Mass-consistent atmospheric energy and moisture budget data from 1979 to present derived from ERA5 reanalysis: Product User Guide

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Acronyms

Acronym	Description
tediv	Divergence of vertical integral of total energy flux
tefle	Vertical integral of eastward total energy flux
tefln	Vertical integral of northward total energy flux
tetend	Tendency of vertical integral of total energy
lhdiv	Divergence of vertical integral of latent heat flux
lhfle	Vertical integral of eastward latent heat flux
lhfln	Vertical integral of northward latent heat flux
lhtend	Tendency of vertical integral of latent heat
wvdiv	Divergence of vertical integral of water vapour flux
wvfle	Vertical integral of eastward water vapour flux
wvfln	Vertical integral of northward water vapour flux
wvtend	Tendency of vertical integral of water vapour
Re	Residual of the dry air mass budget
T	Temperature in Kelvin
T_c	Temperature in Celsius
q	Specific humidity
$\mathbf{v}$	Horizontal wind field vector
p_S	Surface pressure

P	Precipitation
E	Evaporation
	Geopotential
k	Kinetic energy of air
L_v	Latent heat of vaporization
g	Gravitational acceleration (9.81 m s^{-2})
c_p	Specific heat capacity of dry air at constant pressure (1004.70 J kg^{-1} K^{-1})
c_v	Specific heat capacity of dry air at constant volume (717.65 J kg^{-1} K^{-1})
c_l	Specific heat of liquid water (4218.00 J kg^{-1} K^{-1})
c_{pv}	Specific heat of water vapor at constant pressure (1846.10 J kg^{-1} K^{-1})

1. Introduction

1.1. Executive Summary

This dataset provides monthly means of mass-consistent atmospheric energy and moisture budget terms derived from 1-hourly ERA5 reanalysis data. Mass consistency is achieved by iteratively adjusting the wind field every time step. This dataset allows to evaluate atmospheric energy and moisture budget diagnostics for the period from 1979 onward.

1.2. Scope of Documentation

This documentation describes the computation of mass-consistent budget terms using 1-hourly analysed state quantities from ERA5.

1.3. Version History

No previous versions.

2. Product Description

2.1. Product Overview

2.1.1. Data Description

Table 1: Dataset general attributes

Dataset attribute	**Details**
Data type	Gridded
Projection	Regular grid
Horizontal coverage	Global
Horizontal resolution	0.25° x 0.25°
Vertical coverage	Surface to top of atmosphere
Vertical resolution	Single level
Temporal coverage	1979/01 - present
Temporal resolution	Monthly
File Format	NetCDF 4

Table 2: Variables summary

Variable name	Description	Units
Divergence of vertical integral of total energy flux	This parameter is the horizontal rate of flow of total energy integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. The total energy in this parameter is the sum of sensible heat, latent heat (with latent heat of vaporization varying with temperature), kinetic, and potential energy, which is also referred to as the moist static plus kinetic energy. The total energy flux is the horizontal rate of flow of energy per metre. Its horizontal divergence is positive for a total energy flux that is spreading out, or diverging, and negative for a total energy flux that is concentrating, or converging. The sensible heat is referenced to 0 degree Celsius, whereby sensible heat of water vapour is neglected. Winds used for computation of fluxes of total energy are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass. This parameter is truncated at wave number 180 to reduce numerical noise.	W m^{-2}
Vertical integral of eastward total energy flux	This parameter is the eastward component of the total energy flux integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. The total energy in this parameter is the sum of sensible heat, latent heat (with latent heat of vaporization varying with temperature), kinetic, and potential energy, which is also referred to as the moist static plus kinetic energy. This parameter is the horizontal rate of flow of energy per metre in east-west direction. It is positive for a total energy flux in eastward direction, and negative for a total energy flux in westward direction. The sensible heat is referenced to 0 degree Celsius, whereby sensible heat of water vapour is neglected. Winds used for computation of fluxes of total energy are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass.	W m^{-1}
Vertical integral of northward total energy flux	This parameter is the northward component of the total energy flux integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. The total energy in this parameter is the sum of sensible heat, latent heat (with latent heat of vaporization varying with temperature), kinetic, and potential energy, which is also referred to as the moist static plus kinetic energy. This parameter is the horizontal rate of flow of energy per metre in north-south direction. It is positive for a total energy flux in northward direction, and negative for a total energy flux in southward direction. The sensible heat is referenced to 0 degree Celsius, whereby sensible heat of water vapour is neglected. Winds used for computation of fluxes of total energy are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass.	W m^{-1}
Tendency of vertical integral of total energy	This parameter is the rate of change of total energy integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. In this parameter, the total energy is the sum of internal energy, latent heat (with latent heat of vaporization varying with temperature), kinetic, and potential energy. The vertical integral of total energy is the total amount of atmospheric energy per unit area. Its tendency, or rate of change, is positive if the total energy increases and negative if the total energy decreases in an atmospheric column. The sensible heat is referenced to 0 degree Celsius, whereby sensible heat of water vapour is neglected.	W m^{-2}
Divergence of vertical integral of latent heat flux	This parameter is the horizontal rate of flow of latent heat integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. Latent heat is the amount of energy required to convert liquid water to water vapour. The latent heat flux is the horizontal rate of flow per metre. Its horizontal divergence is positive for a latent heat flux that is spreading out, or diverging, and negative for a latent heat flux that is concentrating, or converging. Winds used for computation of fluxes of latent heat are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass. The latent heat of vaporization is computed as a function of temperature. This parameter is truncated at wave number 180 to reduce numerical noise.	W m^{-2}

