A technical guide for the zonal-mean dataset of global atmospheric reanalyses on pressure levels

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The dataset is available at PM: [Add DOI when available] and is described in more detail by PM: [add reference to ESSD paper]. The dataset is divided into two major components. The first is based on dynamical variables and the second provides diabatic heating rates. Both the dynamical variables and heating rates are provided on two distinct grids: the common grid and the original grid. The original grid dataset provides data on the same grid as the products downloaded from reanalysis centers (note that this often differs from the standard model grid). The common grid dataset provides data on a common set of latitudes, longitudes, and pressure levels. Data are interpolated from their original grids to the common grid using bilinear horizontal interpolation. Advanced diagnostics are calculated after interpolation. Section 1 of this technical document describes the structure of the portion of the dataset containing dynamical variables. Section 2 describes the portion of the dataset containing diabatic heating rates.

Notation:

- Overline denotes zonal average (e.g. $\overline{u}$)
- Prime denotes departure from zonal average (e.g. $u' = u - \overline{u}$)

1 Dynamical variables

Contact Patrick Martineau at pmartineau.work@gmail.com to report issues with the dynamical dataset or its documentation.

1.1 Basic zonal-mean quantities

NetCDF files providing data every 6 hours are named ZMD_4xdaily_yyyy_mm.nc, where yyyy and mm denote the year and month, respectively. ZMD simply stands here for zonal mean dataset. Variables are based on instantaneous data at time steps corresponding to 00, 06, 12, and 18UTC. Monthly means are provided in files named ZMD_monthly_yyyy_mm.nc following the same time convention. This is the core of the dataset, on which all other diagnostics described in Section 1 are based. The zonal-mean variables provided are listed in Table 1. These files also include the eddy covariance terms described in Table 2.

Table 1: Zonal mean variables

Variable	Name	Expression
Zonal mean zonal wind	u	$\overline{u}$
Zonal mean meridional wind	v	$\overline{v}$
Zonal mean vertical wind	omega	$\overline{\omega}$
Zonal mean temperature	t	$\overline{T}$
Zonal mean geopotential height	h	$\overline{z}$

Table 2: Variance and covariance (flux) terms. The terms are also provided for zonal wavenumber decompositions: variables with names ending in _k1, _k2, and _k3 contain the wavenumber 1, 2, and 3 contributions, respectively.

Variable	Name	Expression
Zonal variance of zonal wind	uu	$\overline{u'^2}$
Zonal variance of meridional wind	vv	$\overline{v'^2}$
Zonal variance of temperature	tt	$\overline{T'^2}$
Zonal covariance of zonal wind and meridional wind	uv	$\overline{u'v'}$
Zonal covariance of zonal wind and vertical wind	uomega	$\overline{u'\omega'}$
Zonal covariance of meridional wind and temperature	vt	$\overline{v'T'}$

1.2 Eulerian mean diagnostics of momentum

A complete budget of the zonal-mean momentum equation is provided in files named MOM_4xdaily_yyyy_mm.nc and MOM_monthly_yyyy_mm.nc, where MOM stands for momentum. Time follows the same convention as for the basic zonal-mean quantities. The variables provided are listed in Table 3.

$$\frac{\partial \overline{u}}{\partial t} = \underbrace{f\overline{v}}_{a} \underbrace{-\overline{v}\frac{1}{a\cos\phi}\frac{\partial(\overline{u}\cos\phi)}{\partial\phi}}_{b} \underbrace{-\overline{\omega}\frac{\partial\overline{u}}{\partial p}}_{c} \underbrace{-\frac{1}{a\cos^2\phi}\frac{\partial(\cos^2\phi\,\overline{u'v'})}{\partial\phi}}_{d} \underbrace{-\frac{\partial(\overline{u'\omega'})}{\partial p}}_{e} + R \tag{1}$$

Table 3: Terms of the primitive momentum equation. Momentum flux terms are also provided for zonal wavenumbers 1 to 3 (variable names ending with _k1, _k2, and _k3 denote the contributions of wavenumbers 1, 2, and 3, respectively).

