The influence of physical parameterizations on the tangent-linear GEM model:

the role of the subgrid-scale orographic drag scheme in the simplified physics

by

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in collaboration with

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Outline:

> review of the subgrid-scale orographic (**SGO**) parameterization: the simplified version

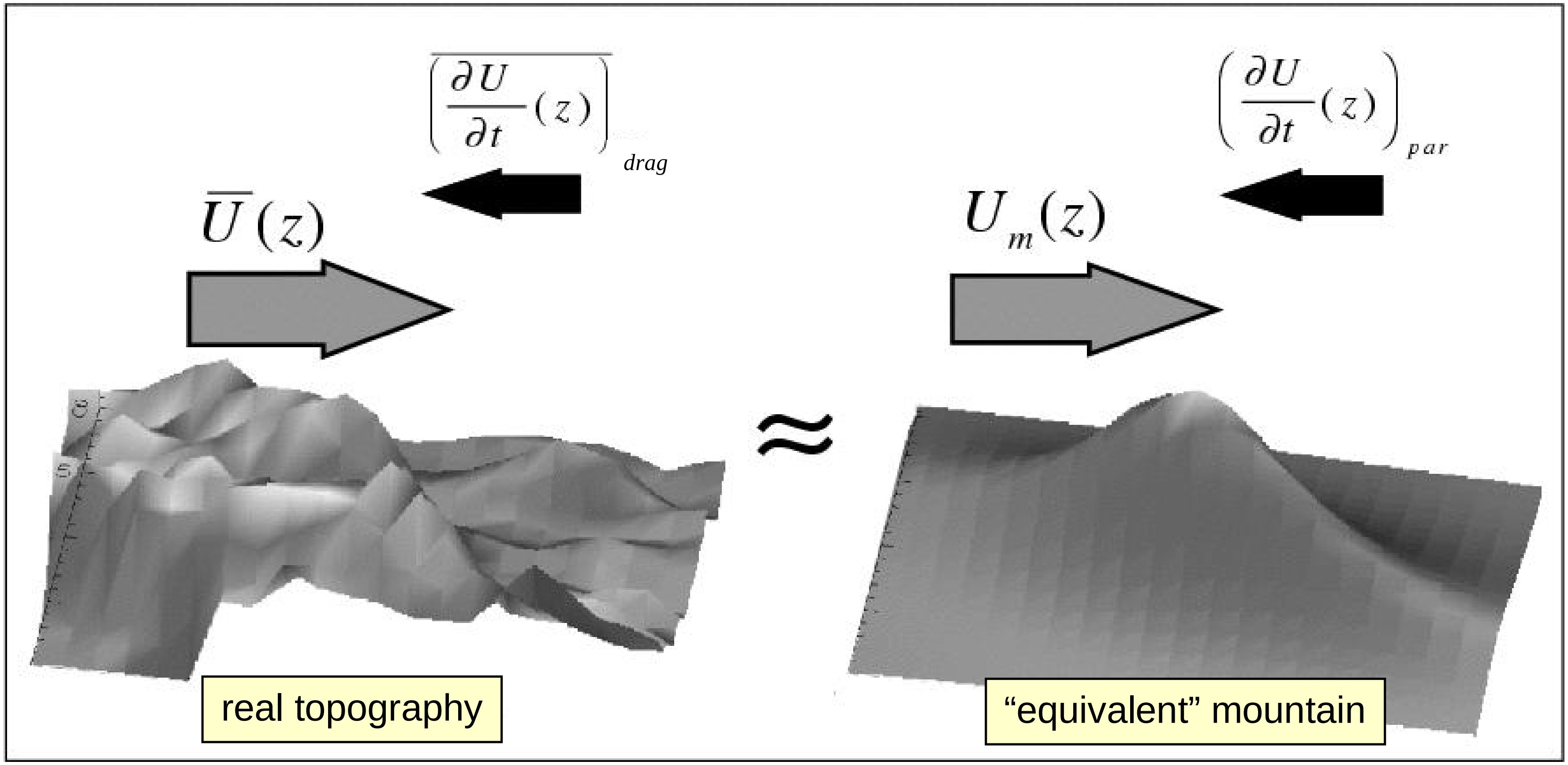
> impact of the simplified SGO parameterization:

- on the properties of singular vectors (**SV**);

- on the calculation of key analysis errors (**KAE**);

- on the behavior of the **4DVar** assimilation system.

The SGO drag: a brief review

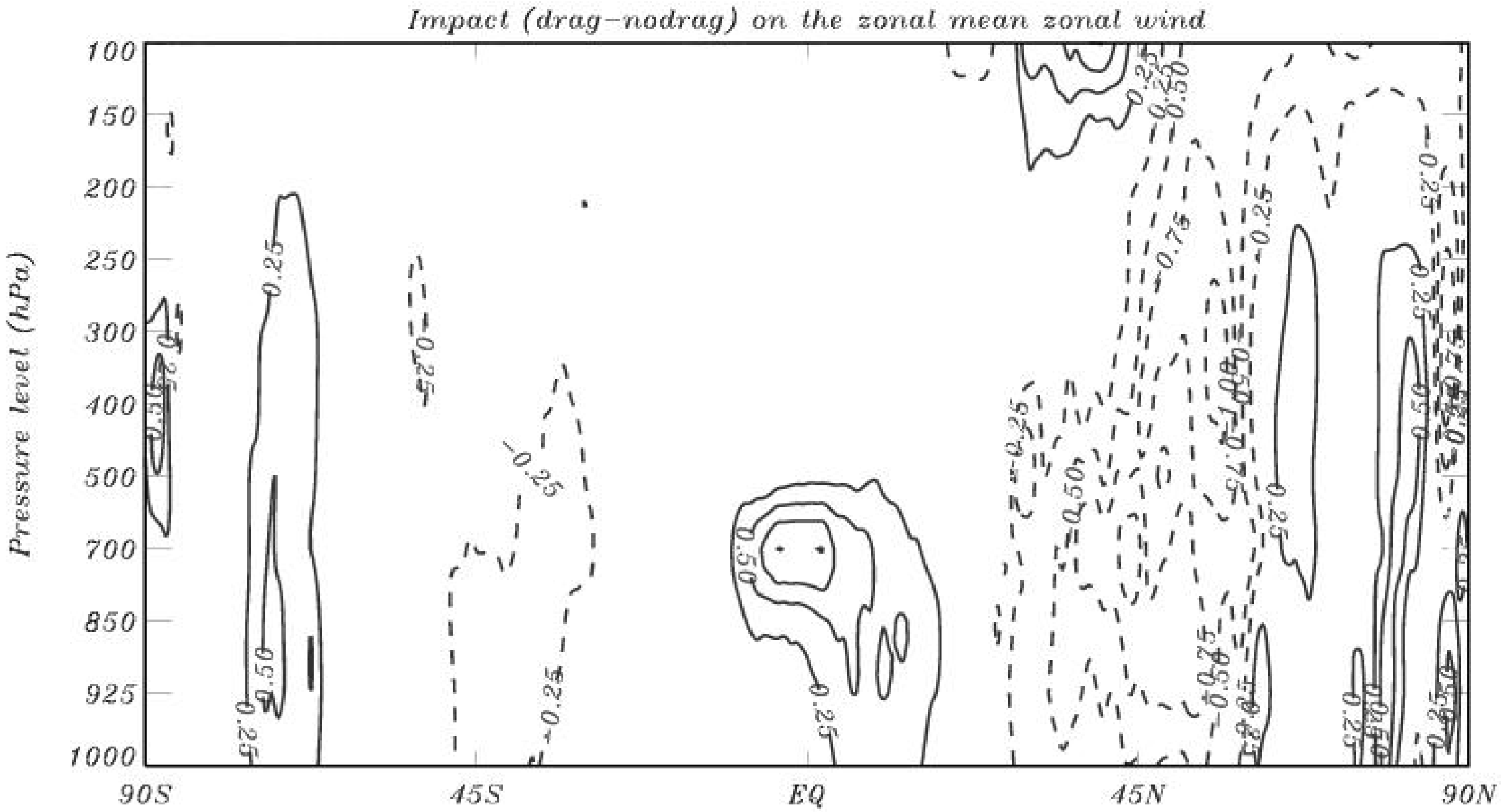


$$\text{SGO drag} = \left(\frac{\partial U}{\partial t}\right)_{par} = \left(\frac{\partial U}{\partial t}\right)_{gwd} + \left(\frac{\partial U}{\partial t}\right)_{llb}$$

gravity wave drag

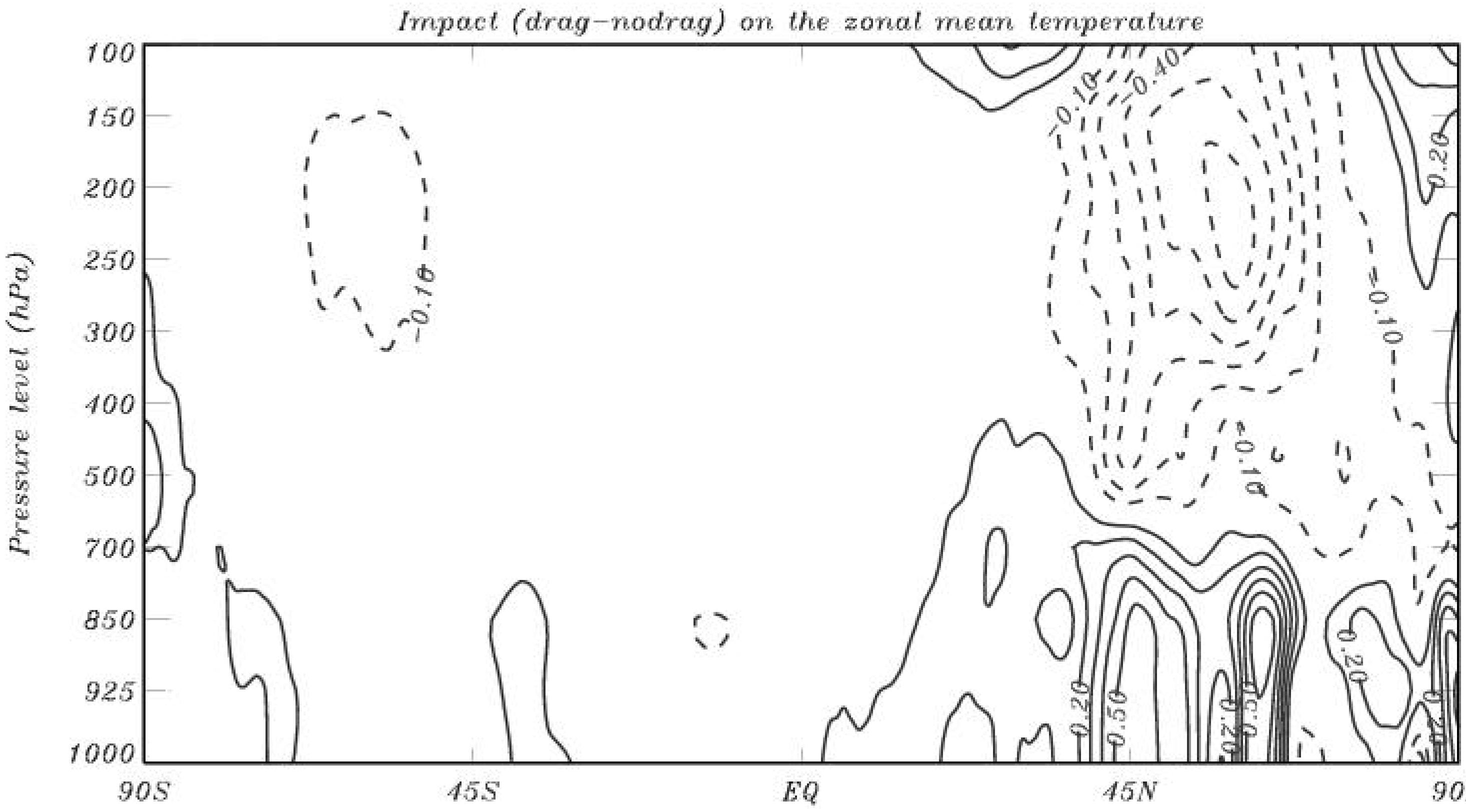
blocking

> The SGO drag has a direct impact on the winds...



Experiment: average change of zonal-mean zonal wind due to blocking term, after 5 days

> …but the SGO drag also impacts the temperature field, through the model dynamics*



Experiment: average change of zonal-mean temperature due to blocking term, after 5 days

* An explanation of this thermal response can be found in "**The subgrid scale orographic blocking parametrization of the GEM model"** by Zadra et al., to appear in *Atmos.Ocean.*

What does "simplified physics" mean ?

full (nonlinear) physics

model dynamics

- nonlinear
- tangent-linear
- adjoint

simplified physics

vertical diffusion (simplified nonlinear, tangent linear, adjoint)
blocking + gwd (simplified nonlinear, tangent linear, adjoint)
large-scale condensation (simplified nonlinear, tangent linear, adjoint)
convection (simplified nonlinear, tangent linear, adjoint)

Example: The simplified SGO parameterization

1- Simplifying the nonlinear scheme:

> choose a less complex scheme:

Ex:

- the full physics of the nonlinear could eventually adopt a new GWD scheme (for instance, the Scinocca-McFarlane 2000 scheme);

- while the simplified physics could keep the original, simpler parametrization (the McFarlane 86 GWD scheme).

