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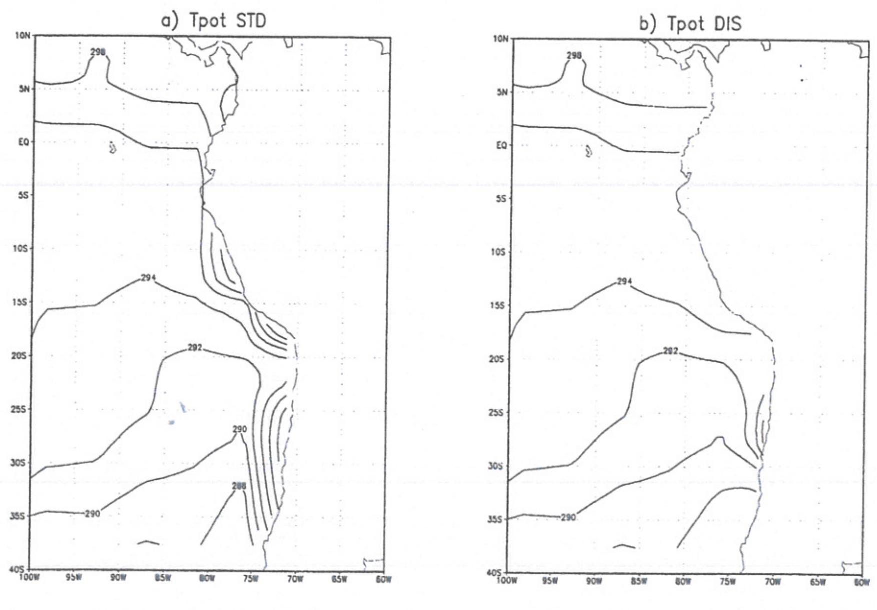
Notes du Pôle de Modélisation

An Improved Interpolation Scheme between an Atmospheric Model and Underlying Surface Grids near Orography and Ocean Boundaries.

Francis Codron, Augustin Vintzileos and Robert Sadourny

Laboratoire de Météorologie Dynamique du CNRS



Octobre 1998 Note n° 9

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Institut Pierre Simon Laplace
des Sciences de l'Environnement Global

CETP - LMD - LODYC - LPCM - LSCE - SA

Université Pierre-et-Marie-Curie
B 102 - T15-E5 - 4, Place Jussieu
75252 Paris Cedex 05 (France)
Tél : (33) 01 44 27 39 83
Fax : (33) 01 44 27 37 76

Université Versailles-Saint-Quentin
College Vauban, 47 Boulevard Vauban
78047 Guyancourt Cedex (France)
Tél : (33) 01 39 25 58 17
Fax : (33) 01 39 25 58 22

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Les flux à l'interface atmosphère-surface dépendent de façon fortement non linéaire des propriétés de la surface. Afin d'en tenir en compte, une tendance actuelle est de calculer tout ou partie des paramétrisations physiques des modèles de circulation générale atmosphériques (AGCM) sur la grille plus fine des modèles de sol ou océaniques qui leur sont couplés. On présente ici une modification d'un schéma d'interpolation classique, qui permet de calculer les valeurs de variables atmosphériques au dessus des points de grille des modèles de surface. En plus des propriétés de conservation des flux et de maintien d'un champ constant, le nouveau schéma permet de créer des discontinuités dans les champs interpolés aux frontières entre différents modèles de surface et au niveau des changements de relief, tout en restant continu ailleurs. Il peut être réglé séparément pour chaque variable. Ce nouveau schéma est ensuite validé par le couplage entre l'AGCM du Laboratoire de Météorologie Dynamique (LMD), et le modèle d'océan Pacifique tropical du Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC). Le couplage est réalisé par la méthode de physique délocalisée. Les résultats montrent une amélioration importante des flux de chaleur sensible et latente dans la région critique proche de la côte Sud-Américaine dans le Pacifique tropical est, ainsi qu'une propagation vers l'ouest au niveau de l'équateur des changements de température océanique induits.

