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DynVarMIP: Assessing the Dynamics and Variability of the Stratosphere-Troposphere System

Edwin P. Gerber[1] and Elisa Manzini[2]
[1] Courant Institute of Mathematical Sciences, New York University, 251 Mercer Street, New York NY 10012, USA.
[2] Max-Planck-Institut für Meteorologie, Bundesstraße 53, 20146 Hamburg, Germany
Correspondence to: Elisa Manzini (elisa.manzini@mpimet.mpg.de)

Abstract. Diagnostics of atmospheric momentum and energy transport are needed to investigate the origin of circulation biases in climate models and to understand the atmospheric response to natural and anthropogenic forcing. Model biases in atmospheric dynamics are one of the factors that increase uncertainty in projections of regional climate, precipitation, and extreme events. Here we define requirements for diagnosing the atmospheric circulation and variability across temporal scales and for evaluating the transport of mass, momentum and energy by dynamical processes in the context of the Coupled Model Intercomparison Project Phase 6 (CMIP6). These diagnostics target the assessments of both resolved and parameterized dynamical processes in climate models, a novelty for CMIP, and are particularly vital for assessing the impact of the stratosphere on surface climate change.

Keywords: Atmosphere, dynamics, momentum and energy transfer, variability, climate and climate change.

1. Introduction

The importance and challenge of addressing the atmospheric circulation response to global warming have recently been highlighted by Shepherd (2014) and Vallis et al. (2015). Understanding circulation changes in the atmosphere, particularly of the mid-latitude storm tracks, has been identified by the World Climate Research Programme (WCRP) as one of the grand challenges in climate research. The storm tracks depend critically on the transport of momentum, heat and chemical constituents throughout the whole atmosphere. Changes in the storm tracks are thus significantly coupled with lower atmosphere processes such as planetary boundary layer, surface temperature gradients and moisture availability (e.g. Garfinkel et al., 2011, Booth et al., 2013) as well as with processes in the stratosphere, from natural variability on synoptic to intraseasonal timescales (e.g. Baldwin and Dunkerton, 2001) to the response to changes in stratospheric ozone (e.g. Son et al., 2008) and other anthropogenic forcings (e.g. Scaife et al., 2012).

Rather then proposing new experiments, the strategy of the “Dynamics and Variability Model Intercomparison Project” (DynVarMIP) is to request additional model output from standard CMIP experiments. This additional output is critical for understanding the role of atmospheric dynamics in

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past, present and future climate. Both resolved processes (e.g. Rossby waves) and parameterized processes (e.g. gravity waves and the planetary boundary layer) play important roles in the dynamics and circulation of the atmosphere in models. DynVarMIP seeks to ensure that sufficient diagnostics of all key processes in climate models are archived. Without this model output, we will not be able to fully assess the dynamics of mass, momentum, and heat transport - essential ingredients in projected circulation changes - nor take advantage of the increasingly accurate representation of the stratosphere in coupled climate models. Our rational is that by simply extending the standard output relative to that in CMIP5 for a selected set of experiments, there is potential for significantly expanding our research capabilities in atmospheric dynamics.

Investigation of the impact of solar variability and volcanic eruptions on climate also relies heavily on atmospheric wave forcing diagnostics, as well as radiative heating rates (particularly in the short wave). By extending our request to the energy budget and including diagnostics such as diabatic heating from cloud-precipitation processes, research on the links between moist processes and atmospheric dynamics will be enabled as well. The interplay between moist processes and circulation is central to the WCRP Grand Challenge on Clouds, Circulation and Climate Sensitivity (Bony et al., 2015).

