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Boundary conditions control in ORCA2

Eugene Kazantsev

INRIA, Moise

Journée thématique

“Que peuvent attendre les modélisateurs de l’assimilation de données ?”

Paris, le 12 février 2013

ORCA-2 configuration of NEMO

- $182 \times 149 \times 31$ nodes in curvilinear (x, y) coordinates;
- z levels with partial steps at the bottom;
- leap-frog scheme with Asselin filter;
- implicit surface pressure gradient with External Gravity Waves filter;
- implicit vertical diffusion with TKE Turbulent Closure Scheme;
- Solar Radiation + Geothermal Heating + BBL + Surface evaporation/precipitation;
- surface wind stress.

$$\begin{aligned}
\frac{\partial u}{\partial t} &= \left(S_x S_y v \right) S_y (\omega + f) - D_x \frac{S_x u^2 + S_y v^2}{2} - S_z \left(S_x w D_z u \right) + D_x A_u^h \xi + D_y A_u^h \omega + \\
&+ g \int_0^z D_x S_z \rho(x, y, \zeta) d\zeta + D_{zz} (A_u^z u) + g D_x (\eta + T_c \phi) \\
\frac{\partial T}{\partial t} &= -D_x (u S_x T) - D_y (v S_y T) - D_z (w S_z T) + A_T^h \left(D_x D_x T + D_y D_y T \right) + \\
&+ D_{zz} (A_T^z T) + \text{Solar Radiation} + \text{Geothermal Heating} + \text{BBL} \\
\xi &= D_x u + D_y v, \quad \omega = D_y u - D_x v, \quad w = \int_H^z \xi(x, y, \zeta) d\zeta; \quad w(x, y, H) = 0
\end{aligned}$$

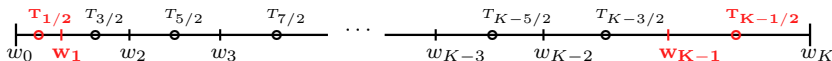
Interpolations and Derivatives

$$\begin{aligned}
(Sw)_{k+1/2} &= \frac{w_{k+1} + w_k}{2} \quad k = 1, \dots, K-1 \\
(DT)_k &= \frac{T_{k+1/2} - T_{k-1/2}}{h} \quad k = 1, \dots, K-1
\end{aligned}$$

$$\begin{aligned}
 \frac{\partial u}{\partial t} &= \left(S_x S_y v \right) S_y (\omega + f) - D_x \frac{S_x u^2 + S_y v^2}{2} - S_z \left(S_x w D_z u \right) + D_x A_u^h \xi + D_y A_u^h \omega + \\
 &+ g \int_0^z D_x S_z \rho(x, y, \zeta) d\zeta + D_{zz} (A_u^z u) + g D_x (\eta + T_c \phi) \\
 \frac{\partial T}{\partial t} &= -D_x (u S_x T) - D_y (v S_y T) - D_z (w S_z T) + A_T^h \left(D_x D_x T + D_y D_y T \right) + \\
 &+ D_{zz} (A_T^z T) + \text{Solar Radiation} + \text{Geothermal Heating} + \text{BBL} \\
 \xi &= D_x u + D_y v, \quad \omega = D_y u - D_x v, \quad w = \int_H^z \xi(x, y, \zeta) d\zeta; w(x, y, H) = 0
 \end{aligned}$$

Interpolations and Derivatives Modified Near the boundary

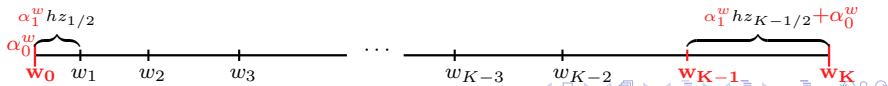
$$\begin{aligned}
 (Sw)_{k+1/2} &= \frac{w_{k+1} + w_k}{2}, \quad k = 1, \dots, K-2, \quad (Sw)_{1/2} = \alpha_0^S + \alpha_1^S w_0 + \alpha_2^S w_1 \\
 (DT)_k &= \frac{T_{k+1/2} - T_{k-1/2}}{h}, \quad i = 2, \dots, K-2, \quad (DT)_1 = \alpha_0^D + \frac{\alpha_1^D T_{1/2} + \alpha_2^D T_{3/2}}{h}
 \end{aligned}$$