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Francis Codron, Augustin Vintzileos and Robert Sadourny

Laboratoire de Météorologie Dynamique du CNRS, Paris, France

Abstract

To take into account the strong non-linearities of vertical fluxes due to small scale heterogeneities of surface properties, more and more coupled general circulation models compute part of their atmospheric physical parameterizations, either the surface fluxes or the whole package, on the finer grid of their ocean or land model. A modification of a traditional interpolation scheme is presented to calculate the values of atmospheric variables over surface models grid points. In addition to the desirable properties of flux conservation and preservation of a constant field, the new scheme allows discontinuities in the interpolated fields at the surface models boundaries and orographic jumps, while remaining continuous elsewhere. It can also be tuned separately for each variable.

The modified scheme is then validated using the circulation model of the Laboratoire de Météorologie Dynamique coupled to the Laboratoire d'Océanographie Dynamique et de Climatologie topical Pacific ocean model using the delocalized physics method. The results show a large improvement of heat and humidity fluxes near the focus region of the south American coast in the south-eastern equatorial Pacific, and a subsequent westward propagation of significant cold SST anomalies.

1 Introduction

Advances in computer power enable global climate models to include more and more components, such as atmosphere, ocean, land and sea ice, or biosphere. Each of these components is often described by its own model, optimized for its specific relevant scales and phenomena; thus the component models may have different grids, the atmospheric one generally being the coarsest. For example, the ocean often has a finer resolution, sometimes still increased at the equator and near the boundaries. The atmosphere has a special role among these climate components because it interacts directly with all the others, the interfacial fluxes providing limit conditions to the underlying surface models in most climate models.

The difficulty comes from the very non-linear response of the surface fluxes to surface conditions. For example, over the ocean, emitted long wave radiation vary with SST^4 . Averaging the surface conditions over an atmospheric grid (AG) box before calculating the fluxes will thus lead to inaccuracies. To prevent this, several methods are possible, which have in common to compute the surface fluxes over the finer surface grid (SG), making a better use of the smaller scale information. The flux-aggregation method, for instance, based on the work of Claussen (1991a,b) consists in calculating the fluxes in the surface layer over each different surface type, before averaging them with fractional-area weights. It has been used by Grötzner *et al* (1995) in their study of the influence of sea-ice inhomogeneities. A similar method is used in the NCAR CSM model (Bryan et al., 1997). Before calculating the fluxes on the SG grid, the relevant atmospheric variables must before be interpolated on it: with flux-aggregation methods only the necessary interfacial ones are calculated , whereas in the delocalized physics approach developed at the Laboratoire de Météorologie Dynamique (LMD), whole atmospheric columns are used (Vintzileos and Sadourny, 1997) to take into account the influence of the surface conditions on processes such as convection.

Some discrepancies can however still remain where surface conditions vary abruptly. At the coast for example, there is a brutal change from one point to the next in albedo, heat capacity, and roughness length. In summer, this causes a differential heating of the atmosphere over the land and ocean, which results locally in a sea breeze. Traditional interpolation schemes, often chosen for their continuity properties, do not yield this discontinuity in atmospheric interpolated fields at the SG coastline. The temperature of the lowest atmospheric layer will then tend to be too warm over the ocean, and too cold over land.

This can cause spurious heat fluxes into the ocean, and also have indirect effects: the drag coefficient which controls the intensity of the ocean-atmosphere fluxes depends on the wind speed and the thermal stability of the lower atmosphere; an unrealistically high air-sea temperature difference will give very stable conditions, and thus limit evaporation, causing abnormally dry conditions in the atmosphere (Lagarde, 1996) and more warming of the ocean. These spurious heat fluxes may be a problem for a realistic climate simulation: not only they influence directly the SST, but they can also increase the oceanic stratification and thus in some regions limit the cooling of the surface through vertical mixing (Koberle and Philander, 1994) or the vertical advection of subsurface anomalies.

Another problematic area is near steep orography, like the Andes. Most atmospheric general circulation models use topography-following sigma coordinates near the surface. Then, orography gradients will yield horizontal gradients in variables which have (generally) a monotonous vertical profile, like potential temperature or specific humidity. As the orography will obviously be sometimes steeper in SG than in AG because of resolution differences, the horizontal temperature gradients, for example, should also be stronger.