2- Constructing the tangent-linear scheme:

Ex: The linearized blocking term

original (nonlinear) ⇨

flow dependent

$$\frac{\partial U}{\partial t} = -\frac{1}{2} k U^2 \ , \qquad k = k(U,T)$$

tangent linear ⇨

trajectory

$$\frac{\partial U'}{\partial t} = (-kU)U' - k'\left(\frac{1}{2} U^2\right)$$

where $$k' = \left(\frac{\partial k}{\partial U}\right) U' + \left(\frac{\partial k}{\partial T}\right) T'$$

disturbance *disturbance*

3- Constructing the adjoint scheme:

> if you write the tangent-linear model as:

$$\begin{bmatrix} U' \\ T' \end{bmatrix}(t^+) = \begin{bmatrix} l_{11} & l_{12} \\ l_{21} & l_{22} \end{bmatrix} \begin{bmatrix} U' \\ T' \end{bmatrix}(t^-)$$

> then the adjoint model will be:

transpose !

$$\begin{bmatrix} U' \\ T' \end{bmatrix}(t^-) = \begin{bmatrix} l_{11} & l_{21} \\ l_{12} & l_{22} \end{bmatrix} \begin{bmatrix} U' \\ T' \end{bmatrix}(t^+)$$

sensitivities (gradients)

Example from the simplified sgo code:

```
do i=il1,il2
 vmod(i) = sqrt ( uu(i,lrefm)**2 + vv(i,lrefm)**2 )
 if (vmod(i).le.vmin)  vmod(i) = vmin
 uub(i) = uu(i,lrefm)/vmod(i)
 vvb(i) = vv(i,lrefm)/vmod(i)
enddo
```

simplified nonlinear scheme

tangent-linear scheme

```
do i=il1,il2
  vmod5(i) = sqrt ( uu5(i,lrefm)**2 + vv5(i,lrefm)**2 )
  if (vmod5(i).le.vmin)  vmod5(i) = vmin
  uub5(i) = uu5(i,lrefm)/vmod5(i)
  vvb5(i) = vv5(i,lrefm)/vmod5(i)
enddo
.
.
.
do i=il1,il2
  vmod(i) = uub5(i)*uu(i,lrefm) + vvb5(i)*vv(i,lrefm)
  if (vmod5(i).le.vmin)  vmod(i) = zero
  uub(i) = ( uu(i,lrefm) - vmod(i)*uub5(i) )/vmod5(i)
  vvb(i) = ( vv(i,lrefm) - vmod(i)*vvb5(i) )/vmod5(i)
enddo
```

adjoint scheme

```
do i=il1,il2
  vmod5(i) = sqrt ( uu5(i,lrefm)**2 + vv5(i,lrefm)**2 )
  if (vmod5(i).le.vmin)  vmod5(i) = vmin
  uub5(i) = uu5(i,lrefm)/vmod5(i)
  vvb5(i) = vv5(i,lrefm)/vmod5(i)
enddo
.
.
.
do i=il2,il1,-1
  vmod(i)     = vmod(i) - vvb(i)*vvb5(i)/vmod5(i)
  vv(i,lrefm) = vv(i,lrefm) + vvb(i)/vmod5(i)
  vvb(i)      = 0.
  vmod(i)     = vmod(i) - uub(i)*uub5(i)/vmod5(i)
  uu(i,lrefm) = uu(i,lrefm) + uub(i)/vmod5(i)
  uub(i)      = 0.
  if (vmod5(i).le.vmin)  vmod(i) = 0.
    vv(i,lrefm) = vv(i,lrefm) + vmod(i)*vvb5(i)
    uu(i,lrefm) = uu(i,lrefm) + vmod(i)*uub5(i)
    vmod(i)     = 0.
  enddo
```

Evaluating the tangent-linear approximation

> Take an initial condition U_o and make a nonlinear 24h integration:

$$U_o \xrightarrow{\text{nonlinear propagation}} U_1$$

> Perturb the initial condition with a realistic disturbance U_o' and make another nonlinear 24h integration:

$$U_o + U_o' \xrightarrow{\text{nonlinear propagation}} U_2$$

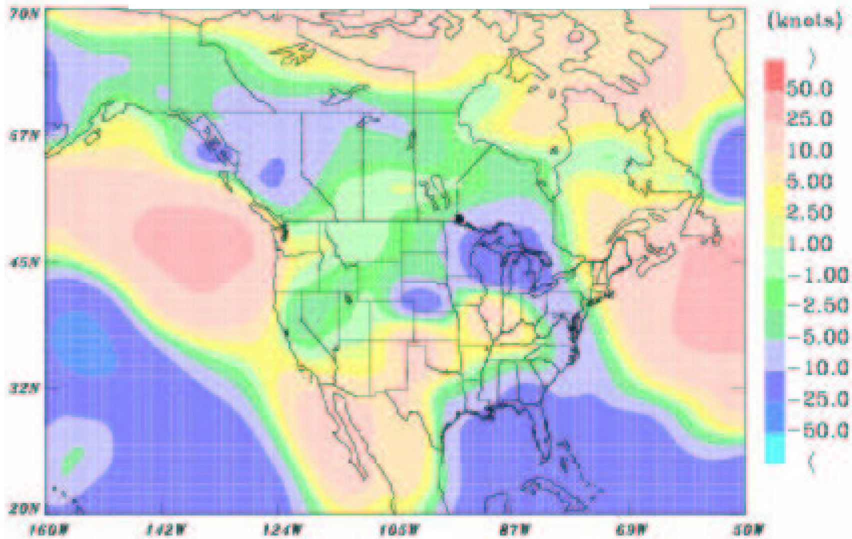
> Propagate the disturbance U_o' for 24h using the tangent-linear model:

$$U_o' \xrightarrow{\text{tangent-linear propagation}} U'$$

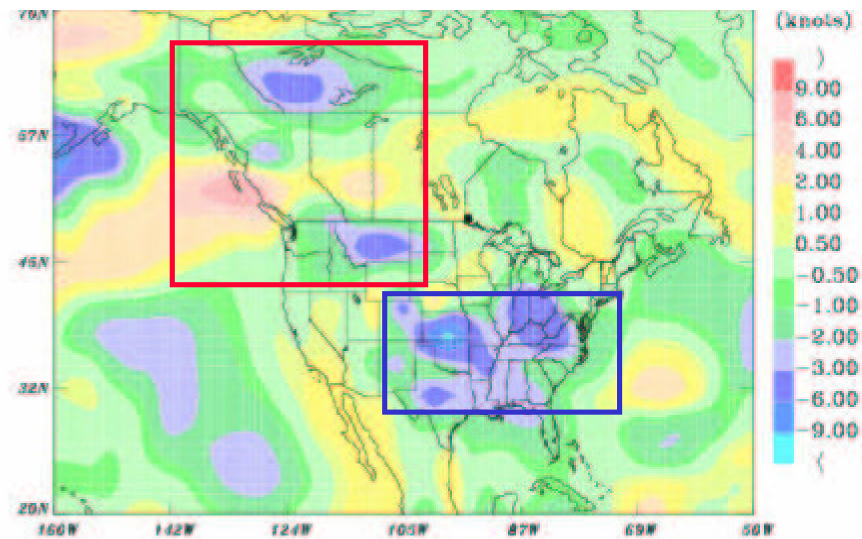
> Compare: $\boxed{U_2 - U_1 \longleftrightarrow U'}$

Ex: TLM test of zonal wind / model level 26 / Dt = 24h / resol. 120X60

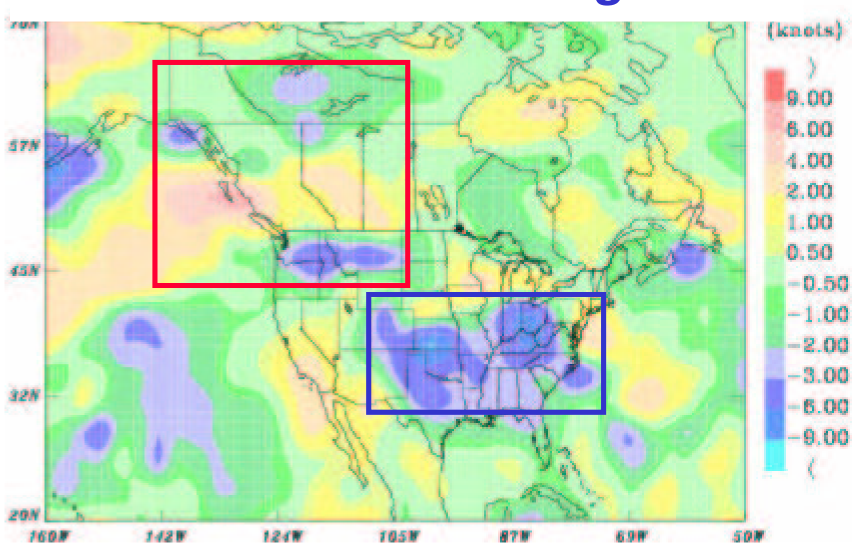
trajectory



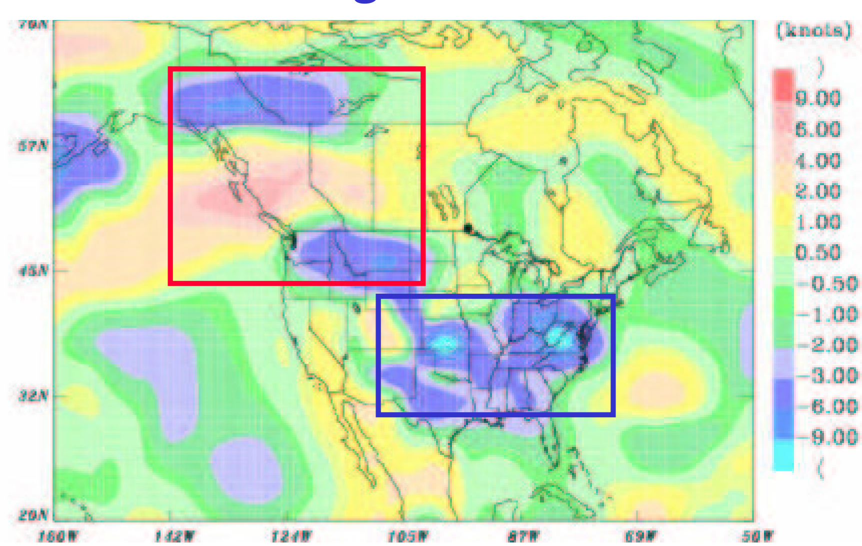
linear integr. -- SGO = on



diff. nonlinear integr.



linear integr. -- SGO = off



Impact of the simplified SGO parameterization on the properties of singular vectors (SV)

> Singular vectors are set of states $\mathbf{X}_i$ orthogonal w.r.t. a specified norm -- for instance the energy norm:

$$\underbrace{< \mathbf{X}_i | \mathbf{X}_j >}_{\textit{scalar product (projections)}} = \int_{vol} \left(\underbrace{\frac{1}{2} \mathbf{U}_i \cdot \mathbf{U}_j}_{\textit{kinetic}} + \underbrace{\alpha \, T_i T_j}_{\textit{potential}} \right) + \int_{surf} \underbrace{\left(\beta \, p_{s,i} \, p_{s,j} \right)}_{\textit{surface pressure}}$$

> Given a basic state, they provide the maximum (energy) growth over a specified period (optimization time interval = OTI):

X_1 has largest growth: $\dfrac{\text{final energy}}{\text{initial energy}}$ is maximum

X_2 has second largest growth, etc...

> The energy at final time is based on the singular vector propagated by the tangent-linear model.
Ex: for the first SV,

initial energy: $$E_1^{ini} = \langle \mathrm{X}_1 | \mathrm{X}_1 \rangle_{ini}$$

final energy: $$E_1^{fin} = \langle L\mathrm{X}_1 | L\mathrm{X}_1 \rangle_{fin}$$

tangent-linear model

energy growth: $$\frac{E_1^{fin}}{E_1^{ini}} = \sigma_1^2$$

growth rate: $$\sigma_1$$

For more details on the calculation of SVs: `http://iweb.cmc.ec.gc.ca/~armabue`

> Note: $$E_1^{fin} = < L\mathrm{X}_1 | L\mathrm{X}_1 >_{fin} = < \mathrm{X}_1 | \underbrace{L^*}_{\boxed{\textit{adjoint}}} L\mathrm{X}_1 >_{fin}$$

and the calculation of SVs may be reduced to an eigenvalue problem* (related to the linear operator $L^* L$) where the eigenvalues are the growth factors σ_i^2 .

> Note also that the amplitude of the SVs is arbitrary. The convention is to choose the amplitudes such that $E^{ini} = 1$ for all SVs.

