Towards a water conserving scheme for stochastically perturbed parametrization tendencies

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Abstract Stochastically perturbed parametrization tendencies (SPPT) are used in operational weather forecasts in order to represent the uncertainty from unresolved scales in the parametrizations and subsequently increase the model spread. SPPT schemes were shown to have a positive effect on forecast skills. However, SPPT schemes, as currently implemented in the integrated forecast system (IFS) from the ECMWF tend to systematically alter the water budget, such that the globally integrated total column water in the atmosphere is decreased compared to deterministic control runs. Globally approximately 0.14mm/day are missing from the budget, which is only a posteriori fixed to avoid an unrealistic drift of the forecast model towards a drier atmosphere. We therefore (i) aim to understand why water is vanishing from the atmosphere in IFS when SPPT is applied and (ii) seek a reformulation of the SPPT scheme that conserves water as in the deterministic control runs but retains the positive effect on forecast skills. It is proposed to carefully perturb all physics parametrization terms in all prognostic equations involving water with a vertically-independent 2D random field in order to essentially perturb the fluxes. In theory this should yield a water conservative SPPT scheme.

Water budget in IFS We assume the water budget to be based on a conservation equation

$$\partial_t q = -\nabla \cdot \mathbf{F} \tag{1}$$

where q is water in all forms, and $\mathbf{F}$ the associated fluxes. Having horizontally periodic boundary conditions for the fluxes and a zero-flux boundary condition at the top of the atmosphere we consider a conservation of water with respect to the surface fluxes (precipitation and evaporation), that are desired to be the only source or sink of water to the model's atmosphere. Vertical integration with respect to pressure p from surface pressure $p_s(t)$, a function of time t, to the top of the model's atmosphere p_{top} yields

$$\partial_t Q + q|_{p=p_s} \partial_t p_s + \int_{p_s(t)}^{p_{\text{top}}} \nabla_H \cdot \mathbf{F}_H dp + P + E = 0 \tag{2}$$

with Q being the total column water. The second term results from interchanging the temporal derivative with the vertical integral having a time-dependent lower boundary $p_s(t)$ and removes the signal of the surface pressure tide from the budget. The third term is referred to as vertically integrated moisture divergence, which should vanish when globally integrated. Precipitation P and evaporation E are taken positive for water leaving the column.

In IFS the water budget of equation (2) can be calculated from standard model output of parameter table 128: At the lowest model level for $q|_{p=p_s}$ the summation of specific rain water (parameter ID 75.128), specific snow water (76.128), specific humidity (133.128), specific cloud liquid (246.128), specific cloud ice (247.128); at the surface total column water (136.128), large scale precipitation (142.128), convective precipitation (143.128), surface pressure (152.128), evaporation (182.128) and vertically integrated moisture divergence (213.128) are used.

Comparing the water budget of a deterministic control forecast to a forecast with standard SPPT settings shows that a residual of -0.14mm/day results as large-scale and convective precipitation are reduced and evaporation is increased with SPPT (Fig. 1). The global distribution of the residual (Fig. 2f) is not uniform and not only negative in sign: The tropics reveal rather short spatial scales, comparably larger in the extra tropics. The budget is usually not closed, where convective or large-scale precipitation is occuring (not shown).

Stochastically perturbed parametrization tendencies The SPPT scheme in IFS is applied as a multiplicative perturbation to the deterministicly parametrized physics tendencies $q_{\text{ten}}^{\text{phy}}$ (excluding the surface fluxes) of specific humidity by

$$q_{\text{ten,pert}}^{\text{phy}} = (1 + \mu r) q_{\text{ten}}^{\text{phy}} \tag{3}$$

r is a 2D horizontal random field with spatial and temporal autocorrelation, therefore especially a single random number in the vertical, μ is a tapering function decreasing towards zero in the boundary layer and also in the stratosphere and being 1 in the troposphere. In practice, a supersaturation limiter is applied afterwards.

The role of random patterns with temporal autocorrelation The SPPT scheme of equation (3) was shown to systematically remove moisture from the atmosphere. The random pattern r is implemented as an autoregressive process that evolves independently of specific humidity q. In contrast, the physics tendencies of the next time step are dependent on q from the last time step, which is directly affected by the realization of r. As r now has some autocorrelation in time, we cannot assume that the physics tendencies and the random pattern r are uncorrelated, and it was shown that they are slightly negativly correlated (P. Watson, pers. comm.). In principle, we might understand this as, given a strong stochastic perturbation in one direction, the system responds in a certain way, presumably to counteract that perturbation, hence the negative correlation. However, from this point of view, it does not follow why a drift towards a drier or wetter atmosphere is preferred. Artifically setting the correlation to zero by decreasing the temporal autocorrelation scale for the random pattern generation towards zero yields a water conservative scheme following equation 2 (Fig. 3). Though, SPPT with no temporal autocorrelation is not desired, as the model spread is likely decreased.