$$\begin{aligned} \frac{\partial u}{\partial t} &= \left(S_x S_y v \right) S_y (\omega + f) - D_x \frac{S_x u^2 + S_y v^2}{2} - S_z \left(S_x w D_z u \right) + D_x A_u^h \xi + D_y A_u^h \omega + \\ &+ g \int_0^z D_x S_z \rho(x, y, \zeta) d\zeta + D_{zz} (A_u^z u) + g D_x (\eta + T_c \phi) \\ \frac{\partial T}{\partial t} &= -D_x (u S_x T) - D_y (v S_y T) - D_z (w S_z T) + A_T^h \left(D_x D_x T + D_y D_y T \right) + \\ &+ D_{zz} (A_T^z T) + \text{Solar Radiation} + \text{Geothermal Heating} + \text{BBL} \\ \xi &= D_x u + D_y v, \quad \omega = D_y u - D_x v, \quad w = \int_H^z \xi(x, y, \zeta) d\zeta; \quad w(x, y, H) = \alpha_0(x, y) \end{aligned}$$

Vertical velocity

$$\begin{aligned} w_{i,j,K-1} &= \alpha_0^{w^b} - \alpha_1^{w^b} h z_{i,j,K-1/2} \xi_{i,j,K-1/2} \\ w_{i,j,k-1} &= w_{i,j,k} - h z_{i,j,k-1/2} \xi_{i,j,k-1/2} \quad \forall k : 2 \leq k \leq K-1 \\ w_{i,j,0} &= w_{i,j,1} + \alpha_0^{w^s} - \alpha_1^{w^s} h z_{i,j,1/2} \xi_{i,j,1/2} \end{aligned}$$



Vertical diffusion

$\frac{\partial}{\partial z} A_u^z \frac{\partial u}{\partial z}$ is replaced by

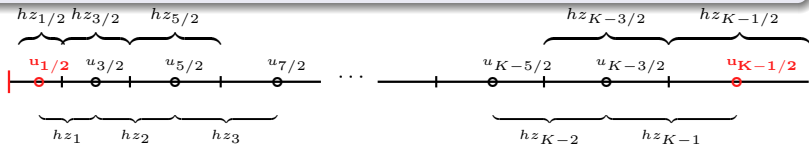
$$(D_{zz} u)_{i,j,1/2} = \frac{(A_u^z)_1}{h z_1 h z_{1/2}} (\alpha_2^{D_{zz} U^s} u_{3/2} - \alpha_1^{D_{zz} U^s} u_{1/2})$$

$$(D_{zz} u)_{i,j,k-1/2} = \frac{1}{h z_{k-1/2}} \left(\frac{(A_u^z)_k}{h z_k} (u_{k+1/2} - u_{k-1/2}) - \frac{(A_u^z)_{k-1}}{h z_{k-1}} (u_{k-1/2} - u_{k-3/2}) \right) \quad \forall k : 2$$

$$(D_{zz} u)_{i,j,K-1/2} = \frac{1}{h z_{K-1/2}} \left[\alpha_2^{D_{zz} U^b} \frac{(A_u^z)_{K-1}}{h z_{K-1}} u_{K-1/2} - \alpha_1^{D_{zz} U^b} \left(\frac{(A_u^z)_K}{h z_K} + \frac{(A_u^z)_{K-1}}{h z_{K-1}} \right) u_{K-3/2} \right] \quad u_{K-3/2}$$

$$\frac{\partial u}{\partial z} \Big|_{w_0} = \alpha_0^{D_{zz} U^s} + \frac{\tau_x}{h z_1 \rho_0}, \quad \frac{\partial v}{\partial z} \Big|_{w_0} = \alpha_0^{D_{zz} U^s} + \frac{\tau_y}{h z_1 \rho_0}, \quad \frac{\partial T}{\partial z} \Big|_{w_0} = \frac{\partial S}{\partial z} \Big|_{w_0} = \alpha_0^{D_{zz} T^s}$$

$$u|_{bottom} = v|_{bottom} = \alpha_0^{D_{zz} U^b} \quad T|_{bottom} = S|_{bottom} = \alpha_0^{D_{zz} T^b} \quad (1)$$



