# Temporal Variability of Inferred Surface Energy Fluxes derived from the ERA5 Energy Budget

Johannes Mayer* (1), Michael Mayer (1,2), Leopold Haimberger (1)

(1) Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria
(2) European Centre for Medium-Range Weather Forecasts, Reading, UK

*johannes.mayer@univie.ac.at

EGU session CL2.1
Wednesday, 06 May 2020, 14:00-15:45

# Motivation

- The energy budget approach is a well known diagnostic method to evaluate the energy imbalance, trends and variability of the Earth's climate system.
- Previous evaluations of the energy budget yield good results, but global means of oceanic surface energy fluxes are still far from the globally averaged ocean heat uptake of $\sim$0.6 W m$^{-2}$ (Wild et al., 2012).
- Furthermore: In-situ measurements as well as satellite observations are still not able to capture Earth's energy imbalance and surface energy fluxes with sufficient accuracy (uncertainties of 10–20 %; Rhein et al. (2013)).
- The new Copernicus ERA5 reanalysis dataset (Hersbach et al., 2020) comes with a lot of improvements over previous reanalyses, and thus provides a good foundation to indirectly estimate surface energy fluxes with unprecedented accuracy.
- How well does ERA5 perform with respect to the atmospheric energy and moisture budget?

| | ERA-Interim | ERA5 |
|---|---|---|
| Period | 1979 – present | Initially 1979 – present, now extended 1950-1978 |
| Streams | 1979-1989, 1989-present | Parallel streams, one/two per decade |
| Assimilation system | 2006, 4D-Var | 2016 ECMWF model cycle (41r2), 4D-Var |
| ***Model input*** (radiation and surface) | As in operations, *(inconsistent sea surface temperature)* | ***Appropriate for climate***, e.g., evolution greenhouse gases, volcanic eruptions, sea surface temperature and sea ice |
| ***Spatial resolution*** | 79 km globally 60 levels to 10 Pa | ***31 km globally*** 137 levels to 1 Pa |
| ***Uncertainty estimate*** | | Based on a 10-member ***4D-Var ensemble*** at 62 km |
| ***Land Component*** | 79km | ERA5L, 9km (separate, forced by ERA5) |
| ***Output frequency*** | 6-hourly Analysis fields | ***Hourly*** (three-hourly for the ensemble), ***Extended list of parameters*** ***~ 9 Peta Byte (1950 - timely updates)*** |
| ***Extra Observations*** | Mostly ERA-40, GTS | Various ***reprocessed CDRs***, ***latest instruments*** |
| Variational Bias correction | Satellite radiances, radiosondes predetermined | Also ozone, aircraft, surface pressure, newly predetermined for radiosondes. |

from Dinand Schepers

# Introduction

- We use a mass-consistent formulation of the atmospheric energy budget, and advanced numerical and diagnostic methods to indirectly estimate surface energy fluxes $F_S$ for the period 1985–2018:

$$F_S = R_{TOA} - \nabla \cdot \frac{1}{g} \int_0^{ps} [(1-q)c_a(T_a) + L_v(T_a)q + \Phi + k]\mathbf{v}dp - AET \quad (1)$$

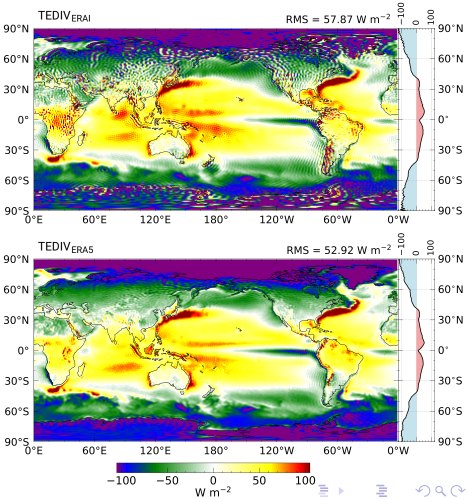
  where enthalpy fluxes associated with water/snow are neglected (Mayer et al., 2017).

