Supplementary Information

Southward migration of the zero-degree isotherm latitude over the Southern Ocean and the Antarctic Peninsula: Cryospheric, biotic and societal implications

Sergi González-Herrero[1,2], Francisco Navarro[3], Luis R. Pertierra[4,5], Marc Oliva[6], Ruzica Dadic[1], Lloyd Peck[7], Michael Lehning[1,8]

[1]WSL Institute for Snow and Avalanche Research (SLF), Davos, Switzerland
[2]Antarctic Group, Agencia Estatal de Meteorología (AEMET), Barcelona, Spain
[3]Departmento de Matemática Aplicada a las TIC, ETSI de Telecomunicación, Universidad Politécnica de Madrid, Madrid, Spain
[4]Plant & Soil Sciences Department, University of Pretoria, Pretoria, South Africa
[5]Millennium Institute Biodiversity of Antarctic and Subantarctic Ecosystems (BASE), Universidad Católica de Chile, Santiago, Chile
[6]Department of Geography, Universitat de Barcelona, Barcelona, Spain
[7]British Antarctic Survey, UKRI-NERC, Cambridge, UK
[8]School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

1. Supplementary tables and figures

Table S1. List of CMIP6 models used in this study

	Center	Model	Reference
1	AWI	AWI-CM-1.1-MR	Semmler et al. (2020)
2	BCC	BCC-CSM2-MR	Wu et al. (2021)
3	CAMS	CSM1.0	Rong et al. (2018)
4	CAS	CAS-ESM2.0	Jin et al. (2021)
5	NCAR	CESM2-WACCM	Danabasoglu et al. (2020)
6	THU	CIESM	Lin et al. (2020)
7	CMCC	CMCC-CM2-SR5	Cherchi et al. (2019)
8	CMCC	CMCC-ESM2	Lovato et al. (2022)
9	EC-Earth-Consortium	EC-Earth3	Döscher et al. (2022)
10	EC-Earth-Consortium	EC-Earth3-Veg	Döscher et al. (2022)
11	CAS	FGOALS-f3-L	He et al. (2019)
12	NOAA-GFDL	GFDL-ESM4	Dunne et al. (2020)
13	INM	INM-CM4.8	Volodin et al. (2018)
14	INM	INM-CM5.0	Volodin et al. (2017)
15	MPI-M	MPI-ESM1.2-HR	Mauritsen et al. (2019)
16	MRI	MRI-ESM2.0	Yukimoto et al. (2019)
17	NCC	NorESM2-MM	Seland et al. (2020)
18	AS-RCEC	TaiESM1	Wang et al. (2021)