These considerations lead us to propose a modified interpolation scheme which, while keeping its usual properties over areas of homogeneous underlying surface types, will create the appropriate discontinuities elsewhere. Its principle can be used in various coupling methods, but it has been tested within the delocalized physics scheme, summarized in section 2. The modified scheme is described in section 3 and tested in 1-dimensional experiments; then using a coupled Pacific Ocean-atmosphere model (section 4). We conclude in section 5, and discuss its possible applications and extensions.

2 The delocalized physics scheme

The delocalized physics scheme provides an interface between an atmospheric model with a horizontal grid AG and an underlying surface grid SG covering various surface components and models: continents, oceans, or ice. Its principle is to compute the atmospheric physical parameterizations on columns constructed over SG points rather than AG points. The method will only be outlined here, an extensive description can be found in Vintzileos and Sadourny (1997).

2.1 Basic design

From now on, variables and indices defined on the atmospheric grid will be noted in capital letters, and those on the surface grid SG in small letters. Before calling the physics package, the atmospheric variables F_M need to be interpolated over SG columns:

$$f_m = \sum_M I_{mM} . F_M \tag{1}$$

where the matrix I_{mM} is obviously sparse as influences must be local. The weights must also verify

$$\sum_M I_{mM} = 1 \tag{2}$$

so that a constant field is preserved by the interpolation.

Physical parameterizations are then computed using the f_m fields, and give vertical fluxes and tendencies g_m . The surface fluxes can be directly passed to the relevant underlying models, and the whole set of variables must be integrated back to the AG grid. As the g_m are usually extensive variables, the scheme must here be area-weighted, and still preserve a constant field:

$$G_M = \frac{\sum_m i_{mM} a_m g_m}{\sum_m i_{mM} a_m} \tag{3}$$

where a_m is the area of the SG mesh.

A desirable property would be that two points m and M of the SG and AG grids interact with each other with identical weights, following the action-reaction principle of Vintzileos and Sadourny. This yields $I_{mM} = i_{mM}$.

One last constraint on the weights set is the energy flux conservation: the global energy flux at the surface must be identical on both AG and SG grids, which reads:

$$\sum_M A_M G_M = \sum_m a_m g_m \tag{4}$$

An obvious set of I_{mM} coefficients satisfying both (2) and (4) is the projection of one grid on the other:

$$I_{mM} = \frac{a_m \cap A_M}{a_m} \tag{5}$$

This works well over land, where different surface types are often defined as fractional areas of A_M for each AG point. However, over the ocean, where SG is typically denser than AG, the interpolated field will be a step function and introduce discontinuities at AG mesh boundaries, whereas the surface properties vary continuously. Different schemes are presented in Vintzileos and Sadourny (1997) which give a smoother interpolated field, while verifying both (2) and

$$A_M = \sum_m I_{mM} a_m \tag{6}$$

which in turn ensures flux conservation (4).

2.2 Validation

The delocalized physics approach has been validated using the Laboratoire de Météorologie Dynamique (LMD) grid point AGCM with the surface grid of the Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC) tropical Pacific Ocean model OPA-6.

The version LMD-5b of the atmospheric model is close to the one used by Harzallah and Sadourny (1995), its main features are summarized in Table 1. The LODYC grid over the tropical Pacific has a much higher resolution (228×94 points from $120°E$ to $290°E$ and from $40°S$ to $48°N$) than the standard atmospheric grid, thus providing a robust test for the method. A 6-point, triangular, quadratic interpolation scheme is used.

Several validation experiments comparing the standard and delocalized physics approaches, both with prescribed SSTs and in coupled mode, are described in Vintzileos and Sadourny (1997). Experiments forced by observed SST show that in the delocalized runs, the wind responds better to small scale SST anomalies, displaying a Gill model solution structure (Gill, 1980), whereas the control runs has no clear response. Comparison with the ERBE data (Barkstrom, 1984) also show a significant improvement in the delocalized case.

The delocalized physics method has then been used for a 30 year coupled Pacific Ocean-Atmosphere run. Vintzileos *et al.* (1998a,b) analyze the mean state, and the seasonal and interannual cycles.

