The Dynamics and Variability Model Intercomparison Project (DynVarMIP) for CMIP6: Assessing the Stratosphere-Troposphere System

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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. Accurate simulation of the storm track climatology and variability has long proved a challenge for climate prediction models, particularly in the austral hemisphere, where the storm track and associated mid-latitude jet stream is generally located too far equatorward and is too persistent (e.g. Kidston and Gerber, 2010; Simpson and Polvani, 2016; Swart and Fyfe, 2012, Wenzel et al., 2016). 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). Wave coupling between the tropics and high latitudes (e.g. Li et al., 2015) makes regional circulation change a global problem, requiring a careful assessment of dynamical processes across all latitudes.

The Dynamics and Variability Model Intercomparison Project (DynVarMIP) is an endorsed participant in the Coupled Model Intercomparison Project Phase 6 (CMIP6). Rather then proposing new experiments, the DynVarMIP requests additional model output from existing CMIP6 experiments. This additional output is critical for understanding the role of atmospheric dynamics in past, present and future climate. Both resolved processes (e.g. Rossby waves, large scale condensation) and parameterized processes (e.g. gravity waves, subgrid-scale convection, 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 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. Charlton-Perez et al., 2013; Lott et al., 2014; Manzini et al., 2014). The stratosphere impacts tropospheric weather (e.g. though blocking events; Anstey et al., 2013; Shaw et al., 2014), and an improved representation of stratospheric processes can improve synoptic weather forecasts (e.g. Gerber et al., 2012; McTaggart-Cowan et al., 2011). Coupling between the stratospheric polar vortices and the tropospheric jet streams enhances subseasonal and seasonal predictability in the midlatitudes (e.g. Baldwin and Dunkerton, 2001; Roff et al., 2011; Sigmond et al., 2013), while in the tropics, the Quasi-Biennial Oscillation affects subseasonal variability and preciptiation (e.g. Yoo and Son, 2016) and provides a source of enhanced interannual predictability (e.g. Boer and Hamilton, 2008). The stratosphere has also been implicated in the ENSO teleconnections to the extratropics (e.g. Bell et al., 2009; Cagnazzo and Manzini 2009) and linked with decadal variability in the Atlantic (e.g. Reichler et al., 2012). Finally, the stratosphere plays an important role in climate change (e.g. Scaife et al., 2012), particularly through ozone loss and recovery over Antarctica (e.g. Gerber and Son, 2014; Min and Son, 2013; Thompson et al., 2011; Wilcox and Charlton-Perez, 2013) and through changes in stratospheric water vapor, which impact surface temperatures and climate sensitivity (e.g. Dessler et al., 2013; Solomon et al., 2010). 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

The DynVarMIP 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:

1. 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?
2. What is the role of atmospheric momentum and heat transport 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?
3. 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., 2016). 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.

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 the HighResMIP (High Resolution Model Intercomparison Project, Haarsma et al., 2016), have also recognized the need for enhanced vertical resolution for daily data. A common proposed request, the "plev19" grid 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 grid 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 pre-industrial control, historical, and idealized 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, Boer et al., 2016) to analyze variability on longer time scales and for a large number experiments, while minimizing storage requirements.

3.2 Atmospheric zonal momentum transport (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. These diagnostics 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 (for both daily and monthly means) are requested on the “plev39” grid of pressure 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 sampling will allow for detailed exploration of the vertical momentum transport, from the surface to the mesosphere. Subsampling is allowed for models with lower vertical resolution or lower model tops. All three dimensional fields, however, are requested on the plev19 grid.

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, and can only be accurately computed from instantaneous fields, as opposed to daily means. Even with the enhanced “plev39” vertical resolution requested above for the standard meteorological variables, we would not be able to reproduce these statistics from the archived output. It is therefore important that these calculations be performed on pressure levels as close to the native grid of the model 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 climate models 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 (Tables 2 and 3) will enable a systematic evaluation of this driving term of the circulation, so far largely unexplored in a multi-model context.

Additional parameterized processes can impact momentum transport in the free atmosphere, including convective momentum transport, vertical diffusion, and sponge layers near the model top (often used to prevent artificial wave reflection). Numerical diffusion can also artificially impact the momentum transport. The impact of these processes will be diagnosed in aggregate, however, as a residual between the total momentum tendency by the resolved flow and gravity waves and the actual change in the resolved flow.