- To do so, the new Copernicus ERA5 reanalysis dataset is used in combination with net TOA fluxes from CERES-EBAF and a product from the University of Reading (Liu and Allan, 2017) for the period prior to CERES (starts in 2000/03). In the following, temporal variability and stability of the inferred surface fluxes are compared with previous evaluations using ERA-Interim, and corresponding ocean-land energy transports are presented.
- Furthermore, an overview of the moisture budget in ERA5 is given.

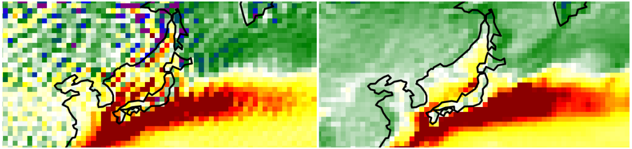
[0] Net top-of-the-atmosphere flux $R_{TOA}$, gravitational constant g, surface pressure $p_S$, specific humidity q, specific heat capacity of dry air $c_a$, temperature of air $T_a$, latent heat of vaporization $L_v$, geopotential $\Phi$, kinetic energy k, horizontal wind vector $\mathbf{v}$, and atmospheric energy tendency AET. Second term on the r.h.s. is the divergence of total energy flux and is denoted as TEDIV.

# Divergence of Total Energy Flux
## Useful Resolution

- 1985-2018 averages of the divergence of the total atmospheric energy flux (TEDIV), spectrally truncated at wave number 180 (equivalent to 1 degree resolution).
- Top figure: TEDIV evaluated with ERA-Interim ($\mathrm{TEDIV}_{\mathrm{ERAI}}$) exhibits pronounced pattern of artificial noise, especially over high topography.
- Bottom figure: TEDIV evaluated with ERA5 ($\mathrm{TEDIV}_{\mathrm{ERA5}}$) is in general smoother, with a $\sim$10 % smaller RMS than $\mathrm{TEDIV}_{\mathrm{ERAI}}$.

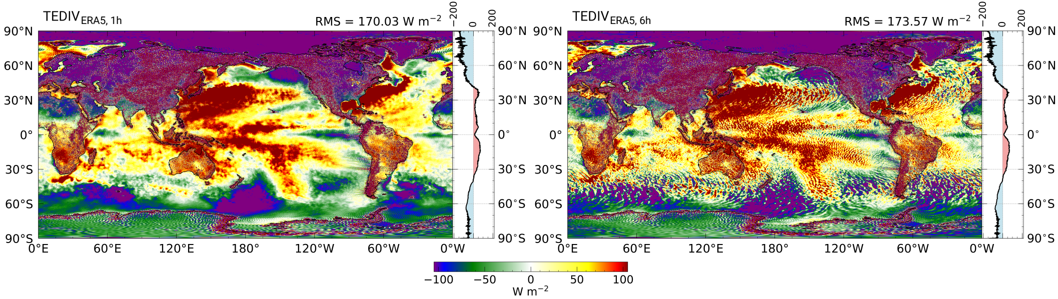



Detailed view:



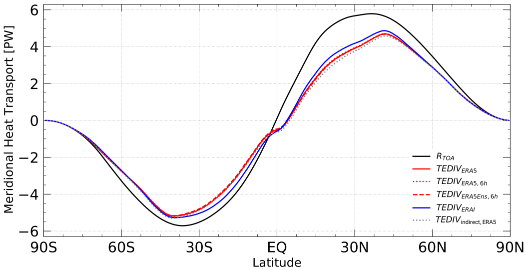
ERA-I ERA5

- Left figure: Monthly mean (Jan 2010) of $\text{TEDIV}_{\text{ERA5}}$ based on 1-hourly evaluation, with full spatial resolution (T639, equivalent to 0.28 degree) .
- Right figure: Same as in the top figure, but based on 6-hourly evaluation → sampling errors at all latitudes.
- Regional differences up to ∼250 W $m^{-2}$ on monthly scale, and still ∼90 W $m^{-2}$ on annual scale.