Variable	Name	Expression (Eq. 1)
Coriolis torque resulting from meridional circulation	fv	a
Meridional advection of momentum	uv	b
Vertical advection of momentum	uw	c
Meridional momentum flux convergence	momconv	d
Vertical momentum flux convergence	vertflux	e

1.3 Transformed Eulerian Mean diagnostics of momentum

A complete budget of the transformed Eulerian mean (TEM) equation set (Andrews and McIntyre, 1976, 1978; Dunkerton, 1978; Edmon et al., 1980; Palmer, 1982; Andrews et al., 1987; Vallis, 2006) is provided in files named TEM_4xdaily_yyyy_mm.nc and TEM_monthly_yyyy_mm.nc following the same naming convention as the basic zonal-mean variables. In the TEM framework, the residual circulation is defined as

$$\overline{v}^* = \overline{v} - \frac{\partial}{\partial p}\left[\frac{\overline{v'\theta'}}{\partial\overline{\theta}/\partial p}\right] \tag{2}$$

$$\overline{\omega}^* = \overline{\omega} + \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left[\frac{\overline{v'\theta'}\cos\phi}{\partial\overline{\theta}/\partial p}\right]. \tag{3}$$

These terms are provided directly in the files, with variable names listed in Table 4.

Table 4: Variables describing the transformed Eulerian mean residual circulation

Variable	Name	Expression
Meridional residual circulation	vstar	Eq. (2)
Vertical residual circulation	omegastar	Eq. (3)

The TEM momentum equation takes the following form:

$$\frac{\partial \overline{u}}{\partial t} = \underbrace{\overbrace{f\overline{v}^*}^{QG}}_{a} \underbrace{-\overline{v}^* \frac{1}{a\cos\phi}\frac{\partial(\overline{u}\cos\phi)}{\partial\phi}}_{b} \underbrace{-\overline{\omega}^*\frac{\partial \overline{u}}{\partial p}}_{c} \underbrace{\overbrace{+\frac{1}{a\cos\phi}\vec{\nabla}\cdot\vec{F}}^{some\ QG\ terms}}_{d} + R \tag{4}$$

Terms provided in the TEM_4xdaily_yyyy_mm.nc and TEM_monthly_yyyy_mm.nc files are listed in Table 5. Note that some terms are labeled as QG; these are based on terms retained in the quasigeostrophic (QG) approximation of the TEM. The vertical and meridional components of Eliassen-Palm (EP) flux divergence are archived in separate variables.

Table 5: Terms of the TEM momentum equation. Terms that involve eddy fluxes are also provided for contributions of zonal wavenumbers 1, 2, and 3 (_k1, _k2, and _k3).

Variable	Name	Expression
Coriolis Torque resulting from meridional residual circulation	fvstar	Eq. (4a)
Meridional advection of momentum	uvstar	Eq. (4b)
Vercical advection of momentum	uomegastar	Eq. (4c)
EP flux divergence (vertical)	EPFD_p_pr	Eq. (4d)
EP flux divergence (meridional)	EPFD_phi_pr	Eq. (4d)
EP flux divergence (vertical & QG approximation)	EPFD_p_qg	Eq. (4d, QG only)
EP flux divergence (meridional & QG approximation)	EPFD_phi_qg	Eq. (4d, QG only)

The divergence of the EP flux is computed using

$$\nabla\cdot\vec{F} = \frac{1}{a\cos\phi}\frac{\partial(F_\phi\cos\phi)}{\partial\phi} + \frac{\partial(F_p)}{\partial p} \tag{5}$$

where the meridional and vertical components are expressed as

$$\{F_\phi, F_p\} = a\cos\phi\left\{\underbrace{\frac{\overline{v'\theta'}}{\partial\overline{\theta}/\partial p}\frac{\partial\overline{u}}{\partial p}\overbrace{-\overline{u'v'}}^{QG}}_{a}, \underbrace{-\frac{\overline{v'\theta'}}{\partial\overline{\theta}/\partial p}\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\overline{u}\cos\phi)\overbrace{+\frac{\overline{v'\theta'}}{\partial\overline{\theta}/\partial p}f}^{QG} - \overline{\omega'u'}}_{b}\right\}. \tag{6}$$

The EP flux itself is provided with the variable names listed in Table 6.

Table 6: EP flux

Variable	Name	Expression
EP flux (vertical)	EPF_p_pr	Eq. (6b)
EP flux (meridional)	EPF_phi_pr	Eq. (6a)
EP flux (vertical & QG approximation)	EPF_p_qg	Eq. (6b, QG only)
EP flux (meridional & QG approximation)	EPF_phi_qg	Eq. (6a, QG only)

2 Diabatic variables

Contact Jonathon Wright at jswright@tsinghua.edu.cn to report issues with the diabatic dataset or its documentation.