Towards water conservation with SPPT Instead of only perturbing the prognostic equation for water vapour, as currently done in the SPPT implementation in IFS, it is proposed to perturb all physics parametrization terms with a vertically independent 2D random field r in all prognostic equation including water, such that (IFS documentation, cycle 41r1, part IV, chapter 7, equations 7.7-7.10 and 7.12)

$$\partial_t q_l = A(q_l) + (1+r)\left(S^{\text{liq}}_{\text{conv}} + S^{\text{liq}}_{\text{strat}} + S^{\text{ice}}_{\text{melt}} - S^{\text{ice}}_{\text{dep}} - S^{\text{liq}}_{\text{evap}} - S^{\text{rain}}_{\text{auto}} - S^{\text{snow}}_{\text{rime}}\right) \tag{4a}$$

$$\partial_t q_i = A(q_i) + (1+r)\left(S^{\text{ice}}_{\text{conv}} + S^{\text{ice}}_{\text{strat}} + S^{\text{ice}}_{\text{dep}} - S^{\text{ice}}_{\text{melt}} - S^{\text{ice}}_{\text{evap}} - S^{\text{snow}}_{\text{auto}}\right) \tag{4b}$$

$$\partial_t q_r = A(q_r) + (1+r)\left(-S^{\text{rain}}_{\text{evap}} + S^{\text{rain}}_{\text{auto}} + S^{\text{snow}}_{\text{melt}} - S^{\text{rain}}_{\text{frz}}\right) \tag{4c}$$

$$\partial_t q_s = A(q_s) + (1+r)\left(-S^{\text{snow}}_{\text{evap}} + S^{\text{snow}}_{\text{auto}} - S^{\text{snow}}_{\text{melt}} + S^{\text{rain}}_{\text{frz}} + S^{\text{snow}}_{\text{rime}}\right) \tag{4d}$$

$$\partial_t q_v = A(q_v) + (1+r)\left(-S_{\text{conv}} - S_{\text{strat}} + S_{\text{evap}}\right) \tag{4e}$$

The reason is, that the physics parametrizations of the above equations act as a source/sink term, respectively. In order to avoid a random source/sink of water on one side of the flux, it is prospposed to carefully perturb the fluxes, such that SPPT acts as a random redistribution of water between different reservoirs of water and grid cells. This is contrast to the current SPPT scheme that yields random sources/sinks of water, which is a priori not conservative because of the temporal autocorrelation issue (see last section). Summing up equations (4) we see that $q_l + q_i + q_r + q_s + q_v$ is a conserved quantity under the assumption that the advection scheme $A()$ is also conservative. Similiar procedure should be done also with the surface fluxes, i.e. the soil moisture should be reduced (increased) by the perturbed surface flux into (out of) the lowermost grid cell. Although the tendencies are directly perturbed and not the fluxes itself, once can in general write a tendency as divergence of a flux. Having no-flux boundary conditions at the top of the atmosphere and also between soil and deeper ground layers, the vertical integral is unchanged when perturbing with a single random number. Some issues are caused with the surface fluxes over the ocean: As long as the water content of the ocean is not affected, this serves theoretically as an infinite source of water. However, advancing SPPT towards a water conservative property this issue might be negligible.

Discussion

References

M Leutbecher et al., 2016. *Stochastic representations of model uncertainties at ECMWF: State of the art and future vision*, ECMWF Technical Memorandum 785.

IFS documentation - Cy41r1, 2015. *Part III: Dynamics and Numerical procedures* and *Part IV: Physical Processes*, ECMWF.