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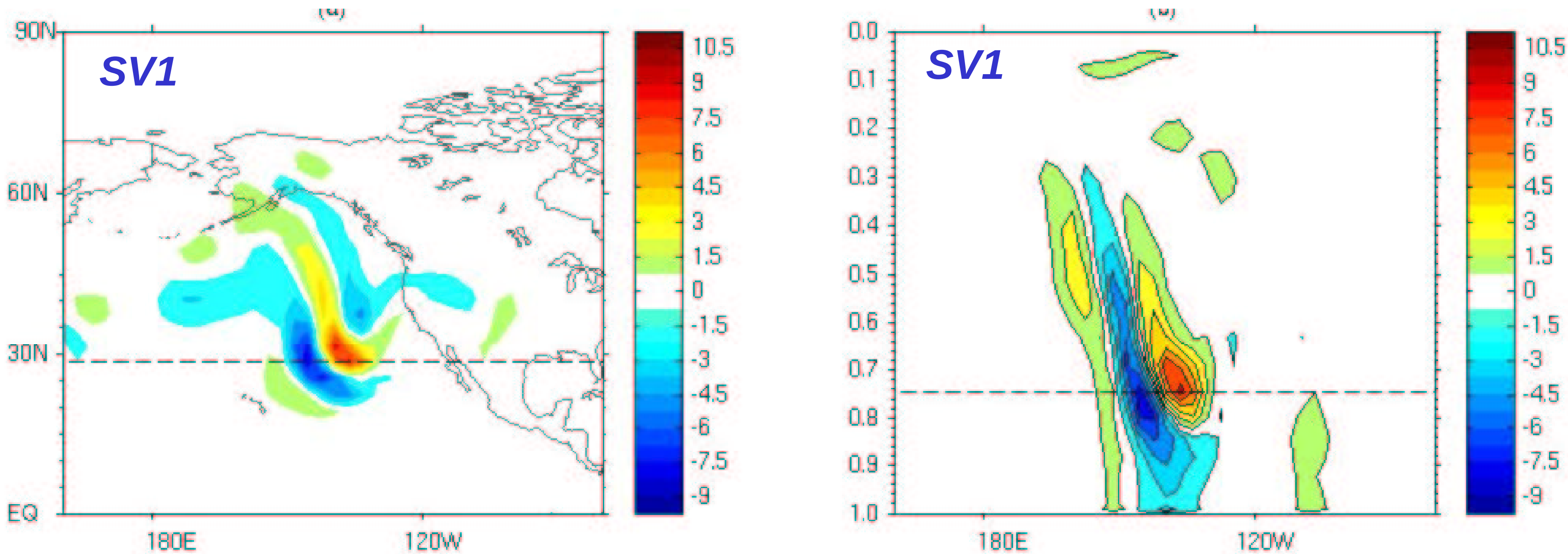
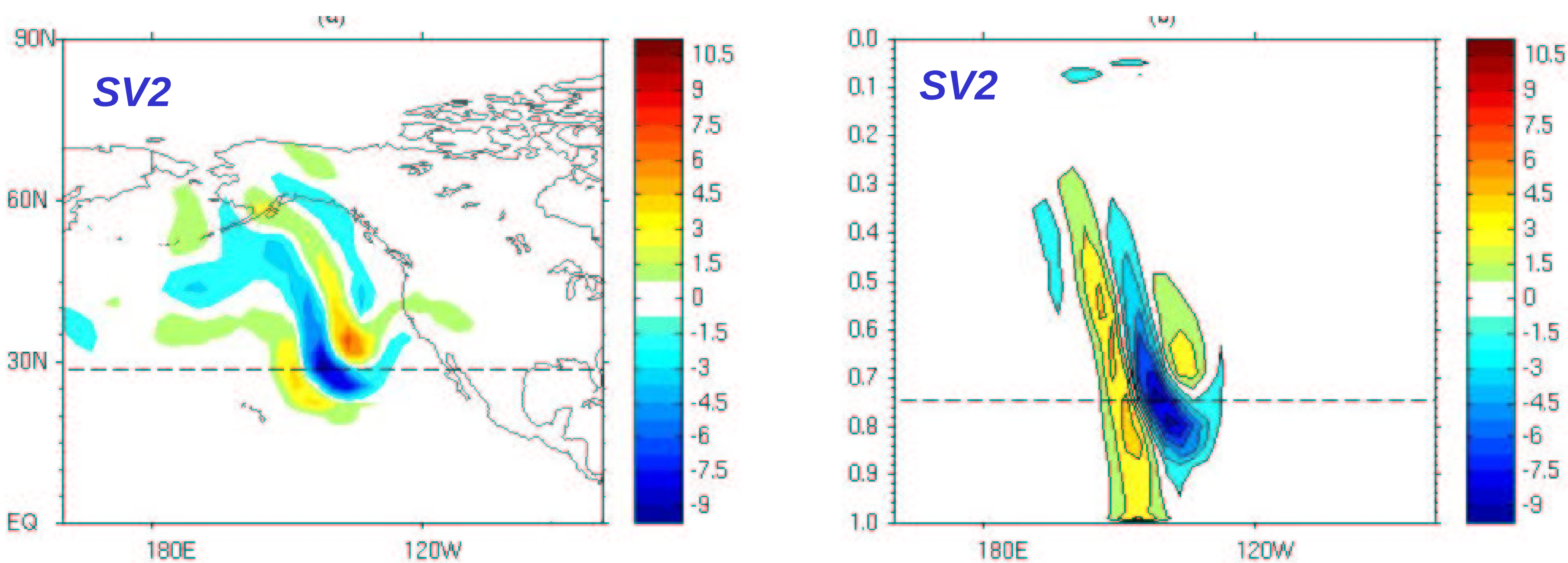
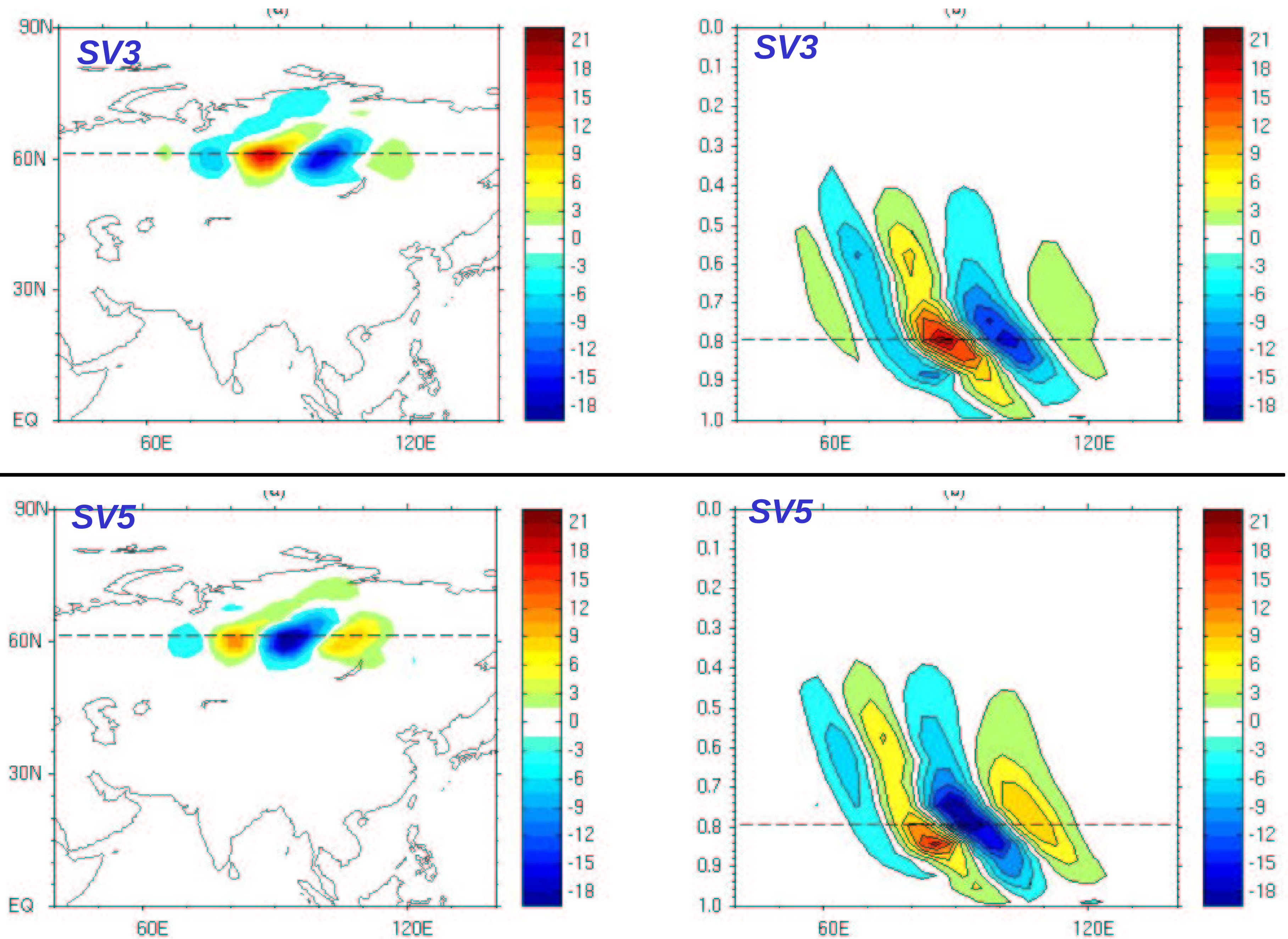
* A Lanczos-type algorithm is used to solve this eigenvalue problem.

Examples: for TT winter / OTI=48h / simpl.phys.: VDIFF only






SV3
90N
60N
30N
EQ
60E
120E
21
18
15
12
9
6
3
0
-3
-6
-9
-12
-15
-18
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SV5

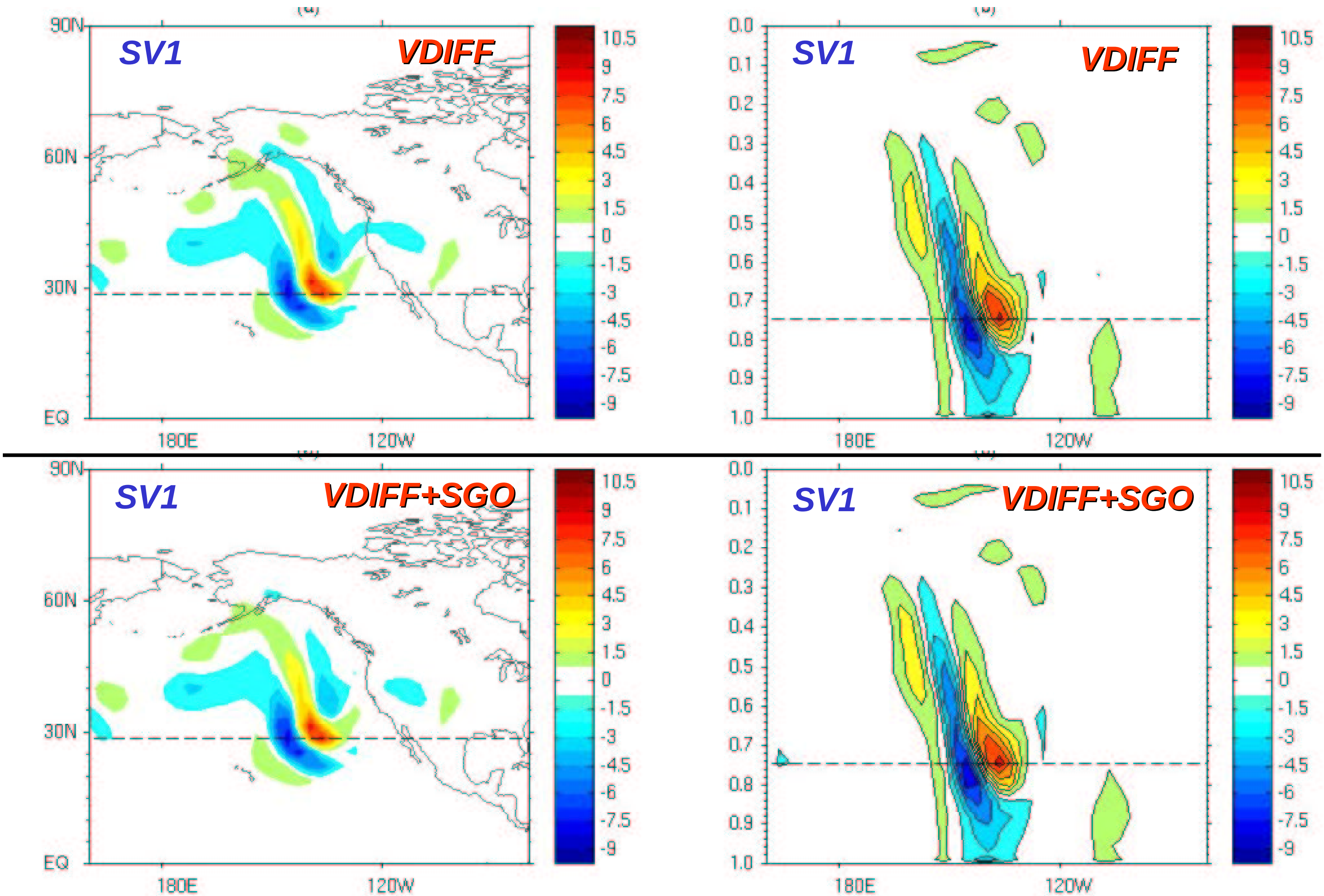
Types of tests:

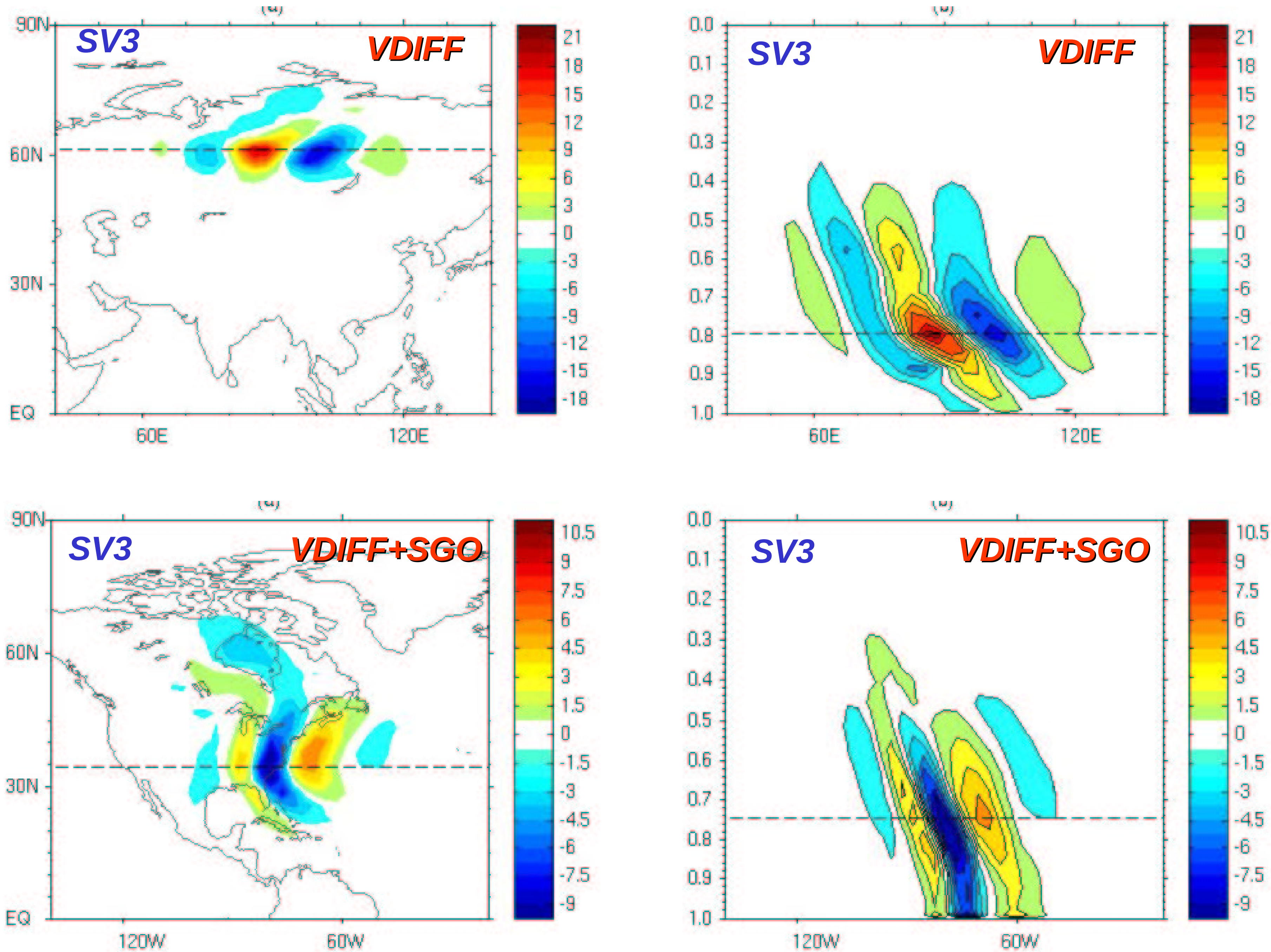
> compare SVs produced by 2 different configurations of the simplified physics;

> take SVs produced by one configuration (ex: only VDIFF) and propagate them with the TLM of another configuration (ex: VDIFF + SGO);

> take SVs produced by one configuration and propagate them using the full nonlinear model.