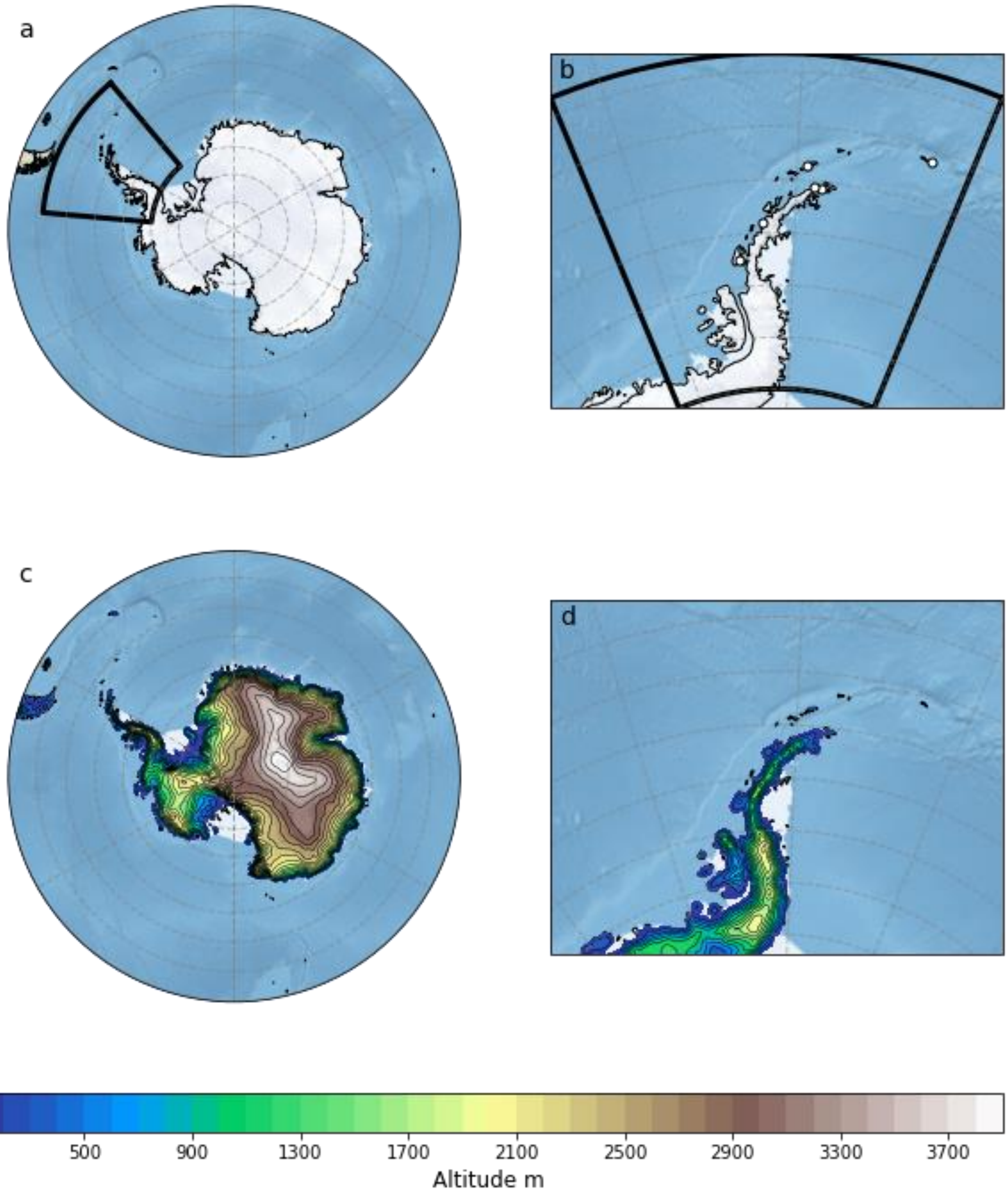

Figure S1. (a) Map of Antarctica, on a polar projection of the southern hemisphere showing the areas south of 50 ºS. (b) Detail of the sector 55˚ - 75˚ S, 40˚ - 85˚ W, encompassing the Antarctic Peninsula region). The position of the 6 stations analysed are shown as white dots. (c,d) as b,c but with ERA5 orography of Antarctica and the AP.

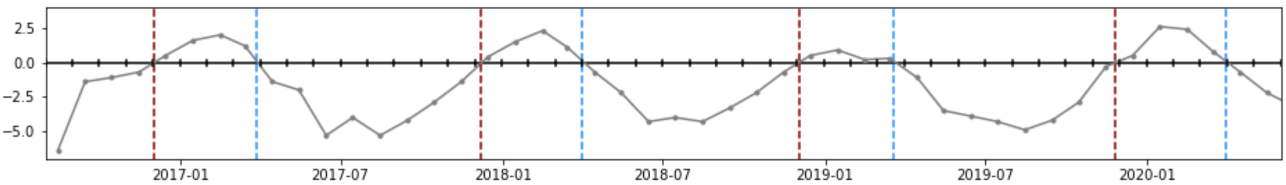

Figure S2. Example of determination of the melting season in Bellinshausen between 2016 and 2020. Each grey point indicates the mean temperature of the month set on the 15th day. The beginning (red dashed line) and the end (blue dashed line) of the melting season is determined by linear interpolation with the neighbouring months.

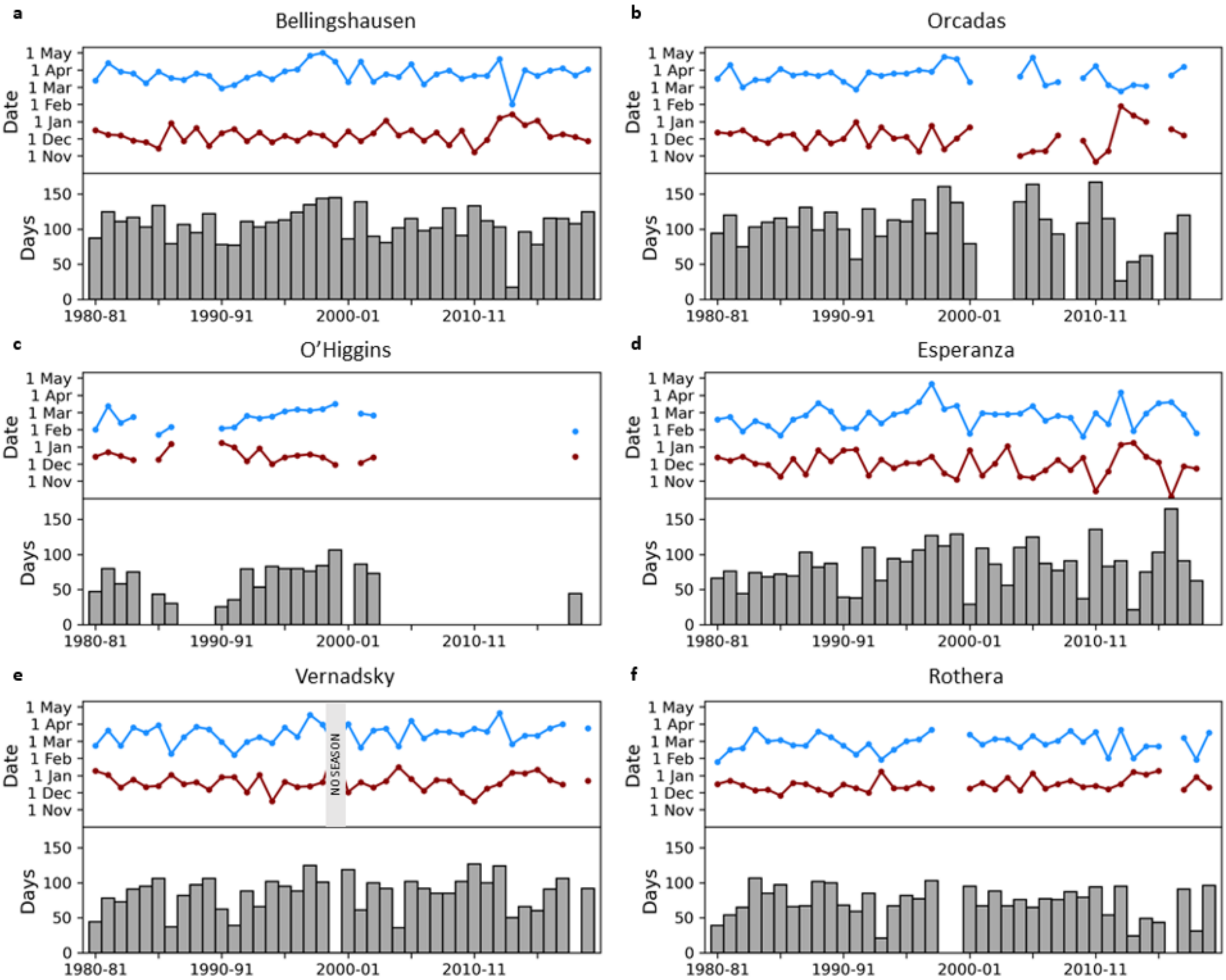

Figure S3. Time series of the melting season for six different stations of the Antarctic Peninsula. Upper panel: Starting (red) and ending (blue) date of the melting season. Lower panel: duration of the melting season.

