National Aeronautics and Space Administration

M21C Land Budgets: Final Summary

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GODDARD EARTH SCIENCES

Land Water and Energy Balance (MERRA-2)

Balance equations from the land ("lnd" Collection) perspective:

MERRA-2 File Specs (p. 71): **WCHANGE = PRECTOTLAND – EVLAND – RUNOFF – BASEFLOW + SPWATR**

MERRA-2 File Specs (p. 72): **ECHANGE = SWLAND + LWLAND – SHLAND – L_v EVLAND – L_f PRECSNOLAND – SPLAND – SPSNOW.**

Wrong!

Revised M-2 balance equations (found by trial-and-error):

For details and plots, see 11 Jun 2024 slides.

WCHANGE = PRECTOTLAND – EVLAND – RUNOFF – BASEFLOW – SPWATR

ECHANGE = SWLAND + LWLAND – SHLAND – EVPSOIL – EVPINTR – EVPTRNS – EVPSBLN
– Lf * PRECSNO – SPLAND – SPSNOW

These errors could be fixed in the documentation. However, there is still a small error in the energy balance equation, and there are inconsistencies in the outputs...

Land Energy Balance (MERRA-2)

National Aeronautics and Space Administration

<u>Inconsistent output</u> within "lnd" Collection:

See 11 June 2024 slides for plots.

EVPSOIL + EVPINTR + EVPTRNS + EVPSBLN **≠** LHLAND **!!! Inconsistent energy balance terms.**

(EVPSOIL + EVPINTR + EVPTRNS) / Lv + EVPSBLN / Ls **≠** EVLAND **!!! Inconsistent energy/water balance.**

In the GCM, prior to output, the turbulent fluxes computed by Catchment (EVAPOUT, SHOUT, HLATN) are adjusted to match what TurbGC expects (per its linearization), with [*]ACC being the difference (computed in Catchment):

```
if(associated(EVLAND)) EVLAND = EVAPOUT-EVACC
if(associated(SHLAND)) SHLAND = SHOUT  -SHACC
if (CATCH_INTERNAL_STATE%CATCH_OFFLINE == 0) then
  !XXX add correction term to latent heat diagnostics (HLATN always allocated)
  !    this will impact the export LHLAND
  HLATN = HLATN - LHACC
  ! also add some portion of the corr. term to evap from soil, int, veg & snow
  SUMEV = EVPICE+EVPSOI+EVPVEG+EVPINT
  where(SUMEV>0.)
    EVPICE = EVPICE - EVACC*EVPICE/SUMEV
    EVPSOI = EVPSOI - EVACC*EVPSOI/SUMEV
    EVPINT = EVPINT - EVACC*EVPINT/SUMEV
    EVPVEG = EVPVEG - EVACC*EVPVEG/SUMEV
  endwhere
endif
```

[In offline mode, we set EVACC=LHACC=SHACC=0.]

Poor choice of var names b/c EV[*] and EVP[*] have different units; made worse by lack of in-code documentation.

Wrong in all* GEOS products!!!

*Except SMAP L4.

→ Adjustment of latent heat components (EVP[*]) is wrong:

- **Error 1: Excludes dewfall, need "`where (SUMEV /= 0.)`".**
- **Error 2: Units are wrong → EVP[*] essentially unchanged.**

[W/m²]

[kg/m2/s] [W/m2] / [W/m2] = **[kg/m2/s]**

Land Energy Balance (MERRA-2)

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Revised M-2 land energy balance:

ECHANGE = SWLAND + LWLAND – SHLAND – EVPSOIL – EVPINTR – EVPTRNS – EVPSBLN
– Lf * PRECSNO – SPLAND – SPSNOW

Why is there still a small error in the revised energy balance?

Note that: SPLAND = SHACC = sensible heat "accounting" term

⇒ SHLAND + SPLAND = sensible heat flux computed by Catchment.

Poor choice of SPLAND short & long names.

Correct M-2 land energy balance:

ECHANGE = SWLAND + LWLAND – SHLAND – LHLAND – LHACC
– Lf * PRECSNO – SPLAND – SPSNOW

Latent heat flux computed by Catchment.

However, the correct balance cannot be verified because M-2 does not write out LHACC.

Because of the units error, we have: LHLAND + LHACC ≅ EVPINTR + EVPSBLN + EVPSOIL + EVPTRNS

For the same reason, the water balance and the energy balance are connected as follows:

EVLAND + SPWATR ≅ (EVPINTR + EVPSOIL + EVPTRNS)/Lv + EVPSBLN/Ls

Approximate equalities!!!

Water Balance Across Land and Atmosphere (MERRA-2)

Land:

WCHANGE = PRECTOTLAND – EVLAND – RUNOFF – BASEFLOW – SPWATR

Atmosphere:

DQVDT_PHY + DQLDT_PHY + DQIDT_PHY = EVAP – PRECCU – PRECLS – PRECSN + QTFILL

"flx" Collection (Turbulence GC)

For land-only grid cells:

✓ $EVLAND_{lnd} = EVAP_{flx}$ (Works b/c EVLAND is adjusted to match what TurbGC expects.)

