Documentation for

Diagnostics from CMIP6, atmospheric reanalyses, and passive-microwave observations used to examine the impact of ocean heat transport on Arctic and Antarctic sea ice

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Contents

1 About this dataset

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Description	Various geophysical diagnostics calculated from model output obtained from the Coupled Model Intercomparison Project phase 6 (CMIP6), for pre-industrial control, historical, SSP3-7.0, and SSP5-8.5 simulations of 20 climate models. Diagnostics include monthly-mean sea ice area, extent, and sea ice-edge latitude, annual ocean and atmospheric meridional energy transports, and annual polar-cap averages of ocean heat content, near surface air temperature, and atmospheric vertical heat fluxes. Analogous sea ice diagnostics from passive-microwave observations, and surface temperature diagnostics from atmospheric reanalysis products (CFSR, CFSv2, ERA5, JRA-55, and MERRA-2), are also included. This data supports the related publication below.[1]
Data format	Network Common Data Form (NetCDF)
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Related publications	See Ref. [1]
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2 Acknowledgements

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3 Terms of use

4 Project and funding information

This dataset was generated during the following research project:

Title	The future of Arctic sea ice
Dates	December 2022 – February 2027
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Principal Investigator	Daniel L. Feltham

5 Documentation

5.1 Introduction

This dataset contains large-scale geophysical diagnostics calculated from output of the Coupled Model Intercomparison Project phase 6 (CMIP6), selected atmospheric reanalysis products, and passive microwave observations of sea ice concentration. The diagnostics are created for and used in a recent study[1] investigating the impact of ocean heat transport on Arctic and Antarctic sea ice under climate change. The geophysical quantities include:

- Atmospheric diagnostics:
  - Net northward atmospheric heat (moist static energy) transport (AHT; yearly means)
  - 'Polar-cap' averages (i.e., averages between reference latitudes ϕ_0 and the north or south pole) of vertical radiative heat fluxes and near-surface air temperature (yearly means, except surface temperature from reanalyses which also include monthly means)
- Ocean diagnostics (all yearly means):
  - Net northward ocean heat transport (OHT)
  - Polar-cap averages and integrals of ocean heat content tendency
  - Polar-cap averages and integrals of the net downward surface heat flux into the ocean
- Sea ice diagnostics (for northern and southern hemispheres):
  - Sea ice area (monthly and yearly means)
  - Sea ice extent (monthly and yearly means)
  - Sea ice-edge latitudes (monthly and yearly means; as a function of longitude and zonal means)
  - Passive microwave observations only: sea ice concentration annual climatologies over the periods 1980–2000 and 2001–2021

There are multiple "variants" of the diagnostics for most quantities in the above lists. This is mainly relevant to ocean diagnostics, because how each quantity is determined depends on what raw data is available per CMIP6 model (see Ref. [1] Methods section for details). For atmospheric (and some ocean) diagnostics which are computed on model native grids, additional variants are saved interpolated to a common set of latitudes, where applicable.

All outputs are saved in netCDF format. Files are organised into directories corresponding to the domain, diagnostic variant, experiment (for CMIP6) and then individual files per model. The next section 5.2 describes how the data is organised, common data structures, and where to find further information and relevant software/code. The specific diagnostics, their basic metadata and descriptions, and extended notes where required, are listed in sections 5.3–5.7.

5.2 General information

5.2.1 Archives

Data are separated into five archives, each of which can be extracted using standard methods (e.g., `tar -xzf` on the command line):

1	`cmip6_atmosphere.tar.gz`	CMIP6 atmospheric diagnostics
2	`cmip6_ocean.tar.gz`	CMIP6 ocean diagnostics
3	`cmip6_sea_ice.tar.gz`	CMIP6 sea ice diagnostics
4	`atmospheric_reanalyses.tar.gz`	Monthly and annual mean near-surface temperature polar-cap averages derived from atmospheric reanalysis products
5	`passive_microwave.tar.gz`	Sea ice diagnostics derived from passive microwave observations of sea ice concentration

5.2.2 File and directory structure

The individual netCDF files under each CMIP6 archive (1–3 above) are further organised into the following directory structure:

```
./<diagnostic>_<variant>
     ./<experiment>
         ./<diagnostic>_<variant>_<experiment>_<model>.nc
```

where the values of `<experiment>`, `<variant>`, and `<model>` are listed and described in Tables 1, 2, and 3, respectively. The values and brief descriptions of each `<diagnostic>` are given in sections 5.3–5.5. The atmospheric reanalysis data and passive microwave sea ice diagnostics, archives 4 and 5, have similar directory structures except there is no `<experiment>` sub-directory or label in the file name. The contents of those archives are described in more detail in sections 5.6 and 5.7, respectively.