While the TEM circulation approximates the Lagrangian transport of mass, trace gases with sinks and sources in the stratosphere, such as ozone, are also strongly affected by quasi-horizontal mixing along isentropic surfaces (e.g. Plumb, 2002). Breaking Rossby waves rearrange mass along isentropic surfaces: this yields no net movement of mass, but a trace gas with horizontal gradient experiences a net transport. The "age of air" can be used to assess the impact of this mixing, and provides complementary information to the TEM for the assessment of the stratospheric circulation (e.g. Waugh and Hall, 2002). The age can be quantified by a so-called "clock tracer," a passive tracer with a unit source near the surface; the age is then simply the difference between the concentration at the surface and other points in the atmosphere. This variable is requested at priority 2: not required for participation, but requested from models that have this capability.

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 2016). These diagnostics will also allow us to connect the CMIP6 with the investigation of weather prediction models by 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 is essential to diagnosing and understanding model biases in the mean state and variability of the atmosphere, and for diagnosing the processes driving circulation changes in response to natural and anthropogenic forcing. A careful dynamic analysis of circulation change is a critical step in developing a fundamental understanding of the underlying mechanisms, and hence for improving 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). We ask for the temperature tendency due to all parameterized physics (e.g. all diabatic processes: radiation, convection, boundary layer, stratiform condensation/evaporation, vertical diffusion, etc). Temperature tendencies due to resolved dynamics and numerical diffusion not associated with parameterized physics are then diagnosed in aggregate, as a residual between the temperature tendency due to all diabatic processes and the actual change in the resolved temperature. To separate the contribution of radiative transfer, we ask for the temperature tendencies due to longwave / shortwave radiative transfer (all sky). If available, the tendencies due to nonorographic / orographic gravity wave dissipation, due to convection (all parameterized types), due to stratiform clouds and precipitation (all type of resolved, large scale clouds and precipitation) and the tendencies due to clear sky longwave / shortwave radiative transfer are requested at priority 2. These would allow for a more careful assessment of dynamical, radiative, moisture and cloud processes on the diabatic heat budget (e.g. Wright and Fuegistaler, 2013; Ming et al., 2016).

Separately diagnosing the short and long wave heating tendencies has proven to be useful for interpreting circulation changes in general (e.g. Fuegistaler et al., 2009; Kim et al., 2013), and is particularly important for understanding the role of solar and volcanic forcings 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.

4. Experiments

The DynVar diagnostics are requested from the Diagnostic, Evaluation, and Characterization of Klima (DECK) experiments and CMIP6 historical simulations (Eyring et al. 2016) and a total of four closely related experiments; one experiment from the Scenario Model Intercomparison Project (ScenarioMIP; O'Neill et al. 2016) and three experiments from the Cloud Feedback Model Intercomparison Project (CFMIP; Webb et al. 2016), as listed in Table 6. To limit the total data storage, the diagnostics are requested for targeted 40-year periods (detailed in Table 6), with the exception of the *1% yr^{-1} CO2 concentration increase* experiment from the DECK, where only monthly mean diagnostics are requested. As indicated by the third column of Table 6, diagnostics from the DECK and CMIP6 historical simulation are required for participation in the DynVarMIP. Diagnostics from the experiments organized by ScenarioMIP and CFMIP are optional, but highly recommended for modeling centers that participate in these MIPs.

Diagnostics from the *pre-industrial control, AMIP*, and CMIP6 historical simulations are most relevant to our first scientific objective, to understand biases in atmospheric circulation and variability. In particular, the circulation in the latter two experiments can be directly compared against atmospheric reanalyses of the observed atmosphere. Comparison against integrations under strong anthropogenic influence (the last 40 years of the *abrupt quadroupling of CO2* experiment and years 2061-2100 from the *SSP5-RCP8.5* experiment) will help reveal how biases in the historical climatology related to biases in the future climate projections (e.g. Wenzel et al. 2016).

Our second objective is to understand the circulation response to anthropogenic forcing, and will be served by analysis of the equilibrated response of the atmosphere to 4xCO2 and the late 21st century circulation in the *SSP5-RCP8.5* experiment. Wu et al. (2013), Grise and Polvani (2014a), and Shaw and Voigt (2015), however, have shown how the initial response of the atmosphere to an abrupt quadroupling of CO2 reveals a great deal about the dynamical mechanism(s) and their associated time scales; hence our request for the first 40 years of this integration. A number of studies from the CMIP5 have also demonstrated the utility of AMIP climate change experiments, the *amip-p4K*, *amip-future4K*, and *amip-4xCO2* organized by the CFMIP, in isolating the mechanisms for circulation changes (e.g. Grise and Polvani, 2014b; He and Soden, 2015; Shaw and Voigt, 2015). We have therefore requested diagnostics from these simulations from modeling centers, which are also participating in the CFMIP.