Energy Balance Across Land and Atmosphere (MERRA-2)

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Land:

ECHANGE = SWLAND + LWLAND – SHLAND – (EVPINTR + EVPSBLN + EVPSOIL + EVPTRNS)
– Lf * PRECSNO – SPLAND – SPSNOW

= SUMEVP

Atmosphere: (Closure to be confirmed by Nathan.)

≠ EFLUX (latent heat flux) by design!!!

DHDT_PHY + DKDT_PHY + DQVDT_PHY + DQIDT_PHY =
(SWNETTOA – SWNETSRF) – (LWTNET + LWGNET) + HFLUX + Lv*EVAP
+ Lf*(FRZRN + SUBSN + SDMCI + COLCNVSN) + Lv*DQVDT_CHM + Lv*DQVDT_FIL – Lf*DQIDT_FIL

"int" Collection (Solar GC)

"flx" Collection (Turb GC)

See 28 June 2024 slides for plots.

For land-only grid cells:

☹ $SWLAND_{lnd}$ ≠ $SWNETSRF_{int}$

☹ $LWLAND_{lnd}$ ≠ $LWGNET_{int}$

✓ $SHLAND_{lnd}$ = $HFLUX_{flx}$

✓ $LHLAND_{lnd}$ = $EFLUX_{flx}$

☹ $SUMEVP_{lnd}$ ≠ $EFLUX_{flx}$

Surface radiation terms in "lnd" and "int" are inconsistent in MERRA-2 (old model, not further investigated here).

Turbulent flux terms in "lnd" and "flx" are consistent (except for the latent heat components b/c of the inconsistency within "lnd", see above).

Summary of Balance Equations (MERRA-2)

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MERRA-2	Evap mass flux	Latent heat	Sensible heat
Expected by Turb GC	**EVLAND**	**LHLAND**	**SHLAND**
Calculated by Catchment	EVLAND+SPWATR	*SUMEVP = EVPINTR+EVPSBLN+EVPSOIL+EVPTRNS	SHLAND+SPLAND

EVLAND, LHLAND, and SHLAND in "lnd" as expected by TurbGC. No "spurious" export for LH.

**Matches the flux calculated by Catchment only approximately.*

Land water:

WCHANGE = PRECTOTLAND – EVLAND – SPWATR – RUNOFF – BASEFLOW

Wrong in M-2 file specs.

Land energy:

ECHANGE ≅ SWLAND + LWLAND – SHLAND – SPLAND – SUMEVP – Lf * PRECSNO – SPSNOW

LHACC ≅ SUMEVP – LHLAND ≠ 0 (LHACC not output!!!)

Land water and energy:

EVLAND + SPWATR ≅ (EVPINTR + EVPSOIL + EVPTRNS)/Lv + EVPSBLN/Ls

For land-only grid cells:

Land vs. atm. water: EVLAND = $EVAP_{flx}$

Land vs. atm. energy: LHLAND = $EFLUX_{flx}$ (and consistent w/ $EVAP_{flx}$)

SHLAND = $HFLUX_{flx}$

SWLAND ≠ $SWNETSRF_{int}$

LWLAND ≠ $LWGNET_{int}$

All variables from "lnd" collection unless subscript indicates otherwise.

Land Water and Energy Balance (M21C)

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M21C	Evap mass flux	Latent heat	Sensible heat
Expected by Turb GC	EVLAND – **SP**EVLAND	LHLAND – **SP**LHLAND	SHLAND – **SP**SHLAND
Calculated by Catchment	**EVLAND**	**LHLAND** = SUM(LHLAND[*])	**SHLAND**

New "spurious" term for LH.

Paradigm shift: *EVLAND, LHLAND, and SHLAND in "lnd" as calculated by Catchment.*

Land water:

WCHANGELAND = PRECTOTCORRLAND – EVLAND – RUNSURFLAND – BASEFLOWLAND

Land energy:

ECHANGELAND = SWLAND + LWLAND – SHLAND – LHLAND – Lf * PRECSNOCORRLAND – SPSNLAND

- *Improved short names of LH components, "spurious" terms, and other exports.*
- *No "spurious" EV, LH, or SH terms in land balance equations.*

Land water and energy:

EVLAND = (LHLANDINTR + LHLANDSOIL + LHLANDTRNS)/Lv + LHLANDSBLN/Ls

LHLAND = LHLANDINTR + LHLANDSOIL + LHLANDTRNS + LHLANDSBLN

For land-only grid cells:

Land vs. atm. water: EVLAND – SPEVLAND = $EVAP_{flx}$

Land vs. atm. energy: LHLAND – SPLHLAND = $EFLUX_{flx}$ (and consistent w/ $EVAP_{flx}$)