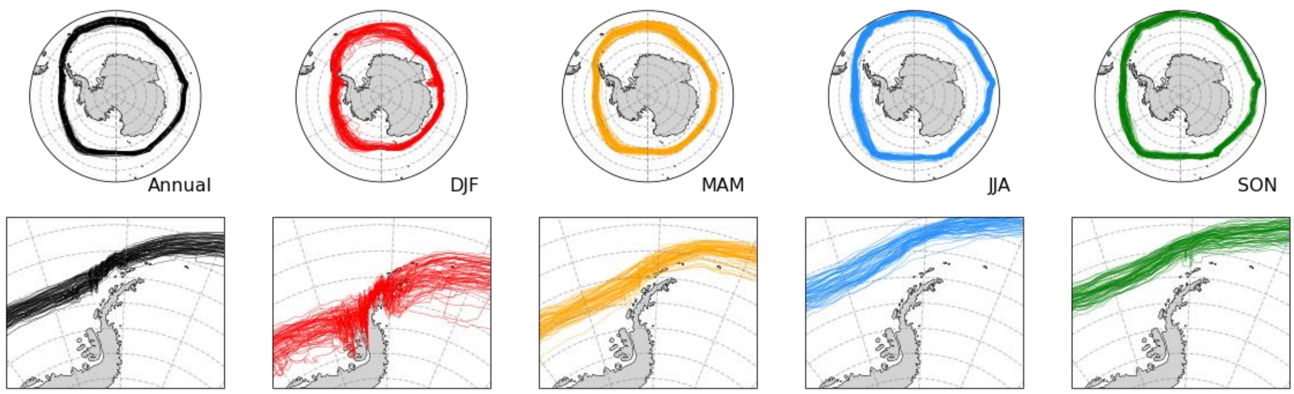

Figure S4. Variability of the mean position of the ZIL from ERA5.

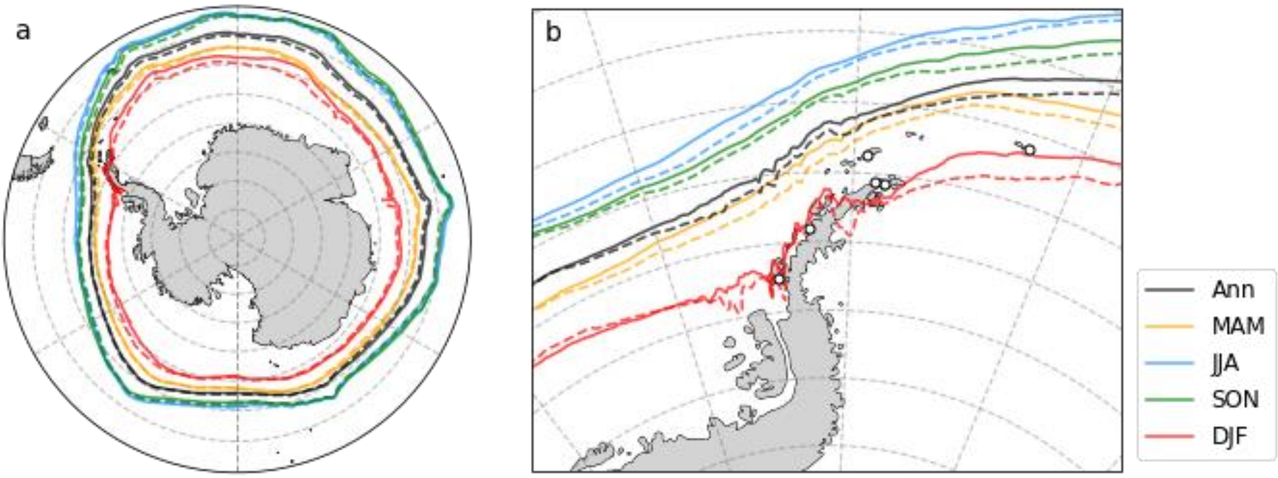

Figure S5. Mean annual and seasonal position of the ZIL from ERA5 for the periods 1961-1990 (solid lines) and 1991-2020 (dashed lines). Scales are not conserved in this projection.