# Meridional Energy Transport

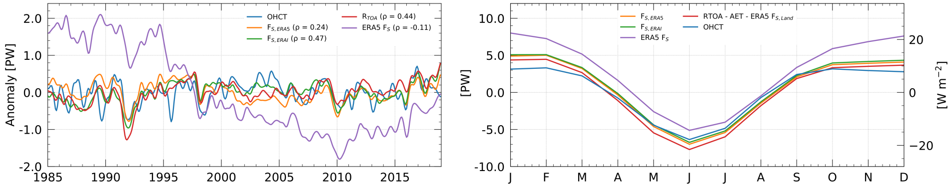
- Peak meridional energy transport (MET) in ERA5 is about 0.4 PW smaller than in ERA-I.
- MET seems to be independent of the temporal and spatial resolution of the data (compare red lines).
- Cross-equatorial energy transport in the atmosphere is between -0.52 (ERA5 ensemble) and -0.64 PW (indirect TEDIV), i.e. southward transport.




Black: Total MET derived from CERES Net TOA flux, red solid: Atmospheric MET derived from ERA5 using 1-hourly data, red dotted: derived from ERA5 using 6-hourly data, red dashed: derived from the ERA5 Ensemble (T319 spectral resolution), and blue solid: derived from ERA-I, gray dotted: derived from indirectly computed TEDIV using parametrized fluxes and forecast tendencies.

# Surface Flux Anomalies over Ocean

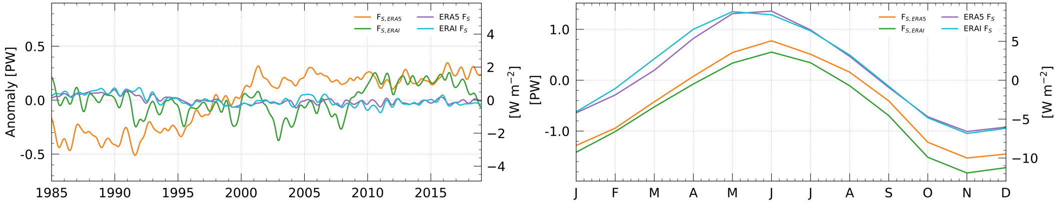
- Inferred oceanic surface flux anomalies derived from ERA5 ($F_{S,ERA5}$) and ERA-I ($F_{S,ERAI}$) agree well the ORAS5 OHCT, particularly from 2000 onwards ($\rho = 0.43$ and $0.58$).
- For the full period 1985–2018, OHCT correlates much better with $F_{S,ERAI}$ ($\rho = 0.47$) than with $F_{S,ERA5}$ ($\rho = 0.24$). Note that ORAS5 uses forcing fluxes from ERA-I.
- Parametrized surface fluxes from ERA5 (violet line) has large discontinuities, with positive anomalies prior to 2000 and negative ones afterwards.
- Similar picture emerges for the annual cycle.




Blue: OHCT derived from ORAS5; Orange, Green: Inferred surface flux anomalies using ERA5 and ERA-Interim; Red: Anomalies of the globally averaged TOA net flux from CERES-EBAF; Violet: Parametrized surface fluxes as stored in ERA5; Red line in the right panel approximates the OHCT using global TOA fluxes from CERES, and atmospheric energy tendency and land heat content from ERA5.