SHLAND – SPSHLAND = $HFLUX_{flx}$

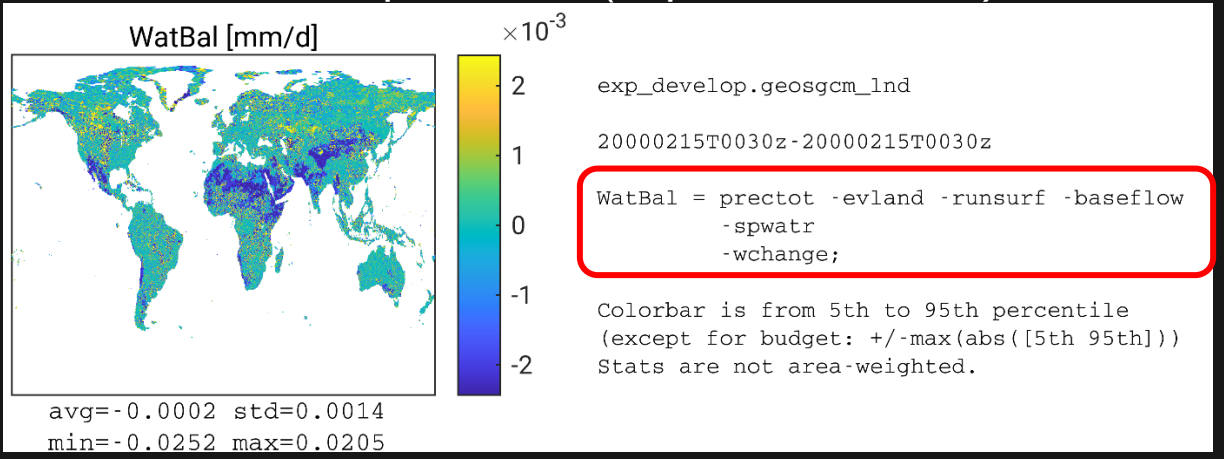
SWLAND = $SWNETSRF_{int}$

LWLAND = $LWGNET_{int}$

All variables from "lnd" collection unless subscript indicates otherwise.

Land Water and Energy Balance (1-day AMIP)

"Develop" branch (exports as in M-2)



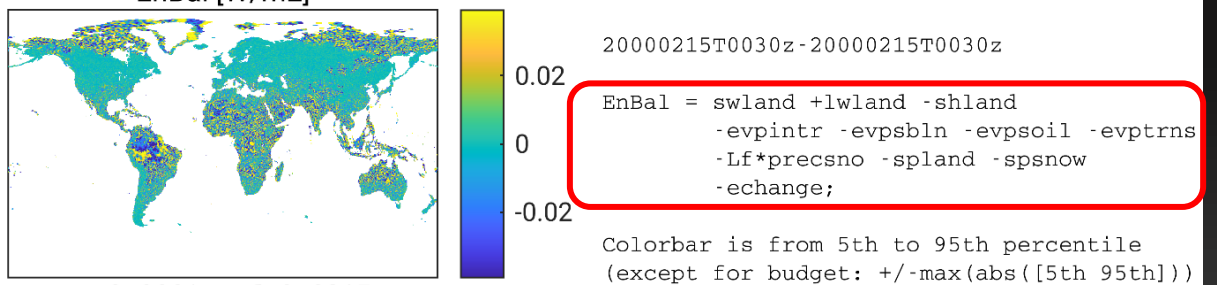
avg=-0.0002 std=0.0014
min=-0.0252 max=0.0205

exp_develop.geosgcm_lnd

20000215T0030z-20000215T0030z

WatBal = prectot -evland -runsurf -baseflow
-spwatr
-wchange;

Colorbar is from 5th to 95th percentile
(except for budget: +/-max(abs([5th 95th]))
Stats are not area-weighted.



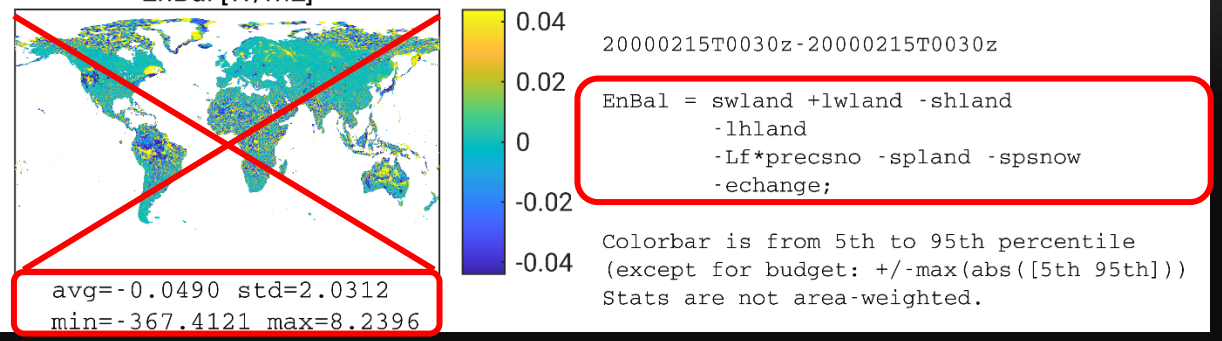
avg=0.0001 std=0.0217
min=-0.1609 max=0.1419

exp_develop.geosgcm_lnd

20000215T0030z-20000215T0030z

EnBal = swland +lwland -shland
-evpintr -evpsbln -evpsoil -evptrns
-Lf*precsno -spland -spsnow
-echange;

Colorbar is from 5th to 95th percentile
(except for budget: +/-max(abs([5th 95th]))
Stats are not area-weighted.



