	50.08	11.16	6.34	13.24	14.18	GISS-E2-1-G-CC	44.10	46.93	10.69	6.26	12.03	14.01
HadGEM2-CC	45.27	51.02	9.87	6.31	11.14	11.55	GISS-E2-1-H	44.17	47.96	9.48	5.58	13.26	17.56
HadGEM2-ES	47.88	50.86	10.72	6.38	15.86	14.48	HadGEM3-GC31-LL	44.33	49.13	8.88	7.04	16.81	14.11
inmcm4	45.08	50.57	10.10	6.53	4.68	11.69	HadGEM3-GC31-MM	43.80	49.01	8.87	7.22	18.13	13.81
IPSL-CM5A-LR	44.63	47.03	13.15	5.11	7.99	12.54	INM-CM4-8	46.74	50.22	10.53	7.88	7.99	14.36
IPSL-CM5A-MR	44.43	47.31	12.96	6.74	7.42	10.27	INM-CM5-0	44.90	49.02	8.56	7.81	16.08	11.62
IPSL-CM5B-LR	44.14	43.08	9.60	3.35	11.01	15.04	IPSL-CM6A-LR	46.11	48.36	11.08	5.40	6.59	13.05
MIROC5	42.45	45.97	6.50	7.40	24.96	10.10	KACE-1-0-G	43.46	50.14	8.86	7.57	19.39	16.93
MIROC-ESM	42.81	46.48	12.65	6.81	6.35	5.30	MCM-UA-1-0	45.02	47.67	11.49	9.34	11.23	8.00
MIROC-ESM-CHEM	41.75	46.41	12.08	6.75	8.81	4.22	MIROC6	42.19	45.69	7.71	7.21	14.64	11.73
MPI-ESM-LR	43.84	46.39	10.54	8.58	6.19	9.89	MIROC-ES2L	34.94	46.15	7.29	7.42	6.26	10.09
MPI-ESM-MR	43.95	45.97	10.89	8.71	8.11	9.21	MPI-ESM-1-2-HAM	45.34	46.54	9.95	8.01	7.95	10.39
MRI-CGCM3	45.73	47.97	13.50	5.58	13.01	13.70	MPI-ESM1-2-HR	44.40	46.93	9.90	7.28	11.33	11.68
NorESM1-M	48.94	48.27	12.13	7.09	6.35	12.15	MPI-ESM1-2-LR	43.61	47.09	11.00	7.90	7.41	11.18
NorESM1-ME	48.39	48.67	11.57	6.99	5.16	14.49	MRI-ESM2-0	42.77	47.08	11.15	6.86	12.88	11.25
							NESM3	44.65	47.87	12.13	7.67	9.01	11.04
							NorCPM1	49.30	50.18	12.77	7.82	4.57	7.99
ERA5	46.60	47.63	9.75	7.17	16.20	12.83	NorESM2-LM	46.00	52.31	11.70	8.38	8.58	5.45
							NorESM2-MM	45.91	50.38	10.96	9.40	10.85	13.64
							SAM0-UNICON	48.44	47.06	13.05	8.06	13.38	13.60
							TaiESM1	48.07	48.10	12.41	6.65	13.83	13.62
							UKESM1-0-LL	47.00	49.62	9.24	6.77	18.03	15.25

Table S2. North Pacific jet metrics as shown in Figure 5 of the main text. In cases where the jet tilt has not been defined it is because at at least one of the longitudes the jet maximum has jumped to outside of the 20°N-65°N range.

CMIP5							CMIP6						
Name	Jet latitude		Jet Speed		Jet Tilt		Name	Jet Latitude		Jet Speed		Jet Tilt	
	DJF	JJA	DJF	JJA	DJF	JJA		DJF	JJA	DJF	JJA	DJF	JJA
ACCESS1-0	37.69	44.35	12.26	4.83	7.33	10.46	ACCESS-CM2	36.05	42.16	10.93	5.77	5.25	10.34
ACCESS1-3	37.83	43.15	12.59	5.29	6.61	9.28	ACCESS-ESM1-5	38.94	44.85	11.63	5.31	7.22	8.33
bcc-csm1-1	36.55	47.20	10.96	7.28	6.28	-	AWI-CM-1-1-MR	36.38	46.30	8.94	7.25	6.23	5.00
bcc-csm1-1-m	35.66	48.39	13.14	6.99	0.95	-	BCC-CSM2-MR	35.49	46.88	11.67	8.62	5.69	3.93
BNU-ESM	37.24	47.63	12.49	6.93	5.19	-	BCC-ESM1	37.04	46.12	10.13	8.38	7.21	2.93
CanESM2	38.38	46.46	13.29	6.04	3.35	2.63	CAMS-CSM1-0	36.13	47.26	10.53	6.35	2.05	5.17
CCSM4	37.66	48.07	11.33	6.07	3.73	-	CanESM5	38.22	45.36	10.33	5.98	6.11	3.84
CESM1-CAM5	36.17	45.86	11.49	5.71	3.30	7.57	CNRM-CM6-1	37.28	40.86	11.38	6.09	8.43	8.41