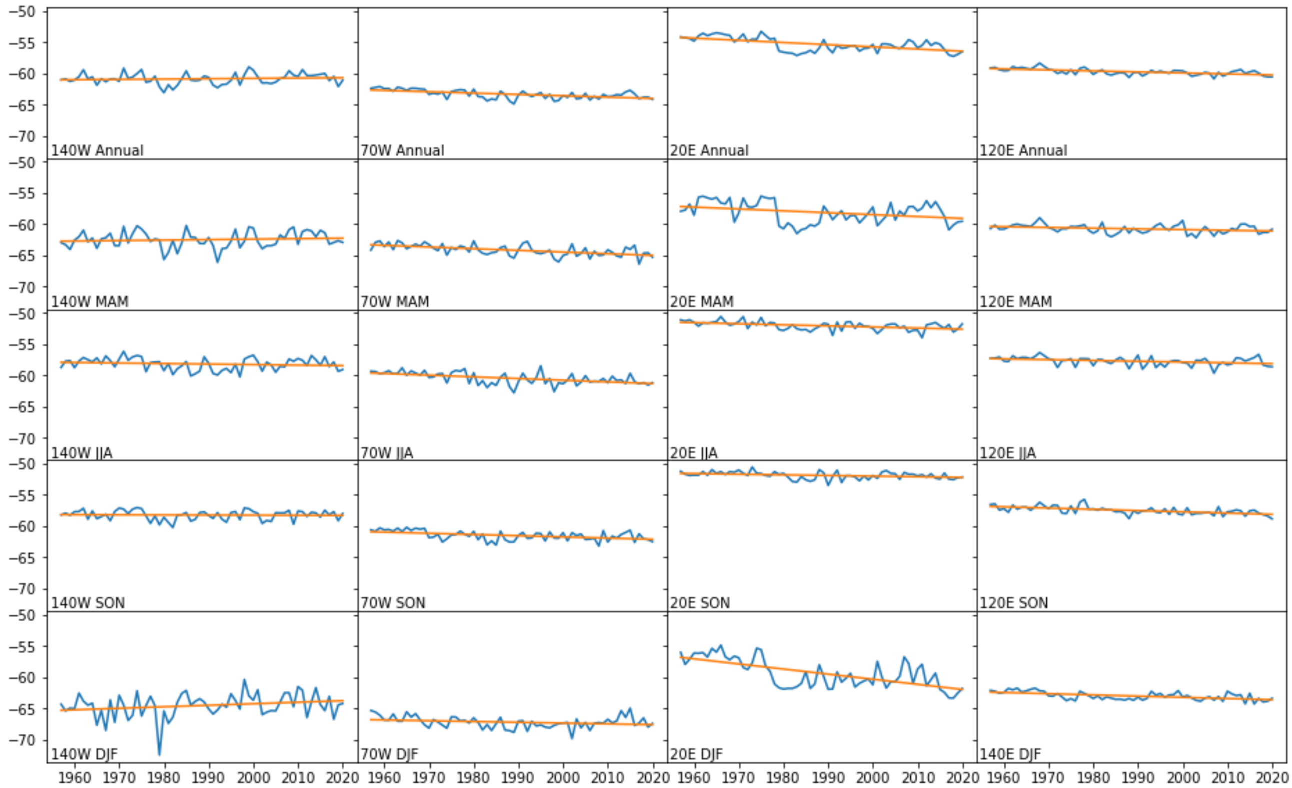

Figure S6. Time series (blue line) of the annual ZIL at different longitudes from ERA5. The yellow line shows the linear trend during the period 1957-2020.

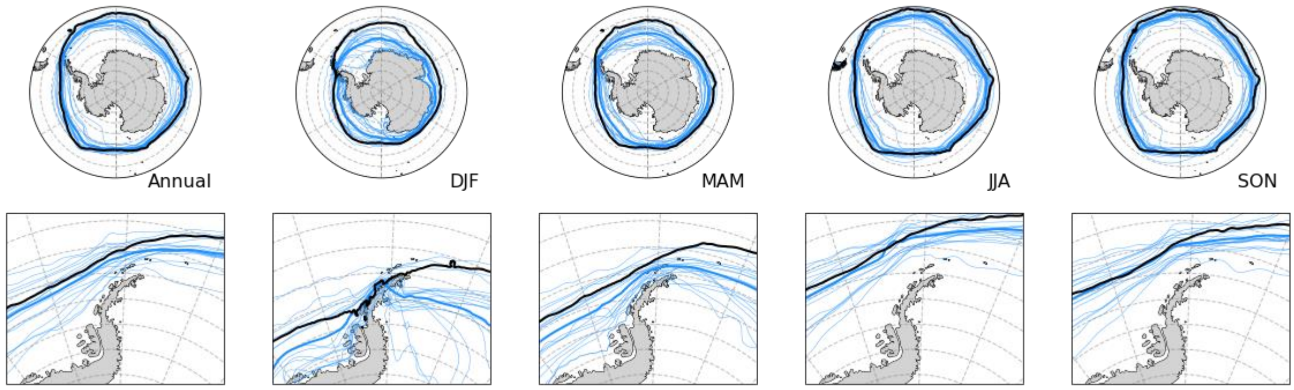

Figure S7. Mean annual ZIL position from 1957 to 2014 in ERA5 (black line) and in the different CMIP6 Historical simulations (blue lines). Dark blue line indicates the mean of the CMIP6 simulations.