avg=-0.0490 std=2.0312
min=-367.4121 max=8.2396

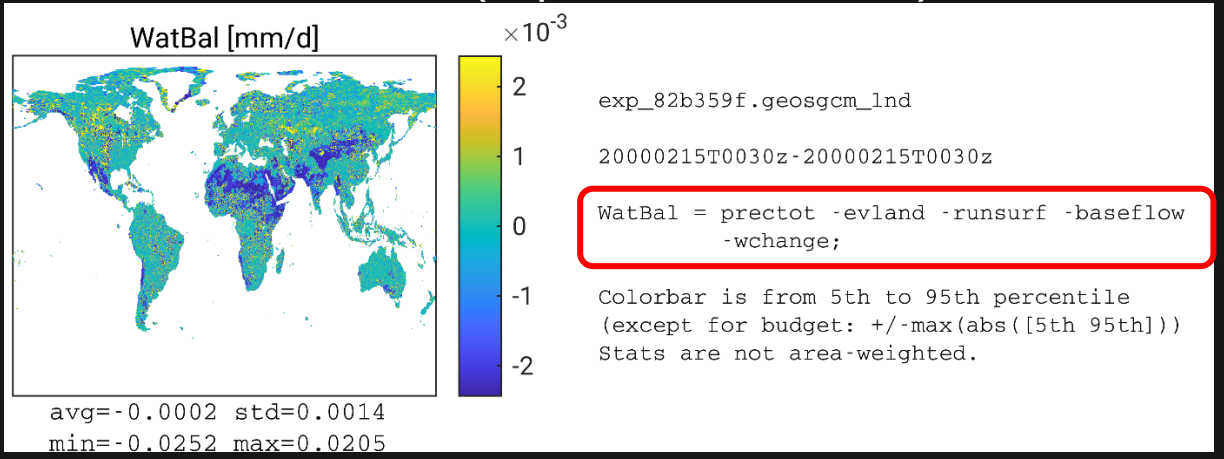
exp_develop.geosgcm_lnd

20000215T0030z-20000215T0030z

EnBal = swland +lwland -shland
-lhland
-Lf*precsno -spland -spsnow
-echange;

Colorbar is from 5th to 95th percentile
(except for budget: +/-max(abs([5th 95th]))
Stats are not area-weighted.

Revised (exports as in M21C*)



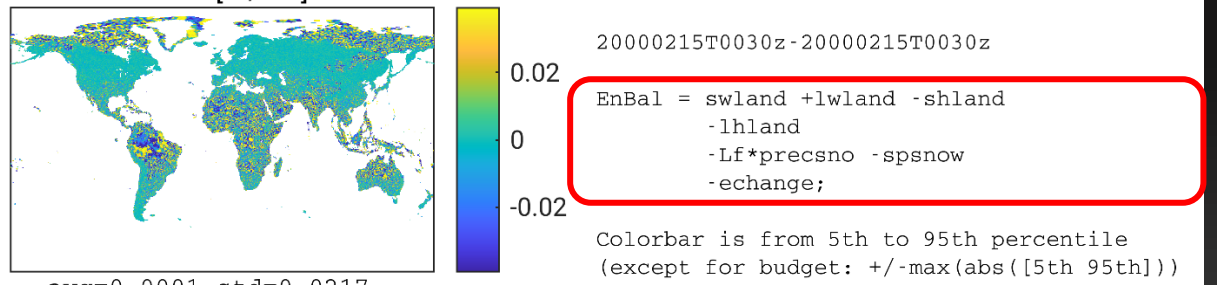
avg=-0.0002 std=0.0014
min=-0.0252 max=0.0205

exp_82b359f.geosgcm_lnd

20000215T0030z-20000215T0030z

WatBal = prectot -evland -runsurf -baseflow
-wchange;

Colorbar is from 5th to 95th percentile
(except for budget: +/-max(abs([5th 95th]))
Stats are not area-weighted.



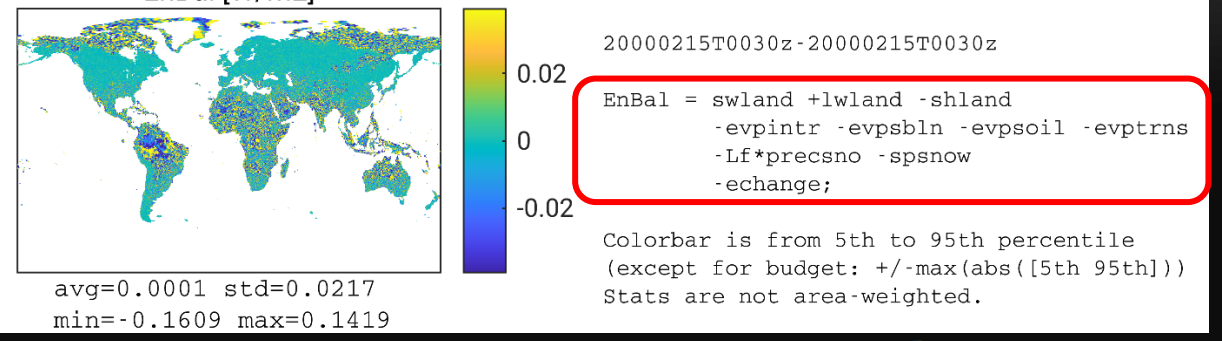
avg=0.0001 std=0.0217
min=-0.1609 max=0.1419

exp_82b359f.geosgcm_lnd

20000215T0030z-20000215T0030z

EnBal = swland +lwland -shland
-lhland
-Lf*precsno -spsnow
-echange;

Colorbar is from 5th to 95th percentile
(except for budget: +/-max(abs([5th 95th]))
Stats are not area-weighted.



avg=0.0001 std=0.0217
min=-0.1609 max=0.1419

exp_82b359f.geosgcm_lnd

20000215T0030z-20000215T0030z

EnBal = swland +lwland -shland
-evpintr -evpsbln -evpsoil -evptrns
-Lf*precsno -spsnow
-echange;

Colorbar is from 5th to 95th percentile
(except for budget: +/-max(abs([5th 95th]))
Stats are not area-weighted.