Comparison of TT SVs / OTI=48h / VDIFF *vs* VDIFF + SGO





SV3
VDIFF
90N
60N
30N
EQ
60E
120E
21
18
15
12
9
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3
0
-3
-6
-9
-12
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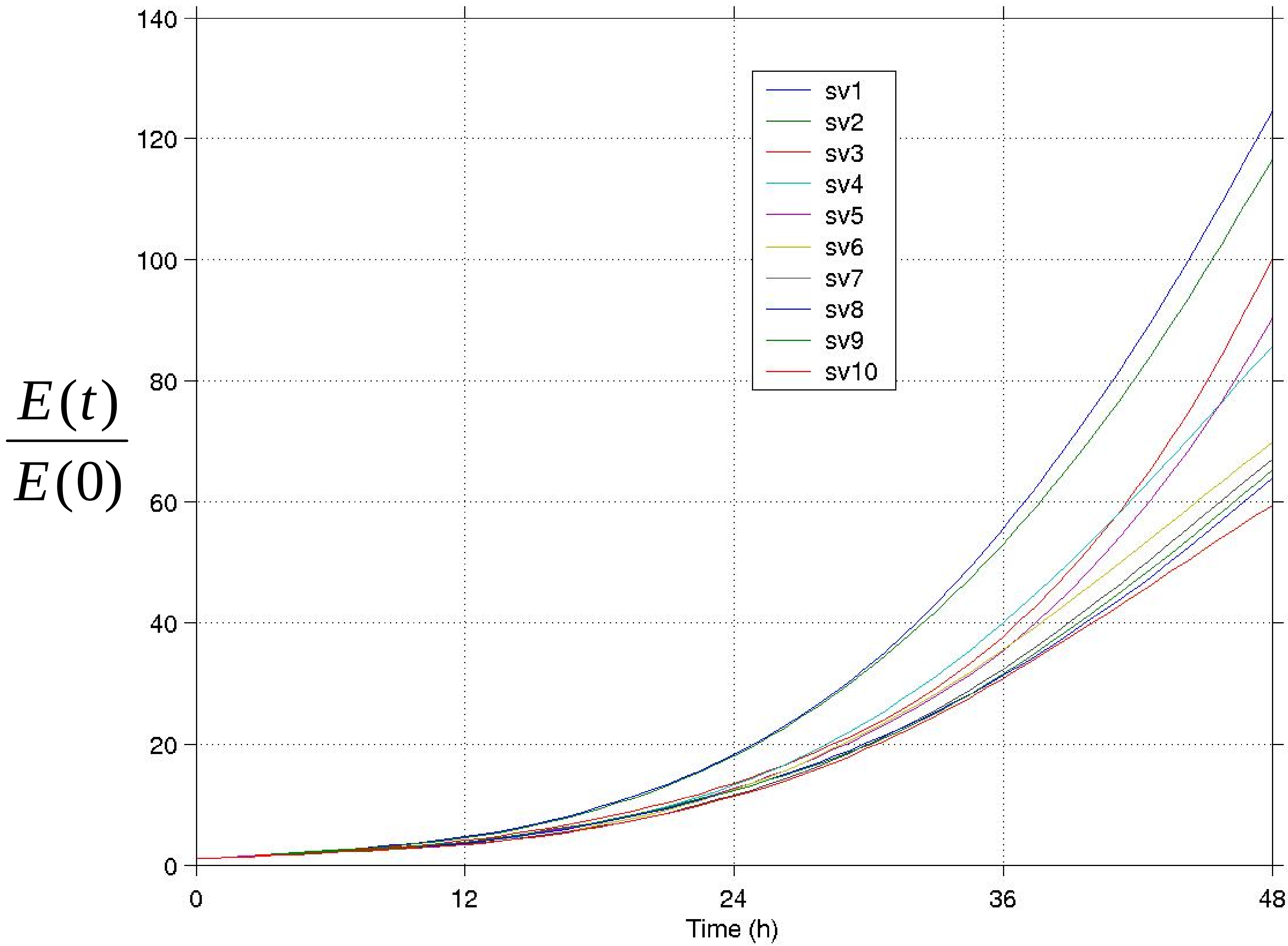
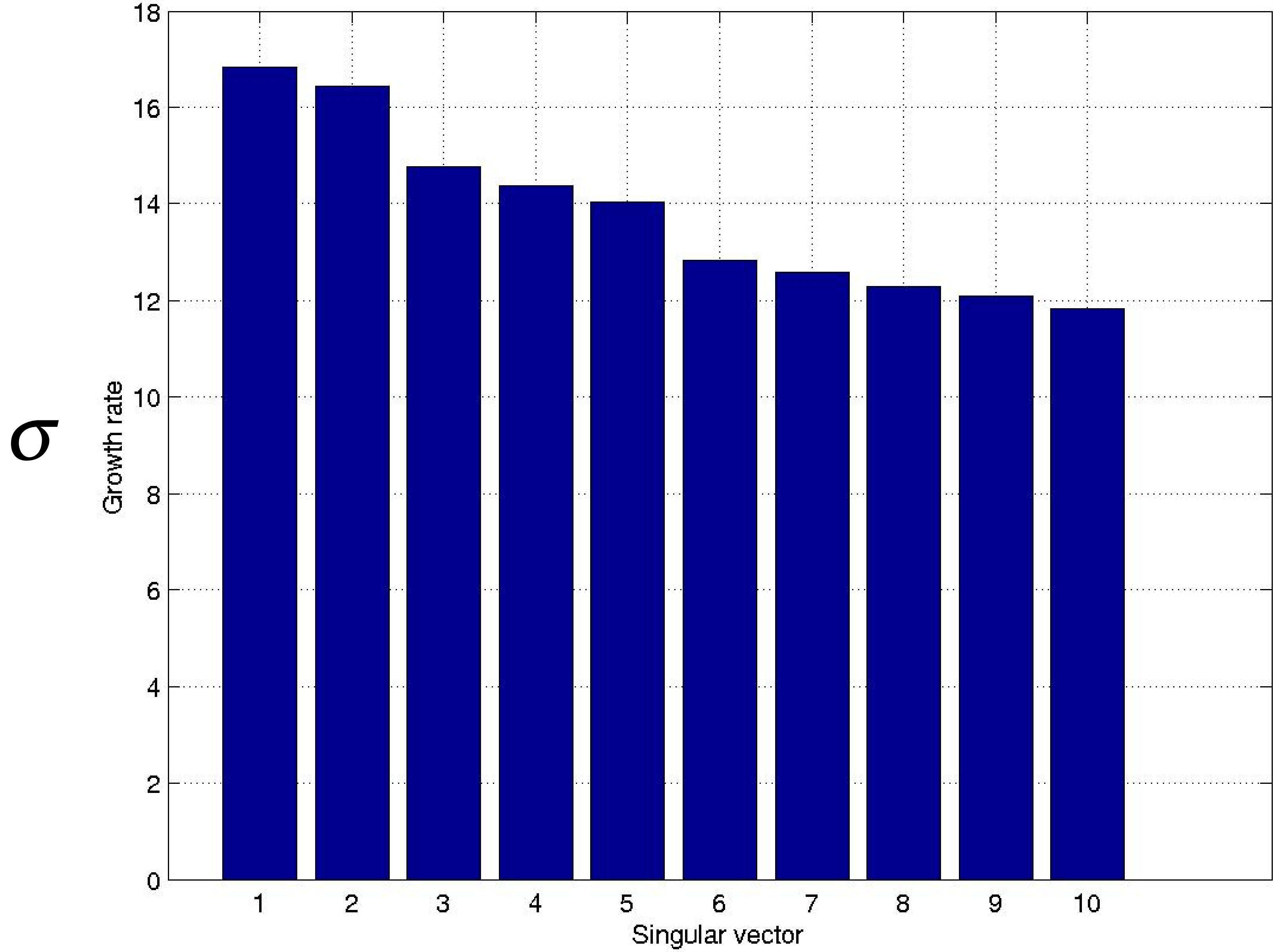
SV3
VDIFF
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
60E
120E
SV3
VDIFF+SGO
90N
60N
30N
EQ
120W
60W
10.5
9
7.5
6
4.5
3
1.5
0
-1.5
-3
-4.5
-6
-7.5
-9
SV3
VDIFF+SGO
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
120W
60W

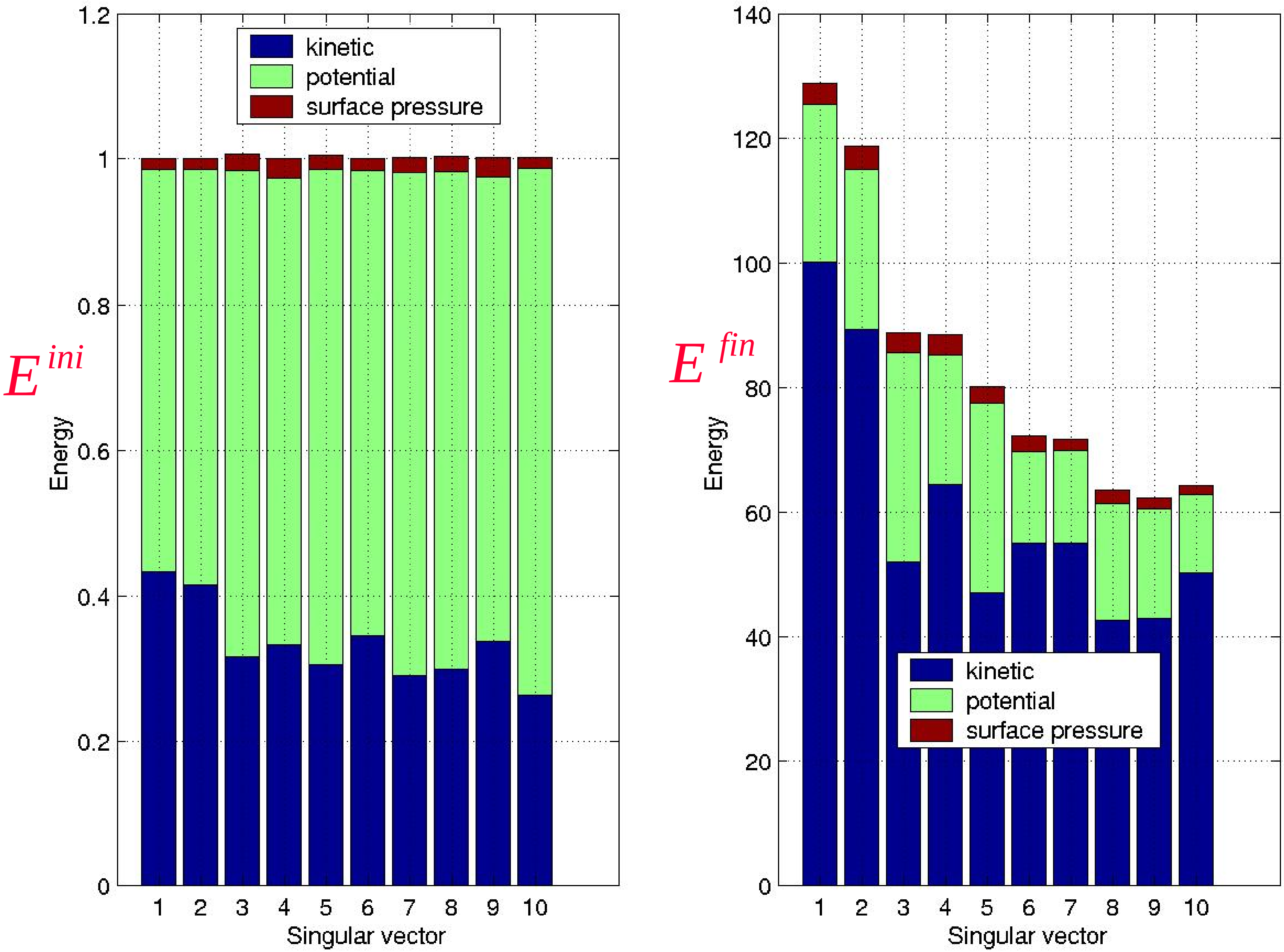
Example of energy growth: OTI=48h / VDIFF only



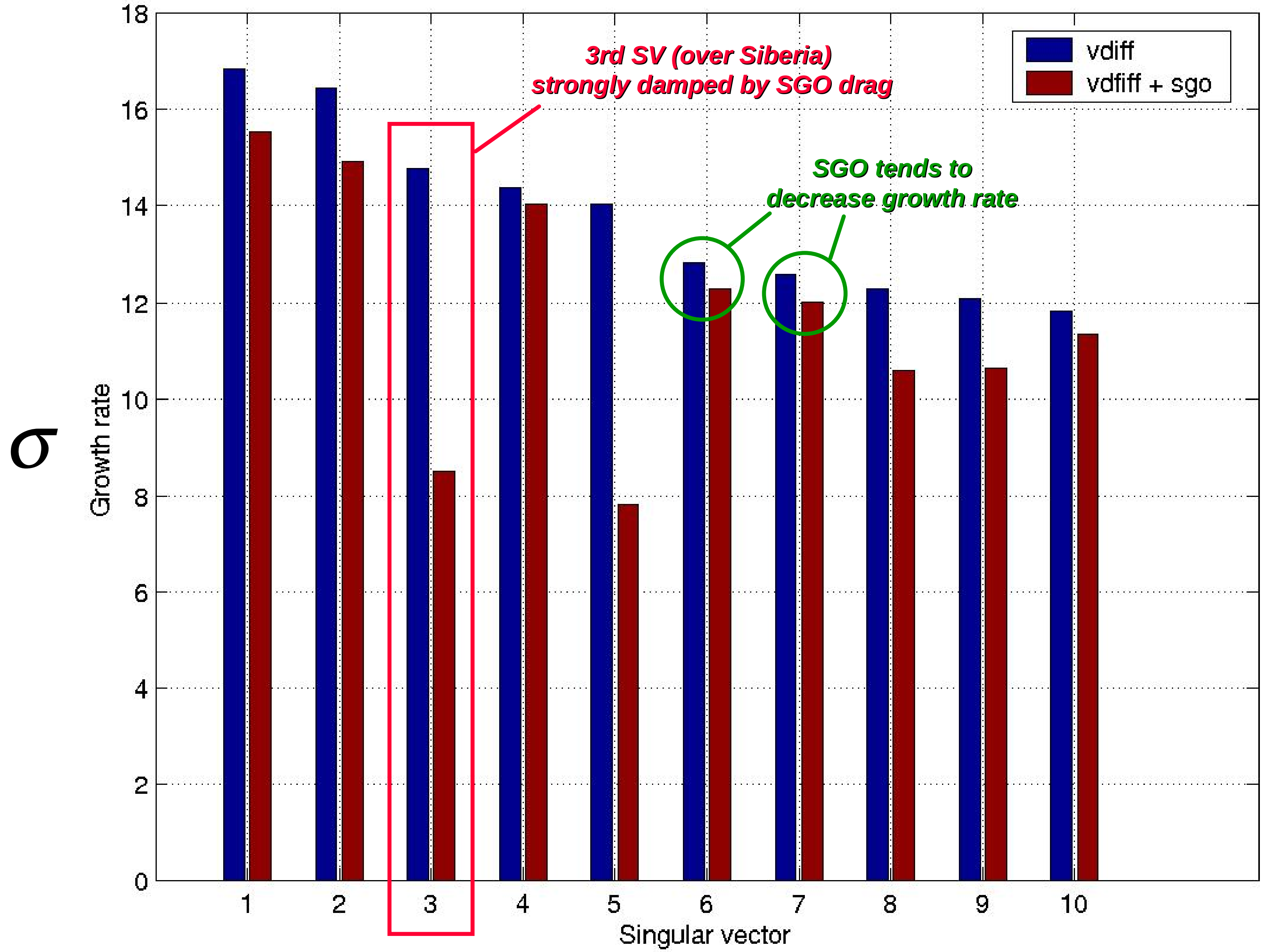
Example of growth-rate spectrum: OTI=48h / VDIFF only