CESM1-WACCM	38.57	50.29	10.08	6.05	4.88	3.74	CNRM-CM6-1-HR	36.22	41.56	12.34	6.10	7.51	6.55
CMCC-CM	35.73	43.00	10.13	7.10	2.15	8.22	CNRM-ESM2-1	37.62	40.90	11.65	6.08	7.91	8.71
CMCC-CMS	36.82	44.01	10.12	7.83	5.31	5.65	E3SM-1-0	35.74	45.42	12.45	7.88	6.24	5.67
CNRM-CM5	37.39	43.32	12.35	6.82	6.26	4.24	E3SM-1-1	36.12	45.71	12.22	8.09	6.70	5.18
CSIRO-Mk3-6-0	34.19	48.97	12.24	5.89	2.88	3.37	EC-Earth3	37.05	45.32	12.72	6.37	3.50	5.21
FGOALS-g2	34.52	37.60	11.76	8.01	3.97	6.43	EC-Earth3-Veg	37.22	45.66	12.50	6.32	3.50	5.21
FIO-ESM	37.77	42.94	12.77	7.22	4.65	6.53	FGOALS-f3-L	36.78	45.37	10.83	6.07	-	6.30
GFDL-CM3	34.95	44.67	12.74	7.04	3.09	5.03	FGOALS-g3	36.10	39.84	12.37	7.20	5.49	7.48
GFDL-ESM2G	37.40	44.70	9.49	6.73	5.72	5.66	FIO-ESM-2-0	35.59	46.41	12.24	6.27	3.05	7.09
GFDL-ESM2M	37.55	44.06	10.89	6.81	3.84	6.27	GFDL-CM4	35.75	44.56	10.95	7.02	7.22	5.07
GISS-E2-H	35.65	42.33	11.97	6.81	5.15	4.41	GFDL-ESM4	35.95	44.49	11.51	6.72	5.47	5.00
GISS-E2-R	36.79	41.16	11.30	7.17	0.82	5.43	GISS-E2-1-G	38.45	44.90	8.84	5.62	2.44	4.55
HadGEM2-AO	37.38	44.78	11.05	4.85	9.90	8.18	GISS-E2-1-G-CC	36.98	45.23	8.79	5.60	-0.63	3.84
HadGEM2-CC	36.90	46.87	10.54	4.50	10.12	2.34	GISS-E2-1-H	34.80	44.37	8.62	5.37	1.67	4.73
HadGEM2-ES	37.70	46.53	10.80	4.81	9.40	2.86	HadGEM3-GC31-LL	36.90	44.12	9.91	5.40	6.88	7.63
inmcm4	39.24	44.83	13.26	6.73	2.64	4.66	HadGEM3-GC31-MM	35.94	43.57	11.01	5.42	4.36	8.62
IPSL-CM5A-LR	35.65	41.82	12.49	4.63	3.86	5.28	INM-CM4-8	42.44	47.23	11.72	6.32	4.38	7.61
IPSL-CM5A-MR	36.52	42.88	12.94	4.32	2.80	7.30	INM-CM5-0	38.71	47.10	9.36	5.80	7.52	6.96
IPSL-CM5B-LR	33.30	39.96	12.73	5.12	2.12	5.72	IPSL-CM6A-LR	35.98	44.18	9.91	6.57	6.95	4.88
MIROC5	34.59	44.80	9.49	7.05	5.13	6.48	KACE-1-0-G	36.61	45.19	10.23	5.19	5.46	7.66
MIROC-ESM	39.28	43.06	13.47	7.23	7.28	4.93	MCM-UA-1-0	38.48	47.90	14.33	5.50	2.73	6.42
MIROC-ESM-CHEM	39.26	43.21	13.87	7.37	8.16	3.71	MIROC6	35.02	44.46	10.89	6.84	3.70	6.28
MPI-ESM-LR	36.61	46.69	9.27	7.61	6.94	4.34	MIROC-ES2L	33.68	44.04	9.19	6.70	4.72	8.81
MPI-ESM-MR	36.79	45.87	8.95	8.09	7.54	4.22	MPI-ESM-1-2-HAM	35.23	47.84	8.16	7.31	4.75	3.20
MRI-CGCM3	34.16	43.65	13.64	5.97	3.01	3.74	MPI-ESM1-2-HR	35.17	45.61	9.96	6.56	1.63	5.01
NorESM1-M	36.46	49.05	9.76	5.37	-	-	MPI-ESM1-2-LR	36.80	46.58	9.53	7.47	5.64	4.38
NorESM1-ME	38.05	49.23	9.11	6.24	8.81	-	MRI-ESM2-0	34.89	43.31	13.24	6.60	3.64	7.47
							NESM3	37.86	48.27	8.98	6.92	5.85	1.87
							NorCPM1	38.21	49.99	9.73	6.82	6.98	-
ERA5	37.68	43.44	10.39	6.39	5.67	8.58	NorESM2-LM	37.25	45.89	10.46	7.16	2.26	7.54
							NorESM2-MM	36.66	46.43	10.94	7.29	4.66	7.27
							SAM0-UNICON	37.16	46.24	11.16	6.47	4.89	5.99
							TaiESM1	36.26	45.00	11.26	5.92	3.41	8.20
							UKESM1-0-LL	38.34	43.47	9.55	5.54	8.67	7.94