5.2.3 NetCDF metadata

Each netCDF file is CF-compliant as far as possible and always has complete variable and global attributes. Common netCDF command-line tools such as `ncdump` can be used to show this metadata; see Example 1. Global metadata always includes a brief description of the diagnostic contained within, in the `title` and/or `comment` attributes, and the source data and (for CMIP6 and reanalyses) model description references in the `source` and `references` attributes. For CMIP6 data, the experiment analysed is given in the `experiment_id` attribute and model name as given in the file names and listed in Table 3 in the `source_id` attribute. The variables corresponding to the diagnostics and any spatial coordinates always include a `long_name` attribute, which is a long description of the variable, and a `standard_name` attribute, which is a CF-controlled vocabulary for the relevant physical quantity or coordinate.

```
netcdf oht_from_hfx_hfy_yr_cc_approx_historical_UKESM1-0-LL {
dimensions:
        time = UNLIMITED ; // (165 currently)
        bnd = 2 ;
        member = UNLIMITED ; // (16 currently)
        ref_lat_n = UNLIMITED ; // (171 currently)
        ref_lat_s = UNLIMITED ; // (171 currently)
variables:
        double time(time) ;
                time:bounds = "time_bnds" ;
                time:calendar = "standard" ;
                time:units = "days since 1850-01-01" ;
        double time_bnds(time, bnd) ;
        int realisation_id(member) ;
        int initialisation_id(member) ;
        int physics_id(member) ;
        int forcing_id(member) ;
        double ref_lat_n(ref_lat_n) ;
                ref_lat_n:long_name = "reference_latitude_north" ;
                ref_lat_n:standard_name = "latitude" ;
                ref_lat_n:units = "degrees_north" ;
        double ref_lat_s(ref_lat_s) ;
                ref_lat_s:long_name = "reference_latitude_south" ;
                ref_lat_s:standard_name = "latitude" ;
                ref_lat_s:units = "degrees_north" ;
        double oht_n(time, member, ref_lat_n) ;
                oht_n:_FillValue = NaN ;
                oht_n:cell_methods = "time: mean ref_lat_n: point" ;
                oht_n:long_name = "Northward ocean heat transport (OHT) calculated [...]
                oht_n:standard_name = "northward_ocean_heat_transport" ;
                oht_n:units = "PW" ;
        double oht_s(time, member, ref_lat_s) ;
                oht_s:_FillValue = NaN ;
                oht_s:cell_methods = "time: mean ref_lat_s: point" ;
                oht_s:long_name = "Northward ocean heat transport (OHT) calculated [...]
                oht_s:standard_name = "northward_ocean_heat_transport" ;
                oht_s:units = "PW" ;

// global attributes:
                :author = "Jake R. Aylmer" ;
                :author_institution = "Centre for Polar Observation and Modelling [...]
                :coauthors = "David Ferreira, Daniel L. Feltham" ;
                :comment = "Climate model diagnostics derived from outputs in the [...]
                :contact = "j.aylmer@reading.ac.uk" ;
                :experiment_id = "historical" ;
                :history = "17:37 UTC 18 May 2024: updated global attributes in [...]
                :references = "[1] Aylmer, J. R., D. Ferreira, and D. L. Feltham, [...]
                :source = "MOHC UKESM1.0-LL model output prepared for CMIP6 CMIP [...]
                :source_id = "UKESM1-0-LL" ;
                :title = "CMIP6 processed diagnostics for UKESM1-0-LL, historical: [...]}
```

Example 1: Metadata and attributes embedded in an output file; some values have been truncated here for space, indicated by `[...]`.

5.2.4 Time coordinates

Every diagnostic except sea ice concentration climatology from passive microwave data is a function of time. The time coordinate variable and its (unlimited) dimension are both always called `time`. All data are either monthly or annual means, indicated as part of the file and sub-directory names (either `mon` or `yr` respectively). Data also contain time coordinate bounds (`time_bnds`) and associated time-averaging metadata in the `cell_methods` variable attribute. The time coordinates themselves are at the centre of time averaging bounds. For CMIP6 data, time units are `days since 0001-01-01` for pre-industrial control simulation data with a `proleptic_gregorian` calendar (see Table 1). For all other experiments and atmospheric reanalysis data, the units are `days since 1850-01-01` with a `standard` calendar. Passive microwave datasets instead use units of `days since 1978-01-01` with a `standard` calendar. In all cases, the first dimension of diagnostic variables corresponds to `time`.

5.2.5 Ensemble members

For CMIP6 data, all variables are computed for multiple ensemble members where available, and these are saved in the same files. In CMIP6, ensemble members are labelled with a "variant_id" consisting of "**r**ealisation", "**i**nitialisation", "**p**hysics", and "**f**orcing" indices; e.g., "r1i1p1f1". The ensemble members analysed for each model (which differ per `experiment`) are listed in Table 3. All netCDF files for CMIP6 data have an unlimited dimension called `member`, which for each diagnostic variable is its second array dimension after `time`. Example 1, line 26 shows that the variable `oht_n` has three dimensions: the first corresponding to `time`, the second corresponding to ensemble `member` (of which there are 16; see line 5), and the third corresponding to reference latitude (see next section). Thus, the ocean heat transport data for the n^{th} ensemble member in this example would be found by extracting the 2D-array `oht[:,n-1,:]`. The corresponding r, i, p, and f values are stored in the 1D-array variables `realisation_id`, `initialisation_id`, `physics_id`, and `forcing_id`. For consistency, there is always a `member` dimension even if only one member is stored in the data file (also allowing the r, i, p, and f values of that one member to be stored in the same way). Reanalysis surface temperature diagnostics also include a length-1 `member` dimension (because it is processed using mostly the same code as for the corresponding CMIP6 data), but passive microwave sea ice data do not include any `member` dimensions (because the data processing was mostly independent).

5.2.6 Northern and southern hemisphere diagnostics and reference latitudes

Many of the diagnostics involve a spatial average or integral of some quantity over a 'polar-cap' domain, i.e., the area between a reference latitude, ϕ_0, and the north or south pole. Such diagnostics are computed for multiple values of ϕ_0, with the values of ϕ_0 saved as coordinate variables `ref_lat_n` (northern hemisphere, averages or integrals between `ref_lat_n` and the north pole) and `ref_lat_s` (southern hemisphere, averages or integrals between `ref_lat_s` and the south pole). These coordinate variables have associated coordinate

Table 1: The CMIP6 experiments for which diagnostics are computed and saved. The experiment is embedded in each netCDF file's metadata and included in the file and directory names, and referred to in this document as `<experiment>`.