The CMIP5 saw a significant upward expansion of models with a more fully resolved stratosphere (e.g. Gerber et al., 2012), and several multi-model studies have investigated the role of the stratosphere in present climate and in projections of future climate (e.g., Anstey et al., 2013; Charlton-Perez et al., 2013; Gerber and Son, 2014; Hardiman et al. 2013; Lott et al., 2014; Manzini et al., 2014; Min and Son, 2013; Shaw et al., 2014; Wilcox and Charlton-Perez, 2013) in addition to many other single model studies. These studies document a growing interest in the role of middle and upper atmosphere in climate (cf. Kidston et al., 2015). New research in this direction will take full advantage of the DynVarMIP diagnostics.

2. Objectives and Scientific Questions

DynVar focuses on the interactions between atmospheric variability, dynamics and climate change, with a particular emphasis on the two-way coupling between the troposphere and the stratosphere. To organize the scientific activity within the MIP, we have identified the following key questions:

- How do dynamical processes contribute to persistent model biases in the mean state and variability of the atmosphere, including biases in the position, strength, and statistics of the storm tracks, blocking events, and the stratospheric polar vortex?
- What is the role of dynamics in shaping the climate response to anthropogenic forcings (e.g. global warming, ozone depletion) and how do dynamical processes contribute to uncertainty in future climate projections and prediction?
- How does the stratosphere affect climate variability at intra-seasonal, inter-annual and decadal time scales?

Investigation of these topics will allow the scientific community to address the role of atmospheric dynamics in the key CMIP6 science questions concerning the origin and consequences of systematic model biases, the response of the Earth System to forcing, and how to assess climate change given climate variability (Eyring et al this Special Issue). In particular, there is a targeted effort to contribute to the storm track theme of the Clouds, Circulation and Climate Sensitivity Grand Challenge. The DynVarMIP focus on daily fields and diagnostics of the atmospheric flow is also relevant to the Grand Challenge on Climate Extremes, and could also enable contributions to the additional theme on Biospheric Forcings and Feedbacks.

3. The Diagnostics

The DynVarMIP requests both enhanced archival of standard variables from the CMIP5 and new diagnostics to enable analysis of both resolved and parameterized processes relevant to the dynamics of the atmosphere. The diagnostics are organized around three scientific themes, as detailed below.

The diagnostics are requested from the DECK experiments, namely the AMIP atmosphere-only model integrations [preferably for a minimum of 3 realizations] and selected 40-year periods of the preindustrial control [years 111-150 after the branching point], abrupt4xCO2 [years 111-150] and 1pctCO2 [years 111-150] coupled model integrations. To allow comparisons with CMIP5, the diagnostics are also requested for 40-year periods of the CMIP6 historical [1961-2000] and the ScenarioMIP RCP8.5 [2061-2100] experiments (cf. Manzini et al. 2014). In addition, the DynVar diagnostics (or relevant subsets thereof) are part of the diagnostic requests of AeroChemMIP, DAMIP, DCPP, HighResMIP, and VolMIP [this Special Issue]. Note that modeling centers need only commit to providing diagnostics to the DECK and the CMIP6 historical experiments, however, to participate in the DynVarMIP.

3.1 Atmospheric variability across scales (short name: *variability*)

The first request of the DynVarMIP is enhanced archival of standard variables (listed in Table 1) as daily and monthly means. While modeling centers have been archiving increasingly fine horizontal resolution (close to the native model grid), vertical sampling has been limited to standard levels that changed little from CMIP3 to 5.

The need for enhanced vertical resolution is particularly acute in the upper troposphere and lower stratosphere (UTLS), where there are steep vertical gradients in dynamical variables (e.g. temperature and wind) and chemical constituents (e.g. water vapor and ozone) across the tropopause. Without this finer vertical resolution, analyses of the UTLS would be limited by vertical truncation errors, preventing us from taking full advantage of increased horizontal resolution offered in new model integrations.

A number of other MIPs, in particular HighResMIP (this Special Issue), have also recognized the need for enhanced vertical resolution for daily data. A common proposed request, the "plev19" set of pressure levels, has consequently been reached (Martin Juckes, personal communication, see: https://earthsystemcog.org/site_media/projects/wip/CMIP6_pressure_levels.pdf). The pressure levels of the plev19 set are 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10, 5, and 1 hPa.