3 The modified interpolation scheme

Whichever interpolation scheme is used, if the coefficients only depend on the relative point locations and not on the different surface types, it will not be able to represent accurately abrupt transitions from ocean to land or orographic contrasts on scales smaller than the atmospheric model mesh size. The simple projection scheme (5) is discontinuous, but at the wrong places, as boundaries in both the atmospheric and surface grids rarely coincide.

3.1 Description

The proposed solution is basically to keep an accurate scheme, but to give an increased weight to values from AG points with the same surface type as the SG point over which the interpolated fields are calculated.

The starting point is the simple 4-point square bilinear interpolation scheme, which yields a set of I_{mM} coefficients. These interpolation coefficients are then modified:

$$I'_{mM} = I_{mM} \times [1 - \mathcal{H}(m, M) \times \Xi(\sigma)] \qquad (7)$$

where $\mathcal{H}(m, M)$ is a rectification function, equal to 0 when the m SG point is of the same nature as the M AG point, and tending towards 1 when M must not influence m values at all because of extreme surface dissimilarities like between ocean and a mountain top. The function $\mathcal{H}$ will depend on surface types and possibly altitude differences; it may also change with the field to be interpolated as temperature and wind, for instance, do not depend on the same surface conditions in the same way. The function $\mathcal{Z}$ is an altitude-dependent coefficient, which represents the decrease with height of the influence of the surface on the atmospheric profile. Its value ranges from 1 at the surface, to 0 at the top of the atmosphere. It can decrease regularly or, more realistically, sharply at the boundary layer top. As is pointed out in the discussion, the function $\mathcal{Z}$ is necessary when flux aggregation is used on more than one vertical level.

The interpolation coefficients must be normalized to satisfy again (2):

$$I''_{mM} = \frac{I'_{mM}}{\sum_M I'_{mM}} \tag{8}$$

The problem with this scheme is for at the integration level: the 3 conditions of energy conservation, invariance of a constant field, and action-reaction cannot be satisfied together, as the I''_{mM} do not verify (6). Among these, the action-reaction principle $i_{mM} = I_{mM}$ appears as the least essential to keep: the problematic oceanic SG points near the coast will have f_m values partially extrapolated from neighboring oceanic AG points. This does not mean that the $g_m a_m$ flux should not be integrated to its overlying AG atmospheric column. Thus, the original set I_{mM} will be used for the integration.

3.2 One-dimensional experiments

A series of one dimensional experiments is performed to illustrate how the new scheme functions. The surface grid consists in 100 regularly spaced points between two atmospheric grid points at abscissae 0 and 100; the atmospheric field

F is 1 at $x = 0$ and 2 at $x = 100$. The interpolated field with a simple linear scheme is then: $f(x) = 1 + x/100$ for any surface configuration.

The new scheme is tested using a set of 8 different surface condition distributions listed in Table 2. Both the surface type (ocean-land) and altitude are varying. A function

$$\mathcal{H}(x,i) = \begin{cases} d\varphi(x,i) \,/\, (1000 + d\varphi(x,i)) & \text{for same surface type} \\ .5 \times [1 + d\varphi(x,i) \,/\, (1000 + d\varphi(x,i))] & \text{for different surface types} \end{cases} \tag{9}$$

is used, where $d\varphi(x,i)$ is the absolute value of the geopotential difference between SG point x and AG point i. The weight of an atmospheric land point is thus divided at least by two in the interpolation over an oceanic point.

The results are displayed on Figure 1. Panel 1d confirms that for a smooth topography, the interpolated field $f(x)$ is unchanged from the linear scheme. Otherwise, f is monotonous and discontinuous at the coast and abrupt changes in topography. Comparison between panels 1e and 1f, and 1g and 1h, shows that the gap is greater when there is an ocean-atmosphere contrast in addition to an altitude jump. These were the desired characteristics for the new scheme.