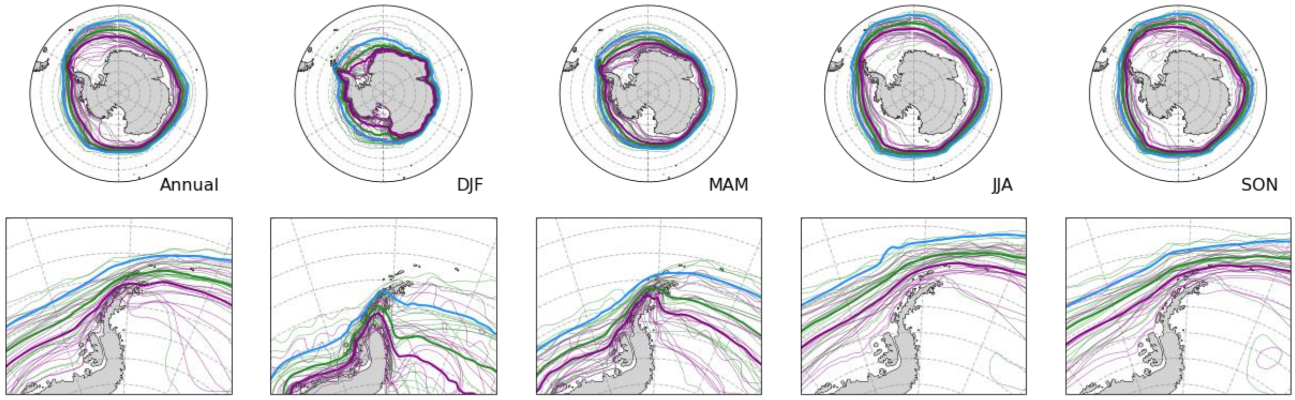

Figure S8. As in Figure 10 but for CMIP SSP5-8.5

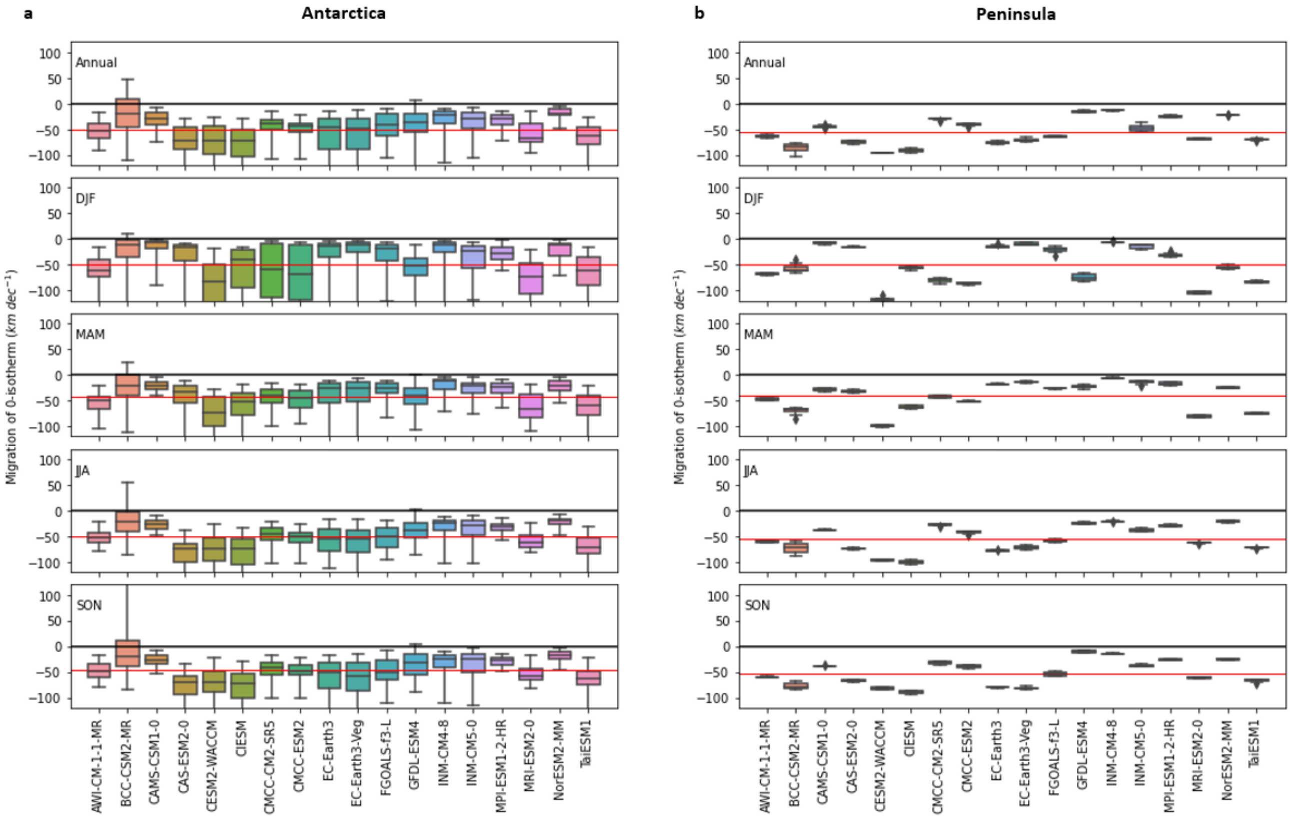

Figure S9. As in Figure 11 but for CMIP SSP5-8.5

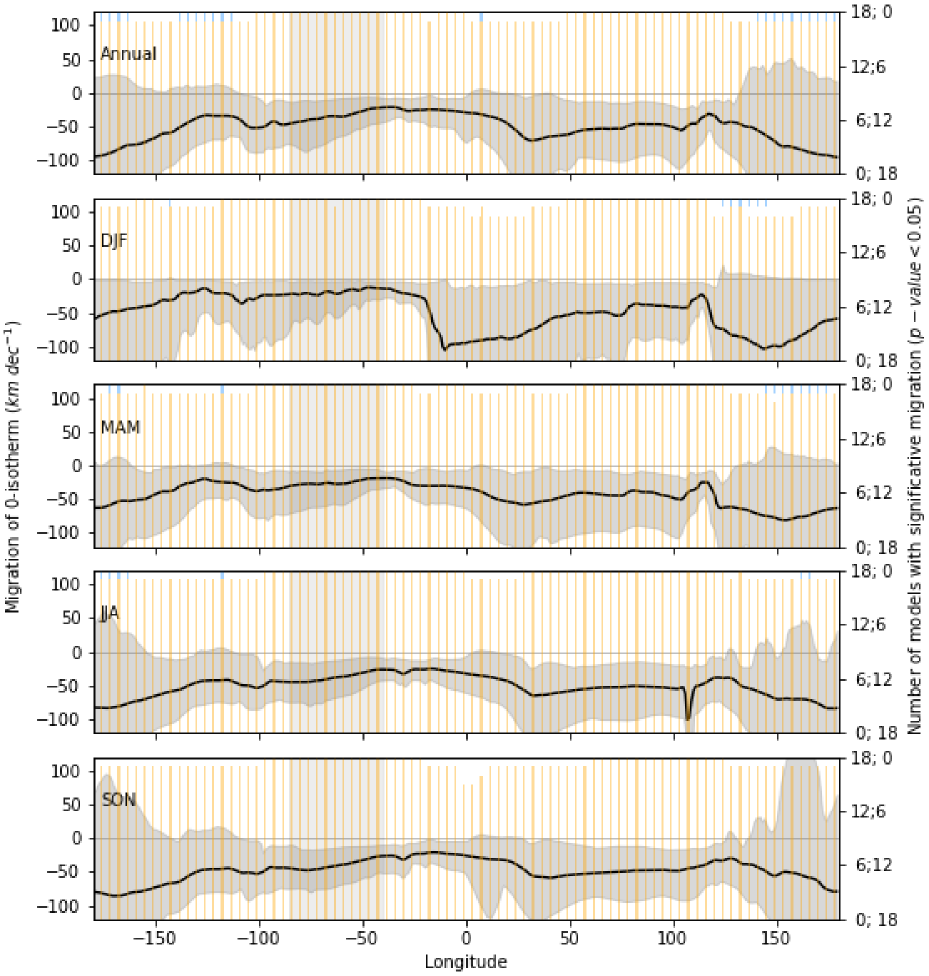

Figure S10. As in Figure 12 but for CMIP SSP5-8.5

2. Computational procedures and software environment

Data was analysed using Python language with IPython environment (Pérez and Granger, 2007) and a number of different libraries. ERA5 datasets were downloaded using the Climate Data Store (CDS) infrastructure, using the Copernicus CDS API service. NetCDF4 module was used as Python interface to netCDF files of ERA5 reanalysis. Statistical analysis was conducted using the netCDF4, Pandas (McKinney, 2010), SciPy (Virtanen et al., 2020) and NumPy (Harris et al., 2020) libraries. To visualize the data, Matplotlib (Hunter, 2007) and Cartopy libraries have been used.

References

Cherchi, A., Fogli, P.G., Lovato, T., Peano, D., Iovino, D., Gualdi, S., Masina, S., Scoccimarro, E., Materia, S., Bellucci, A., Navarra, A., 2019. Global Mean Climate and Main Patterns of Variability in the CMCC-CM2 Coupled Model. J Adv Model Earth Syst 11, 185–209. https://doi.org/10.1029/2018MS001369