`<experiment>`	Description	Comments
`piControl`	CMIP pre-industrial control simulation (lengths vary; see Table 3)[15]	Datetime coordinates for all models and diagnostics are set to a reference date of 0001-01-01, regardless of the coordinates/reference time of the original raw data
`historical`	CMIP historical simulation (1850–2014)[15]	
`ssp370`	ScenarioMIP SSP3-7.0 simulation (2015–2100)[16]	
`ssp585`	ScenarioMIP SSP5-8.5 simulation (2015–2100)[16]	Some models provide data beyond 2100 but we only analysed and archived up to 2100

bounds (`ref_lat_n_bnds` and `ref_lat_s_bnds`, respectively): pairs of values for each reference latitude giving the latitude ranges being averaged over, which are always the reference latitude and 90°N or −90°N. The method (`mean` or `sum`) is noted in the diagnostic variable's `cell_methods` attribute. The diagnostic variables themselves have a third dimension corresponding to `ref_lat_n` or `ref_lat_s`. Thus in almost all cases (exceptions given below) there is a northern and southern hemisphere variable in each file, indicated by `_n` and `_s` respectively. For diagnostics which are averages poleward of a reference latitude, this corresponds to whether "poleward" means between the reference latitude and the north pole (`_n`) or between the reference latitude and the south pole (`_s`).

For atmospheric and ocean heat transport diagnostics, while the calculation is fundamentally similar the interpretation of the difference between `aht_n` and `aht_s` (and between `oht_n` and `oht_s`) is different. This is because both represent estimates of the same physical quantity, that is, the *net northward* depth and zonally integrated heat transport. For the technical explanation of these quantities see the related publication to this dataset;[1] in general, analysis of the northern (southern) hemisphere should use the `_n` (`_s`) variables for the heat transports. The heat transport diagnostics also do not have reference latitude coordinate bounds (because they are point estimates; this is also noted in the `cell_methods` variable attributes in these cases). See also Example 1.

Two exceptions to this aspect of the data structure are:

- Passive microwave sea ice diagnostics: these are all saved separately per hemisphere, because the source data[12,13] are also separated by hemisphere
- Ocean heat transport computed from CMIP6 variable `hfbasin`: in this case there is no separate calculation of northward ocean heat transport and only one variable, `oht`, is provided with a single reference latitude coordinate variable, `ref_lat`, i.e., without `_n` or `_s`. See CMIP6 ocean diagnostics.

Table 2: Meaning of diagnostic variant labels in general use across all diagnostics, indicated in file and directory names and referred to in this document as `<variant>`. Note these are not CMIP-endorsed terms (`gn` is, but here it is just used to indicate that no spatial interpolation was used).

`<variant>`	Description
`gn`	Computed on the **n**ative **g**rid
`gn_interp`	Computed on the **n**ative **g**rid, and then linearly **interp**olated to a standard set of reference latitudes (for ease of comparison among models)
`cc_approx`	Relevant to area averages/integrals of quantities, and typically curvilinear grids only: area averages/integrals northward (southward) of latitude ϕ_0 are **approx**imated by identifying grid cells whose **c**ell **c**entre latitudes $\phi_{cc} \geq \phi_0$ ($\phi_{cc} \leq \phi_0$).

Values of reference latitudes For the (primarily atmospheric) diagnostics with variant `gn` (see Table 2), the reference latitudes are all of the model's native grid cell latitude boundaries. This variant is only calculated when the native grid is a regular longitude–latitude grid (hence primarily atmospheric diagnostics). In cases where model output does not provide grid cell boundaries, they have been determined from the given grid cell centre coordinates.

For the (primarily ocean) diagnostics with variant `cc_approx`, a set of fixed reference latitudes ϕ_0 are chosen in advance. For polar-cap averages or integrals in the northern hemisphere, these are the equator and 50°–85°N inclusive in steps of 1°N. Then, for each ϕ_0, integrals or averages are computed over all grid cells whose centre latitude $\phi_{cc} \geq \phi_0$. This approximates the polar-cap average or integral at ϕ_0 for curvilinear grids (hence primarily ocean diagnostics). A similar set of reference latitudes in °S and procedure is used for polar-cap averages or integrals in the southern hemisphere (but note that latitudes are always saved in °N). For ocean heat transport diagnostics with the `cc_approx` variant, fixed reference latitudes are −80°N to 90°N inclusive in steps of 1°N for both the northern and southern hemisphere versions of the diagnostic (i.e., the `_n` and `_s` variables respectively).

For consistency of comparison between diagnostics, those that have been computed from native grid cell latitude boundaries (i.e., the `gn` variant) have also been linearly interpolated to the same set of fixed reference latitudes stated above (except atmospheric heat transport, which is interpolated to reference latitudes −90°N to 90°N inclusive in steps of 1°N). These are saved in the versions of the diagnostics with filename variant label `gn_interp`.

Finally, note that the equatorial reference latitude in both northern and southern hemisphere versions of atmospheric diagnostics can be used to compute global means (or integrals) by averaging (or adding) the two individual hemispheric values.

Table 3: CMIP6 models and general metadata. From left to right: model name as appearing in filenames and netCDF `source_id` attributes; length of pre-industrial (PI) control simulation in years; primary variant of CMIP6 sea ice diagnostics (others other available for some models); method used to compute ocean heat transport (OHT) and thus corresponding available ocean diagnostics (see section 5.4.3); ensemble members available per experiment. In the latter, member indices i, p, and f (see section 5.2.5) are 1 unless otherwise stated.