Lastly, diagnostics are requested from the full 150 year record from the *1 % yr^{-1} CO2 concentration increase* experiment, specifically to determine the time of emergence in circulation changes. To limit the cost of archiving this data, only monthly mean fields are requested.

Our final objective, to understand the role of stratosphere in surface climate and variability, will be served by a number of these simulations. The *pre-industrial control* and final 40 years of the *abrupt quadroupling of CO2* integrations, however, will be particularly ideal for understanding the role of stratosphere in natural, unforced variability in past and future climates, respectively.

The DynVar diagnostics (or relevant subsets thereof) have been coordinated with diagnostic requests of other CMIP6 endorsed MIPs. The TEM and stratospheric circulation diagnostics are highly relevant to integrations with ozone depleting substances in the Aerosols and Chemistry (AeroChemMIP; Collins et al. 2016) and to the short term response of the atmosphere to volcanic forcing, as detailed in the Volcanic Forcings Model Intercomparison Project (VolMIP; Zanchettin et al. 2016). The zonal mean long and short wave heating rates have been requested for integrations focused on solar variability in the Detection and Attribution MIP (DAMIP; Gillett et al. 2016). Zonal mean geopotential height has been requested as part of the Decadal Climate Prediction Project (DCPP; Boer et al. 2016). Finally, the enhanced archival of daily data and gravity wave drag diagnostics were coordinated with the High Resolution Model Intercomparison Project (HighResMIP; Haarsma et al. 2016).

5. Analysis Plan

The DynVarMIP has been organized in response to 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; Charlton-Perez et al., 2013; Manzini et al., 2014). An analysis plan for the MIP was formulated at an open workshop held in Helsinki, Finland in June 2016. The workshop was attended by approximately 70 scientists from around the world, with broad representation from the modeling and research communities, and held jointly with a subset of the SPARC Reanalysis Intercomparison Project (S-RIP). Three groups were organized to coordinate analysis of the DynVarMIP research objectives.

The first group focused on model biases, and will begin with a systematic analysis of the TEM circulation and momentum budget in CMIP6 models. A community paper (or potentially a series of papers) is being organized to follow up more systematically on Hardiman et al. 2013, which compared the residual circulation across a subset of CMIP5 models where the relevant diagnostics could be collected on an ad hoc basis. The first paper will focus the momentum and heat balances of the historical climate, where it can be directly compared with observations. Several of the group members are involved in the S-RIP chapter on the Brewer-Dobson Circulation, bringing expertise on potential limitations in our understanding of the momentum and heat budgets in reanalysis.

Two approaches were suggested for the DynVarMIP objective on the response of the circulation to anthropogenic forcing. The first is to extend the systematic, community organized analysis of the heat and momentum budgets to climate change scenarios, with an emphasis on links between models' ability to capture the past climate with their projections of future circulation changes. The second is to continue informal coordination of research on the underlying mechanisms. Based on past experience, we have found that research on a mechanistic understanding of the atmosphere is often best organized organically, rather than from a top down approach. The potential for a review paper on model hierarchies, which help link basic research to comprehensive climate models, was raised, and will be explored in greater detail at the upcoming WCRP workshop on model hierarchies in November, 2016.

A third group focused on the natural variability of the atmosphere, with a particular emphasis on initial condition predictability (i.e. predictability of the first kind; Lorenz, 1975) in CMIP6 models across a range of time scales, from synoptic to decadal. Charlton et al. (2013) concluded that a better representation of the stratosphere in climate models strongly impacts the variability of the stratosphere, and it is an open question as to the extent which this improves the representation of natural variability in the troposphere. Subseasonal variability was identified as an important, but less explored area in climate research. It is also a time scale for which the stratosphere is particularly relevant, and a review paper was proposed to motivate more systematic analysis of variability on this time scale in CMIP6 models.

To ensure continued participation and collaboration with the modeling centers, representatives from the modeling centers have been invited to participate in the scientific analysis and papers. A future workshop (tentatively set for 2019 at which time CMIP6 data is expected to be available) will be arranged to ensure completion of the analysis.