Danabasoglu, G., Lamarque, J.F., Bacmeister, J., Bailey, D.A., DuVivier, A.K., Edwards, J., Emmons, L.K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M.M., Large, W.G., Lauritzen, P.H., Lawrence, D.M., Lenaerts, J.T.M., Lindsay, K., Lipscomb, W.H., Mills, M.J., Neale, R., Oleson, K.W., Otto-Bliesner, B., Phillips, A.S., Sacks, W., Tilmes, S., van Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J.E., Kinnison, D., Kushner, P.J., Larson, V.E., Long, M.C., Mickelson, S., Moore, J.K., Nienhouse, E., Polvani, L., Rasch, P.J., Strand, W.G., 2020. The Community Earth System Model Version 2 (CESM2). J Adv Model Earth Syst 12, e2019MS001916. https://doi.org/10.1029/2019MS001916

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F.J., Docquier, D., Echevarria, P., Fladrich, U., Fuentes-Franco, R., Gröger, M., Hardenberg, J. V., Hieronymus, J., Karami, M.P., Keskinen, J.P., Koenigk, T., Makkonen, R., Massonnet, F., Ménégoz, M., Miller, P.A., Moreno-Chamarro, E., Nieradzik, L., Van Noije, T., Nolan, P., O’donnell, D., Ollinaho, P., Van Den Oord, G., Ortega, P., Prims, O.T., Ramos, A., Reerink, T., Rousset, C., Ruprich-Robert, Y., Le Sager, P., Schmith, T., Schrödner, R., Serva, F., Sicardi, V., Sloth Madsen, M., Smith, B., Tian, T., Tourigny, E., Uotila, P., Vancoppenolle, M., Wang, S., Wårlind, D., Willén, U., Wyser, K., Yang, S., Yepes-Arbós, X., Zhang, Q., 2022. The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6. Geosci Model Dev 15, 2973–3020. https://doi.org/10.5194/GMD-15-2973-2022