<model>	PI	Ice-edge	OHT	Ensemble member(s)			
	years	variant	method	piControl	historical	ssp370	ssp585
AWI-CM-1-1-MR[17–21]	500	025deg_dis	residual	r1	r1–5	r1–5	r1
CESM2[22–26]	1200	05deg_bil	residual	r1	r4,10,11	r4,10,11	r4,10,11
CESM2-FV2[22,27–30]	150	01deg_bil	residual	r1; i=p=2	r1; i=p=2	r1; i=p=2	r1; i=p=2
CESM2-WACCM[22,31–34]	500	05deg_bil	residual	r1	r1–3	r1	r1–3
*CNRM-CM6-1[35–39]	500	1deg_bil	hfx/hfy	r1i1p1f2	r1–6; f=2	r1–6; f=2	r1–6; f=2
CNRM-CM6-1-HR[35,40–43]	300	025deg_bil	hfx/hfy	r1; f=2	r1; f=2	r1; f=2	r1; f=2
*CNRM-ESM2-1[44–48]	500	1deg_bil	hfx/hfy	r1; f=2	r1; f=2	r1; f=2	r1; f=2
CanESM5[49–53]	1051	1deg_bil	residual	r1; p=2	r1–25; p=2	r1–25; p=2	r1–25; p=2
CanESM5-CanOE[49,54–57]	500	1deg_bil	residual	r1; p=2	r1–3; p=2	r1–3; p=2	r1–3; p=2
GFDL-ESM4[58–62]	500	1deg_bil	hfbasin	r1	r1	r1	r1
GISS-E2-2-G[63–67]	296	gn	hfbasin	r1; p=3	r1–5; p=3	r1–5; p=3	r1–5; p=3
†IPSL-CM6A-LR[68–72]	1000	1deg_bil	residual	r1	r1–32	r1–10,14	r1–4,6,14
MIROC6[73–77]	800	1deg_bil	hfbasin	r1	r1	r1	r1
MPI-ESM1-2-HR[78–82]	500	05deg_bil	residual	r1	r1–10	r1–10	r1–2
MPI-ESM1-2-LR[83–87]	1000	1deg_bil	residual	r1	r1–10	r1–10	r1–10
MRI-ESM2-0[88–92]	700	05deg_bil	hfbasin	r1	r1–5	r1–5	r1–5
NorESM2-LM[93–97]	501	1deg_bil	hfbasin	r1	r1–3	r1	r1
NorESM2-MM[93,98–101]	500	1deg_bil	hfbasin	r1	r1	r1	r1
UKESM1-0-LL[102–106]	1880	1deg_bil	hfx/hfy	r1; f=2	r1–4,8–12,16–19; f=2 r5–7; f=3	r1–12,16–19; f=2	r1–4,8; f=2
UKESM1-1-LL[102,107–109]	462	1deg_bil	hfbasin	r1; f=2	r1; f=2	r1; f=2	—

*no OHT diagnostics for `piControl` | †model actually provides 2000 year `piControl` simulation, but only the first 1000 are analysed due to incomplete ocean data.

5.2.7 Methods and code availability

Details about the physical assumptions and definitions going into the calculation of these diagnostics are described in the Methods section of the related publication to this dataset.[1] The raw data are processed using Python and, in the case of the sea ice-edge latitude, Climate Data Operators (CDO),[110] to interpolate sea ice concentration to regular longitude–latitude grids. All code is publicly available on GitHub, and the version of the repository used to produce the present dataset with full documentation of computational methods and software requirements is archived online.[111] The repository also includes an interface to simplify the selection/loading of models and diagnostics (particularly in cases where there are multiple possible diagnostics corresponding to the same physical quantity). If using this code (which is not required to view or analyse this data), the three CMIP6 archives should be extracted into the same directory.

5.3 CMIP6 atmospheric diagnostics

This section provides a summary of each diagnostic ("Diagnostic name" referring to the directory name) and available variants in the `cmip6_atmosphere.tar.gz` archive.

5.3.1 Atmospheric heat transport

Diagnostic name	`aht_from_net_flux_yr_<variant>`
Variant(s)	`gn`, `gn_interp`
Coordinate variable(s)	`time`, `ref_lat_n`, `ref_lat_s`
Diagnostic variable(s)	`aht_n`, `aht_s`
Diagnostic dimensions	(`time`, `member`, `ref_lat_n`), (`time`, `member`, `ref_lat_s`)
Diagnostic units	PW
Description	Northward atmospheric heat (moist static energy) transport (AHT) deduced from the net heat flux into the atmospheric column, which is averaged annually and integrated northwards (to give `aht_n`) or southwards (to give `aht_s`) of reference latitudes.

5.3.2 Vertical heat fluxes

Diagnostic name	`f_down_area_mean_yr_<variant>`
Variant(s)	`gn`, `gn_interp`
Coordinate variable(s)	`time`, `ref_lat_n`, `ref_lat_s`
Diagnostic variable(s)	`f_down_n`, `f_down_s`
Diagnostic dimensions	(`time`, `member`, `ref_lat_n`), (`time`, `member`, `ref_lat_s`)
Diagnostic units	$\mathrm{W\,m^{-2}}$
Description	Surface downwelling longwave radiation in air, averaged annually and everywhere poleward of reference latitudes.

Diagnostic name	f_olr_area_mean_yr_<variant>
Variant(s)	gn, gn_interp
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	f_olr_n, f_olr_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	$W\,m^{-2}$
Description	Top of atmosphere outgoing longwave radiation, averaged annually and everywhere poleward of reference latitudes.