2.1 Model-generated heating rates

Zonal-mean diabatic heating rates are related to the dynamical quantities described above through the zonal-mean thermodynamic equation:

$$\underbrace{\frac{\partial\overline{\theta}}{\partial t}}_{a} + \underbrace{\frac{\overline{v}}{a}\frac{\partial\overline{\theta}}{\partial\phi}}_{b} + \underbrace{\overline{\omega}\frac{\partial\overline{\theta}}{\partial p}}_{c} + \underbrace{\frac{1}{a\cos\phi}\frac{\partial(\overline{v'\theta'}\cos\phi)}{\partial\phi}}_{d} + \underbrace{\frac{\partial(\overline{\omega'\theta'})}{\partial p}}_{e} + \underbrace{\overline{\mathcal{X}}}_{f} = \underbrace{\overline{\frac{\theta}{c_pT}\dot{Q}}}_{g} \tag{7}$$

The term on the right-hand side of Eq. 7 represents diabatic heating due to physical processes, such as latent heating, radiative transfer, and vertical diffusion. Three model-generated diabatic terms are included with the OG and CG zonal-mean data sets, including the total heating due to parameterized physics and components due to long-wave and short-wave radiative transfer (Table 7). NetCDF files providing data every 6 hours are named DIAB_4xdaily_yyyy_mm.nc, where yyyy and mm denote the year and month, respectively. Variables are based on time-averaged potential temperature tendencies in units of $\mathrm{K\,day^{-1}}$, with central times corresponding to 03, 09, 15, and 21UTC. The time axis of the diabatic data set therefore lags that of the dynamical data set by 3 h. Monthly means are provided in files named DIAB_monthly_yyyy_mm.nc following the same naming convention.

Table 7: Model-generated diabatic heating diagnostics.

Variable	Name	Expression
Total diabatic heating due to parametrized physics	ttdiab	Eq. (7g)
Diabatic heating due to long-wave radiation	ttlwhr	Eq. (7g, LW only)
Diabatic heating due to short-wave radiation	ttswhr	Eq. (7g, SW only)

Unlike the dynamical diagnostics described in section 1 and in the following sub-section, the terms listed in Table 7 are not derived from the basic variables listed in Table 1. Instead, the zonal-mean diabatic heating terms are computed from the physical temperature tendency diagnostics produced during the reanalysis model forecast step. Not all reanalyses store these forecast products or make them publicly available. Heating rates are currently provided in this data set for only eight of the fourteen reanalyses: ERA-40, ERA-Interim, NCEP–NCAR, CFSR, JRA-25, JRA-55, MERRA, and MERRA-2. Heating rate forecasts were not archived for CFSv2, and are therefore only available for CFSR through December 2010.

2.2 Diagnosed heating rates

To supplement the model-generated diabatic diagnostics, terms on the left-hand side of Eq. 7 are computed using the 6-hourly core variables and covariance terms provided in the zonal-mean dataset (Section 1.1). Terms that include potential temperature are obtained from the corresponding terms expressed as functions of temperature (see Tables 1 and 2). The residual term $\overline{\mathcal{X}}$, which is computed by substituting the model-generated diabatic heating into the right-hand side of Eq. 7, collects the effects of numerical errors and analysis increments. A set of files named THRM_4xdaily_yyyy_mm.nc provides diagnosed heating rates and dynamical heating diagnostics as listed in Table 8. Although these diagnostics are based on the core variables and covariance terms, they are constructed to match the model-generated diabatic heating rates, and are therefore provided 6-hourly at 03, 09, 15, and 21Z. The term $\partial\overline{\theta}/\partial t$ is calculated as a central difference, while the meridional and pressure derivatives are calculated by applying the numerical methods described in Appendix 2 to quantities averaged across the two time steps bracketing each time window. Monthly means for the terms listed in Table 8 are provided in files named THRM_monthly_yyyy_mm.nc. These diagnostics are initially only provided for the reanalyses and time periods with model-generated heating rates; however, files for additional reanalyses or periods covered in the zonal-mean dataset can be provided upon request.

Table 8: Diagnosed terms from the zonal-mean thermodynamic equation.

Variable	Name	Expression
Time rate of change in potential temperature	tt_time	Eq. (7a)
Meridional advection of potential temperature	ttv_mean	Eq. (7b)
Vertical advection of potential temperature	ttw_mean	Eq. (7c)
Meridional covariance term	ttv_eddy	Eq. (7d)
Vertical covariance term	ttw_eddy	Eq. (7e)
Estimated total diabatic heating	tt_diag	Eq. (7a)–(7e)
Residual	tt_resid	Eq. (7f)

Appendix 1: Dataset structure

A complete diagram of the structure of the data set is shown in Figure 1. For both the original grid and the common grid, the data is provided for the atmospheric reanalyses and companion products listed in Table 10.