Dunne, J.P., Horowitz, L.W., Adcroft, A.J., Ginoux, P., Held, I.M., John, J.G., Krasting, J.P., Malyshev, S., Naik, V., Paulot, F., Shevliakova, E., Stock, C.A., Zadeh, N., Balaji, V., Blanton, C., Dunne, K.A., Dupuis, C., Durachta, J., Dussin, R., Gauthier, P.P.G., Griffies, S.M., Guo, H., Hallberg, R.W., Harrison, M., He, J., Hurlin, W., McHugh, C., Menzel, R., Milly, P.C.D., Nikonov, S., Paynter, D.J., Ploshay, J., Radhakrishnan, A., Rand, K., Reichl, B.G., Robinson, T., Schwarzkopf, D.M., Sentman, L.T., Underwood, S., Vahlenkamp, H., Winton, M., Wittenberg, A.T., Wyman, B., Zeng, Y., Zhao, M., 2020. The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics. J Adv Model Earth Syst 12, e2019MS002015. https://doi.org/10.1029/2019MS002015

Harris, C.R., Millman, K.J., van der Walt, S.J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N.J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M.H., Brett, M., Haldane, A., del Río, J.F., Wiebe, M., Peterson, P., Gérard-Marchant, P., Sheppard, K., Reddy, T., Weckesser, W., Abbasi, H., Gohlke, C., Oliphant, T.E., 2020. Array programming with NumPy. Nature. https://doi.org/10.1038/s41586-020-2649-2

He, B., Bao, Q., Wang, X., Zhou, L., Wu, X., Liu, Y., Wu, G., Chen, K., He, S., Hu, W., Li, Jiandong, Li, Jinxiao, Nian, G., Wang, L., Yang, J., Zhang, M., Zhang, X., 2019. CAS FGOALS-f3-L Model Datasets for CMIP6 Historical Atmospheric Model Intercomparison Project Simulation. Adv Atmos Sci 36, 771–778. https://doi.org/10.1007/S00376-019-9027-8/METRICS

Hunter, J.D., 2007. Matplotlib: A 2D graphics environment. Comput Sci Eng 9, 90–95. https://doi.org/10.1109/MCSE.2007.55

Jin, J., Zhang, H., Dong, X., Liu, H., Zhang, M., Gao, X., He, J., Chai, Z., Zeng, Q., Zhou, G., Lin, Z., Yu, Yi, Lin, P., Lian, R., Yu, Yongqiang, Song, M., Zhang, D., 2021. CAS-ESM2.0 Model Datasets for the CMIP6 Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP). Adv Atmos Sci 38, 296–306. https://doi.org/10.1007/s00376-020-0188-2

Lin, Y., Huang, X., Liang, Y., Qin, Y., Xu, S., Huang, W., Xu, F., Liu, L., Wang, Y., Peng, Y., Wang, L., Xue, W., Fu, H., Zhang, G.J., Wang, B., Li, R., Zhang, C., Lu, H., Yang, K., Luo, Yong, Bai, Y., Song, Z., Wang, M., Zhao, W., Zhang, F., Xu, J., Zhao, X., Lu, C., Chen, Y., Luo, Yiqi, Hu, Y., Tang, Q., Chen, D., Yang, G., Gong, P., 2020. Community Integrated Earth System Model (CIESM): Description and Evaluation. J Adv Model Earth Syst 12, e2019MS002036. https://doi.org/10.1029/2019MS002036

Lovato, T., Peano, D., Butenschön, M., Materia, S., Iovino, D., Scoccimarro, E., Fogli, P.G., Cherchi, A., Bellucci, A., Gualdi, S., Masina, S., Navarra, A., 2022. CMIP6 Simulations With the CMCC Earth System Model (CMCC-ESM2). J Adv Model Earth Syst 14, e2021MS002814. https://doi.org/10.1029/2021MS002814

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T., Esch, M., Fast, I., Fiedler, S., Fläschner, D., Gayler, V., Giorgetta, M., Goll, D.S., Haak, H., Hagemann, S., Hedemann, C., Hohenegger, C., Ilyina, T., Jahns, T., Jimenéz-de-la-Cuesta, D., Jungclaus, J., Kleinen, T., Kloster, S., Kracher, D., Kinne, S., Kleberg, D., Lasslop, G., Kornblueh, L., Marotzke, J., Matei, D., Meraner, K., Mikolajewicz, U., Modali, K., Möbis, B., Müller, W.A., Nabel, J.E.M.S., Nam, C.C.W., Notz, D., Nyawira, S.S., Paulsen, H., Peters, K., Pincus, R., Pohlmann, H., Pongratz, J., Popp, M., Raddatz, T.J., Rast, S., Redler, R., Reick, C.H., Rohrschneider, T., Schemann, V., Schmidt, H., Schnur, R., Schulzweida, U., Six, K.D., Stein, L., Stemmler, I., Stevens, B., von Storch, J.S., Tian, F., Voigt, A., Vrese, P., Wieners, K.H., Wilkenskjeld, S., Winkler, A., Roeckner, E., 2019. Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO2. J Adv Model Earth Syst 11, 998–1038. https://doi.org/10.1029/2018MS001400

McKinney, W., 2010. Data Structures for Statistical Computing in Python, in: Proceedings of the 9th Python in Science Conference. pp. 56–61. https://doi.org/10.25080/majora-92bf1922-00a

Pérez, F., Granger, B.E., 2007. IPython: A system for interactive scientific computing. Comput Sci Eng 9, 21–29. https://doi.org/10.1109/MCSE.2007.53

Rong, X., Li, Jian, Chen, H., Xin, Y., Su, J., Hua, L., Zhou, T., Qi, Y., Zhang, Z., Zhang, G., Li, Jianduo, 2018. The CAMS Climate System Model and a Basic Evaluation of Its Climatology and Climate Variability Simulation. Journal of Meteorological Research 32, 839–861. https://doi.org/10.1007/S13351-018-8058-X/METRICS