The models solution depend on initial and **boundary** conditions :

$$\frac{\partial T}{\partial t} = -D_x(uS_xT) - D_y(vS_yT) - D_z^{(\alpha)}(wS_z^{(\alpha)}T) + A_T^h \left(D_{xx}T + D_{yy}T \right) + D_{zz}^{(\alpha)}(A_T^z)T$$

- The model $x(t) = \mathcal{M}_{0,t}(x_0, \alpha)$

We calculate the derivatives and their adjoints with respect to

$$x_0, \alpha$$

by **TAPENADE 3.6** (**Tropics team, INRIA**) that allows us

- to avoid a HUGE development/coding (a double of the classical one, at least)
- to obtain immediately the derivative with respect to any parameter we want.

TAPENADE 3.6 (Tropics team, INRIA) with the Memory Usage Optimization:

search for push/pop

```
CALL PUSHREAL8ARRAY(sold, nx*ny*nz)
CALL PUSHREAL8ARRAY(told, nx*ny*nz)
CALL PUSHREAL8ARRAY(vold, nx*ny*nz)
CALL PUSHREAL8ARRAY(uold, nx*ny*nz)
CALL PUSHREAL8ARRAY(ssh, nx*ny)
CALL PUSHREAL8ARRAY(s, nx*ny*nz)
CALL PUSHREAL8ARRAY(t, nx*ny*nz)
CALL PUSHREAL8ARRAY(v, nx*ny*nz)
CALL PUSHREAL8ARRAY(u, nx*ny*nz)
```

replace by

```
call push_uvts(u,v,t,s,ssh)
```

Procedure push/pop_uvts(u,v,t,s,ssh):

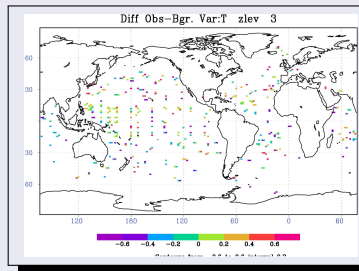
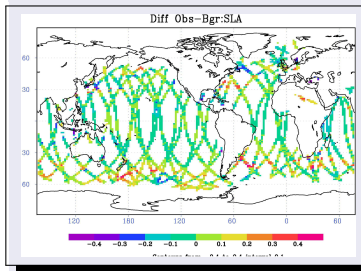
- does not push $n - 1$ step and pops appropriate values (divides the required memory by 2)
- does not push u, v, t, s in **lower level** routines
- does not push values **on continents** (divides by 2)
- pushes values in **Real*4** format (divides by 2)
- eventually pushes only odd timesteps and interpolate when popping (divides by 2)

Total reduction of required memory is **up to 25 times**.

10 hours window \implies 10 days window.

ECMWF data issued from Jason-1 and Envisat altimetric missions and ENACT/ENSEMBLES data banque.

January, 1, 2006.



Difference between observations and background during the 1st of January.

The model: $x_N = \mathcal{M}_{0,N}(x_0, \alpha)$ with $x = (u, v, T, S, ssh)^T$

Cost function J

$$J = \|x_0 - x_{bgr}\|_{B^{-1}}^2 + \|\alpha - \alpha_{bgr}\|_{B^{-1}}^2 + \sum_{n=0}^N t_n \|\mathcal{H}\mathcal{M}_{0,n}(x_0, \alpha) - y_n\|_{R^{-1}}^2$$

Matrices: $B^{-1} = \text{diag}(10^{-4})$,

$R^{-1} = \text{diag}(1/\sigma_u, 1/\sigma_v, 1/\sigma_T, 1/\sigma_S, 1/\sigma_{ssh})$ where $\sigma_u^2 = \frac{1}{N_{obs}} \sum (u_{obs} - u_{bgr})^2$