The diagnostics in Table 1 will allow for evaluation of atmospheric variability across time and spacial scales, e.g. the assessment of model biases in blocking events, the tropospheric storm tracks, and the stratospheric polar vortices. Comparison between the preindustrial control, historical, and idealized (e.g. 1pctCO2 and RCP8.5) integrations will allow for evaluation of the response of atmospheric variability to external forcings.

Novel to CMIP6 is also the daily zonal mean geopotential (zmzg, Table 1), tailored to the need of DCPP (Decadal Climate Prediction Project) to analyze variability on longer time scales and for a large number experiments, while minimizing storage requirements.

3.2 Atmospheric zonal momentum transporialt (short name: *momentum*)

The second group of diagnostics focuses on the transport and exchange of momentum within the atmosphere and between the atmosphere and surface, and are listed in Tables 2, 3 and 4. Within this group, a number of new (to CMIP) diagnostics and variables are requested. The goal of this set is to properly evaluate the role of both the resolved circulation and the parameterized dynamical processes in momentum transport. As daily timescales must be archived to capture the role of synoptic processes, we focus on the zonal mean circulation, thereby greatly reducing the total output that must be stored permanently. We have also prioritized the new variables, as noted in Tables 2, 3 and 4. Priority 1 variables are essential to the MIP and required for participation. Priority 2 variables would be very valuable to the MIP, but not are necessary for participation.

The zonal mean quantities are requested on the "plev39" vertical levels: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 170, 150, 130, 115, 100, 90, 80, 70, 50, 30, 20, 15, 10, 7, 5, 3, 2, 1.5, 1, 0.7, 0.5, 0.4, 0.3, 0.2, 0.15, 0.1, 0.07, 0.05, and 0.03 hPa. This fine sampling would allow for detailed exploration of the vertical momentum transport. Subsampling is allowed for models with lower vertical resolution or lower model tops.

Models largely resolve the planetary and synoptic scale processes that dominate the transport of momentum within the free atmosphere. Quantification of this transport, however, depends critically on vertical and horizontal wave propagation. The Transformed Eulerian Mean (TEM) framework allows one to efficiently quantify this momentum transport by waves, in addition to estimating the Lagrangian transport of mass by the circulation (e.g. Andrews and McIntyre, 1976; 1978). In the stratosphere, the TEM circulation is thus far more relevant to transport of trace gases (e.g. ozone and water vapor) than the standard Eulerian mean circulation (e.g. Butchart 2014). We have therefore request diagnostics based on the TEM framework (see Table 2). The details of these calculations are presented in the Appendix, and further insight can be found in the textbooks by Andrews et al., (1987; pages 127-130) and Vallis (2006; chapter 12).

As seen in the Appendix, the TEM diagnostics depend critically on the vertical structure of the circulation, i.e. vertical derivatives of basic atmospheric state and of wave fluxes. Even with the enhanced "plev19" vertical resolution requested above, we would not be able to reproduce these statistics from the archived output. It is therefore important that these calculations be performed on the native grid of the model (or as close as possible), before being interpolated to standard levels for archival purposes.

Dynamical processes, which need to be parameterized because they are not resolved on the grid of the model, also play an important role in momentum transport. Gravity waves transport momentum from the surface to the upper troposphere and beyond, but cannot be properly resolved at conventional GCM resolution. Their wave stresses play a key role in the large scale circulation of the troposphere (e.g. the storm tracks; Palmer et al., 1986) and are primary driver of the stratospheric circulation (e.g. Alexander et al., 2010, and references therein). Atmospheric circulation changes have been shown to be sensitive to the parameterization of gravity waves (e.g., Sigmond and Scinocca, 2010). The availability of tendencies from gravity wave processes (Table 2 and 3) will enable a systematic evaluation of this driving term of the circulation, so far largely unexplored in a multi-model context.