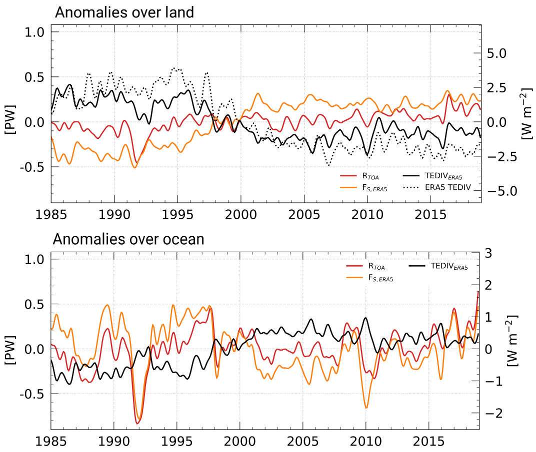
# Surface Flux Anomalies over Land

- Parametrized surface fluxes over land are on average ∼1 W m$^{-2}$, whereas inferred fluxes derived from ERA5 and ERA-I are at -2.8 W m$^{-2}$ and -4.2 W m$^{-2}$ for the period 1985–2018.
- From 2000 onwards, inferred surface fluxes derived from ERA5 (-1.5 W m$^{-2}$) are superior to those from ERA-I (-3.92 W m$^{-2}$), with good temporal stability.
- Annual cycle: Inferred fluxes peak in June, parametrized fluxes in May/June and are mostly 5 W m$^{-2}$ larger.




Orange, green: Inferred surface fluxes using ERA5 and ERAI in combination with CERES-EBAF/DEEP-C; Violet, cyan: Parametrized surface fluxes from ERA-I and ERA5;

# Ocean-Land Energy Transport



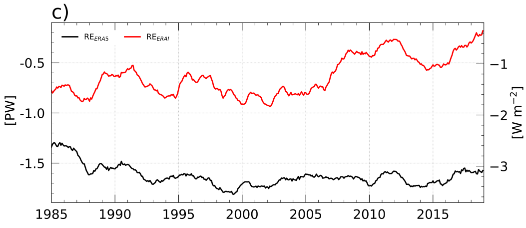

- Ocean-land energy transport in ERA5 is too weak at all times, i.e. inferred surface fluxes are too negative over land and too positive over the ocean, which is however better balanced from 2000 onwards.
- $TEDIV_{ERA5}$ mean over the ocean is 6.57 W m$^{-2}$ for 1985–2018 and increases to 6.97 W m$^{-2}$ for 2000–2018, whereas $TEDIV_{ERAI}$ mean is 6.02 W m$^{-2}$ and 5.98 W m$^{-2}$ for the same periods.
- For comparison, TEDIV without a mass-correction applied (dotted line) is stronger from 2000 onwards (surface fluxes closer to 0), but even weaker prior to 2000 → mass-adjustment also helps to reduce temporal discontinuities.

Black: TEDIV derived from ERA5; Black dotted: TEDIV as stored in ERA5

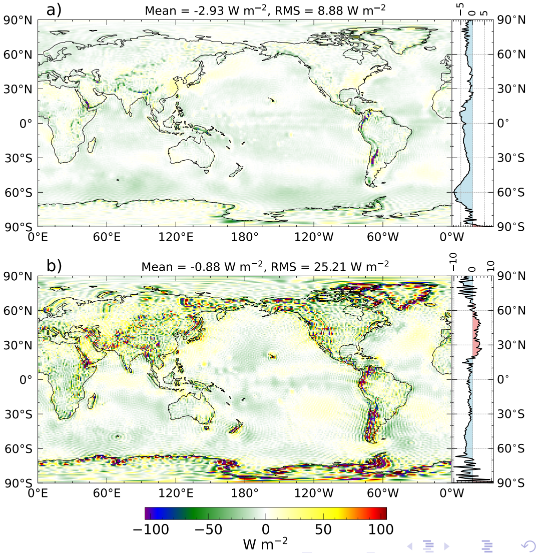
Red: Net TOA radiation; Orange: Inferred surface flux;

# Energy Budget Residuals

- ERA5 budget residual (panel a) is substantially larger than that of ERA-I (panel b).
- However, ERA5 budget residual is in general smoother and more homogeneous.
- Time series of the globally averaged budget residual (panel c) show strong variation in ERA-I, while ERA5 exhibit a reasonably good temporal stability since the early 1990s.