Minimization is performed by M1QN3 (JC Gilbert, C.Lemarechal)

Data Assimilation – Forecast

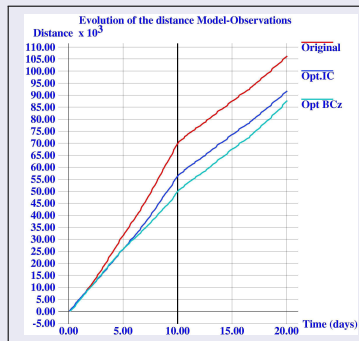
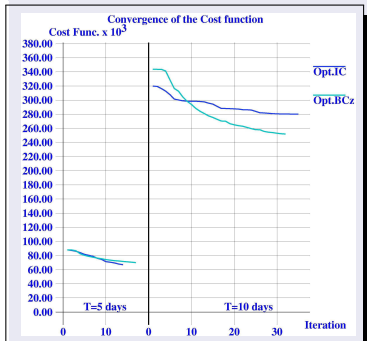
Assimilation window — 10 days (Jan. 1-10, 2006),

Test time — 20 or 30 days (Jan. 1-31, 2006).

The model: $x(t) = \mathcal{M}_{0,t}(x_0, \alpha)$ with $x = (u, v, T, S, ssh)^T$

$$\text{Distance: } \xi(t) = \sum_{n=0}^t \|\mathcal{H}\mathcal{M}_{0,n}(x_0, \alpha) - y_n\|_{R^{-1}}$$

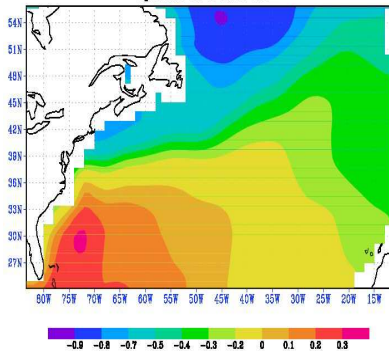
Convergence of J and evolution of ξ



20 Cost function calls with $T = 5$ days and 40 calls with $T = 10$ days.

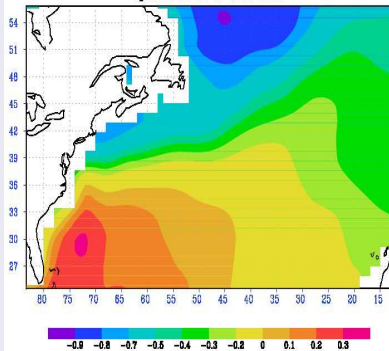
SSH, North Atlantic, January, 1-30 2006.

Opt.IC:SSH Jan,01 00hr



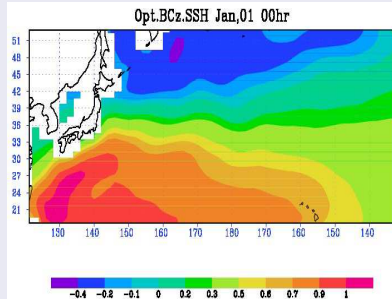
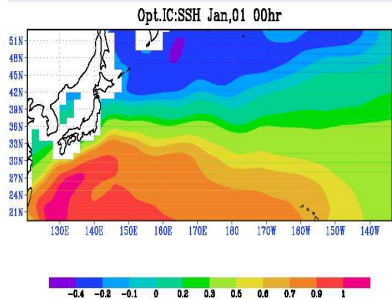
Optimal IC

Opt.BCz.SSH Jan,01 00hr



Optimal BCz

SSH, North Pacific, January, 1-30 2006.