Table 9: Reanalysis data sets, directory names, and references

Name	Directory	Reference
ERA-40	era_40	Uppala et al. (2005)
ERA-Interim	era_interim	Dee et al. (2011)
ERA-20C	era_20c	Poli et al. (2016)
NCEP-NCAR	ncep_ncar	Kalnay et al. (1996)
NCEP-DOE	ncep_doe	Kanamitsu et al. (2002)
CFSR	ncep_cfsr	Saha et al. (2010, 2014)
20CR (v2)	20th_Century_Reanalysis_v2	Compo et al. (2011)
20CR (v2c)	20th_Century_Reanalysis_v2c	Compo et al. (2011)
JRA-25	jra_25	Onogi et al. (2007)
JRA-55	jra_55	Kobayashi et al. (2015)
JRA-55C	jra_55c	Kobayashi et al. (2014)
JRA-55AMIP	jra_55AMIP	Kobayashi et al. (2014)
MERRA	nasa_merra	Rienecker et al. (2011)
MERRA-2	nasa_merra2	Gelaro et al. (2017)

Appendix 2: Numerical methods

Derivatives are evaluated using a three point stencil

$$\frac{\partial f(x)}{\partial x} \approx \frac{f(x+\Delta x) - f(x-\Delta x)}{2\Delta x}. \tag{8}$$

where x represents latitude or pressure. For derivatives taken with respect to pressure, the centered difference scheme is first computed for half-levels and then linearly interpolated back to the original pressure levels. Vertical derivatives at the lowermost and uppermost pressure levels and at the poles are not provided.

Appendix 3: Grids

All variables are archived each month as functions of time, pressure, and latitude. In the case of monthly means, dimensions are the same, except time has only one element. The variables are provided on two grids: the original grid and the common grid. For the original grid datasets, all diagnostics are applied on the grid on which the standard reanalysis products were downloaded. For the common grid, all variables are first interpolated to a 2.5° by 2.5° grid before diagnostics are computed. More information about the grids is provided in *PM:* ESSD reference paper.

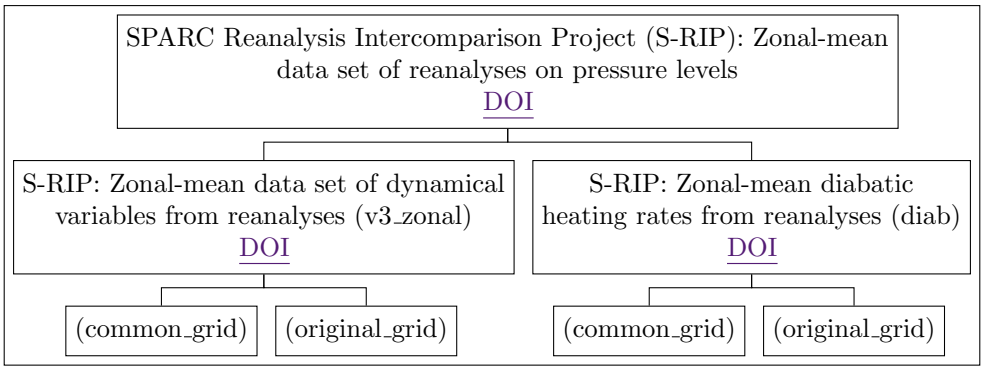

Figure 1: Data hierarchy

Appendix 4: Data sources and permissions

Permission for the publication of this dataset has been acquired from all relevant data producers, including ECMWF, JMA, NASA GMAO, NCEP, and the University of Colorado CIRES. Rights to core data (Table 1) and diabatic heating rates (Table 7) remain with the original producers of the reanalyses, who should be cited accordingly (see below). All derived variables (Tables 1 through 6) are provided through the Centre for Environmental Data Analysis (CEDA) under the Open Government License (http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/). Scientific publications using any part of this dataset should reference the data DOI ([JSW:CEDA doi]) and cite the description paper by [JSW:ESSD paper].

Sources and dates of access for reanalysis products included in the dataset are provided in Table 10 for the dynamical variables and Table 11 for the diabatic variables. Additional information on the terms and conditions of use for reanalysis products in the S-RIP zonal-mean reanalysis dataset is provided below.