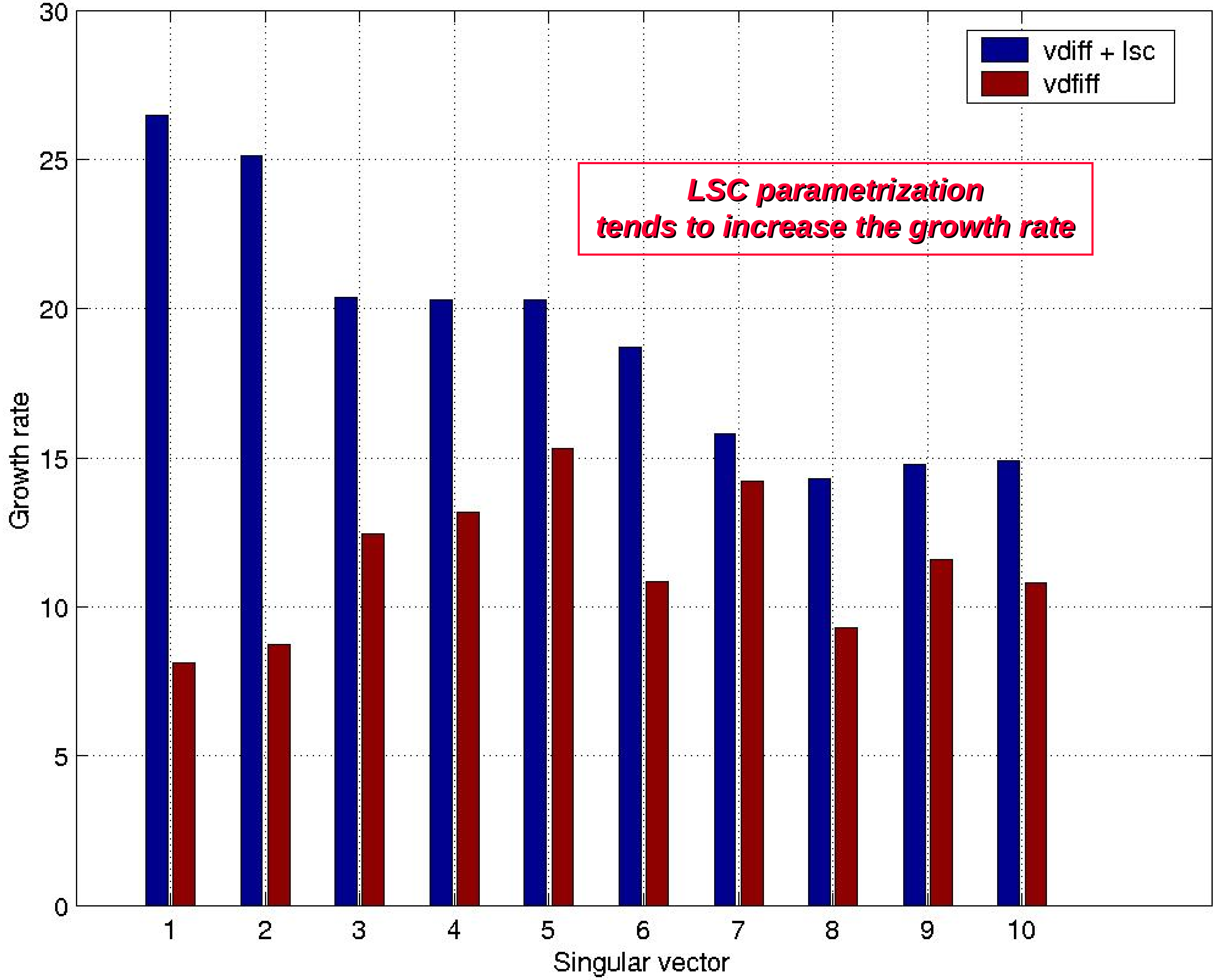
Example of energy partition: OTI=48h / VDIFF only



Example: impact of SGO on the growth-rate spectrum

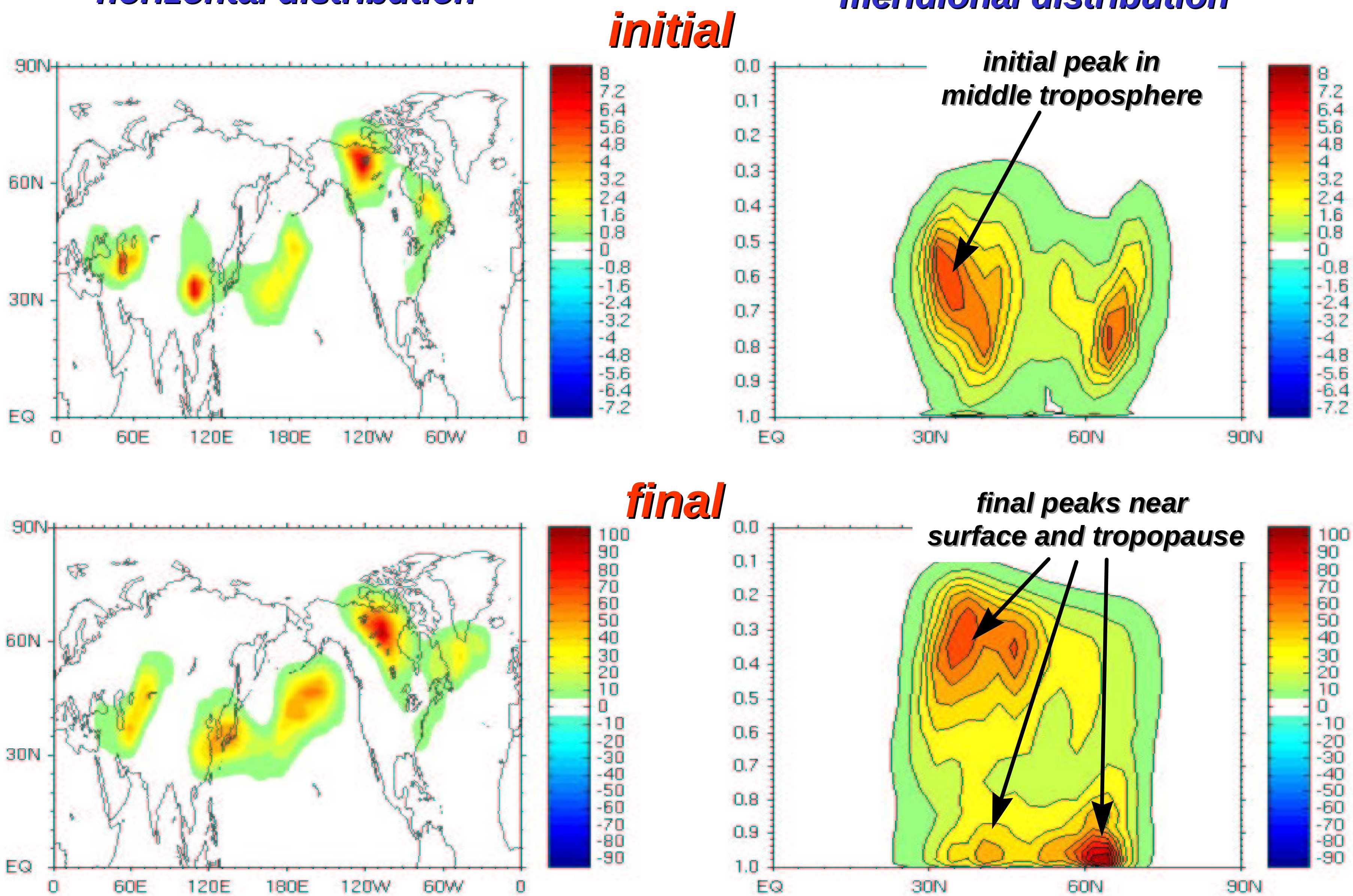


Example: impact of LSC on the growth-rate spectrum



Examples of spatial distribution of SV energy
10 SVs / OTI=24h / simpl.phys.: VDIFF only

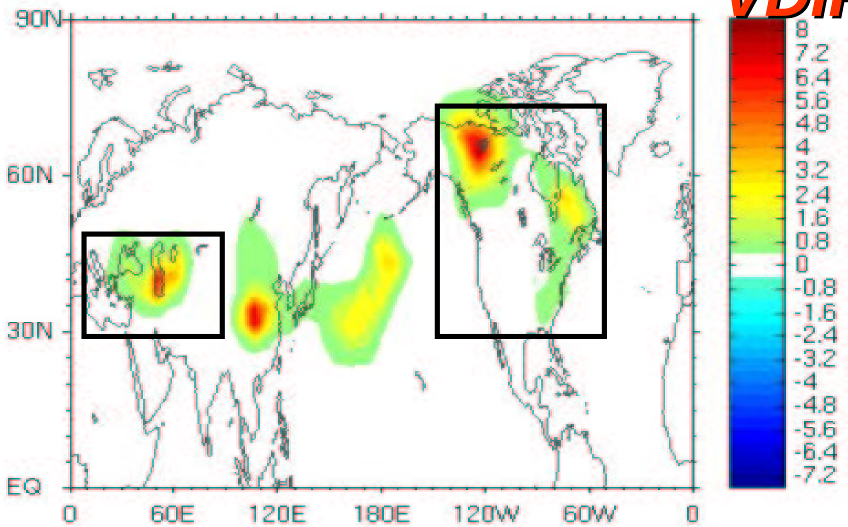
horizontal distribution ***meridional distribution***

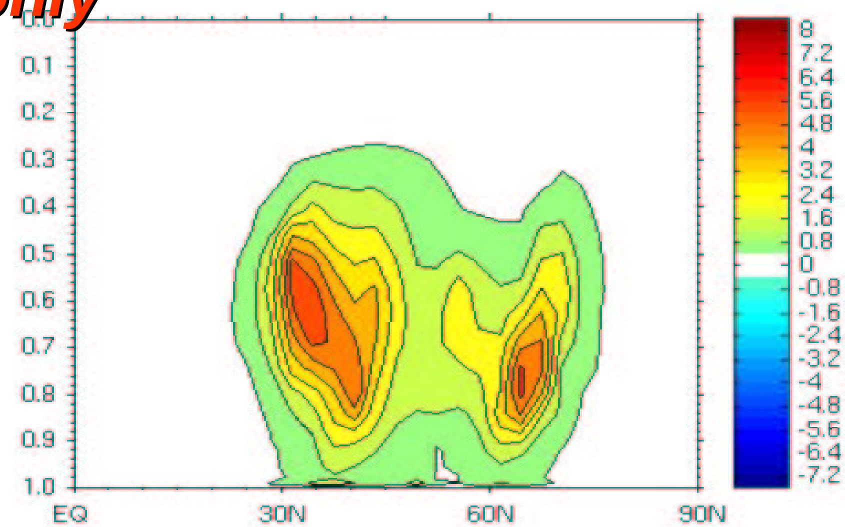


Impact of SGO on the initial energy distribution
10 SVs / OTI=24h

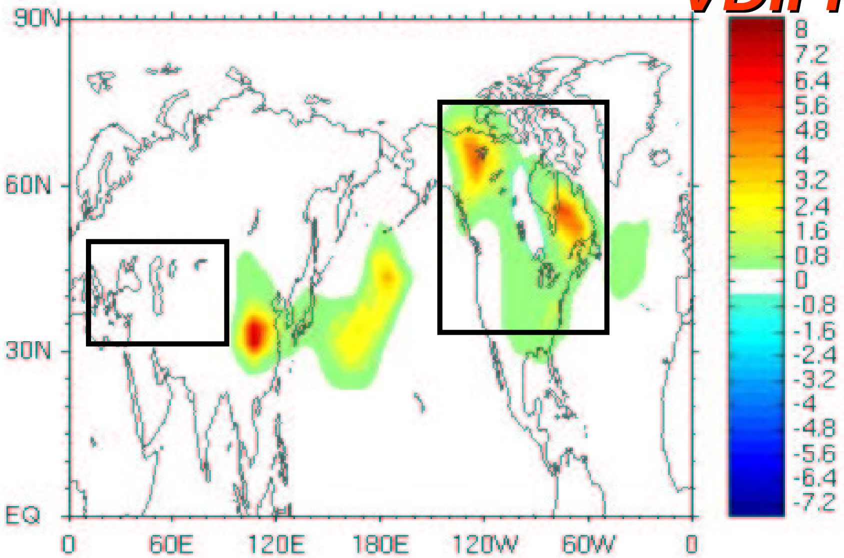
horizontal distribution ***meridional distribution***