Diagnostics to archive the parameterized surface stresses are listed in Table 4. A number of studies have documented that the large scale circulation and storm track structure are sensitive to the surface drag (e.g. Chen et al. 2007; Garfinkel et al. 2011; Polichtchouk and Shepherd, in 2016). These diagnostics will also allow us to connect the CMIP6 with the investigation of weather prediction models by in the Working Group on Numerical Experimentation (WGNE) Drag Project (http://collaboration.cmc.ec.gc.ca/science/rpn/drag_project/). To understand how models arrive at the total surface stress, we also request the component due to turbulent processes, usually parameterized by the planetary boundary layer (PBL) scheme, including those stresses that come from subgrid orographic roughness elements. The role of other processes could then be diagnosed by residual.

Evaluation of the resolved and parameterized processes that effect the circulation are essential to diagnosing and understanding persistent model biases in the mean state and variability of the atmosphere. In addition, a fundamental understanding of the underlying mechanisms driving the response of the atmosphere to external forcing will improve confidence in future projections. We need to know that models not only agree in the response, but that they agree for the same reasons.

3.3 The atmospheric heat budget (short name: *heat*)

This set of diagnostics allows us to understand the interaction between radiation, moisture, and the circulation. As with our momentum diagnostics, we request only zonal mean statistics, to limit the additional storage load (Table 5).

Breaking down the short and long wave heating tendencies is particularly important for understanding the role of solar and volcanic forcing on the circulation. It will allow us to separate the direct impact of changes in solar radiation and aerosol loading from the atmospheric response to these perturbations, and enable analysis to break down feedbacks in Earth System models. Additional tendencies are requested for gravity wave diagnostics, so that their contribution to the heat budget can be quantified and compared.

4. Analysis Plan

DynVarMIP is holding a workshop in June 2016 to organize the exploitation of the requested diagnostics.. The goal of the workshop is to coordinate analysis of the CMIP6 simulations, avoid duplicate efforts, and ensure that our three scientific questions are investigated. At the June workshop, we are planning to discuss and organize intermodel comparison papers to investigate the momentum and heat balances of the historical climate (where it can be compared with observations and reanalysis), and how model biases there relate to differences in the models's atmospheric circulation response to external forcing, both in the idealized DECK perturbation experiments and in the RCP8.5. A follow up workshop will be planned for 2018 or 2019 to ensure that scientific work continues forward.

The DynVarMIP has been based on our experience in coordinating community based, collaborative analysis of coupled climate models from the CMIP5 through the SPARC DynVar activity (e.g. Gerber et al., 2012). To enhance participation and collaboration with the modeling centers, representatives have been invited to attend both the workshops and to participate in the scientific analysis and papers.

We have found that research on a mechanistic understanding of the atmosphere and on rectifying model biases is often best organized organically, rather than from a top down approach. The TEM diagnostics, for example, have been used in a number of CMIP5 studies (e.g. Hardiman et al., 2013; Manzini et al., 2014), but had to be assembled on an ad hoc basis with a limited number models. DynVarMIP is seeking to expand this research by making the key diagnostics available to all.

5. Conclusions and Outlook

The goal of the DynVarMIP is to evaluate and understand the role of dynamics in climate model biases and in the response of the climate system to external forcing. This goal is motivated by the fact that biases in the atmospheric circulation greatly limit our ability to project regional climate change, and compromise our ability to project changes in extreme events.

Rather then proposing new experiments, DynVarMIP has organized a targeted list of variables and diagnostics to characterize the role of both resolved and parameterized dynamical processes in the large scale circulation of climate models. The DynVarMIP effort emerges from the needs of an international community of scientists with strong connections to the modeling centers, with a long history (from the SPARC/GRIPS workshops in the mid 1990s; Pawson et al., 2000). Given this participation, we expect that the new diagnostics can be efficiently produced and will be fully utilized.