ECMWF

Scientific publications using ECMWF products should cite the overview papers by Uppala et al. (2005) for ERA-40, Dee et al. (2011) for ERA-Interim, and/or Poli et al. (2016) for ERA-20C. The terms and conditions for the use of ERA-40, ERA-Interim, and ERA-20C products are identical, and may be viewed at http://apps.ecmwf.int/datasets/data/interim-full-daily/licence/.

JMA

Scientific publications using JMA products should cite the overview papers by Onogi et al. (2007) for JRA-25, Kobayashi et al. (2015) for JRA-55, and/or Kobayashi et al. (2014) for JRA-55C and JRA-55AMIP. JRA-25 and JRA-55 products contained in the S-RIP zonal-mean reanalysis dataset have been released for public use by JMA. Questions regarding original JMA products (i.e., core variables or diabatic heating rates) may be directed by email to jra@met.kishou.go.jp.

NASA GMAO

Scientific publications using NASA GMAO products should cite the overview papers by Rienecker et al. (2011) for MERRA and/or Gelaro et al. (2017) for MERRA-2, along with any appropriate DOI(s) (see Tables 10 and 11). Terms and conditions for the use of Earth science data produced by NASA, including these reanalysis products, may be viewed at https://earthdata.nasa.gov/nasa-data-policy.

NOAA–NCEP

Scientific publications using NCEP products should cite the overview papers by Kalnay et al. (1996) for NCEP-NCAR, Kanamitsu et al. (2002) for NCEP-DOE, and/or Saha et al. (2010, 2014) for CFSR. Users of core variables from the NCEP-NCAR or NCEP-DOE reanalyses are requested to include "NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/" or similar text in their acknowledgments.

NOAA–CIRES

Scientific publications using products from 20CR-v2 or 20CR-v2c should cite the overview paper by Compo et al. (2011), and are requested to include a version of the following text in their acknowledgments as appropriate:

v2: "Support for the Twentieth Century Reanalysis Project dataset is provided by the U.S. Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and Office of Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office."

v2c: "Support for the Twentieth Century Reanalysis Project version 2c dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office."

Table 10: Sources and dates of data access for core reanalysis variables.

Name	URL or DOI	Date accessed
ERA-40	http://www.ecmwf.int/en/forecasts/datasets/era-40-dataset-sep-1957-aug-2002	2010-11-24
ERA-Interim	http://www.ecmwf.int/en/research/climate-reanalysis/era-interim	2014-04-07
ERA-20C	https://doi.org/10.5065/D6VQ30QG	2015-12-31
NCEP-NCAR	http://www.esrl.noaa.gov/psd	2015-09-12
NCEP-DOE	http://www.esrl.noaa.gov/psd	2015-09-12
CFSR	http://dx.doi.org/10.5065/D69K487J	2012-05-27
20CR (v2)	https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html	2013-07-02
20CR (v2c)	http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.html	2016-04-05
JRA-25	http://rda.ucar.edu/datasets/ds625.0/	2015-10-06
JRA-55	http://dx.doi.org/10.5065/D6HH6H41	2014-12-23
JRA-55C	https://doi.org/10.5065/D67H1GNZ	2015-12-31
JRA-55AMIP	https://doi.org/10.5065/D6TB14ZD	2015-12-31
MERRA	http://doi.org/10.5067/8D4LU4390C4S	2015-09-25
MERRA-2	http://doi.org/10.5067/QBZ6MG944HW0	2016-08-26

Table 11: Sources and dates of access for reanalysis diabatic heating products.

Name	URL or DOI	Date accessed
ERA-40	http://apps.ecmwf.int/datasets/data/era40-daily[a]	2017-08-02
ERA-Interim	http://apps.ecmwf.int/datasets/data/interim-full-daily[a]	2017-08-07
NCEP-NCAR	http://rda.ucar.edu/datasets/ds090.0	2017-08-25
CFSR	https://doi.org/10.5065/D69K487J	2017-07-20
JRA-25	http://rda.ucar.edu/datasets/ds625.0	2017-07-25
JRA-55	https://doi.org/10.5065/D6HH6H41	2017-08-04
MERRA	https://doi.org/10.5067/RP02UMM6LH1B	2017-08-01
	https://doi.org/10.5067/DNZTCFMAG3FW	
MERRA-2	https://doi.org/10.5067/9NCR9DDDOPFI	2017-08-27
	https://doi.org/10.5067/3UGE8WQXZAOK	

[a] Data accessed via the ECMWF Web API (https://software.ecmwf.int)

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