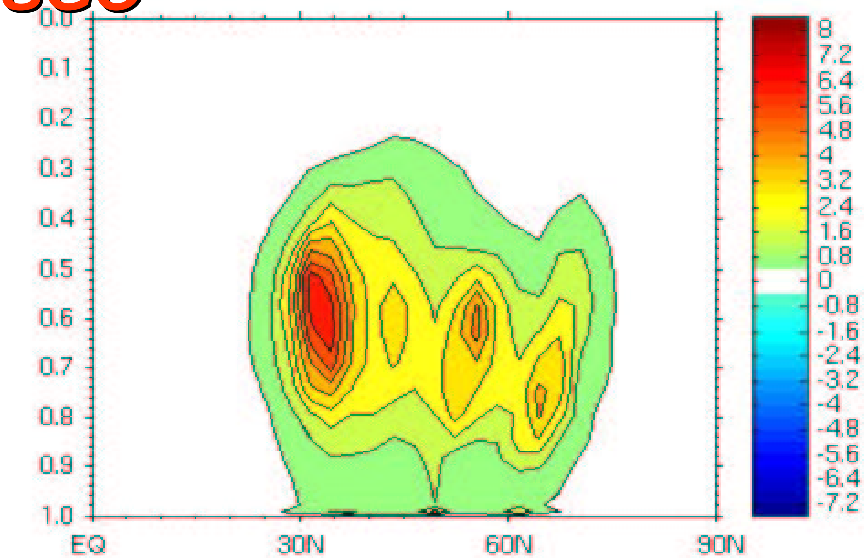
VDIFF only



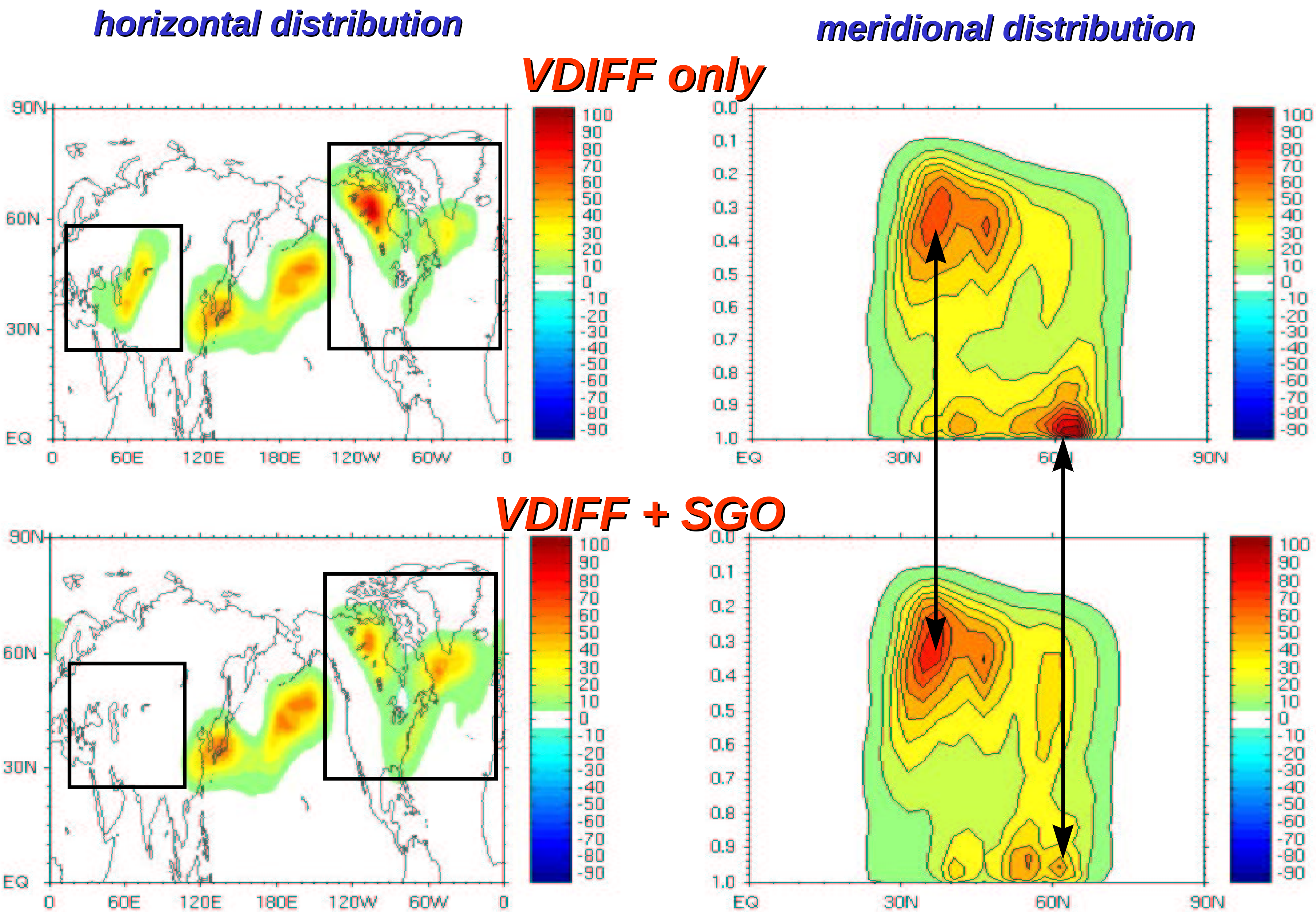


VDIFF + SGO





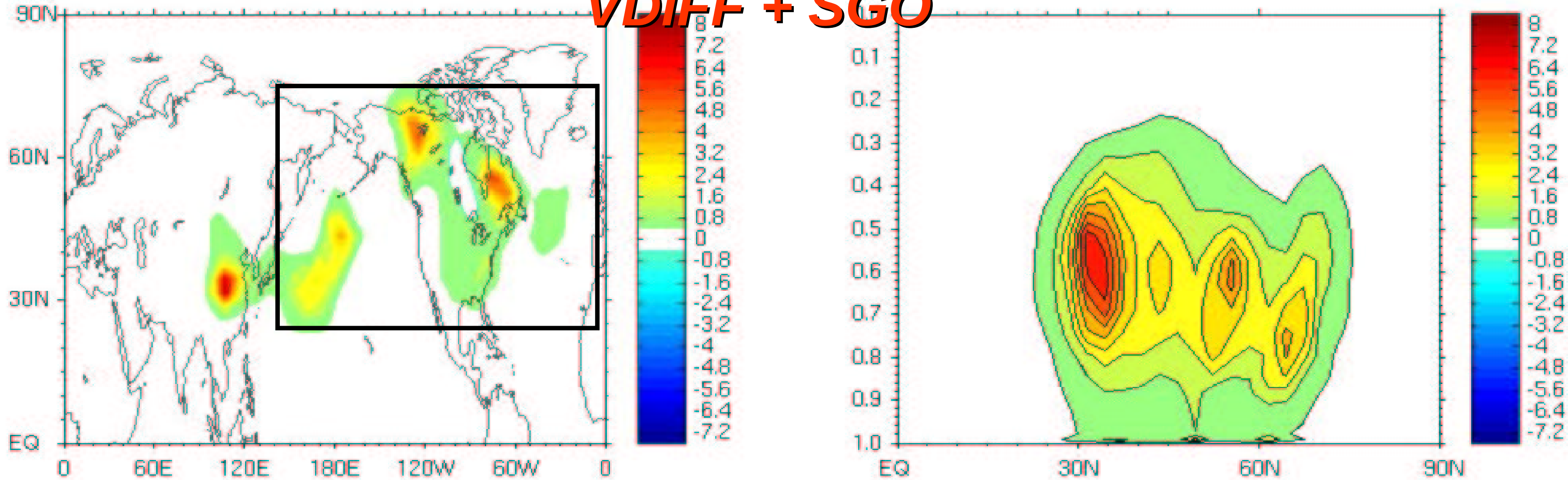
Impact of SGO on the final energy distribution
10 SVs / OTI=24h



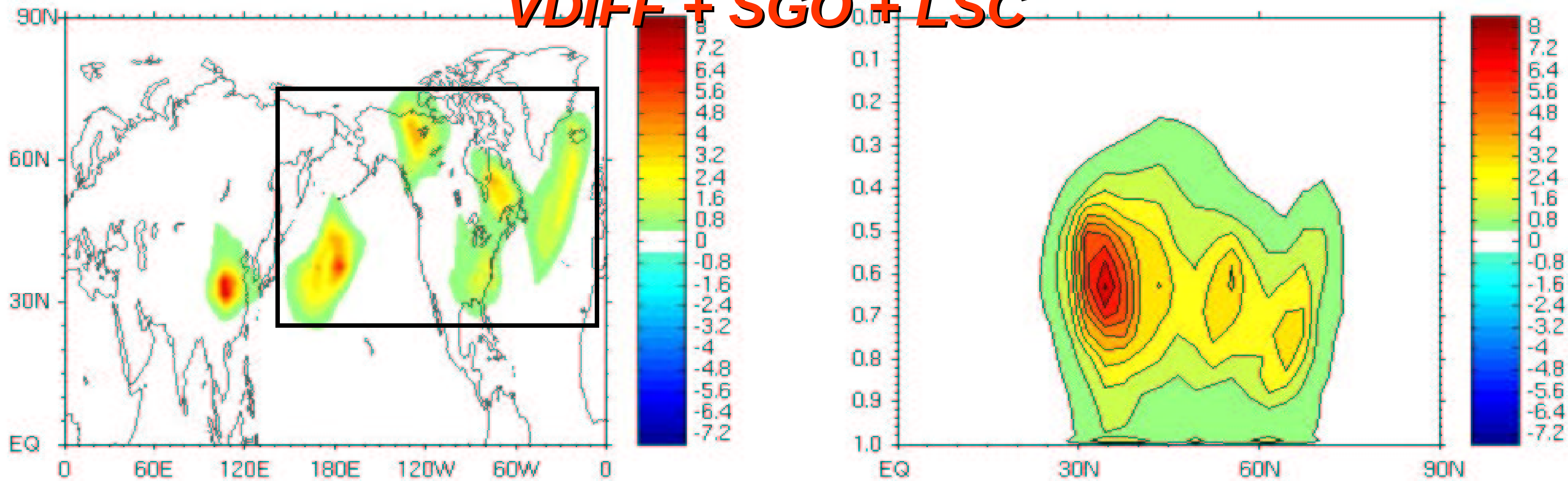
Impact of LSC on the initial energy distribution
10 SVs / OTI=24h

horizontal distribution *meridional distribution*

VDIFF + SGO



VDIFF + SGO + LSC

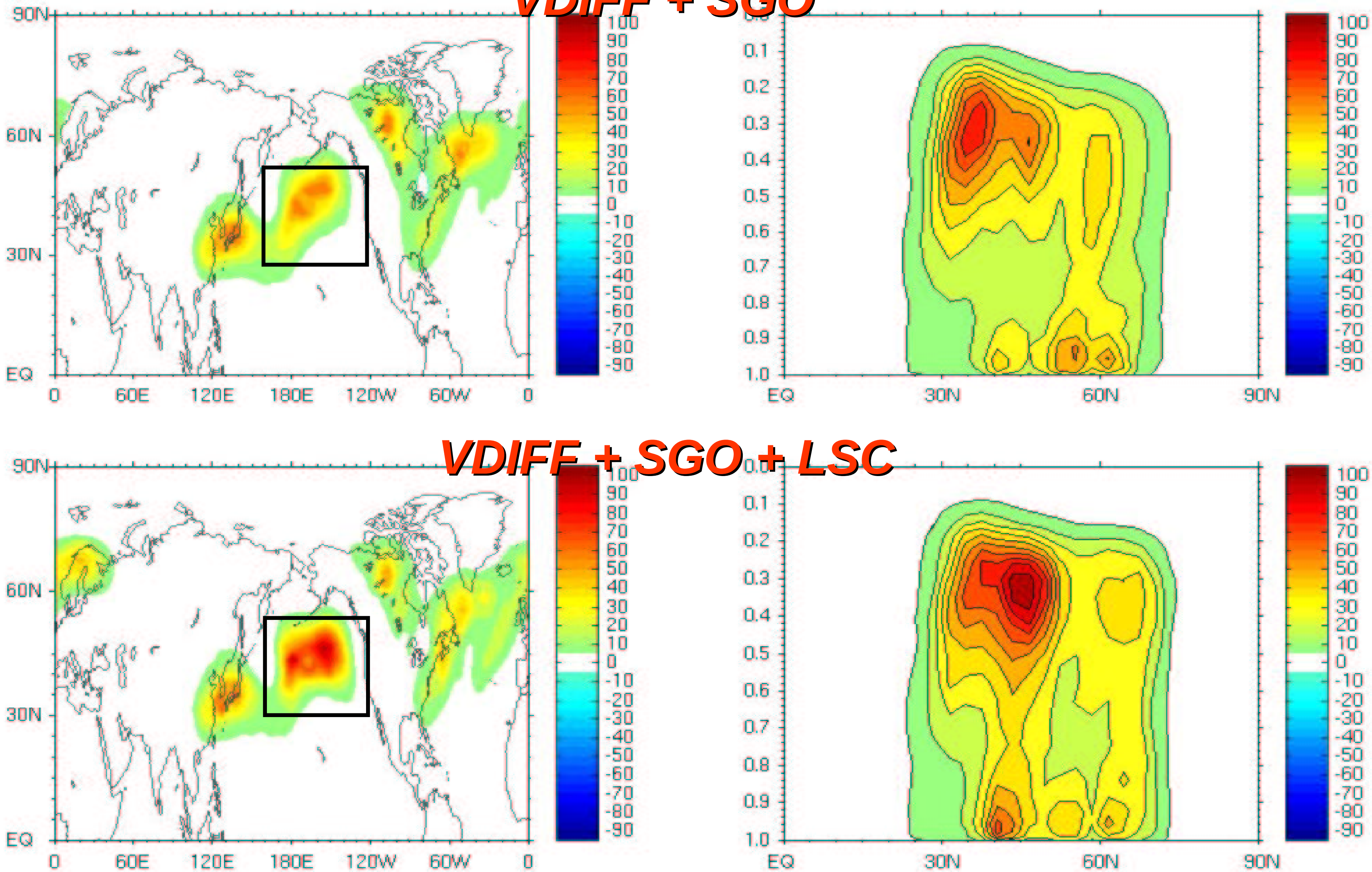


Impact of LSC on the final energy distribution
10 SVs / OTI=24h

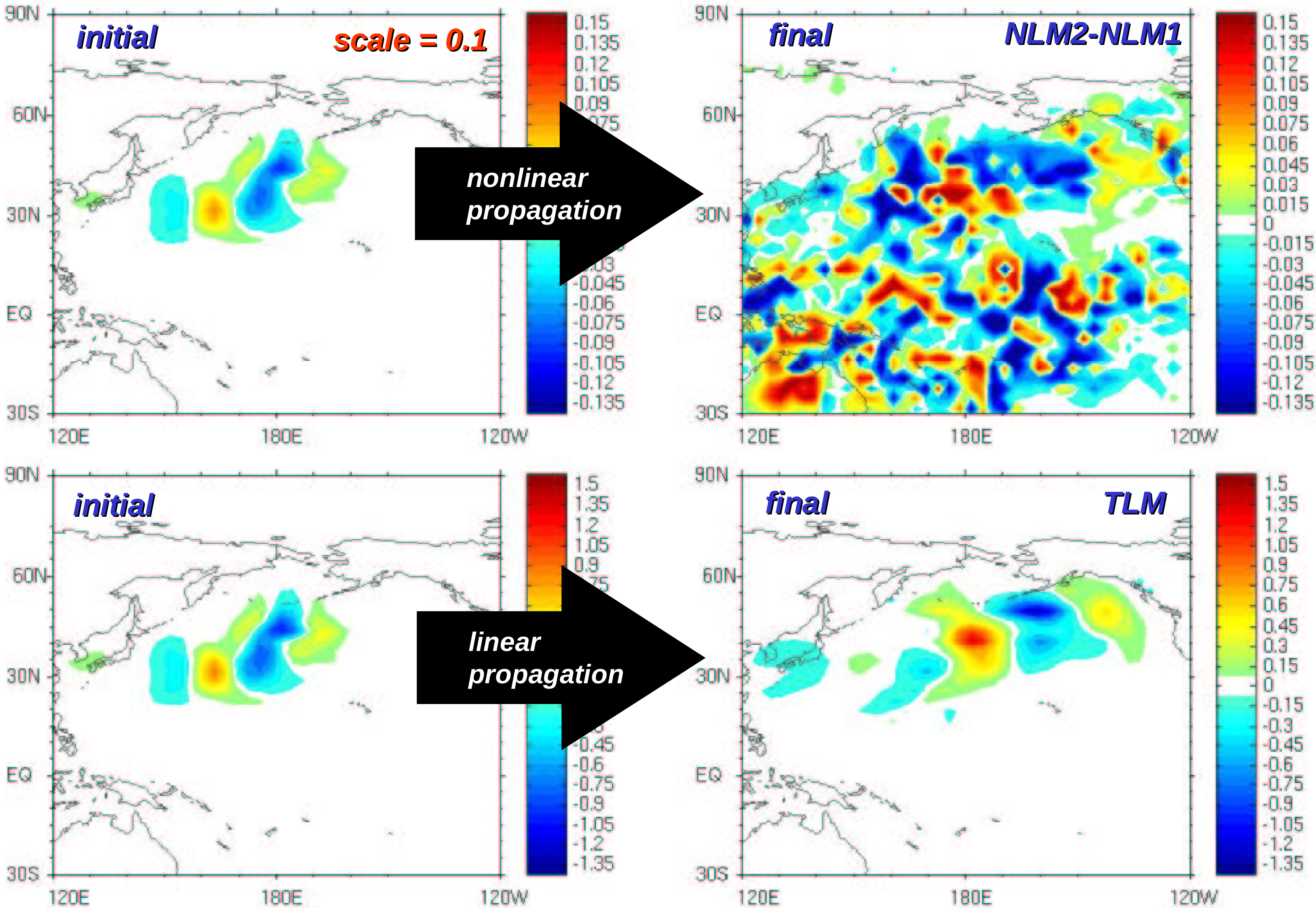
horizontal distribution *meridional distribution*