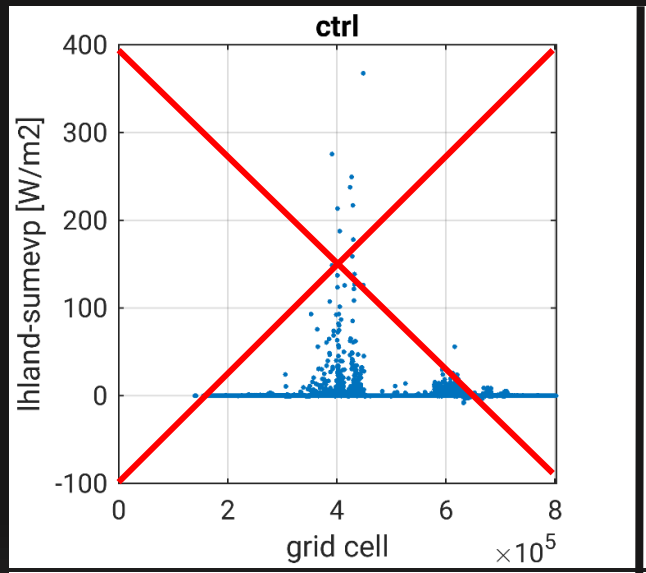
*Variable names in graphics do not reflect new M21C short names.

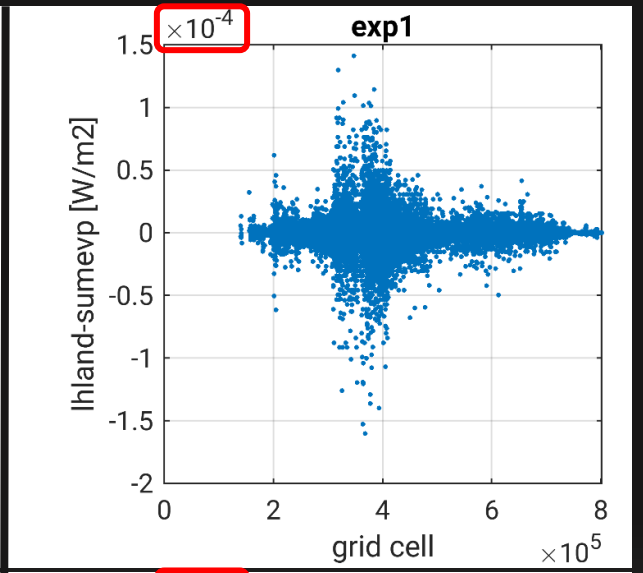
Consistency Across Water and Energy Budgets (1-day AMIP)

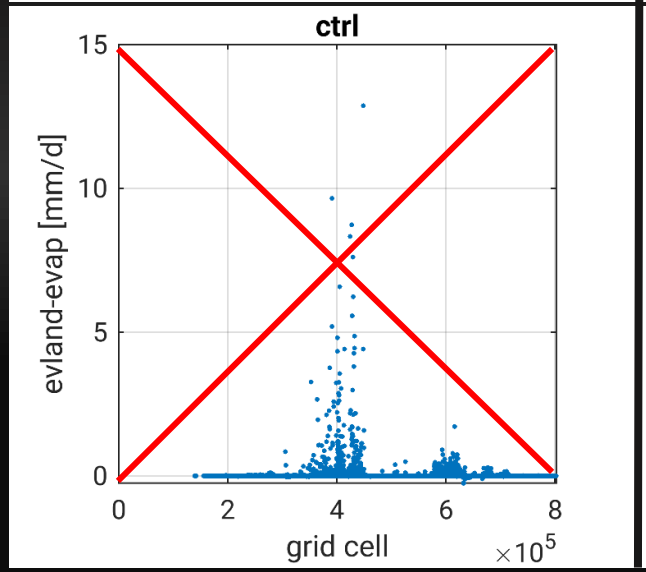
20000215_0030z

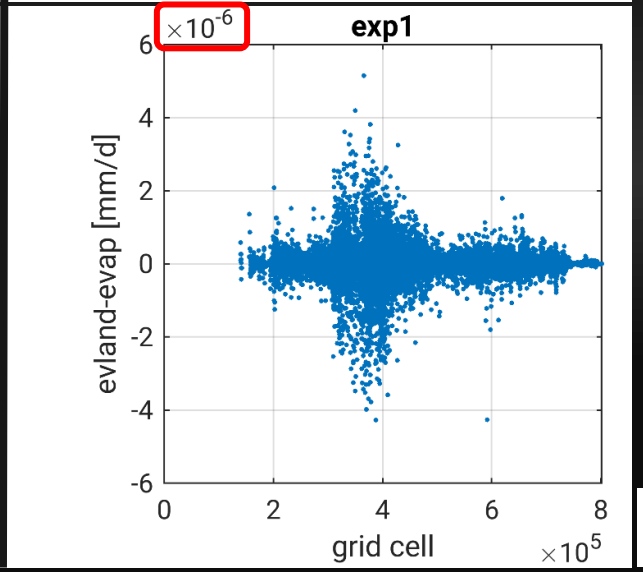
"Develop" branch (exports as in M-2)