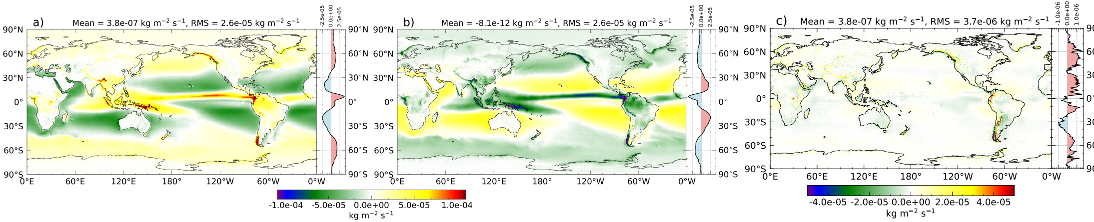



Black: Global ERA5 residual, Red: Global ERA-I residual

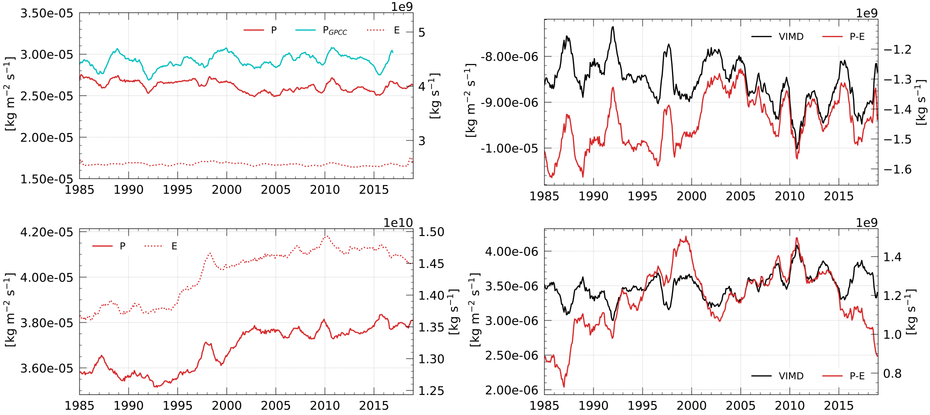


# Moisture Budget in ERA5

- P-E (panel a) and vertically integrated moisture flux divergence (panel b) are in reasonably good agreement, largest differences are over high topography as shown by the moisture budget residual (panel c).
- (Next page) Globally averaged moisture budget residual over both land and ocean is very small for the period 2005–2015, otherwise relatively large.
- (Next page) P and E is relatively stable over land, but exhibit a positive trend over the ocean.
- (Next page) Moisture flux divergence exhibit also a weak positive (negative) trend over the ocean (land), i.e. ocean-land moisture transport increases over time.



# Moisture Transport




Top: Land averages; Bottom: Ocean averages
Left: Red: Precipitation; Cyan: Precipitation from GPCC (Schneider et al., 2016); Red dotted: Evaporation;
Right: Black: Moisture flux divergence; Red: P-E

[0] Conversion factor from kg $s^{-1}$ to mm $day^{-1}$ is x86400.

# Conclusion

1. The higher temporal and spatial resolution of ERA5 drastically reduces artificial noise and sampling errors in computed atmospheric energy budgets.
2. Inferred surface fluxes derived from ERA5 are closer to the mean oceanic heat uptake (and closer to zero over land) compared to results using ERA-I data.
3. Ocean-land energy transport in ERA5 is too weak at all times, which is however better from 2000 onwards.
4. ERA5 energy budget residual is smoother and temporally more stable, but is on average much larger than the ERA-I budget residual. Reasons need to be investigated.
5. Precipitation, evaporation, and ocean-land moisture transport exhibit a positive trend over the given time span. From 2005 onwards, P-E and VIMD agree remarkably well.

Outlook:

- Paper about the energy and mass budget in ERA5 is in preparation.

# References I


Hersbach, Hans et al. "The ERA5 Global Reanalysis". In: *Quart. J. Roy. Meteorol. Soc.* 146 (2020). in press.

Liu, Chunlei and Richard Allan. *Reconstructions of the radiation fluxes at top of atmosphere and net surface energy flux in the period 1985-2015 from DEEP-C project*. 2017. URL: http://researchdata.reading.ac.uk/111/.

Mayer, Michael, Leopold Haimberger, John M. Edwards, and Patrick Hyder. "Toward Consistent Diagnostics of the Coupled Atmosphere and Ocean Energy Budgets". In: *Journal of Climate* 30.22 (2017), pp. 9225–9246.