We are coordinating our efforts with several other MIPs. Transport plays a key role in the AerChemMIP experiments with ozone depleting substances, making the TEM diagnostics particularly relevant. The short-term VolMIP experiments and the DAMIP experiments focus in large part on stratosphere-troposphere coupling, where the momentum and heat budget diagnostics are directly relevant. Lastly, gravity wave effects and high frequency eddy processes are foci of the HiResMIP. The availability of dynamically oriented diagnostics within the DECK and the CMIP6 historical will provide the benchmark for these MIPs and others as well.

Data availability: The model output generated by the DynVarMIP diagnostic request will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. As in CMIP5, it will be freely accessible through data portals after registration. In order to document CMIP6's scientific impact and enable ongoing support of CMIP, users are obligated to acknowledge CMIP6, the participating modelling groups, and the ESGF centres. See Eyring et al (this Special Issue) for further details.

Appendix: TEM recipe

This technical appendix outlines and gives recommendation on how to calculate the TEM diagnostics for the momentum budget DynVarMIP output request (Table A1, subset of Table 2, section 3.2). For the calculation of the TEM diagnostics we follow Andrews et al (1983, 1987). We recommend calculating the diagnostics on pressure levels, on a grid very close or identical to that of the dynamical core of the atmospheric model. For non-hydrostatic dynamical models in geometric-z coordinate, prior to the diagnostic calculation it is necessary to transform the input variables to pressure coordinates, as demonstrated by Hardiman et al (2010).

Given that the TEM diagnostics are usually displayed in a log-pressure vertical coordinate system (e.g., Butchart 2014), we thereafter detail how to transform the results to a standard log-pressure vertical coordinate and so obtain the formulation of Andrews et at (1987), which is the one of our data request, but for a re-scaling of the EP-flux.

Coordinates, averages and frequency

We recommend interpolating the fields of interest to pressure levels prior to taking zonal and temporal averages (for both inline and offline calculations). Ideally, the pressure levels should be as close as possible to the average position of the model levels, to minimize the impact of the interpolation.

Flux quantities with multiplying factors (e.g., heat flux v'θ') composed of anomalies from the zonal mean (e.g., v' = v – zonal mean [v]) should be computed from high frequency data (6-hourly or higher frequency) and their products then computed before averaging to daily or monthly mean.

Time averages are calculated by averaging over the day or month periods, either "offline" from model outputs at 6-hour or higher frequency or directly computed over all time steps (i.e., "online"). Similarly, zonal averages are calculated averaging over all available longitudes, either offline (more commonly) or online (seldom done).

Input

The input to the calculation of the TEM diagnostics, is given in Table A2. In the following to simplify the writing of the TEM recipe, for the input we use:

T for air temperature, ta variable in CMOR
u for eastward wind velocity, ua variable in CMOR
v for northward wind velocity, va variable in CMOR
ω for omega, wap variable in CMOR (vertical component of velocity in pressure coordinates, positive down)
p for pressure [Pa], plev dimension in CMOR
ϕ for latitude [radiant], derived from the latitude [degrees north] dimension in CMOR

Recommended constants for the calculation of the TEM diagnostics:

$p_0 = 101325$ Pa , surface pressure
$R = 287.058\ \mathrm{J\ K^{-1}kg^{-1}}$, gas constant for dry air
$C_p = 1004.64\ \mathrm{J\ K^{-1}kg^{-1}}$, specific heat for dry air, at constant pressure
$g_0 = 9.80665\ \mathrm{ms^{-1}}$, global average of gravity at mean sea level
$a = 6.37123 \times 10^6$ m , earth's radius
$\Omega = 7.29212 \times 10^{-5}\ \mathrm{s^{-1}}$, earth's rotation rate
$f = 2\Omega \sin\phi$, Coriolis parameter
$\pi = 3.14159$, pi, mathematical constant

The following derivation of the TEM diagnostics makes use of the potential temperature, defined by:

$$\theta = T(p_0/p)^k$$

where $k = R/C_p$ is the ratio of the gas constant, R, to the specific heat, C_p, for dry air.