Vertical integral of eastward latent heat flux	This parameter is the eastward component of the latent heat flux integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. Latent heat is the amount of energy required to convert liquid water to water vapour. This parameter is the horizontal rate of flow of latent heat per metre in east-west direction. It is positive for a latent heat flux in eastward direction, and negative for a latent heat flux in westward direction. Winds used for computation of fluxes of latent heat are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass. The latent heat of vaporization is computed as a function of temperature.	$W m^{-1}$
Vertical integral of northward latent heat flux	This parameter is the northward component of the latent heat flux integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. Latent heat is the amount of energy required to convert liquid water to water vapour. This parameter is the horizontal rate of flow of latent heat per metre in north-south direction. It is positive for a latent heat flux in northward direction, and negative for a latent heat flux in southward direction. Winds used for computation of fluxes of latent heat are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass. The latent heat of vaporization is computed as a function of temperature.	$W m^{-1}$
Tendency of vertical integral of latent heat	This parameter is the rate of change of latent heat integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. Latent heat is the amount of energy required to convert liquid water to water vapour. The vertical integral of latent heat is the total amount of latent heat per unit area. Its tendency, or rate of change, is positive if the latent heat increases and negative if the latent heat decreases in an atmospheric column. The latent heat of vaporization is computed as a function of temperature.	$W m^{-2}$
Divergence of vertical integral of water vapour flux	This parameter is the horizontal rate of flow of water vapour integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. The water vapour flux is the horizontal rate of flow per metre. Its divergence is positive for a water vapour flux that is spreading out, or diverging, and negative for a water vapour flux that is concentrating, or converging. Winds used for computation of fluxes of water vapour are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass. This parameter is truncated at wave number 180 to reduce numerical noise.	$kg m^{-2} s^{-1}$
Vertical integral of eastward water vapour flux	This parameter is the eastward component of the water vapour flux integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. This parameter is the horizontal rate of flow of water vapour per metre in east-west direction. It is positive for a water vapour flux in eastward direction, and negative for a water vapour flux in westward direction. Winds used for computation of fluxes of water vapour are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass.	$kg m^{-1} s^{-1}$
Vertical integral of northward water vapour flux	This parameter is the northward component of the water vapour flux integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. This parameter is the horizontal rate of flow per metre in north-south direction. It is positive for a water vapour flux in northward direction, and negative for a water vapour flux in southward direction. Winds used for computation of fluxes of water vapour are mass-adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air mass.	$kg m^{-1} s^{-1}$

Tendency of vertical integral of water vapour	This parameter is the rate of change of water vapour integrated over an atmospheric column extending from the surface of the Earth to the top of the atmosphere. The vertical integral of water vapour is the total amount of atmospheric moisture per unit area. Its tendency, or rate of change, is positive if the water vapour increases and negative if the water vapour decreases in an atmospheric column.	$kg\ m^{-2}\ s^{-1}$

Table 3: versions history

Version	Release date	Changes from previous version
1.0	2022-05-31	(first release)

2.2. Input Data

Table 4: Input datasets

Dataset	Summary	Variables used
ERA5	Provides global 1-hourly analyzed state quantities on 137 atmospheric model levels as well as analyzed surface parameters. Data are represented either on a reduced Gaussian grid N320 or as spectral coefficients with T639 triangular truncation (see ERA5 data documentation).	Temperature, vorticity, divergence, surface geopotential, and logarithm of surface pressure in spherical harmonics. Specific humidity and total column water vapour in grid space.