Optimal IC

Optimal BCz

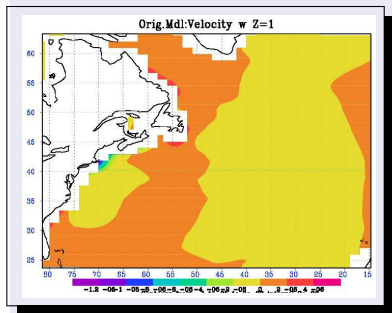
Modified formula

$$w_{i,j,K-1} = \alpha_0^{w^b} - \alpha_2^{w^b} h z_{i,j,K-1/2} \xi_{i,j,K-1/2}$$

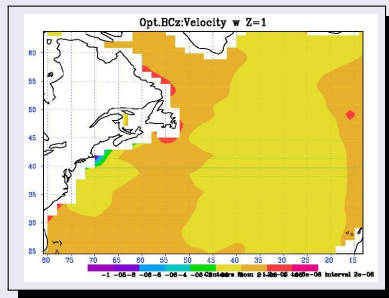
$$w_{i,j,k-1} = w_{i,j,k} - h z_{i,j,k-1/2} \xi_{i,j,k-1/2} \quad \forall k : 1 \leq k \leq K-2$$

$$w_{i,j,0} = w_{i,j,1} + \alpha_0^{w^s} - \alpha_2^{w^s} h z_{i,j,1/2} \xi_{i,j,1/2}$$

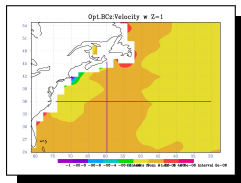
North Atlantic, January, 30, 2006, surface



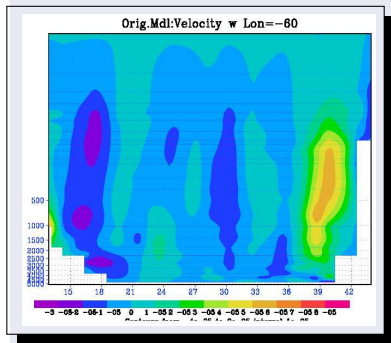
Original model



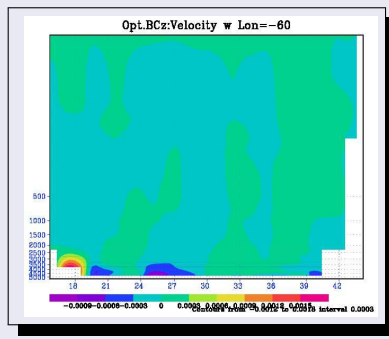
Optimal BCz



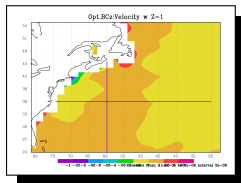
North Atlantic, January, 30, 2006, $y-z$ section



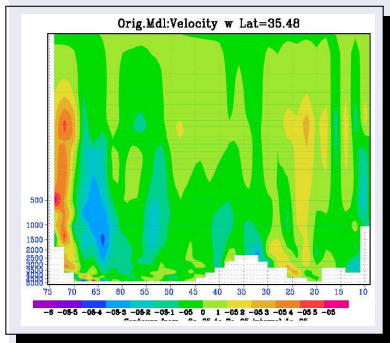
Original model



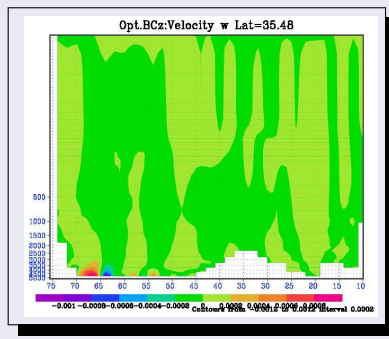
Optimal BCz



North Atlantic, January, 30, 2006, $x - z$ section

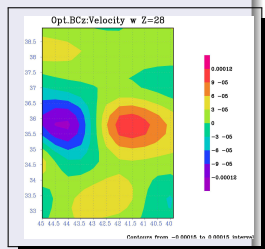
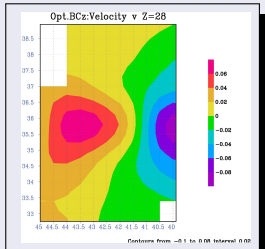
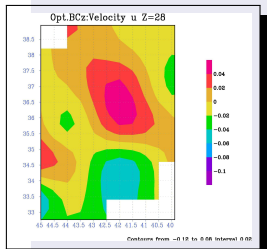