Diagnostic name	f_sw_surf_area_mean_yr_<variant>
Variant(s)	gn, gn_interp
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	f_sw_surf_n, f_sw_surf_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	$W\,m^{-2}$
Description	Surface net downward shortwave radiation radiation, averaged annually and everywhere poleward of reference latitudes.

Diagnostic name	f_sw_toa_area_mean_yr_<variant>
Variant(s)	gn, gn_interp
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	f_sw_toa_n, f_sw_toa_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	$W\,m^{-2}$
Description	Top of atmosphere net downward shortwave radiation radiation, averaged annually and everywhere poleward of reference latitudes.

Diagnostic name	f_up_area_mean_yr_<variant>
Variant(s)	gn, gn_interp
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	f_up_n, f_up_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	$W\,m^{-2}$
Description	Sum of surface upwelling longwave radiation and net upward sensible and latent heat fluxes, averaged annually and everywhere poleward of reference latitudes.

5.3.3 Surface temperature

Diagnostic name	tas_area_mean_yr_<variant>
Variant(s)	gn, gn_interp
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	tas_n, tas_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	K
Description	Near-surface air temperature, averaged annually and everywhere poleward of reference latitudes.

5.4 CMIP6 ocean diagnostics

This section provides a summary of each diagnostic and available variants in the cmip6_ocean.tar.gz archive. Note that, for the majority of models, only the cc_approx variant (see Table 2) is available, as the gn and gn_interp variants are only available for regular longitude–latitude ocean grids (which is uncommon and in this dataset only applies to the model GISS-E2-2-G[63]). An exception is ocean heat transport computed directly from from the CMIP6 model output hfbasin, which is labelled as a native grid diagnostic as it is in fact computed on the native grid (by the model developers, where available).

5.4.1 Surface heat flux

Diagnostic name	hfds_area_mean_yr_<variant>
Variant(s)	gn, gn_interp, cc_approx
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	hfds_n, hfds_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	$\mathrm{W\,m^{-2}}$
Description	Net downward heat flux into the ocean surface, averaged annually and over the ocean poleward of reference latitudes.

Diagnostic name	hfds_hor_int_mean_yr_<variant>
Variant(s)	gn, gn_interp, cc_approx
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	hfds_n, hfds_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	PW
Description	Net downward heat flux into the ocean surface, averaged annually and integrated over the ocean poleward of reference latitudes.

5.4.2 Ocean heat content tendency

The following diagnostics are depth-integrated ocean heat content tendencies integrated or averaged poleward of reference latitudes calculated from a variety of source data and methods. Which method is used for each model depends on which ocean model outputs it provides. In CMIP6, the ocean heat content tendency variables are called `opottemptend` if the model uses **pot**ential temperature as the prognostic ocean temperature variable, or `ocontemptend` if it uses **con**servative temperature. In the subset of CMIP6 models included in this dataset, conservative temperature is only used by one model.[68]

Diagnostic name	`o*temptend_ver_int_area_mean_yr_<variant>`
Variant(s)	`cc_approx`
Coordinate variable(s)	`time`, `ref_lat_n`, `ref_lat_s`
Diagnostic variable(s)	`o*temptend_ver_int_n`, `o*ttemptend_ver_int_s`
Diagnostic dimensions	(`time`, `member`, `ref_lat_n`), (`time`, `member`, `ref_lat_s`)
Diagnostic units	$\mathrm{W\,m^{-2}}$
Description	Tendency of ocean conservative (`* = con`) or potential (`* = pot`) temperature expressed as heat content integrated vertically and averaged annually and over the ocean poleward of reference latitudes.

Diagnostic name	`o*temptend_ver_int_from_hfds_hfbasin_hor_int_yr_<variant>`
Variant(s)	`cc_approx`, `gn_interp`
Coordinate variable(s)	`time`, `ref_lat_n`, `ref_lat_s`
Diagnostic variable(s)	`o*temptend_ver_int_n`, `o*temptend_ver_int_s`
Diagnostic dimensions	(`time`, `member`, `ref_lat_n`), (`time`, `member`, `ref_lat_s`)
Diagnostic units	PW
Description	Tendency of ocean conservative (`* = con`) or potential (`* = pot`) temperature expressed as heat content integrated vertically and averaged annually, integrated over the ocean poleward of reference latitudes. This diagnostic is computed as a residual of the ocean heat transport from CMIP6 output `hfbasin` and horizontally integrated net surface heat flux into the ocean from CMIP6 output `hfds`.

Diagnostic name o*temptend_ver_int_from_hfds_hfx_hfy_area_mean_<variant>
Variant(s) cc_approx
Coordinate variable(s) time, ref_lat_n, ref_lat_s
Diagnostic variable(s) o*temptend_ver_int_n, o*temptend_ver_int_s
Diagnostic dimensions (time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units $\mathrm{W\,m^{-2}}$
Description Tendency of ocean conservative (* = con) or potential (* = pot) temperature expressed as heat content integrated vertically and averaged annually and over the ocean poleward of reference latitudes. This diagnostic is computed from the 2D-residual of ocean heat transport convergence calculated from CMIP6 outputs hfx and hfy (an intermediate diagnostic not saved here), and the net surface heat flux into the ocean from CMIP6 output hfds.