6. 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 emerged from the needs of an international community of scientists with strong connections to the modeling centers, continuing a collaborative effort 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 CMIP6 activities. 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 DAMIP experiments focused on solar variability in large part depend 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. (2016) 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). The diagnostics must be calculated on pressure surfaces, ideally spaced very close to, if not identical to, the native levels 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 and the TEM mass stream-function.

Coordinates, averages and frequency

Fields of interest must be interpolated to pressure levels prior to taking zonal and temporal averages. Ideally, the pressure levels should be as close as possible to the average position of the model levels, to minimize the impact of interpolation. The TEM diagnostics are particularly sensitive to vertical derivatives, and it is important to keep the full vertical resolution of the atmospheric model until interpolating the final results to the standardized output levels for archival.

Flux quantities with multiplying factors (e.g., heat flux $v'\theta'$) composed of anomalies from the zonal mean (e.g., $v' = v - \bar{v}$, where the overbar indicates a zonal mean) should be computed from instantaneous 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 from instantaneous model output at 6-hour or higher frequency or (where available) directly computed over all time steps. Similarly, zonal averages are calculated averaging over all available longitudes. Zonal averages in the lower atmosphere can pose a problem when pressure surfaces intersect the surface. We recommend that modeling centers either (1) extrapolate the required variables below the surface before computing the diagnostics (see, for example, Trenberth et al., 1993) or (2) take a representative average over all longitudes that are still above the surface. With the second option, a zonal average should be marked missing only if the pressure level is below the surface at more than half of all longitudes. Likewise, a time average should be take over time steps for which the data is available, and only marked missing if more than half the data is missing.

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, variable ta in the Climate Model Output Rewriter (CMOR)
u for eastward wind velocity, ua variable in CMOR
υ 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
$R = 287.058$ J $\mathrm{K^{-1}kg^{-1}}$, gas constant for dry air
$C_p = 1004.64$ J $\mathrm{K^{-1}kg^{-1}}$, specific heat for dry air, at constant pressure
$g_0 = 9.80665\ \mathrm{ms^{-1}}$, global average of gravity at mean sea level
$a = 6.37123 \text{ x } 10^6$ m , earth's radius
$\Omega = 7.29212 \text{ x } 10^{-5}\ \mathrm{s^{-1}}$, 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:

$$\theta = T(p_0/p)^k \qquad (1)$$

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, $\mathbf{F}$, 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, $\mathbf{F} = \{F_{(\phi)}, F_{(p)}\}$, with northward and vertical components respectively defined by:

$$F_{(\phi)} = a \cos \phi \{\frac{\partial \bar{u}}{\partial p} \psi - \overline{u'v'}\} \qquad (2)$$

$$F_{(p)} = a \cos \phi \{\left[f - \frac{\partial \bar{u} \cos \phi}{a \cos \phi \partial \phi}\right] \psi - \overline{u'\omega'}\} \qquad (3)$$

where:

$$\psi = \overline{v'\theta'} / \frac{\partial \bar{\theta}}{\partial p} \qquad (4)$$

is the eddy stream-function.

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

$$\nabla \cdot \mathbf{F} = \frac{\partial F_{(\phi)} \cos\phi}{a\cos\phi \partial\phi} + \frac{\partial F_{(p)}}{\partial p} \qquad (5)$$

The Transformed Eulerian mean northward and vertical velocities are respectively defined by:

$$\bar{v}^* = \bar{v} - \frac{\partial\psi}{\partial p} \qquad (6)$$

$$\bar{\varpi}^* = \bar{\varpi} + \frac{\partial \psi\cos\phi}{a\cos\phi\partial\phi} \qquad (7)$$

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

$$\Psi(p) = \frac{2\pi a cos\phi}{g_0} \left[\int_p^0 \bar{v} dp - \psi\right] \qquad (8)$$

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

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

$$\frac{\partial\bar{u}}{\partial t}|_{\mathrm{adv}(\bar{v}^*)} = \bar{v}^*\left[f - \frac{\partial\bar{u}\cos\phi}{a\cos\phi\partial\phi}\right] \qquad (9)$$

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

$$\frac{\partial\bar{u}}{\partial t}|_{\mathrm{adv}(\bar{\varpi}^*)} = -\bar{\varpi}^* \frac{\partial\bar{u}}{\partial p} \qquad (10)$$