Revised (exports as in M21C*)









LHLAND
= LHLANDINTR
+ LHLANDSOIL
+ LHLANDTRNS
+ LHLANDSBLN

EVLAND
= (LHLANDINTR
+ LHLANDSOIL
+ LHLANDTRNS)/Lv
+ LHLANDSBLN /Ls

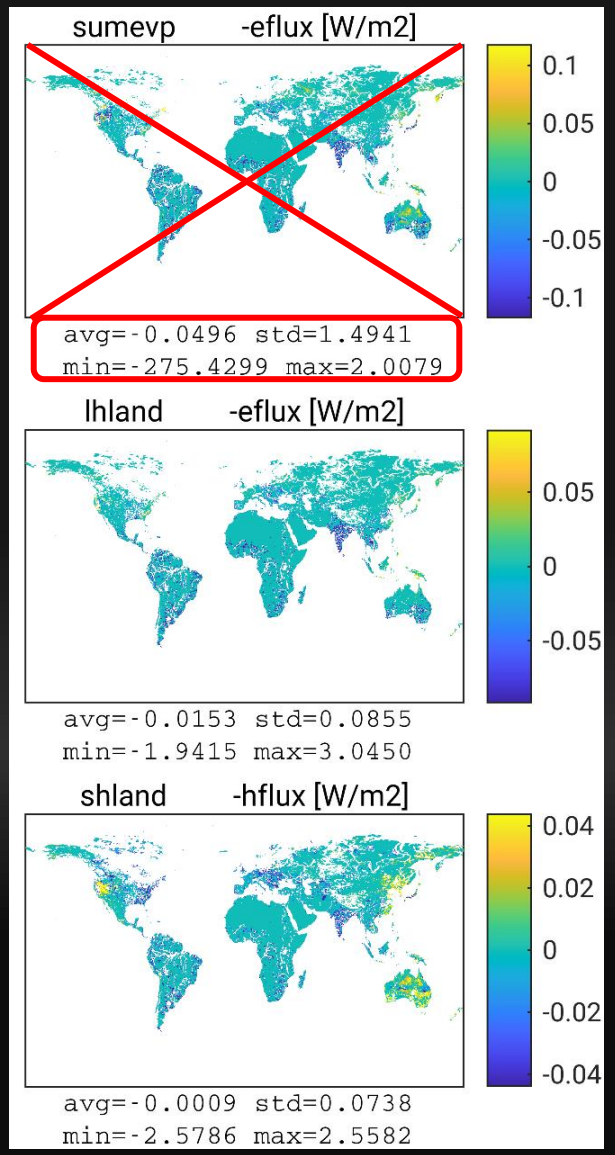
Here, "evap" refers to the mass flux computed from the "lnd" LH components as follows:

evap=(evptrns+evpsoil+evpintr)/Lv + evpsbln/Ls

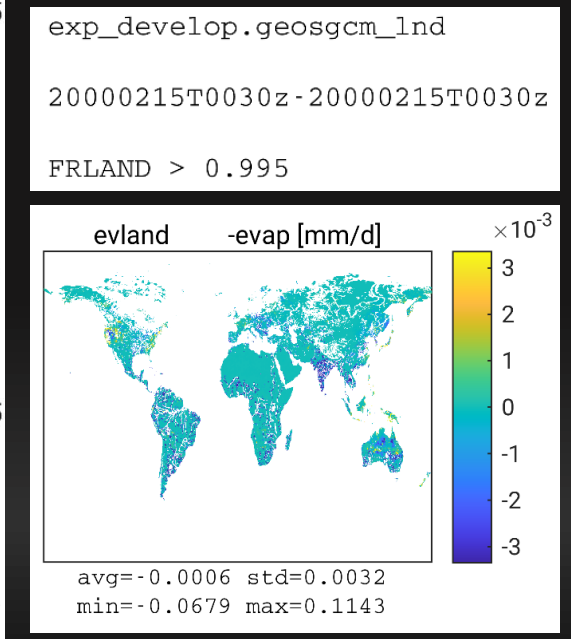
*Variable names in graphics do not reflect new M21C short names.