Seland, Ø., Bentsen, M., Olivié, D., Toniazzo, T., Gjermundsen, A., Graff, L.S., Debernard, J.B., Gupta, A.K., He, Y.C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Schanke Aas, K., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., Karset, I.H.H., Landgren, O., Liakka, J., Moseid, K.O., Nummelin, A., Spensberger, C., Tang, H., Zhang, Z., Heinze, C., Iversen, T., Schulz, M., 2020. Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. Geosci Model Dev 13, 6165–6200. https://doi.org/10.5194/GMD-13-6165-2020

Semmler, T., Danilov, S., Gierz, P., Goessling, H.F., Hegewald, J., Hinrichs, C., Koldunov, N., Khosravi, N., Mu, L., Rackow, T., Sein, D. V., Sidorenko, D., Wang, Q., Jung, T., 2020. Simulations for CMIP6 With the AWI Climate Model AWI-CM-1-1. J Adv Model Earth Syst 12, e2019MS002009. https://doi.org/10.1029/2019MS002009

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S.J., Brett, M., Wilson, J., Millman, K.J., Mayorov, N., Nelson, A.R.J., Jones, E., Kern, R., Larson, E., Carey, C.J., Polat, İ., Feng, Y., Moore, E.W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E.A., Harris, C.R., Archibald, A.M., Ribeiro, A.H., Pedregosa, F., van Mulbregt, P., Vijaykumar, A., Bardelli, A. pietro, Rothberg, A., Hilboll, A., Kloeckner, A., Scopatz, A., Lee, A., Rokem, A., Woods, C.N., Fulton, C., Masson, C., Häggström, C., Fitzgerald, C., Nicholson, D.A., Hagen, D.R., Pasechnik, D. v., Olivetti, E., Martin, E., Wieser, E., Silva, F., Lenders, F., Wilhelm, F., Young, G., Price, G.A., Ingold, G.L., Allen, G.E., Lee, G.R., Audren, H., Probst, I., Dietrich, J.P., Silterra, J., Webber, J.T., Slavič, J., Nothman, J., Buchner, J., Kulick, J., Schönberger, J.L., de Miranda Cardoso, J.V., Reimer, J., Harrington, J., Rodríguez, J.L.C., Nunez-Iglesias, J., Kuczynski, J., Tritz, K., Thoma, M., Newville, M., Kümmerer, M., Bolingbroke, M., Tartre, M., Pak, M., Smith, N.J., Nowaczyk, N., Shebanov, N., Pavlyk, O., Brodtkorb, P.A., Lee, P., McGibbon, R.T., Feldbauer, R., Lewis, S., Tygier, S., Sievert, S., Vigna, S., Peterson, S., More, S., Pudlik, T., Oshima, T., Pingel, T.J., Robitaille, T.P., Spura, T., Jones, T.R., Cera, T., Leslie, T., Zito, T., Krauss, T., Upadhyay, U., Halchenko, Y.O., Vázquez-Baeza, Y., 2020. SciPy 1.0: fundamental algorithms for scientific computing in Python. Nat Methods 17, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Volodin, E.M., Mortikov, E. V., Kostrykin, S. V., Galin, V.Y., Lykosov, V.N., Gritsun, A.S., Diansky, N.A., Gusev, A. V., Yakovlev, N.G., 2017. Simulation of modern climate with the new version of the INM RAS climate model. Izvestiya - Atmospheric and Ocean Physics 53, 142–155. https://doi.org/10.1134/S0001433817020128/METRICS

Volodin, E.M., Mortikov, E. V., Kostrykin, S. V., Galin, V.Y., Lykossov, V.N., Gritsun, A.S., Diansky, N.A., Gusev, A. V., Iakovlev, N.G., Shestakova, A.A., Emelina, S. V., 2018. Simulation of the modern climate using the INM-CM48 climate model. Russian Journal of Numerical Analysis and Mathematical Modelling 33, 367–374. https://doi.org/10.1515/RNAM-2018-0032/MACHINEREADABLECITATION/RIS

Wang, Y.C., Hsu, H.H., Chen, C.A., Tseng, W.L., Hsu, P.C., Lin, C.W., Chen, Y.L., Jiang, L.C., Lee, Y.C., Liang, H.C., Chang, W.M., Lee, W.L., Shiu, C.J., 2021. Performance of the Taiwan Earth System Model in Simulating Climate Variability Compared With Observations and CMIP6 Model Simulations. J Adv Model Earth Syst 13, e2020MS002353. https://doi.org/10.1029/2020MS002353

Wu, T., Yu, R., Lu, Y., Jie, W., Fang, Y., Zhang, J., Zhang, L., Xin, X., Li, L., Wang, Z., Liu, Y., Zhang, F., Wu, F., Chu, M., Li, J., Li, W., Zhang, Yanwu, Shi, X., Zhou, W., Yao, J., Liu, X., Zhao, H., Yan, J., Wei, M., Xue, W., Huang, A., Zhang, Yaocun, Zhang, Yu, Shu, Q., Hu, A., 2021. BCC-CSM2-HR: A high-resolution version of the Beijing Climate Center Climate System Model. Geosci Model Dev 14, 2977–3006. https://doi.org/10.5194/GMD-14-2977-2021

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., Yabu, S., Yoshimura, H., Shindo, E., Mizuta, R., Obata, A., Adachi, Y., Ishii, M., 2019. The Meteorological Research Institute Earth System Model Version 2.0, MRI-ESM2.0: Description and Basic Evaluation of the Physical Component. Journal of the Meteorological Society of Japan. Ser. II 97, 931–965. https://doi.org/10.2151/JMSJ.2019-051