VDIFF + SGO

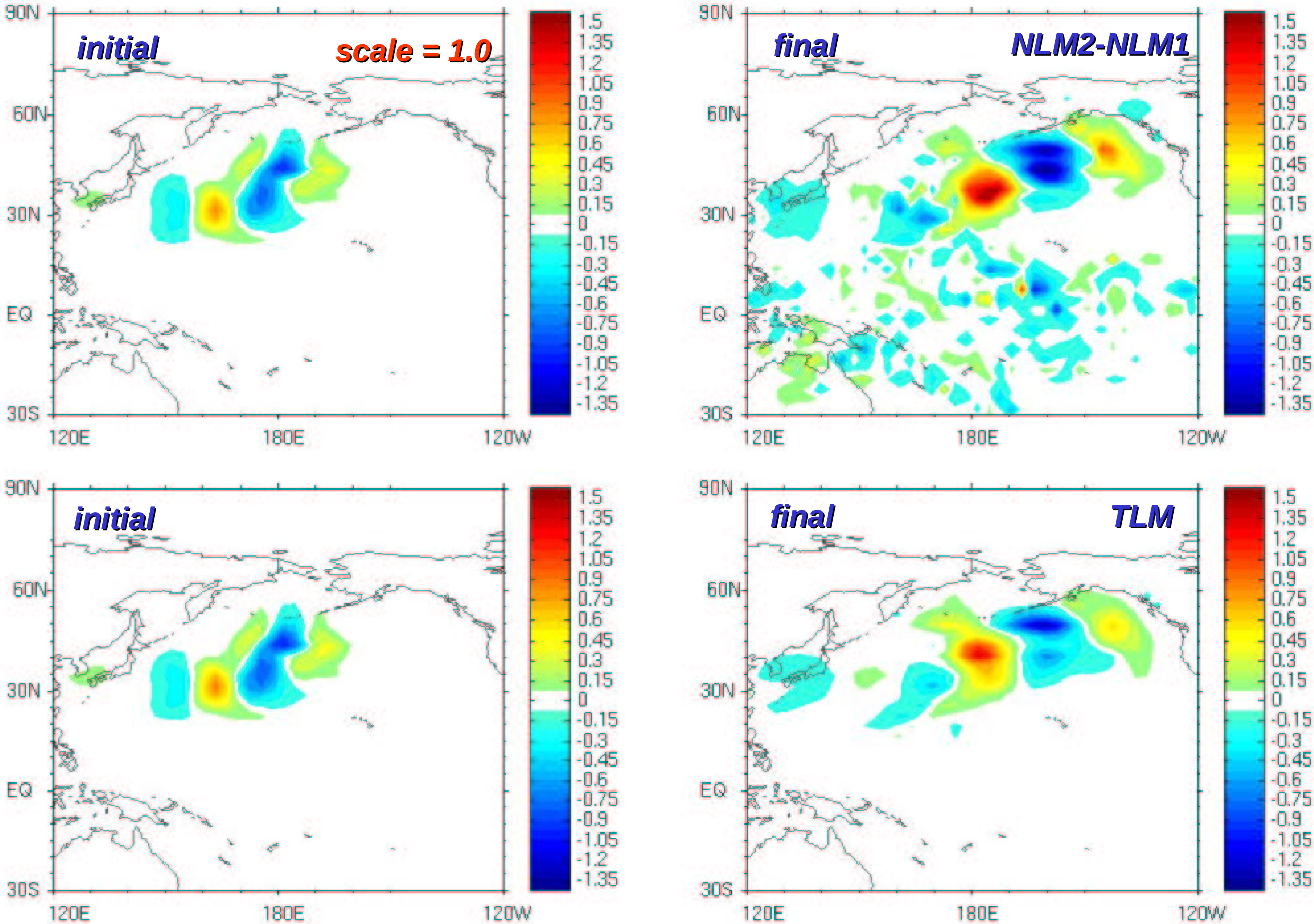
VDIFF + SGO + LSC



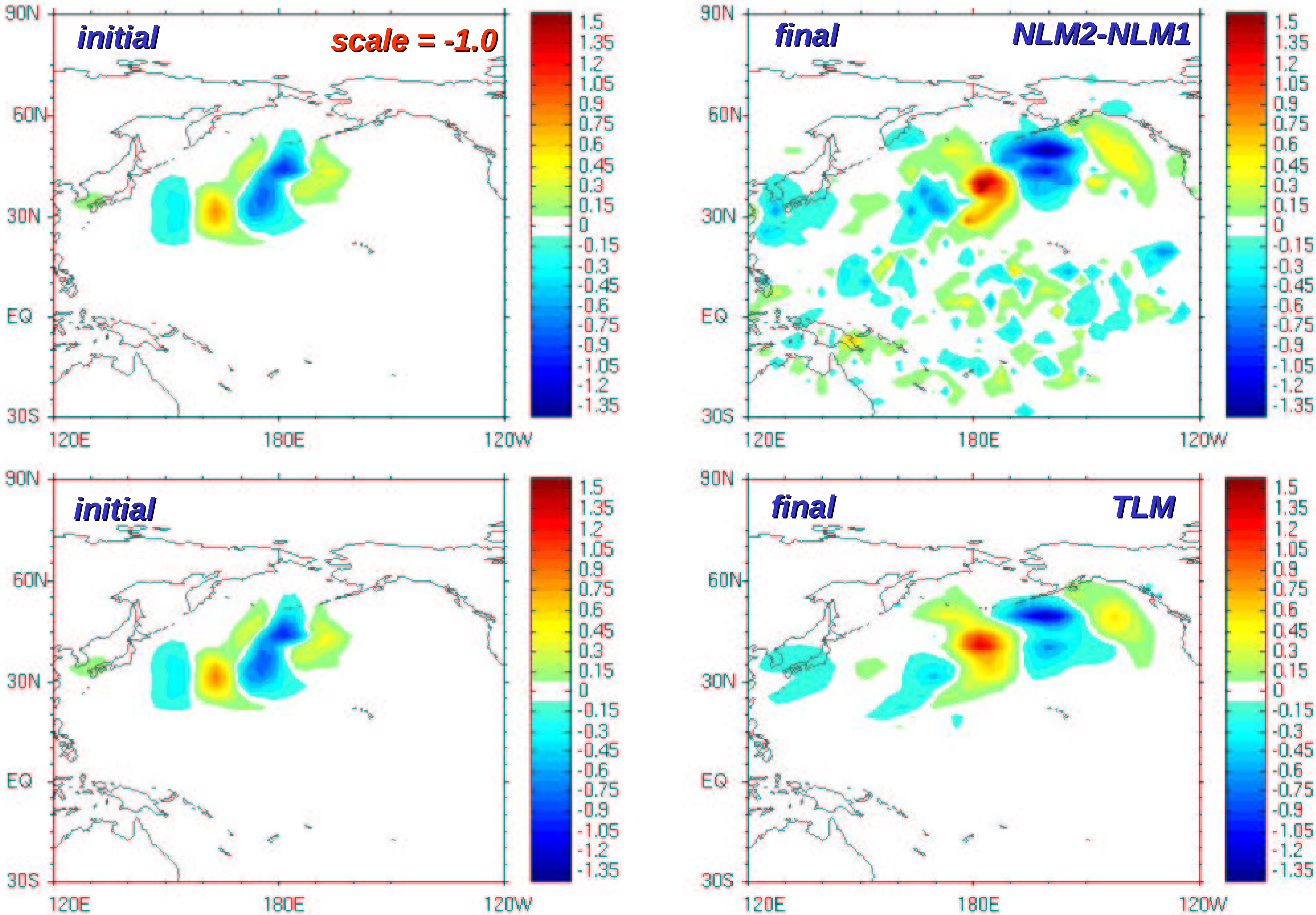
Linear *vs.* nonlinear prop. of SV1 / TT level=18 / OTI=24h



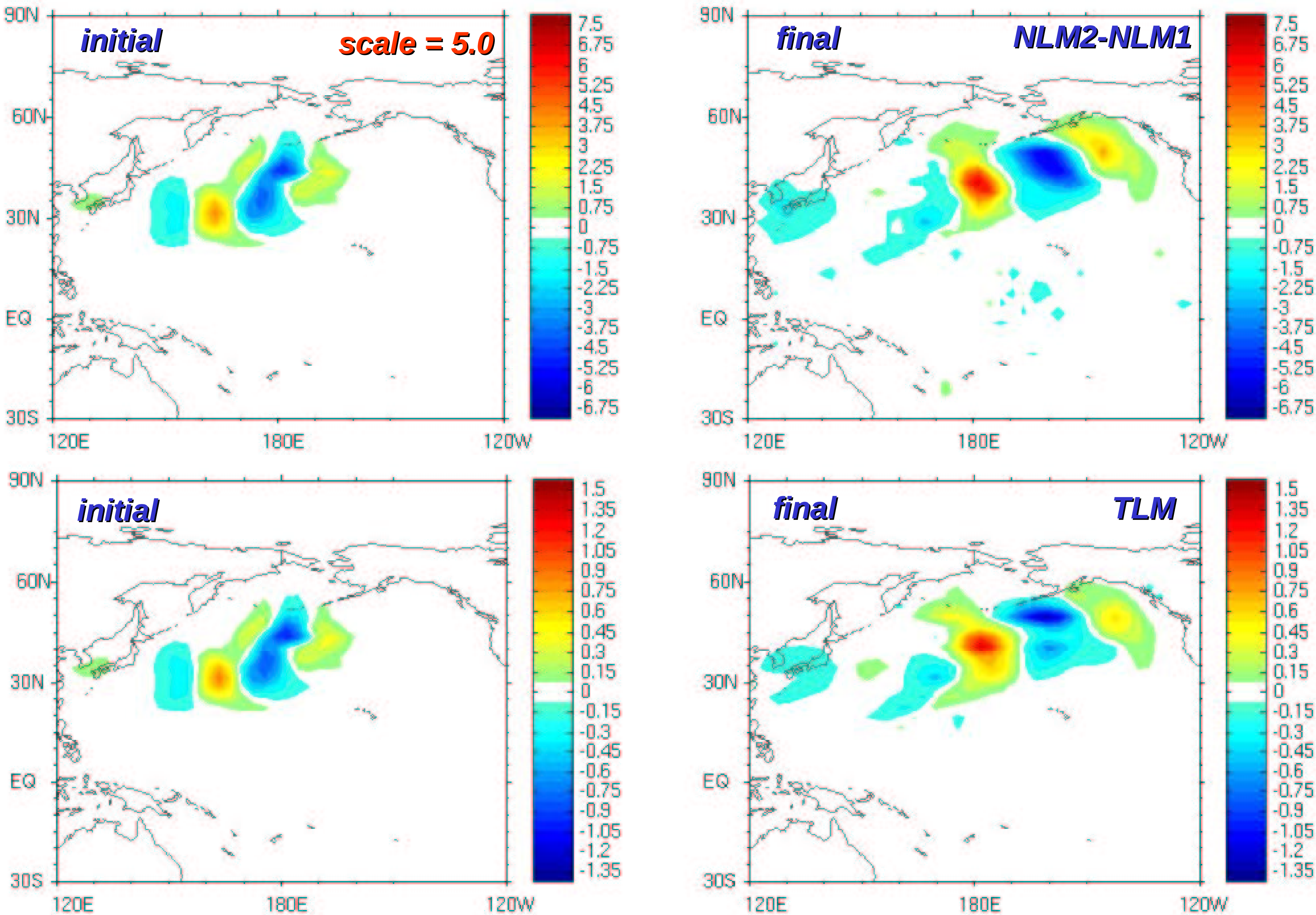
Linear *vs.* nonlinear prop. of SV1 / TT level=18 / OTI=24h



Linear *vs.* nonlinear prop. of SV1 / TT level=18 / OTI=24h



Linear *vs.* nonlinear prop. of SV1 / TT level=18 / OTI=24h



Impact of the simplified SGO parameterization on the calculation of key analysis errors (KAE)

> KAE = sensitivity of 24h forecast errors w.r.t. initial conditions (analysis).

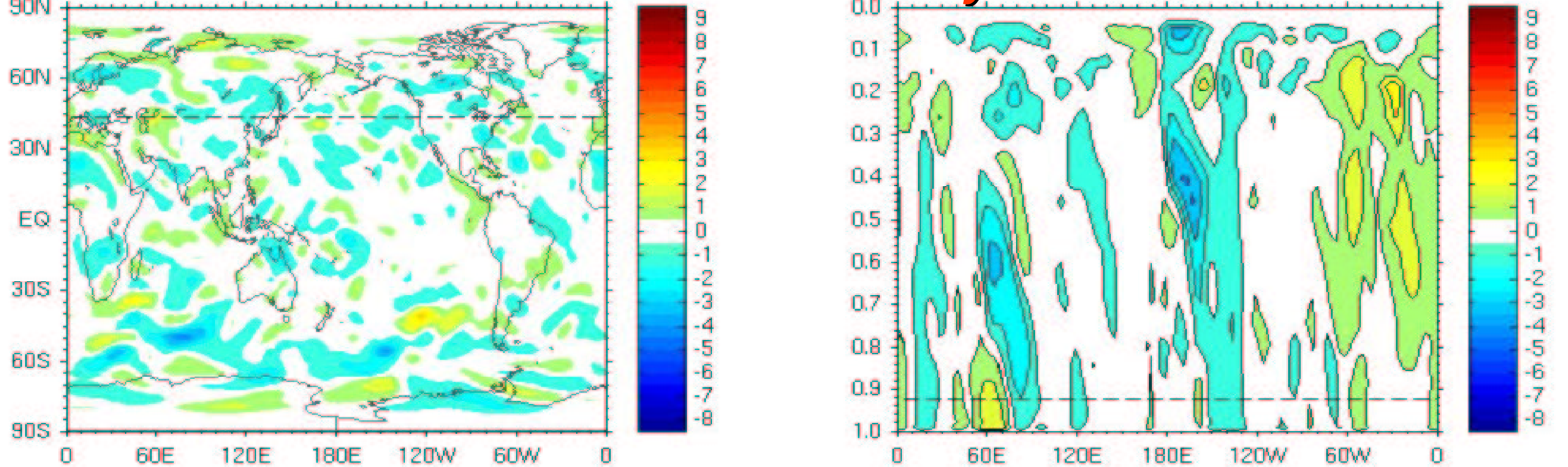
> The algorithm uses tangent-linear and adjoint integrations to find corrections to the initial analysis that reduce the 24h forecast error.

> Errors are measured according to the total energy norm.