2.3. Method

2.3.1. Background

All ERA5 input fields are transformed (for details see below) to a full Gaussian grid F480 (quadratic grid with respect to the native spectral resolution T639) to avoid aliasing effects. Vorticity and divergence are used to compute the horizontal wind vector at each atmospheric level. Before individual budget terms are computed, the three-dimensional wind field is iteratively adjusted according to the diagnosed imbalance between divergence of vertically integrated dry mass flux and tendency of dry air. This procedure is repeated every time step.

Mass Adjustment

Mass-consistent wind fields are obtained by computing the residual of the mass continuity of dry air, which reads as follows

$$Re = \nabla \cdot \dfrac{1}{g} {\displaystyle\int_0^{p_S}} \left[(1 - q)\textbf{v}\right] \; dp + \dfrac{1}{g} \dfrac{\partial}{\partial t} {\displaystyle\int_0^{p_S}} (1 - q) \; dp,$$

where g is the gravitational acceleration, p_S is the surface pressure, q is the specific humidity, and **v** is the horizontal wind vector. The first term on the right side is the divergence of vertically integrated dry mass flux, and second term describes the surface pressure tendency induced by dry air. Inverting the Laplacian of Re and taking the gradient yields a vertically integrated erroneous mass flux, which is converted to a two-dimensional spurious wind field. This spurious divergent wind is subtracted from the original wind field at each level (barotropic wind field correction) making it consistent with the analyzed mass tendency of dry air. After a second iteration of this procedure, mass-adjusted wind fields are used to compute atmospheric energy and moisture budget terms.

Atmospheric Energy Budget

Atmospheric energy fluxes and tendencies are computed according to a simplified version of the energy budget as proposed by Mayer et al. (2017), where vertical and lateral enthalpy fluxes associated with water and snow are consistently neglected, such that

$$F_{TOA} - \underbrace{\nabla\cdot \dfrac{1}{g} {\displaystyle \int_0^{p_S}} [(1 - q) c_p T_c + L_v (T_c) q + \Phi + k] \; \textbf{v}\; dp}_{\text{tediv} = \nabla\cdot (\text{tefle, tefln})^T} - \underbrace{\dfrac{\partial}{\partial t} \dfrac{1}{g} {\displaystyle\int_0^{p_S}} [(1 - q) c_v T_c + L_v (T_c) q + \Phi + k] dp}_{\text{tetend}} - F_S = 0$$

where c_p is the specific heat capacity of dry air at constant pressure, T_c is the air temperature measured in Celsius, $L_v(T)$ is the temperature-dependent latent heat of vaporization, is the potential energy, k is the kinetic energy, and c_v is the specific heat capacity of dry air at constant volume. The vertical fluxes F_{TOA} and F_S describe the net energy flux at the top of the atmosphere and net surface heat (radiative plus turbulent) flux, which are both not included in this dataset. The second term describes the divergence of the vertical integral of moist static plus kinetic energy flux (i.e., the divergence of north- and eastward energy fluxes), and the third term is the tendency of the vertical integral of total energy. Note that the *total energy* is the sum of internal energy c_vT_c, latent heat L_vq, potential energy , and kinetic energy k, whereas the *moist static plus kinetic energy* contains the sensible heat c_pT_c instead of the internal energy. For the sake of simplicity, however, the 'moist static plus kinetic energy' as used in the divergence term is also referred to as the 'total energy' in this dataset, although it contains the sensible heat and not the internal energy. The temperature-dependent latent heat of vaporization is computed according to the IFS documentation, Part IV, and is defined as

$$L_v(T_c) = L_v(T_0) + (c_{pv} - c_l)*(T - T_0),$$

where $L_v(T_0) = 2.5008\times10^6$ J kg^{-1} is the latent heat at the triple point temperature T_0 (in Kelvin), c_{pv} is the specific heat capacity of water vapour at constant pressure, c_l is the specific heat of liquid water, and T is the air temperature measured in Kelvin. To derive energy budget terms with constant latent heat of vaporization (as provided by ERA5), latent heat terms can be subtracted and replaced by corresponding water vapour terms multiplied by $L_v(T_0)$. The potential energy is computed as described in the IFS documentation, Part III.