TEM Diagnostics

First, the input variables are zonally averaged and the anomalies from the respective zonally averaged quantities are calculated. The zonally averaged quantities are denoted: $\bar{\theta}, \bar{u}, \bar{v}$ and $\bar{\omega}$. The anomalies: θ', u', v' and ω'.

Thereafter, fluxes and their zonal averages are calculated, for: $\overline{u'v'}$, the northward flux of eastward momentum; $\overline{u'\omega'}$, the upward flux of eastward momentum; and $\overline{v'\theta'}$, the northward flux of potential temperature.

Now we can proceed to calculate the Eliassen-Palm flux, **F**, its divergence, $\nabla \cdot \mathbf{F}$, the Transformed Eulerian mean velocities, $\bar{v}^*$ and $\bar{\omega}^*$, the mass stream-function, Ψ.

The Eliassen-Palm flux is a 2-dimesional vector, $\mathbf{F} = \{F_{(\phi)}, F_{(p)}\}$, defined by:

$$F_{(\phi)} = a\cos\phi\,\{\frac{\partial\bar{u}}{\partial p}\psi - \overline{u'v'}\}\text{ , the northward component}$$

$$F_{(p)} = a\cos\phi\,\{\left[f - \frac{\partial\,\bar{u}\cos\phi}{a\cos\phi\,\partial\phi}\right]\psi - \overline{u'\omega'}\}\text{ , the vertical component}$$

where: $\psi = \overline{v'\theta'}/\frac{\partial\bar{\theta}}{\partial p}$ is the eddy stream-function

The Eliassen-Palm divergence, $\nabla \cdot \mathbf{F}$,is defined by:

$$\nabla \cdot \mathbf{F} = \frac{\partial\,F_{(\phi)}\cos\phi}{a\cos\phi\,\partial\phi} + \frac{\partial F_{(p)}}{\partial p}$$

The Transformed Eulerian mean velocities, $\bar{v}^*$ and $\bar{\omega}^*$, are defined by:

$$\bar{v}^* = \bar{v} - \frac{\partial\psi}{\partial p}\text{ , the northward component}$$

$$\bar{\omega}^* = \bar{\omega} + \frac{\partial\,\psi\cos\phi}{a\cos\phi\,\partial\phi}\text{ , the vertical component}$$

The mass stream-function (in units of kg s^{-1}), at level p, is defined by:

$$\Psi(p) = \frac{2\pi a cos\phi}{g_0}\,[\int_p^0 \bar{v}dp - \psi]$$

with upper boundary condition (at $p = 0$): $\psi = 0$ and $\Psi = 0$

The eastward wind tendency, $\frac{\partial \bar{u}}{\partial t}|_{\text{adv}(\bar{v}^*)}$, due to the TEM northward wind advection and Coriolis term is given by:

$$\frac{\partial \bar{u}}{\partial t}|_{\text{adv}(\bar{v}^*)} = \bar{v}^*[f - \frac{\partial\, \bar{u}\cos\phi}{a\cos\phi\,\partial\phi}]$$

The eastward wind tendency, $\frac{\partial \bar{u}}{\partial t}|_{\text{adv}(\bar{\omega}^*)}$, due to the TEM vertical wind advection is given by:

$$\frac{\partial \bar{u}}{\partial t}|_{\text{adv}(\bar{\omega}^*)} = \bar{\omega}^* \frac{\partial \bar{u}}{\partial p}$$

Transformation to log-pressure coordinate

We define a log-pressure coordinate (Andrews et al 1987) by:

$z = -\mathrm{H}\ln(p/p_0)$, $\quad p = p_0 e^{-z/H}$

where: $H = RT_s/g_0$ is a mean scale height of the atmosphere. We recommend to use $H = 7$ km , corresponding to $T_s \approx 240$ K , a constant reference air temperature.