Transformation to log-pressure coordinate

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

$$z = -\mathrm{H}\ln(p/p_0) \qquad (11)$$

$$p = p_0 e^{-z/H} \qquad (12)$$

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, $\widehat{\mathbf{F}} = \{\widehat{F}_{(\phi)}, \widehat{F}_{(z)}\}$, is then obtained from the pressure coordinate by:

$$\widehat{F}_{(\phi)} = \frac{p}{p_0} F_{(\phi)} \qquad (13)$$

$$\widehat{F}_{(z)} = -\frac{H}{p_0} F_{(p)} \qquad (14)$$

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:

$$\nabla_{(z)} \cdot \widehat{\mathbf{F}} = \frac{\partial \widehat{F}_{(\phi)} \cos\phi}{a \cos\phi \partial\phi} + \frac{\partial \widehat{F}_{(z)}}{\partial z} = \frac{p}{p_0} \nabla \cdot \mathbf{F} \qquad (15)$$

The Transformed Eulerian Mean upward wind velocity is:

$$\overline{w}^* = -\frac{H}{p} \overline{\omega}^* \qquad (16)$$

Output

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

$\widehat{F}_{(\phi)}$ → epfy, northward component of the Eliassen-Palm Flux, Eq. (13)

$\widehat{F}_{(z)}$ → epfz, upward component of the Eliassen-Palm Flux, Eq. (14)

$\overline{v}^*$ → vtem, Transformed Eulerian Mean northward wind, Eq. (6)

$\overline{w}^*$ → wtem, Transformed Eulerian Mean upward wind, Eq. (16)

$\widehat{\Psi}$ → psitem, Transformed Eulerian Mean mass stream-function, Eq. (8)

$\nabla_{(z)} \cdot \widehat{\mathbf{F}}$ → utendepfd, tendency of eastward wind due to EP Flux divergence, Eq. (15)

$\frac{\partial \overline{u}}{\partial t}|_{\mathrm{adv}(\overline{v}^*)}$ → utendvtem, tendency of eastward wind due to TEM northward wind advection and the Coriolis term, Eq. (9)

$\frac{\partial \overline{u}}{\partial t}|_{\mathrm{adv}(\overline{\omega}^*)}$ → utendwtem, tendency of eastward wind due to TEM upward wind advection, Eq. (10)

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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
ps	Surface Air 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) on the plev39 grid. The zonal mean zonal wind is requested, as it would otherwise be unavailable at this vertical resolution.

Name (priority)	Long name [unit]	Frequency
ua (1)	eastward wind [m s^{-1}]	monthly & daily
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
mnstrage (2)	mean age of stratospheric air [yr]	monthly

Table 3. Momentum (atmosphere). Monthly mean variables (3D, grid: XYZT) on the plev19 grid.

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 (atmosphere). 2D zonal mean variables (2D grid: YZT) on the plev39 grid. The zonal mean temperature is requested, as it would otherwise be unavailable at this vertical resolution.

Name (priority)	Long name [unit]	Frequency
ta (1)	air temperature [K]	monthly
tntmp (1)	tendency of air temperature due to model physics [K s^{-1}]	monthly
tntrl (1)	tendency of air temperature due to longwave heating, all sky [K s^{-1}]	monthly
tntrs (1)	tendency of air temperature due to shortwave heating, all sky [K s^{-1}]	monthly
tntrlcs (2)	tendency of air temperature due to longwave heating, clear sky [K s^{-1}]	monthly
tntrscs (2)	tendency of air temperature due to shortwave heating, clear sky [K s^{-1}]	monthly
tntc (2)	tendency of air temperature due to convection [K s^{-1}]	monthly
tntscp (2)	tendency of air temperature due to stratiform clouds and precipitation [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

Table 6. Experiments and integration years for which the DynVarMIP diagnostics are requested.

Experiment	Collection Period(s)	Tier
DECK (Eyring et al., 2016)		
AMIP	1979-2014 (ideally for 3 ensemble members)	1
Pre-industrial control	111-150 years after the branching point	1
Abrupt quadrupling of CO2 concentration	years 1-40 and 111-150	1
1 % yr^{-1} CO2 concentration increase	years 1-150 (**monthly mean data only**)	1
CMIP6 historical simulation		
Past ~ 1.5 centuries	1961-2000	1
ScenarioMIP (O'Neill et al., 2016)		
SSP5-RCP8.5	2061-2100	2
CFMIP (Webb et al., 2016)		
amip-p4K	1979-2014	2
amip-future4K	1979-2014	2
amip-4xCO2	1979-2014	2

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