Atmospheric Moisture Budget

The atmospheric moisture budget can be written as

$$\underbrace{\nabla \cdot \dfrac{1}{g} {\displaystyle\int_0^{p_S}} (q \textbf{v}) \; dp}_{\text{wvdiv} = \nabla\cdot (\text{wvfle, wvfln})^T} + \underbrace{\dfrac{1}{g} \dfrac{\partial}{\partial t} {\displaystyle\int_0^{p_S}} q \; dp}_{\text{wvtend}} + P + E = 0,$$

where precipitation P and evaporation E (not in this dataset) are surface mass fluxes in units kg m^{-2} s^{-1}. The first term describes the divergence of the vertical integral of atmospheric water vapour flux, the second term describes the tendency of the vertical integral of atmospheric water vapour (i.e., total column vapour). That is, atmospheric fluxes and tendencies of water vapour must balance surface freshwater fluxes P+E. The divergence term of the moisture budget also employs mass-adjusted wind fields **v**, albeit it is affected only weakly by spurious divergent winds. Note that tendency terms in this dataset are computed as exact difference from 00 UTC at the first of month to 00 UTC at the first of following month divided by the number of seconds.

2.3.2. Model / Algorithm

The following pseudo code describes the mass-adjustment procedure and subsequent computation of energy and moisture budget terms. All spectral transformations (i.e., gradient and divergence computations, Laplace inversion) were performed with routines from OpenIFS .

$$\begin{align} &\text{for each time step do } \\ &\qquad \Phi_S \;\;\; \leftarrow \text{ Read surface geopotential} \\ &\qquad vort \: \leftarrow \text{ Read vorticity} \\ &\qquad div \;\;\; \leftarrow \text{ Read divergence} \\ &\qquad T \;\;\;\;\;\;\; \leftarrow \text{ Read temperature} \\ &\qquad q \;\;\;\;\;\;\;\: \leftarrow \text{ Read specific humidity} \\ &\qquad p_S \;\;\;\;\: \leftarrow \text{ Read logarithm of surface pressure} \\ &\qquad tcwv \leftarrow \text{ Read total column water vapour} \\ &\qquad \\ &\qquad \text{Transform all input fields to full Gaussian grid F480} \\ &\qquad \\ &\qquad \textbf{v} \leftarrow \text{ Compute horizontal wind field using } vort, div \\ &\qquad wvtend \leftarrow \text{ Compute tendency of the vertical integral of water vapour using } tcwv \\ &\qquad mtend \;\;\leftarrow \text{ Compute tendency of vertically integrated atmospheric mass using } p_S \\ &\qquad \\ &\qquad \text{for each correction step do } \\ &\qquad\qquad mdiv \;\;\;\leftarrow \text{ Compute divergence of vertically integrated atmospheric mass flux using } \textbf{v} \\ &\qquad\qquad wvdiv \;\leftarrow \text{ Compute vertically integrated water vapour divergence using } \textbf{v}, q \\ &\qquad\qquad errdiv \leftarrow mdiv - wvdiv + mtend - wvtend \\ &\qquad\qquad \textbf{v}_{err} \;\;\;\;\;\; \leftarrow \text{ Compute spurious two-dimensional wind field using } errdiv \\ &\qquad\qquad \text{ for each atmospheric level } i \text{ in } \textbf{v} \text{ do } \textbf{v}_i \leftarrow \textbf{v}_i - \textbf{v}_{err} \\ &\qquad \text{end do} \\ &\qquad \\ &\qquad T_c \leftarrow T - 273.15 \\ &\qquad lhtend \;\;\leftarrow \text{ Compute tendency of the vertical integral of latent heat using } q, T_c \\ &\qquad tetend \;\; \leftarrow \text{ Compute tendency of the vertical integral of total energy using } \textbf{v}, q, T_c, \Phi_S \\ &\qquad lhfle, lhfln \;\;\;\leftarrow \text{ Compute vertical integral of latent heat fluxes using } \textbf{v}, q, T_c \\ &\qquad tefle, tefln \;\;\;\;\leftarrow \text{ Compute vertical integral of total energy fluxes using } \textbf{v}, q, T_c, \Phi_S \\ &\qquad wvfle, wvfln \leftarrow \text{ Compute vertical integral of water vapour fluxes using } \textbf{v}, q \\ &\qquad lhdiv \;\;\leftarrow \text{ Compute divergence of the vertical integral of latent heat fluxes using } lhfle, lhfln \\ &\qquad tediv \;\;\leftarrow \text{ Compute divergence of the vertical integral of total energy fluxes using } tefle, tefln \\ &\qquad wvdiv \leftarrow \text{ Compute divergence of the vertical integral of water vapour fluxes using } wvfle, wvfln \\ &\text{end do} \end{align}$$