The Eliassen-Palm Flux in log-pressure coordinate, $\hat{\mathbf{F}} = \{\hat{F}_{(\phi)}, \hat{F}_{(z)}\}$, is then obtained from the pressure coordinate form by:

$$\hat{F}_{(\phi)} = \frac{p}{p_0} F_{(\phi)}$$

$$\hat{F}_{(z)} = -\frac{H}{p_0} F_{(p)}$$

The Andrews et al (1987) formulation is then multiplied by the constant reference density $\rho_s = p_0/RT_s$, which is used in the definition of the background density profile $\rho_0 = \rho_s e^{-z/H}$ in the log-pressure coordinate system. Here, this scaling is not applied, to maintain the unit of the Eliassen-Palm flux in m^3 s^{-2}.

The Eliassen-Palm divergence in log-pressure coordinate is:

$$\nabla_{(z)} \cdot \hat{\mathbf{F}} = \frac{\partial\, \hat{F}_{(\phi)}\cos\phi}{a\cos\phi\,\partial\phi} + \frac{\partial \hat{F}_{(z)}}{\partial z} = \frac{p}{p_0} \nabla \cdot \mathbf{F}$$

The Transformed Eulerian Mean upward wind velocity is:

$$\bar{w}^* = -\frac{H}{p}\bar{\omega}^*$$

Output

In summary, the TEM recipe output maps to the CMOR variables listed in Table A1 as follows:

$\hat{F}_{(\phi)}$ → epfy, northward component of the Eliassen-Palm Flux

$\hat{F}_{(z)}$ → epfz, upward component of the Eliassen-Palm Flux

$\bar{v}^*$ → vtem, Transformed Eulerian Mean northward wind

$\overline{w}^*$ → wtem, Transformed Eulerian Mean upward wind

$\hat{\Psi}$ → psitem, Transformed Eulerian Mean mass stream-function

$\mathbf{\nabla}_{(z)} \cdot \hat{\mathbf{F}}$ → utendepfd, tendency of eastward wind due to EP Flux divergence

$\frac{\partial \bar{u}}{\partial t}|_{\mathrm{adv}(\bar{v}^*)}$ → utendvtem, tendency of eastward wind due to TEM northward wind advection and the Coriolis term

$\frac{\partial \bar{u}}{\partial t}|_{\mathrm{adv}(\bar{\omega}^*)}$ → utendwtem, tendency of eastward wind due to TEM upward wind advection

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TABLES

Table 1: Variability. Standard (already in CMIP5) variables at daily and monthly mean frequency. New: more vertical levels (plev19) for 3D daily and the zonal mean geopotential height, 2D.

Name	Long name [unit]	Dimension, Grid
psl	Sea Level Pressure [Pa]	2D, XYT
pr	Precipitation [kg m^{-2} s^{-1}]	2D, XYT
tas	Near-Surface Air Temperature [K]	2D, XYT
uas	Eastward Near-Surface Wind [m s^{-1}]	2D, XYT
vas	Northward Near-Surface Wind [m s^{-1}]	2D, XYT
ta	Air Temperature [K]	3D, XYZT
ua	Eastward Wind [m s^{-1}]	3D, XYZT
va	Northward Wind [m s^{-1}]	3D, XYZT
wap	omega (=dp/dt) [Pa s^{-1}]	3D, XYZT
zg	Geopotential Height [m]	3D, XYZT
hus	Specific Humidity [1]	3D, XYZT
zmzg	Geopotential Height [m]	2D, YZT

Table 2: Momentum (atmosphere). Zonal mean variables (2D, grid: YZT).