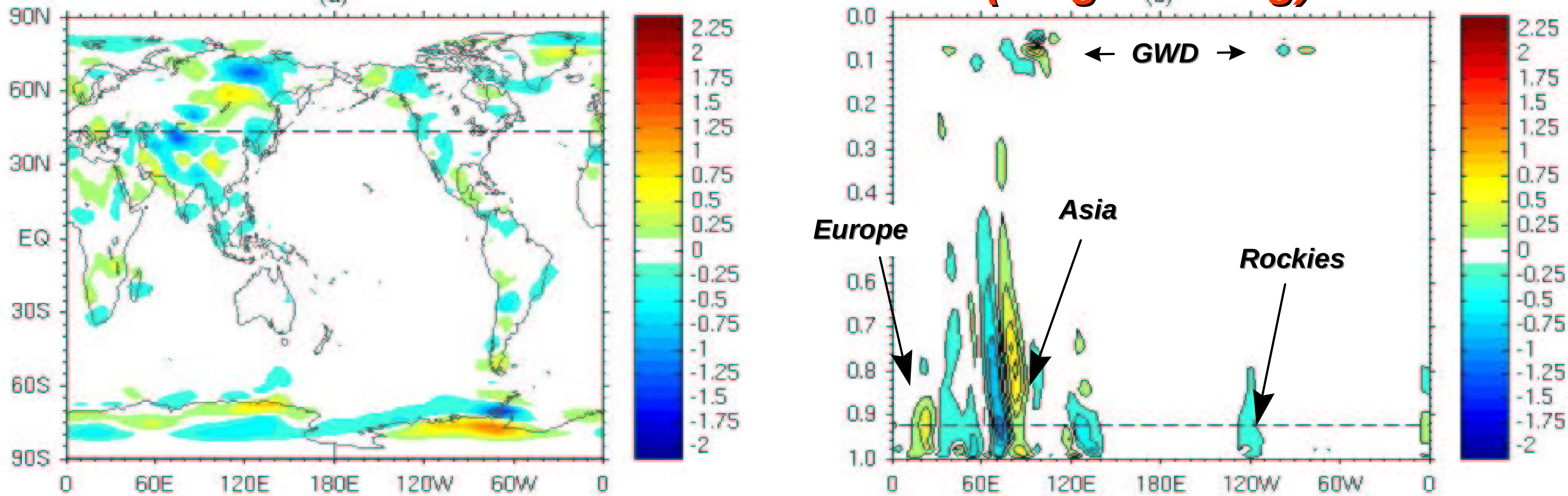
For more details on KAEs:
`http://iweb.cmc.ec.gc.ca/~afsdjmo/SENSIB/sensib.html`

Impact of SGO on KAEs / zonal wind

reference / VDIFF only

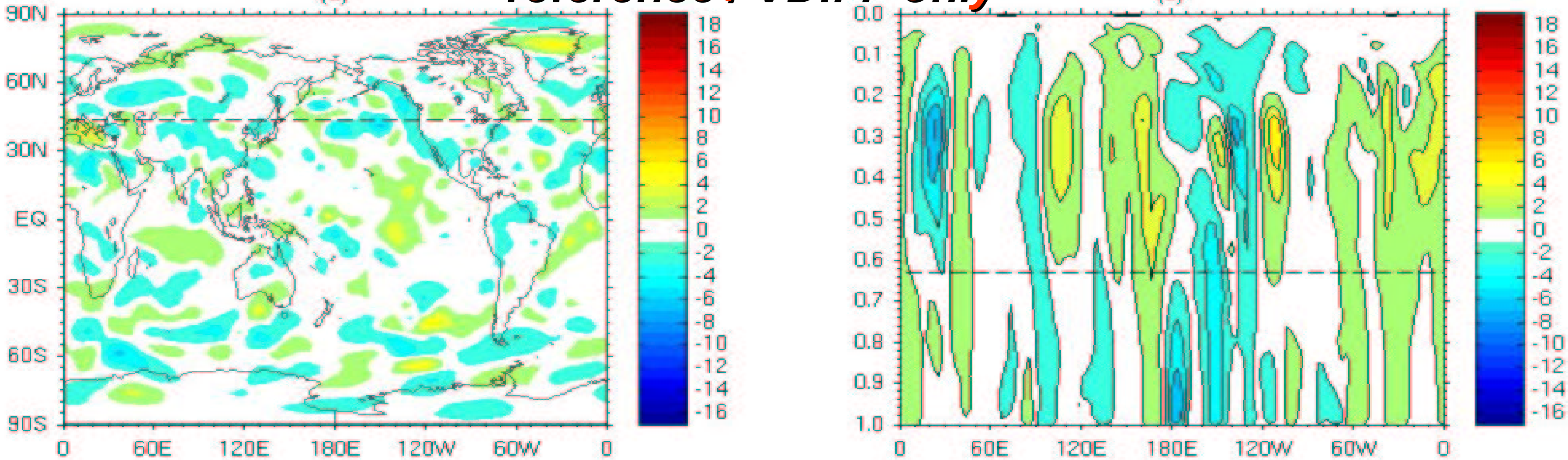


difference when SGO is activated (drag - nodrag)

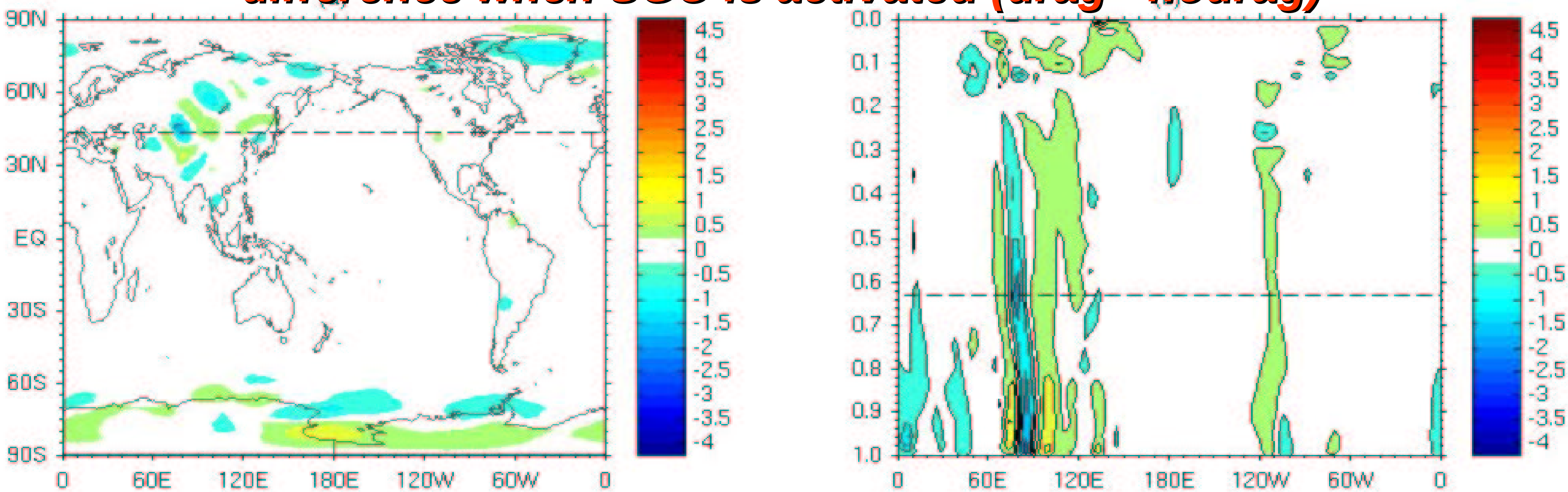


Propagated KAEs (after 24h) / zonal wind

reference / VDIFF only



difference when SGO is activated (drag - nodrag)



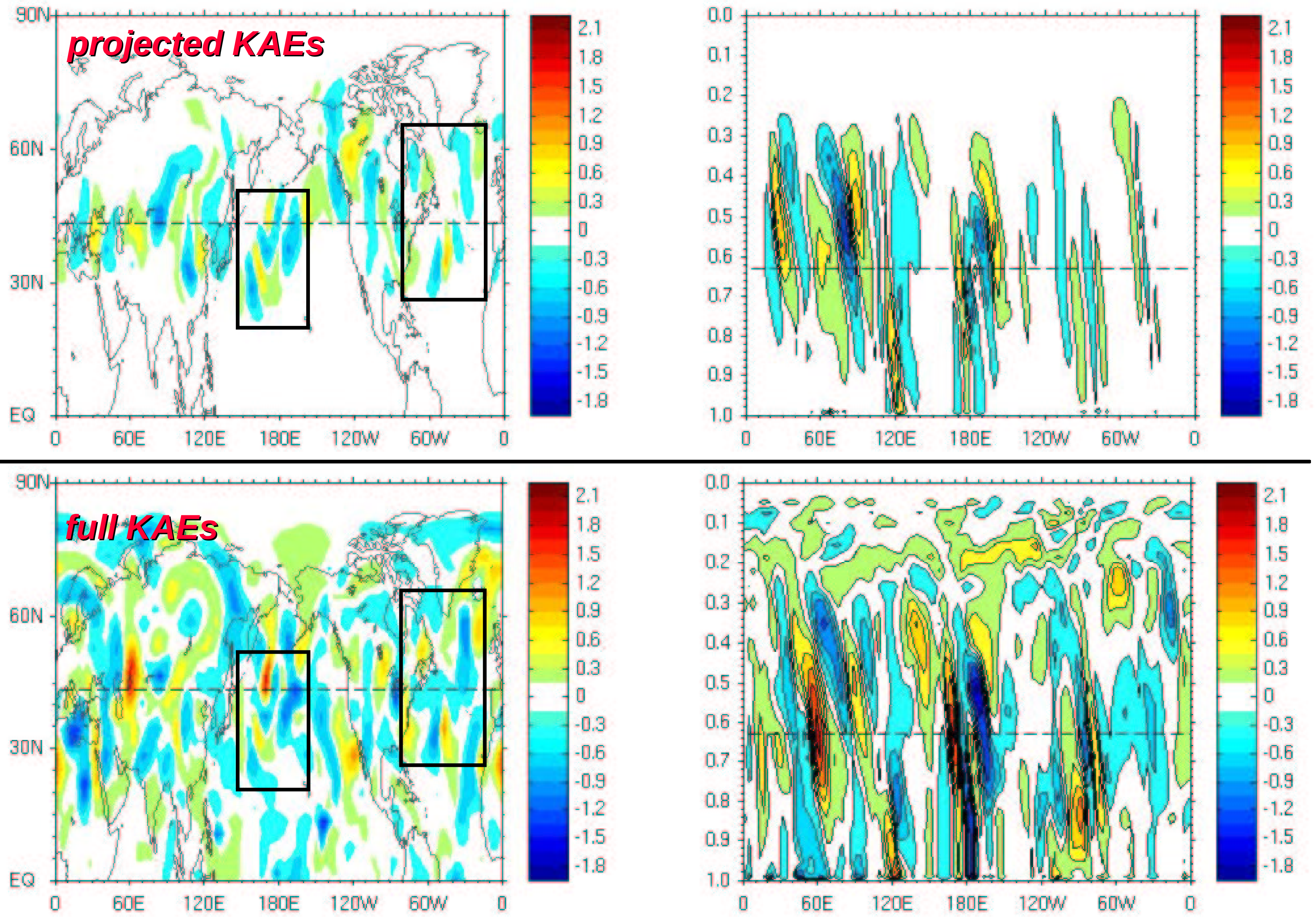
Test: projection of KAEs on the SV space

> A projection of KAEs on the leading SVs provides the the most unstable components of the analysis corrections.

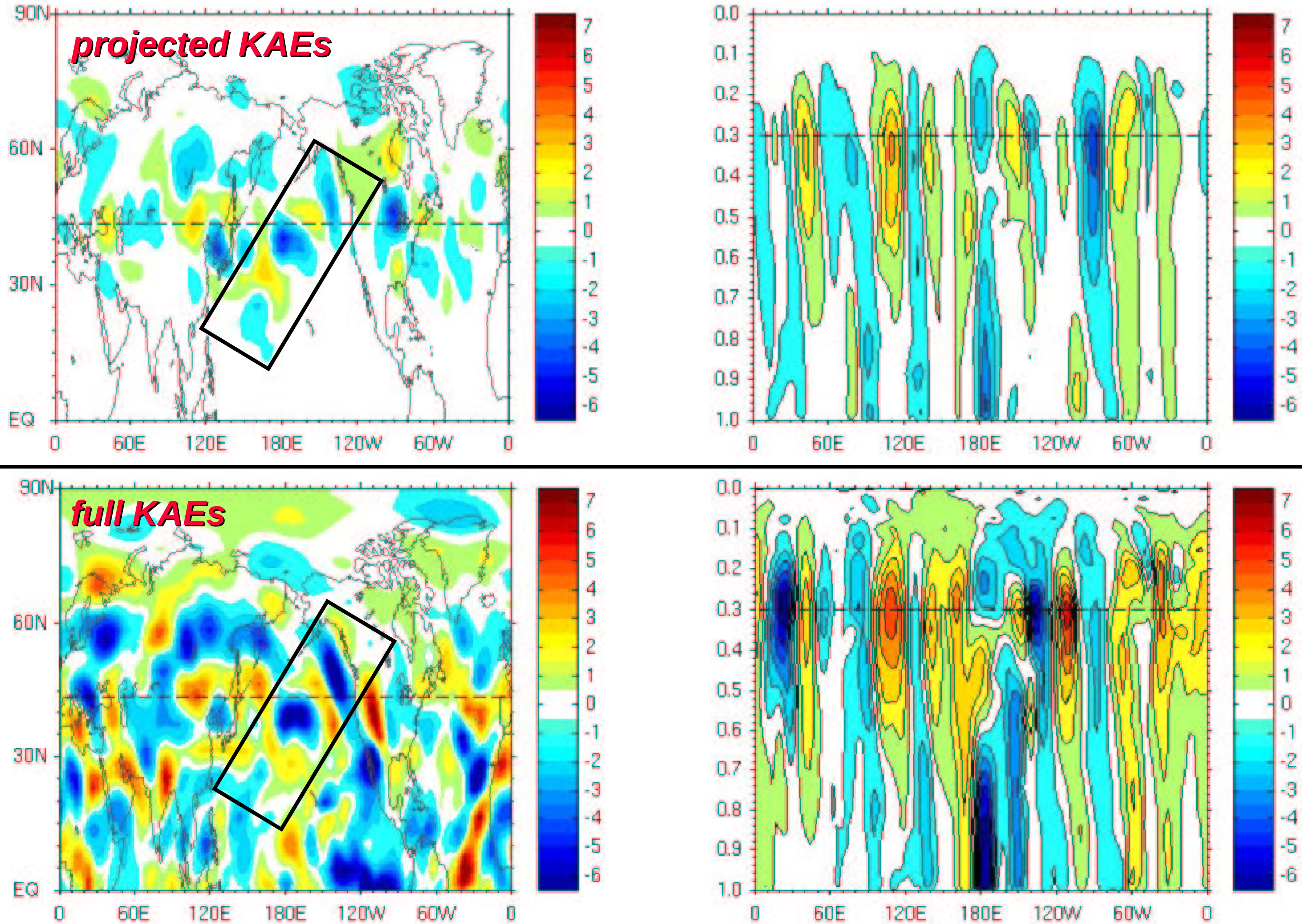
> In this test, the KAEs are projected (using the energy norm) on the 50 leading SVs, with an OTI=24h.

> The projected KAEs are propagated using the TLM for 24h, and the result is compared with the structure of forecast errors.

Projection of KAEs on 50 SVs / TT / initial time



Projection of KAEs on 50 SVs / UU / final time



Summary

> Adding the SGO to the simplified physics improves the consistency between the tangent-linear and the nonlinear model.

> The SGO scheme tends to decrease the growth rate of the leading extra-tropical SVs, especially those over continents.

> The simplified SGO parameterization has a non-negligible impact on the amplitude of the KAEs' (especially on low-level winds).

Future work

> Evaluate the impact of other physical processes (ex: LSC, convection) in the simplified physics, as well as the use of other norms (ex: add a moist term to the energy norm).

> Further tests of sensitivity analysis with SGO scheme (ex: daily sensitivity analysis -- see seminar by Stephane Laroche next week !)

> Low-resolution experiments suggest that the SGO scheme may smooth and speed up the minimization process in 4DVar assimilations. Tests at higher resolutions will be made soon.