Diagnostic name o*temptend_ver_int_from_hfds_hfx_hfy_hor_int_<variant>
Variant(s) cc_approx
Coordinate variable(s) time, ref_lat_n, ref_lat_s
Diagnostic variable(s) o*temptend_ver_int_n, o*temptend_ver_int_s
Diagnostic dimensions (time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units PW
Description Tendency of ocean conservative (* = con) or potential (* = pot) temperature expressed as heat content integrated vertically and averaged annually, integrated over the ocean poleward of reference latitudes. This diagnostic is computed from the 2D-residual of ocean heat transport convergence calculated from CMIP6 outputs hfx and hfy, and the net surface heat flux into the ocean from CMIP6 output hfds.

Diagnostic name o*temptend_ver_int_hor_int_yr_<variant>
Variant(s) cc_approx
Coordinate variable(s) time, ref_lat_n, ref_lat_s
Diagnostic variable(s) o*temptend_ver_int_n, o*temptend_ver_int_s
Diagnostic dimensions (time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units PW
Description Tendency of ocean conservative (* = con) or potential (* = pot) temperature expressed as heat content integrated vertically and averaged annually, integrated over the ocean poleward of reference latitude. This diagnostic is computed directly from the CMIP6 output o*temptend.

5.4.3 Ocean heat transport

The following three diagnostics are ocean heat transport that, as with the ocean heat content tendency diagnostics in the previous section, are calculated from a variety of source data and methods depending on raw model output. Table 3 includes a short key in the column "OHT method" corresponding to one of the diagnostics below, indicating which is available for each model.

Table 3 "OHT method" key: "hfbasin":

Diagnostic name	`oht_from_hfbasin_yr_<variant>`
Variant(s)	`gn`, `gn_interp`
Coordinate variable(s)	`time`, `ref_lat`
Diagnostic variable(s)	`oht`
Diagnostic dimensions	(`time`, `member`, `ref_lat`)
Diagnostic units	PW
Description	Global, northward ocean heat transport computed on the native grid, annually averaged. For variant `gn`, no non-trivial data processing is applied; this merely saves the global component of CMIP6 model output `hfbasin` in a standard format. In this case, OHT is located at model latitudes (i.e., latitude varies across models). A second version, variant `gn_interp`, is saved which interpolates the `gn` data to standard reference latitudes (see section 5.2.6).

Table 3 "OHT method" key: "residual":

Diagnostic name	`oht_from_hfds_o*temptend_ver_int_yr_<variant>`
Variant(s)	`cc_approx`
Coordinate variable(s)	`time`, `ref_lat_n`, `ref_lat_s`
Diagnostic variable(s)	`oht_n`, `oht_s`
Diagnostic dimensions	(`time`, `member`, `ref_lat_n`), (`time`, `member`, `ref_lat_s`)
Diagnostic units	PW
Description	Global, northward ocean heat transport computed by integrating the residual of annually-averaged ocean heat content tendency (direct CMIP6 output `ocontemptend` or `opottemptend`, vertically integrated) and net surface ocean heat flux (direct CMIP6 output `hfds`) northward (`_n`) or southward (`_s`) of reference latitudes.

Table 3 "OHT method" key: "hfx/hfy":

Diagnostic name	oht_from_hfx_hfy_yr_<variant>
Variant(s)	cc_approx
Coordinate variable(s)	time, ref_lat_n, ref_lat_s
Diagnostic variable(s)	oht_n, oht_s
Diagnostic dimensions	(time, member, ref_lat_n), (time, member, ref_lat_s)
Diagnostic units	PW
Description	Global, northward ocean heat transport determined by first computing the ocean heat transport convergence (OHTC) on the native ocean grid from CMIP6 outputs hfx and hfy, annually averaging, and integrating northward (_n) or southward (_s) of reference latitudes.

5.5 CMIP6 sea ice diagnostics

This section provides a summary of each diagnostic and available variants in the cmip6_sea_ice.tar.gz archive.

5.5.1 Ice edge latitude

Diagnostic name	iel_mon_<variant>
Variant(s)	025deg_bil, 025deg_dis, 05deg_bil, 1deg_bil, 2deg_bil, 4deg_bil, gn
Coordinate variable(s)	time, lon, siconc_threshold
Diagnostic variable(s)	iel_n, iel_s
Diagnostic dimensions	(time, member, lon) for both
Diagnostic units	°N
Description	Monthly sea ice-edge latitude as a function of time and longitude (lon; in °E and in the range −180°E to 180°E). Here, <variant> refers to the interpolation resolution and method applied to raw, monthly-mean sea ice concentration data before application of the sea ice-edge latitude diagnostic code.[112] For example, 025deg_bil means raw sea ice concentration was interpolated to a 0.25° resolution regular longitude–latitude grid using bilinear interpolation. The variant dis refers to distance-weighted interpolation. The variant gn in this context means that the sea ice-edge latitude is computed on the native grid in cases where this is already a regular grid. The sea ice-edge is defined by a sea ice concentration contour which is taken to be 15%; this value is also stored as a scalar coordinate variable of iel_n and iel_s, called siconc_threshold.

Diagnostic name	iel_zm_mon_<variant>
Variant(s)	025deg_bil, 025deg_dis, 05deg_bil, 1deg_bil, 2deg_bil, 4deg_bil, gn
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	iel_zm_n, iel_zm_s
Diagnostic dimensions	(time, member) for both
Diagnostic units	°N
Description	Zonal-mean sea ice-edge latitude as a function of time. Each <variant> of this diagnostic is simply the zonal-mean of the corresponding iel_mon_<variant> diagnostic.