Rhein, M. et al. "Observations: Ocean". In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by T.F. Stocker et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013. Chap. 3, 255–316.

Schneider, U., A. Becker, P. Finger, A. Meyer-Christoffer, B. Rudolf, and M. Ziese. *GPCC Full Data Reanalysis Version 7.0: Monthly Land-Surface Precipitation from Rain Gauges built on GTS based and Historic Data*. Boulder CO, 2016. URL: https://doi.org/10.5065/D6000072.

Wild, Martin, Doris Folini, Christoph Schär, Norman Loeb, Ellsworth Dutton, and Gert König-Langlo. "The global energy balance from a surface perspective". In: *Climate Dynamics* 40 (Nov. 2012).

# Mean Values in W $m^{-2}$

| Term | Mean 1985-2018 | RMS 1985-2018 | Mean 2000-2018 | RMS 2000-2018 |
|---|---|---|---|---|
| $TEDIV_{ERA5}$ Ocean | 6.57 | 51.44 | 6.97 | 52.32 |
| $TEDIV_{ERA5}$ Land | -16.10 | 56.40 | -17.08 | 56.09 |
| $TEDIV_{ERA5}$ Global | 0.00 | 52.92 | 0.00 | 53.44 |
| $TEDIV_{ERAI}$ Ocean | 6.02 | 53.65 | 5.98 | 54.53 |
| $TEDIV_{ERAI}$ Land | -14.76 | 67.12 | -14.66 | 68.27 |
| $TEDIV_{ERAI}$ Global | -0.00 | 57.87 | -0.00 | 58.84 |
| ERA5 $F_S$ Ocean | 7.84 | 36.39 | 5.40 | 35.81 |
| ERA5 $F_S$ Land | 0.77 | 5.54 | 0.65 | 5.52 |
| ERA5 $F_S$ Global | 5.79 | 30.81 | 4.02 | 30.33 |
| ERAI $F_S$ Ocean | 8.61 | 33.74 | 7.24 | 34.01 |
| ERAI $F_S$ Land | 1.03 | 6.95 | 0.88 | 7.04 |
| ERAI $F_S$ Global | 6.41 | 28.68 | 5.40 | 28.91 |
| $F_{S,ERA5}$ Ocean | 1.91 | 37.70 | 1.62 | 38.05 |
| $F_{S,ERA5}$ Land | -2.83 | 16.11 | -1.50 | 16.20 |
| $F_{S,ERA5}$ Global | 0.54 | 32.93 | 0.72 | 33.23 |
| $F_{S,ERAI}$ Ocean | 2.46 | 37.75 | 2.61 | 38.31 |
| $F_{S,ERAI}$ Land | -4.17 | 41.96 | -3.92 | 42.91 |
| $F_{S,ERAI}$ Global | 0.54 | 39.02 | 0.72 | 39.70 |

# Mean Values in W $m^{-2}$

| Term | Mean 1985-2018 | RMS 1985-2018 | Mean 2000-2018 | RMS 2000-2018 |
|---|---|---|---|---|
| $R_{TOA}$ Ocean | 8.49 | 56.69 | 8.61 | 56.55 |
| $R_{TOA}$ Land | -18.90 | 55.09 | -18.55 | 55.37 |
| $R_{TOA}$ Global | 0.55 | 56.23 | 0.74 | 56.21 |
| $RE_{ERA5}$ Ocean | -3.19 | 6.05 | -3.25 | 6.32 |
| $RE_{ERA5}$ Land | -2.28 | 13.50 | -2.51 | 13.54 |
| $RE_{ERA5}$ Global | -2.93 | 8.88 | -3.04 | 9.03 |
| $RE_{ERAI}$ Ocean | -1.24 | 14.92 | -1.09 | 15.55 |
| $RE_{ERAI}$ Land | 0.01 | 40.59 | 0.00 | 41.62 |
| $RE_{ERAI}$ Global | -0.88 | 25.21 | -0.77 | 25.96 |
| OHCT | 2.72e10 | 3.10e10 | 2.73e10 | 3.12e10 |