2.3.3. Validation

The divergence fields in this dataset exhibit zero global mean suggesting optimal computations and good accuracy. Tendency terms are temporally stable and exhibit long-term global zero mean indicating good reliability. Indirectly estimated oceanic F_S derived from tediv and tetend in combination with F_{TOA} from CERES-EBAF (not in this dataset) agrees with the observation-based ocean heat uptake to within 1 W m^{-2} (see Mayer et al. 2022). All fields are in good qualitative agreement with known patterns of the respective quantities, but satisfaction of physical constraints (e.g., magnitude of ocean-to-land energy and moisture transport or temporal stability) is much improved compared to earlier evaluations (see Mayer et al. 2021 and 2022 for comprehensive evaluation).

3. Known issues

1. The divergence terms (tediv, lhdiv, wvdiv) with full spectral resolution show artificial pattern of numerical noise over high topography, which are thus spectrally truncated at wave number 180. The divergence fields with full spectral resolution (see example in Fig. 1) can be reconstructed by computing the divergence of corresponding north- and eastward fluxes provided in this dataset.

2. The ocean-to-land energy transport as estimated from tediv exhibits an unrealistically strong gradual change in the late 1990s and early 2000s, which likely stems from changes in the observing system that has been assimilated by ERA5 (see Mayer et al. 2021 for discussion).
3. Global ocean and land averages of wvdiv exhibit a reasonably strong but statistically insignificant trend over the available period, see Mayer et al. (2021) for further details.

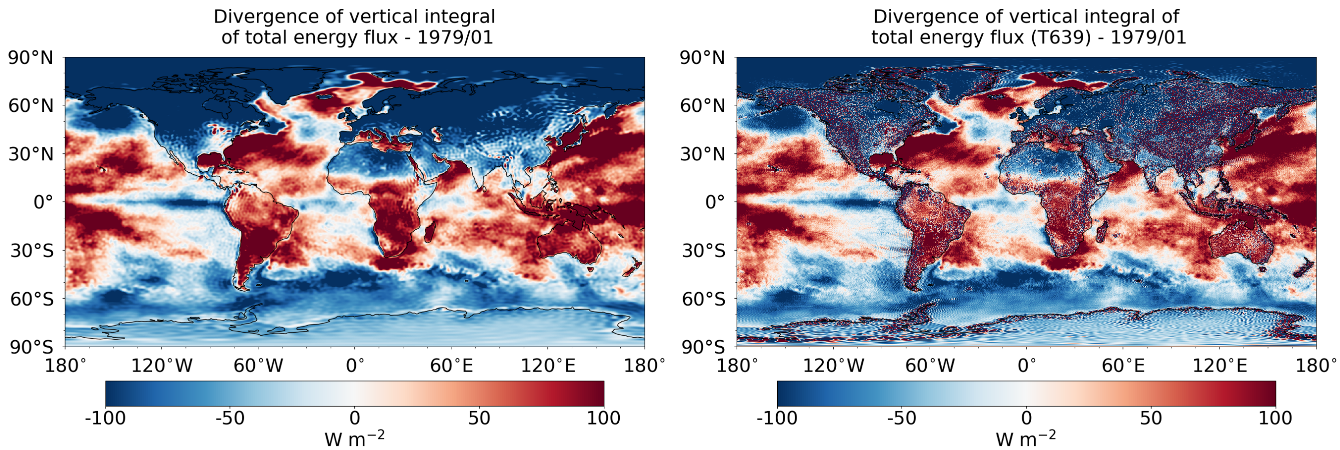

Figure 1: The divergence of the vertical integral of total energy flux (left) truncated at wave number 180, and (right) with full spectral resolution T639.

4. Licence, Acknowledgement and Citation

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References

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