Original model



Optimal BCz

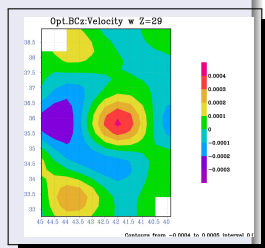
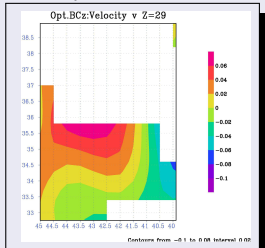
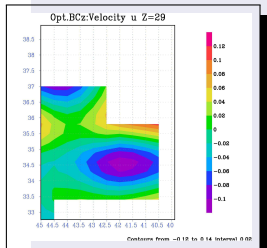
Levels $z = 28$ and $z = 29$



Velocity u

Velocity v

Velocity w



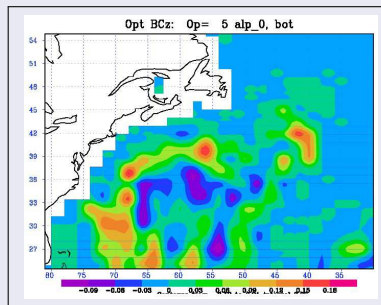
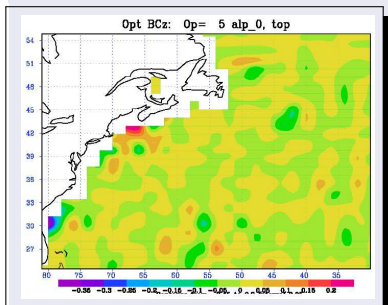
Velocity u

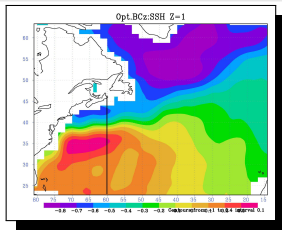
Velocity v

Velocity w

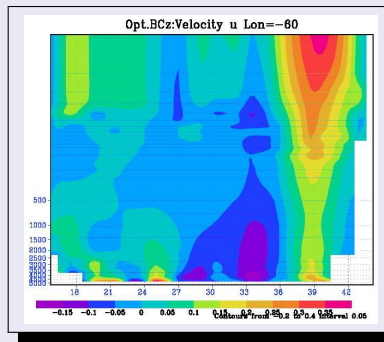
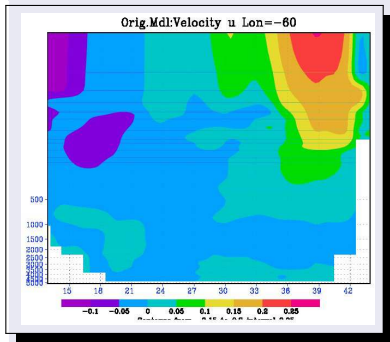
$$\left. \frac{\partial u}{\partial z} \right|_{w_0} = \alpha_0^{D_{zz}U^s} + \frac{\tau_x}{hz_1\rho_0}, \quad \left. \frac{\partial v}{\partial z} \right|_{w_0} = \alpha_0^{D_{zz}U^s} + \frac{\tau_y}{hz_1\rho_0},$$
$$u|_{bottom} = v|_{bottom} = \alpha_0^{D_{zz}U^b}$$

North Atlantic





North Atlantic, January, 30, 2006, Velocity u , $y - z$ section



Original model

Optimal BCz

North Atlantic

Modification of the SSH in the North Atlantic is strongly related to the **boundary conditions of u and v especially on the bottom.**