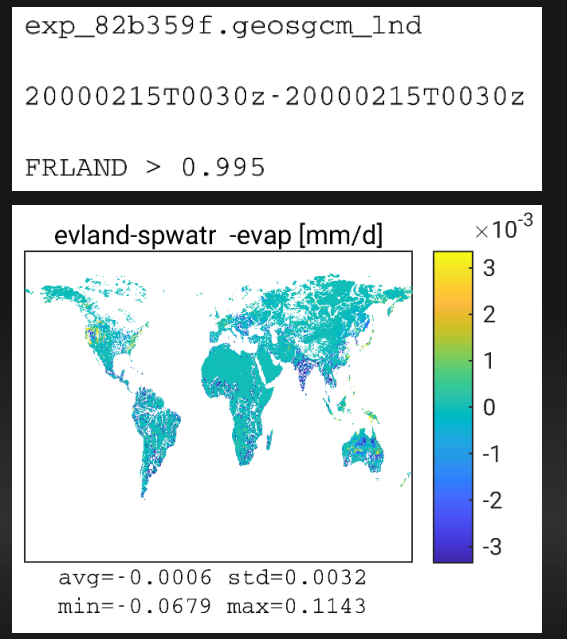
Consistency Between Atm. and Land Exports (1-day AMIP)

"Develop" branch (exports as in M-2)

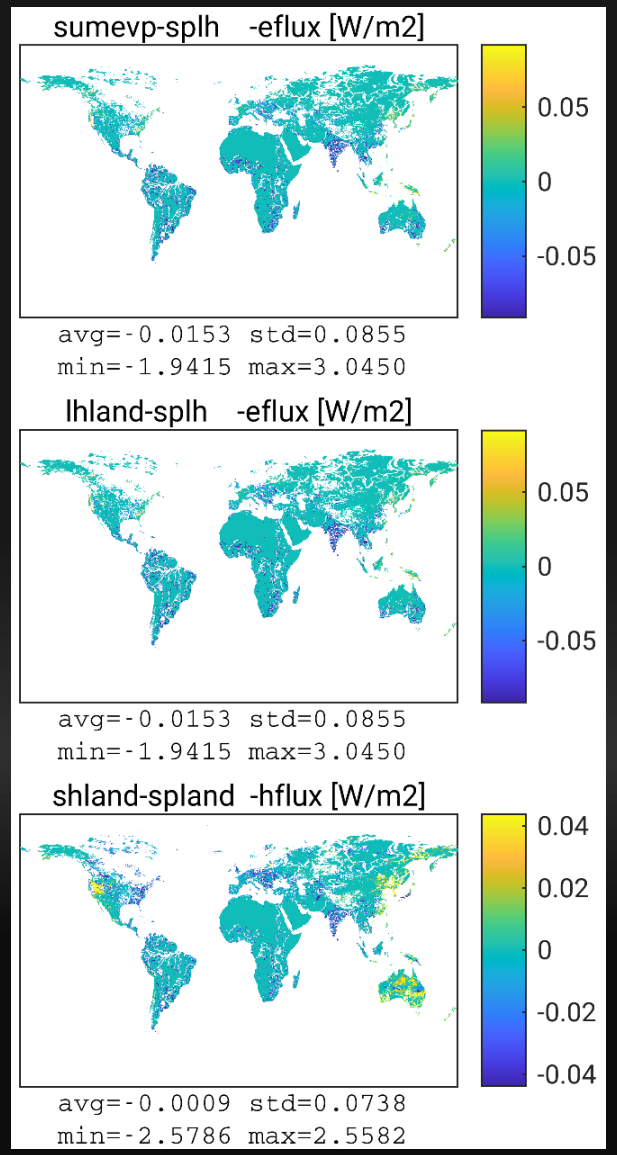


EVAP, EFLUX, and HFLUX from "flx"





Revised (exports as in M21C*)



*Variable names in graphics do not reflect new M21C short names.

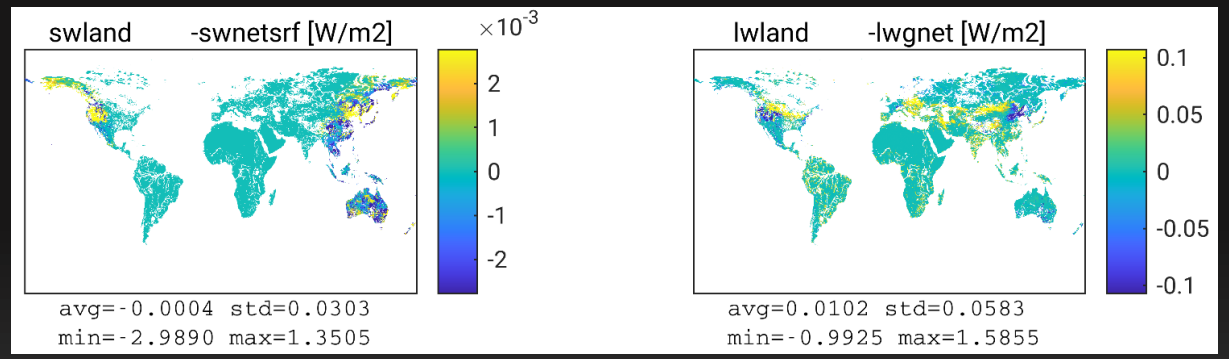
Consistency Between Atm. and Land Exports (1-day AMIP)

"Develop" branch (exports as in M-2)

```
exp_develop.geosgcm_lnd

20000215T0030z-20000215T0030z

FRLAND > 0.995
```