Name (priority)	Long name [unit]	Frequency
epfy (1)	northward component of the Eliassen-Palm Flux [m^3 s^{-2}]	monthly & daily
epfz (1)	upward component of the Eliassen-Palm Flux [m^3 s^{-2}]	monthly & daily
vtem (1)	Transformed Eulerian Mean northward wind [m s^{-1}]	monthly & daily
wtem (1)	Transformed Eulerian Mean upward wind [m s^{-1}]	monthly & daily
utendepfd (1)	tendency of eastward wind due to Eliassen-Palm Flux divergence [m s^{-2}]	monthly & daily
utendnogw (1)	tendency of eastward wind due to nonorographic gravity waves [m s^{-2}]	daily
utendogw (1)	tendency of eastward wind due to orographic gravity waves [m s^{-2}]	daily
utendvtem (1)	tendency of eastward wind due to TEM northward wind advection and the Coriolis term [m s^{-2}]	daily
utendwtem (1)	tendency of eastward wind due to TEM upward wind advection [m s^{-2}]	daily
psitem (2)	Transformed Eulerian Mean mass stream-function [kg s^{-1}]	daily

Table 3. Momentum (atmosphere). Monthly mean variables (3D, grid: XYZT)

Name (priority)	Long name [unit]	Frequency
utendnogw (1)	tendency of eastward wind due to nonorographic gravity waves [m s^{-2}]	monthly
utendogw (1)	tendency of eastward wind due to orographic gravity waves [m s^{-2}]	monthly
vtendnogw (1)	tendency of northward wind due to nonorographic gravity waves [m s^{-2}]	monthly
vtendogw (1)	tendency of northward wind due to orographic gravity waves [m s^{-2}]	monthly

Table 4. Momentum (surface). 2D variables (Grid: XYT)

Name (priority)	Long name [unit]	Frequency
tauu (1)	surface downward eastward wind stress [Pa]	daily
tauv (1)	surface downward northward wind Stress [Pa]	daily
tauupbl (2)	surface downward eastward wind stress due to boundary layer mixing [Pa]	daily
tauvpbl (2)	surface downward northward wind stress due to boundary layer mixing [Pa]	daily

Table 5. Heat. 2D zonal mean variables (Grid: YZT)

Name (priority)	Long name [unit]	Frequency
zmtnt (1)	tendency of air temperature due to diabatic processes [K s^{-1}]	monthly
tntrl (1)	tendency of air temperature due to longwave heating [K s^{-1}]	monthly
tntrs (1)	tendency of air temperature due to shortwave heating [K s^{-1}]	monthly
tntnogw (2)	tendency of air temperature due to nonorographic gravity wave dissipation [K s^{-1}]	monthly
tntogw (2)	tendency of air temperature due to orographic gravity wave dissipation [K s^{-1}]	monthly

Note: There is currently duplication in the database for the names of the tendency of air temperature due to longwave / shortwave heating. This is still an open issue. As well, CF standard names might need to be requested for tntnogw and tntogw.

Table A1. Momentum budget variable list (2D monthly / daily zonal means, YZT)

Name	Long name [unit]
epfy	northward component of the Eliassen-Palm Flux [m^3 s^{-2}]
epfz	upward component of the Eliassen-Palm Flux [m^3 s^{-2}]
vtem	Transformed Eulerian Mean northward wind [m s^{-1}]
wtem	Transformed Eulerian Mean upward wind [m s^{-1}]
psitem	Transformed Eulerian Mean mass stream-function [kg s^{-1}]
utendepfd	tendency of eastward wind due to Eliassen-Palm Flux divergence [m s^{-2}]
utendvtem	tendency of eastward wind due to TEM northward wind advection and the Coriolis term [m s^{-2}]
utendwtem	tendency of eastward wind due to TEM upward wind advection [m s^{-2}]

Table A2. Input for a TEM diagnostic program (CMOR convention)

Name	Long name [unit]	Dimension	Frequency
ta	Air temperature [K]	3D	HF = 6-hour or higher frequency
ua	Eastward Wind [m s^{-1}]	3D	HF = 6-hour or higher frequency
va	Northward Wind [m s^{-1}]	3D	HF = 6-hour or higher frequency
wap	omega (=dp/dt) [Pa s^{-1}]	3D	HF = 6-hour or higher frequency