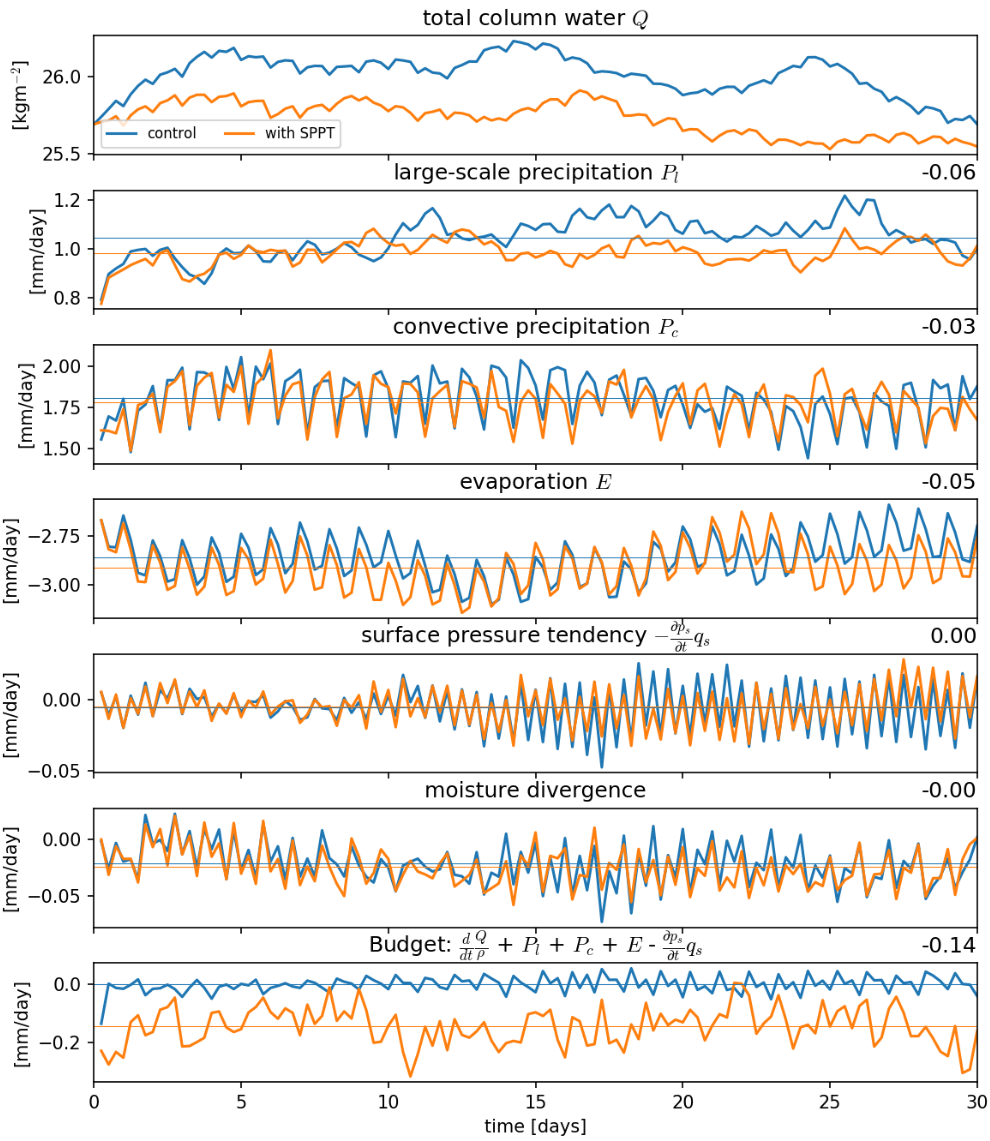

Figure 1: Globally integraed water budget in IFS for a deterministic control forecast (blue) and with stanard SPPT settings, including boundary layer and stratosphere tapering, supersaturation fix and autocorrelation of the random patterns (orange). The respective forecasts started on 1 August 2000. Thin horizontal lines represent temporal means over the shown period. Numbers in the top-right denote the difference SPPT minus control of the temporal means in mm/day.

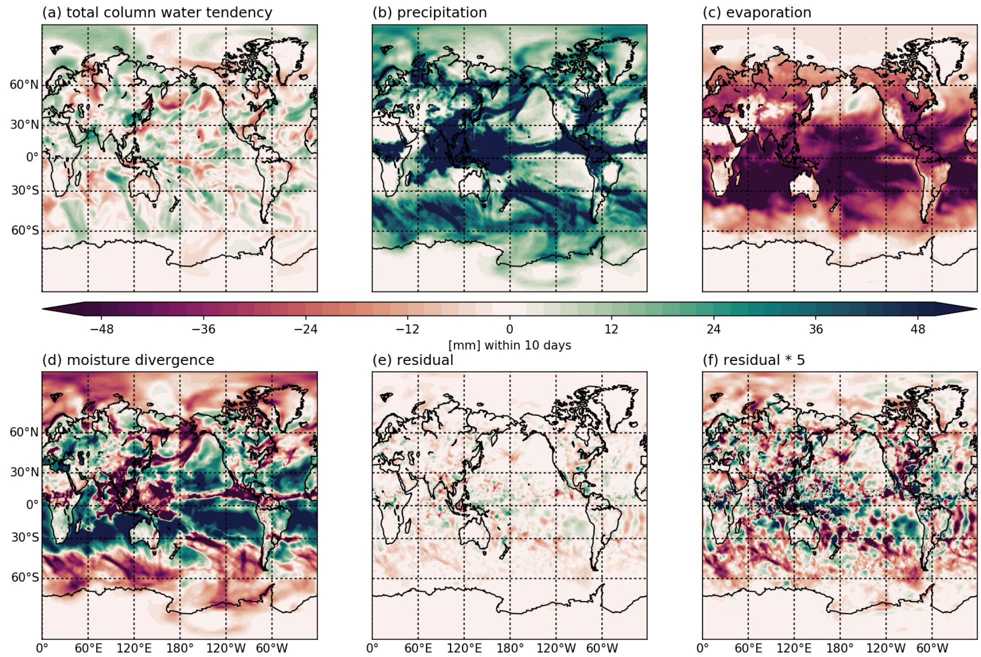

Figure 2: Temporally integrated water budget over the first 10 days of the forecast using SPPT (same forecast as in Fig. 1). The residual is the sum of total column water tendency (a), precipiation (b, large-scale plus convective), evaporation (c), vertically integrated moisture divergence (d) and the surface pressure term (not shown). To highlight the structure of the residual (f) is the same as (e) but multiplied by a factor of 5. The residual for the deterministic control forecast is negligible compared to the residual using SPPT (not shown).