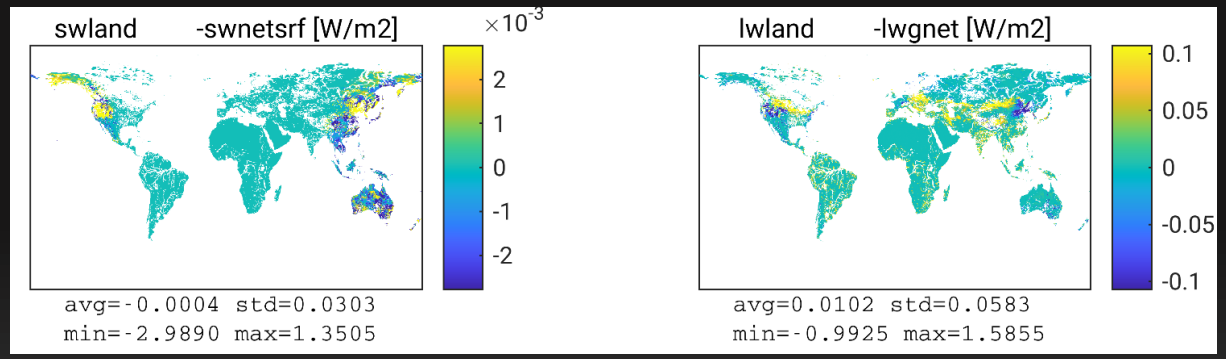
SWNETSRF and LWGNET from "int"

Revised (exports as in M21C)

```
exp_82b359f.geosgcm_lnd

20000215T0030z-20000215T0030z

FRLAND > 0.995
```

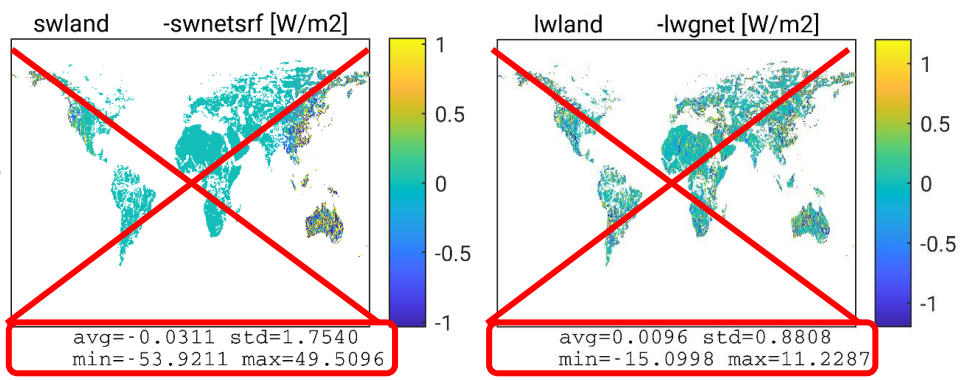


MERRA-2 (Old model!)

```
MERRA2.tavg1_2d_lnd_Nx

19970226T0030-19970226T0030

FRLAND > 0.995
```



*Variable names in graphics do not reflect new M21C short names.

Summary (1/3)

Because of the nature of the land-atmosphere coupling problem, the surface turbulent fluxes calculated by Catchment do not match those expected by Turbulence GC.

The difference must be captured in "spurious" (or "accounting") terms.

MERRA-2:

- The water and energy balance equations in the M-2 file specs are wrong and need to be corrected!
- Owing to a bug in the source code, the surface turbulent fluxes in "lnd" are an inconsistent mix of what is calculated by Turb GC and what is calculated by Catchment.
- The LHACC "accounting" term for the latent heat flux is not written out. A fortuitous side effect of the aforementioned bug is that LHACC can be (approximately) diagnosed from the existing output, allowing for an approximately correct formulation of the land energy balance.
- The inconsistencies do not apply in offline (land-only) mode because the "accounting" terms for the surface turbulent fluxes are all zero.
- Inadequate in-code documentation and confusing variable names contributed to the bug.
- The long and short names in the M-2 file specs are unclear.
- The surface radiation terms do not match between "int" (SolarGC) and "lnd" (SurfaceGC).

Summary (2/3)

M21C:

- Surface radiation terms from “lnd” (SurfaceGC) and “int” (SolarGC) are consistent (newer model).
- Paradigm shift: “lnd” contains surface turbulent fluxes calculated by Catchment (not Turb GC).
  - Implemented for M21C in GEOSgcm_GridComp PR#963 and GEOSgcm_App PR#630.
  - Simpler land water and energy balance equations.
  - Surface turbulent fluxes from “lnd” and “flx” are consistent (after consideration of “spurious” terms).
  - New output of “spurious” term for latent heat.
  - Added in-code documentation and revised in-code variable names.
  - Improved long and short names in M21C file specs (“export” variables).
  - A very minor and exceedingly rare residual energy balance error (“snow mass-limited sublimation from top snow layer”) was addressed in GEOSgcm_GridComp PR#946.
- Remaining issues:
  - Regrid method for “lnd” is BILINEAR_MONOTONIC. Do we need conservative regridding?
  - The spatial pattern of balance residuals is persistent, and residuals are larger than roundoff. Acceptable?
  - Verify land water and energy balances with new M21C sample output.

Summary (3/3)

- The surface turbulent flux issues of MERRA-2 apply to all current GEOS products (except SMAP L4).
- The inconsistency in surface turbulent flux outputs may impact “ocn”, “gmichem”, and “S2S” output.
- For M21C, many variable long names were updated.
- **The bug fixes and long name updates must be:**
  1) **merged into “develop” (**GEOSgcm_GridComp PR#957, GEOSgcm_App PR#621**) and**
  2) **adopted in GEOS-FP file specs.**