Diagnostic name	iel_zm_yr_<variant>
Variant(s)	025deg_bil, 025deg_dis, 05deg_bil, 1deg_bil, 2deg_bil, 4deg_bil, gn
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	iel_zm_n, iel_zm_s
Diagnostic dimensions	(time, member) for both
Diagnostic units	°N
Description	Annual-mean, zonal-mean sea ice-edge latitude as a function of time. Each <variant> of this diagnostic is simply the annual mean of the corresponding iel_zm_mon_<variant> diagnostic.

5.5.2 Area and extent

Diagnostic name	sia_mon
Coordinate variable(s)	time
Diagnostic variable(s)	sia_n, sia_s
Diagnostic dimensions	(time, member) for both
Diagnostic units	10^6 km^2
Description	Sea ice area in each hemisphere computed on the native grid from monthly-mean sea ice concentration fields. Sea ice area is the sum of all northern or southern hemisphere grid cell areas multiplied by their sea ice area fractions (concentrations).

Diagnostic name	sia_yr
Coordinate variable(s)	time
Diagnostic variable(s)	sia_n, sia_s
Diagnostic dimensions	(time, member) for both
Diagnostic units	10^6 km^2
Description	Annual-mean sea ice area in each hemisphere computed on the native grid from monthly-mean sea ice concentration fields (i.e., annual mean of sia_mon diagnostic).

Diagnostic name	sie_mon
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	sie_n, sie_s
Diagnostic dimensions	(time, member) for both
Diagnostic units	10^6 km^2
Description	Sea ice extent in each hemisphere computed on the native grid from monthly-mean sea ice concentration fields. Sea ice extent is the sum of all northern or southern hemisphere grid cell areas that contain sea ice concentration above a specified threshold. That threshold is taken (as typical) to be 15%; this value is also stored as a scalar coordinate variable of sie_n and sie_s, called siconc_threshold.

Diagnostic name	sie_yr
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	sie_n, sie_s
Diagnostic dimensions	(time, member) for both
Diagnostic units	10^6 km^2
Description	Annual-mean sea ice extent in each hemisphere computed on the native grid from monthly-mean sea ice concentration fields (i.e., annual mean of sie_mon diagnostic).

5.6 Atmospheric reanalysis surface temperature diagnostics

This section provides a summary of the diagnostics and available variants in the reanalyses.tar.gz archive. The only physical diagnostics are near-surface air temperature polar-cap averages for five atmospheric reanalyses. Here, monthly averages are included in addition to yearly averages, as well as the grid cell areas used in the calculations (not provided with the reanalysis raw data). The directory structure is:

```
./<diagnostic>_<variant>
     ./<diagnostic>_<variant>_<reanalysis>.nc
```

where the values of <reanalysis> are given in Table 4.

Table 4: Atmospheric reanalyses analysed with citations to product descriptions and source data (these references are embedded in the netCDF metadata for each diagnostic listed in section 5.6). The year range indicates that available in this dataset (some of these products are, at the time writing, continuously updated and will have more recent raw data available now).

`<reanalysis>`	Description	Year range
`CFSR`	Climate Forecast System Reanalysis (CFSR)[2,5]	1979–2010
`CFSv2`	Climate Forecast System Version 2 (CFSv2)[3,6]	2011–2023
`ERA5`	European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5)[8,9]	1979–2023
`JRA-55`	Japanese 55-year Reanalysis (JRA-55)[4,7]	1958–2023
`MERRA-2`	Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2)[10,11]	1980–2023

Diagnostic name `areacella`
Coordinate variable(s) `lon`, `lat`
Diagnostic variable(s) `areacella`
Diagnostic dimensions (`lat`, `lon`)
Diagnostic units m^2
Description Atmosphere grid cell areas.

Diagnostic name `tas_area_mean_mon_<variant>`
Variant(s) `gn`, `gn_interp`, `cc_approx`
Coordinate variable(s) `time`, `ref_lat_n`, `ref_lat_s`
Diagnostic variable(s) `tas_n`, `tas_s`
Diagnostic dimensions (`time`, `member`, `ref_lat_n`), (`time`, `member`, `ref_lat_s`)
Diagnostic units K
Description Near-surface air temperature, averaged everywhere poleward of reference latitudes, computed from monthly reanalysis datasets. Dimension `member` has size 1 (see section 5.2.5).

Diagnostic name `tas_area_mean_yr_<variant>`
Variant(s) `gn`, `gn_interp`, `cc_approx`
Coordinate variable(s) `time`, `ref_lat_n`, `ref_lat_s`
Diagnostic variable(s) `tas_n`, `tas_s`
Diagnostic dimensions (`time`, `member`, `ref_lat_n`), (`time`, `member`,`ref_lat_s`)
Diagnostic units K
Description Annual-mean near-surface air temperature, averaged everywhere poleward of reference latitudes, computed from monthly reanalysis datasets (i.e., annual mean of `tas_area_mean_mon` diagnostic). Dimension `member` has size 1 (see section 5.2.5).

5.7 Passive microwave sea ice diagnostics

5.7.1 Data structure

The CMIP6 sea ice diagnostics are also computed for passive microwave observations of sea ice concentration obtained from the National Snow and Ice Data Center (NSIDC). Raw (and final) data are monthly averages from January 1979 to December 2022. Here, there are two products, NSIDC-0051[12] commonly referred to as "NASA Team" and NSIDC-0079[13] commonly referred to as "Bootstrap", representing different methods of converting measured brightness temperature into sea ice concentration.[113] Raw data is separated by hemisphere, so here diagnostics are also separated by hemisphere unlike the CMIP6 diagnostics. In the archive `passive_microwave.tar.gz`, the directory structure is:

```
./<diagnostic>_<variant>
    ./<diagnostic>_<variant>_<hemi>_passive_microwave_<dataset_id>.nc
```

where `<hemi>` is either `nh` or `sh` and `<dataset_id>` is either `nsidc-0051` or `nsidc-0079`. All diagnostics (section 5.7.3) are computed for both hemispheres and both datasets.