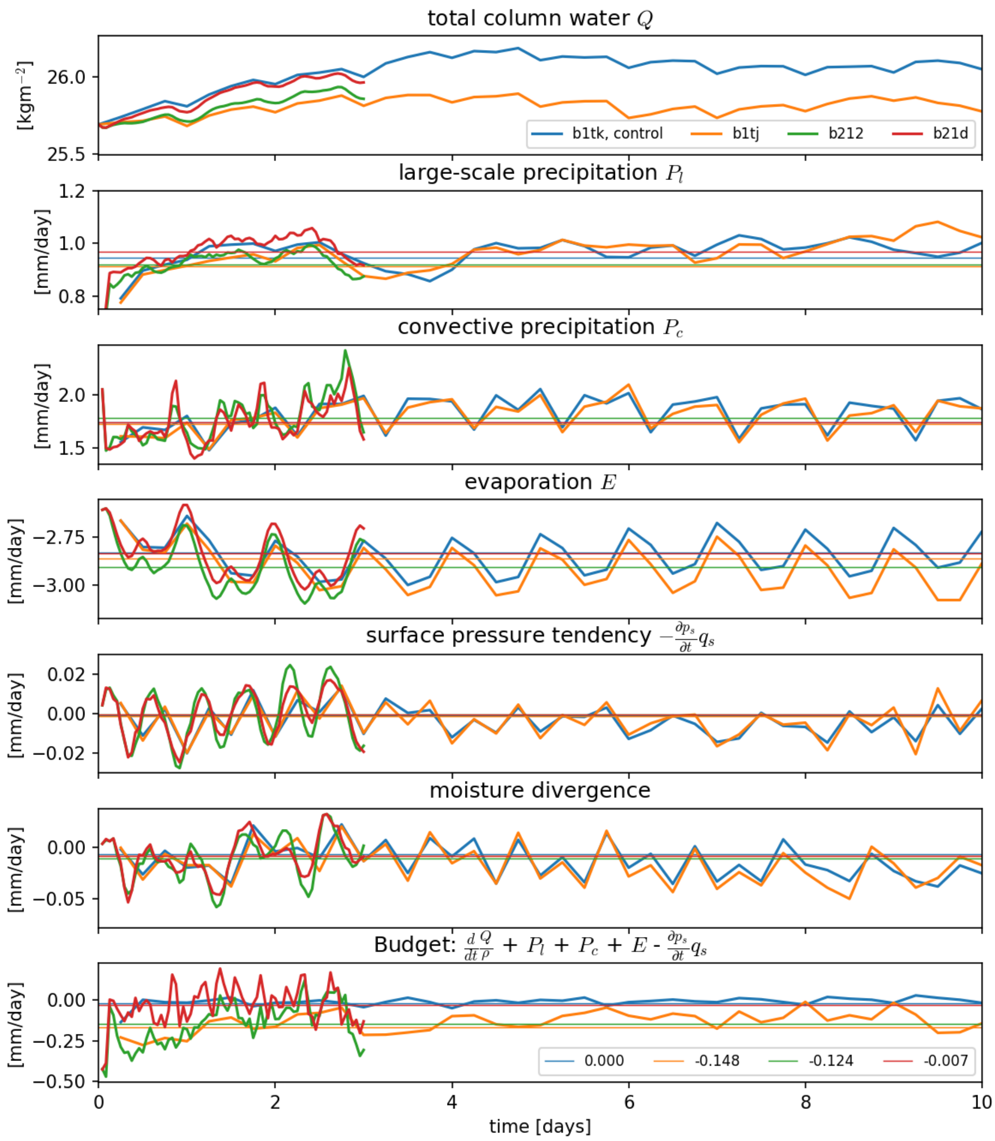

Figure 3: Same as Fig. 1 for the forecast experiments b1tk (no SPPT control forecast, blue line) and b1tj (standard SPPT settings, orange line) only for a shorter forecast lead time. Additionally, the forecast experiments b212 (no boundary layer or stratospheric tapering, green line) and b21d (random patterns without temporal autocorrelation, red line) are shown. The numbers in the legend denote the budget residual's temporal average.