Only α_0 on the Bottom for u and v , only in the Vertical diffusion

$\frac{\partial}{\partial z} A_u^z \frac{\partial u}{\partial z}$ is replaced by

$$\begin{aligned} (D_{zz}u)_{i,j,1/2} &= \frac{(A_u^z)_1}{hz_1 hz_{1/2}} (u_{3/2} - u_{1/2}) \\ (D_{zz}u)_{i,j,k-1/2} &= \frac{1}{hz_{k-1/2}} \left(\frac{(A_u^z)_k}{hz_k} (u_{k+1/2} - u_{k-1/2}) - \frac{(A_u^z)_{k-1}}{hz_{k-1}} (u_{k-1/2} - u_{k-3/2}) \right) \quad \forall k : 2 \\ (D_{zz}u)_{i,j,K-1/2} &= \frac{1}{hz_{K-1/2}} \left[\frac{(A_u^z)_{K-1}}{hz_{K-1}} u_{K-1/2} - \left(\frac{(A_u^z)_K}{hz_K} + \frac{(A_u^z)_{K-1}}{hz_{K-1}} \right) u_{K-3/2} \right] \\ u|_{bottom} &= \alpha_0^u \quad v|_{bottom} = \alpha_0^v \end{aligned} \quad (2)$$

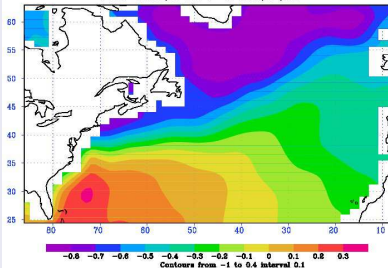
Control space dimension

Initial conditions:	1 707 245
Full vertical boundary:	1 197 792
Only bottom:	33 272

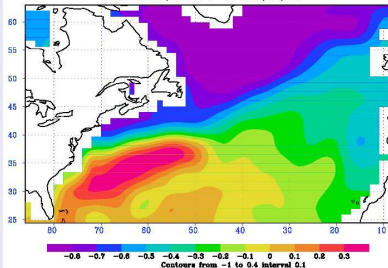
SSH in the restrained control experiment

North Atlantic

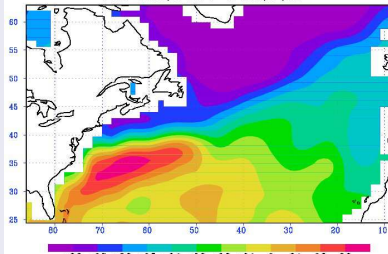
BCz Bot.U,V:SSH Z=1 JAN,01,00hr



BCz Bot.U,V:SSH Z=1 JAN,11,00hr

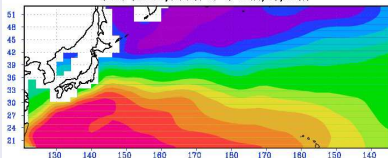


BCz Bot.U,V:SSH Z=1 JAN,31,00hr



North Pacific

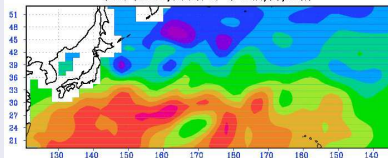
BCz Bot.U,V:SSH Z=1 JAN,01,00hr



-0.5 -0.2 -0.1 0 0.1 0.2 0.4 0.5 0.6 0.7 0.8 0.9

Contours from -0.5 to 1.1 interval 0.1

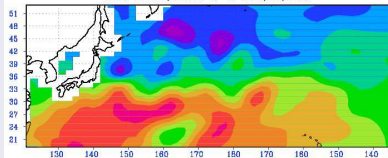
BCz Bot.U,V:SSH Z=1 JAN,11,00hr



-0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2

Contours from -0.8 to 1.4 interval 0.2

BCz Bot.U,V:SSH Z=1 JAN,31,00hr



-0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2

Contours from -0.8 to 1.4 interval 0.2

Extending the set of control parameters we can

- find a way to **compensate model errors**
- showing the **most influent parameter** and the **most important geographical regions**.

Automatic adjoint code generation helps us

- to generate TLM/AM almost immediately,
- to avoid a HUGE development/coding,
- to obtain immediately the derivative with respect to any parameter we want.

<http://www-ljk.imag.fr/membres/Kazantsev/orca2/index.html>