5.7.2 Preparation of raw data

The calculations of sea ice area, extent, and sea ice-edge latitude follow the same methods as the corresponding CMIP6 diagnostics. However, there are three additional, preparatory steps that are applied to the raw passive microwave sea ice concentration data:

1. **North 'pole-hole' masks:** a circular region centred on the north pole is always missing data because the satellite orbits do not pass exactly over the north pole. The size of this region gets smaller with time as the satellite and instrument source changes. This region is assumed to have a sea ice concentration greater than the threshold concentration used to determine the sea ice edge latitude and sea ice extent. For sea ice area, the region is assumed to have a concentration of 100%; caution should thus be taken with sea ice area diagnostics in the northern hemisphere. Pole-hole masks are included as auxiliary files for reference.

2. **Northern hemisphere valid ice mask:** an auxiliary, monthly data mask is applied to the northern hemisphere data (both NSIDC datasets) which removes spurious signals in the data based on climatology of known past sea ice coverage from independent observations.[14] There is no analogous mask for the southern hemisphere.

3. **Missing data (both hemispheres):** raw daily data (not used) is unavailable for a substantial period of December 1987 to January 1988. The corresponding monthly raw data is already set to missing in NSIDC-0079 but not in NSIDC-0051. For consistency, for all diagnostics these two months are set to missing for both datasets.

Full details of the methods can be found in the documentation of passive microwave data processing code that is available online.[111]

5.7.3 Diagnostics

Diagnostic name	iel_mon_05deg_bil
Coordinate variable(s)	time, lon, siconc_threshold
Diagnostic variable(s)	iel
Diagnostic dimensions	(time, lon)
Diagnostic units	°N
Description	Monthly sea ice-edge latitude as a function of time and longitude (lon; in °E and in the range −180°E to 180°E).

Diagnostic name	iel_yr_05deg_bil
Coordinate variable(s)	time, lon, siconc_threshold
Diagnostic variable(s)	iel
Diagnostic dimensions	(time, lon)
Diagnostic units	°N
Description	Annual-mean sea ice-edge latitude as a function of time and longitude (lon; in °E and in the range −180°E to 180°E). This is the annual mean of the passive microwave iel_mon_05deg_bil diagnostic.

Diagnostic name	iel_zm_mon_05deg_bil
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	iel_zm
Diagnostic dimensions	(time,)
Diagnostic units	°N
Description	This is the zonal-mean of the passive microwave iel_mon_05deg_bil diagnostic.

Diagnostic name	iel_zm_yr_05deg_bil
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	iel_zm
Diagnostic dimensions	(time,)
Diagnostic units	°N
Description	This is the annual mean of the passive microwave iel_zm_mon_05deg_bil diagnostic.

Diagnostic name	sia_mon_<variant>
Variant(s)	gn, gr
Coordinate variable(s)	time
Diagnostic variable(s)	sia
Diagnostic dimensions	(time,)
Diagnostic units	10^6 km^2
Description	Sea ice area (of the northern or southern hemisphere) computed on the native grid (gn) or the interpolated, regular 0.5° grid used for computation of the ice edge (gr), from monthly-mean sea ice concentration fields.

Diagnostic name	sia_yr_<variant>
Variant(s)	gn, gr
Coordinate variable(s)	time
Diagnostic variable(s)	sia
Diagnostic dimensions	(time,)
Diagnostic units	10^6 km^2
Description	This is the annual mean of the passive microwave sia_mon_<variant> diagnostic.

Diagnostic name	sie_mon_<variant>
Variant(s)	gn, gr
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	sie
Diagnostic dimensions	(time,)
Diagnostic units	10^6 km^2
Description	Sea ice extent (of the northern of southern hemisphere) computed on the native grid (gn) or the interpolated, regular 0.5° grid used for computation of the ice edge (gr), from monthly-mean sea ice concentration fields.

Diagnostic name	sie_yr_<variant>
Variant(s)	gn, gr
Coordinate variable(s)	time, siconc_threshold
Diagnostic variable(s)	sie
Diagnostic dimensions	(time,)
Diagnostic units	10^6 km^2
Description	This is the annual mean of the passive microwave sie_mon_<variant> diagnostic.

Diagnostic name	siconc_gn_climatology
Coordinate variable(s)	None
Diagnostic variable(s)	lon, lat, siconc
Diagnostic dimensions	(y, x) for all
Diagnostic units	lon: °E; lat: °N; siconc: 1
Description	Two-dimensional maps of sea ice concentration annual-mean climatologies over the year ranges stated in the filenames, and also coded as global attributes in the files (time_climatology_start and time_climatology_end). Two time climatologies are included for each hemisphere: 1980–2000 and 2001–2021. These are computed on the native grid, which is not a regular longitude–latitude grid; lon and lat are two-dimensional auxiliary coordinate variables of the same dimensions as siconc that together give the longitude and latitudes of each corresponding grid point. Above, y and x are the vertical and horizontal dimensions of the grid which differ per hemisphere (but are the same for both NSIDC datasets).

Finally, there is an additional directory auxiliary which contains satellite north 'pole-hole' masks on the raw data native grid (gn) and on the interpolated, 0.5° regular longitude–latitude grid used in the computation of the ice edge latitude (gr); see section 5.7.2.

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