4 Validation experiment

The new scheme has been tested using the LMD AGCM coupled to the LODYC Tropical Pacific Ocean model OPA6 with the delocalized physics method. A control experiment (run STD) uses the standard 4-points bilinear interpolation scheme, slightly different from the 6-points second-order scheme used in the validation experiments from Vintzileos and Sadourny. The results with either scheme are very similar, but the discontinuous scheme is easier to implement in a 4-points context. The modified discontinuous scheme is used in a sensitivity experiment (run DIS) for all atmospheric variables except the wind. The $\mathcal{Z}$ function is proportional to $\sigma = \frac{p}{p_0}$ and thus decreases exponentially with height.

4.1 Simulation in forced mode

The focus will be on the south-eastern Pacific area. This region appears quite crucial for the tropical Pacific Climate, and its realistic simulation is essential. Very sharp ocean-land contrasts are also found here near the Andes, making it a good testing place for the problem studied. To isolate the effect of the change of interpolation scheme, the different fields are first studied on the first coupling time step. The variables are thus identical for all runs on the AG grid before the interpolation, as is the SST. The date is 1, January, in the southern hemisphere summer.

Figure 2 shows the potential temperature $\Theta = T\left(\frac{p_s}{p}\right)^{\kappa}$ on the lowest atmospheric layer, interpolated with the standard (Fig. 2a) and modified (Fig. 2b) scheme. With the standard scheme, the expected high Θ over land leads to a high temperature over some oceanic regions, whereas with the new scheme, there are only weak gradients of Θ all over the ocean, except near the coast at 25 S. Here, there is a coastal plain, and the lack of a topographic step reduces the discontinuity in the interpolated field. The DIS field appears more realistic, as the high Θ in STD are mainly artifacts due to the coarse AG resolution. This is made very clear by Figure 2c which shows the difference between the two runs. It follows closely the AG grid boundaries, and leads to an ocean-atmosphere sensible heat flux difference shown in Figure 2d which reaches $50\,W.m^{-2}$, the heat flux being positive when from the ocean into the atmosphere.

To study the effects on evaporation, it is necessary to discriminate between the two mechanisms discussed in the introduction: changes of the interpolated water vapor field, and of the exchange coefficient through differences of the thermal stability of the lower atmosphere (the wind at the first time step is identical in both runs). So, we made a third experiment DISQ where only the liquid and water vapor fields were interpolated with the new scheme. The drag coefficient is thus the same in STD and DISQ. The results are displayed on Figure 3. The mixing ratio is generally higher in DISQ, the air being dryer over land. The evaporation difference (Fig. 3b) has the opposite sign, thus mostly warming the ocean. However, this effect is canceled by the changes in the drag coefficient. Figure 3c shows the difference between runs DIS and DISQ, which have the same mixing ratios but different air temperatures. The air-sea temperature difference is much lower in DIS, and the resulting instability increases the evaporation. The net effect on the latent heat flux is thus of the same sign and magnitude as the one on the sensible heat flux.

Figure 3d shows the total difference in sensible and latent heat flux between the two schemes. It is everywhere positive near the coast, and reaches $100\,W.m^{-2}$ at latitudes between 25 S and 40 S where the insolation is highest at the date studied , a value that compares to the mean total energy flux.

4.2 Coupled simulations

In a longer coupled run, these lower heat fluxes into the ocean will lead to colder SSTs, which will in turn increase back the fluxes. A new equilibrium should be reached, with various feedback mechanisms also intervening. A complete analysis is however beyond the scope of this paper, and only some basic fields will be shown.

Figure 6 shows the mean SST for the COADS data set (Oberhuber, 1988), to compare with the first 5 year-average SST in the STD and DIS runs (Fig 4 a,b) and their difference (Fig 5). The standard run SST has anomalous warm patches at several places near the east coast which are much weaker in DIS. The new scheme produces a SST colder by several degrees at the coast, the interesting thing being that a difference of about 0.5 degrees is able to propagate some distance off the coast and up to 120 W in the cold tongue. These results are very robust when the duration of the analysis is changed, and do not display a strong seasonal cycle off the coast. This 0.5 degree difference can affect the behavior of the model through the change of the mean zonal and meridional SST gradients, or changes in the stability of the upper oceanic layers near the east coast. To give an idea of the importance of a 0.5 degree difference, the standard deviation of the mean SST in the Niño3 box for a 30-year standard run is $0.38°C$, and $0.3°C$ degrees for interannual anomalies.

5 Conclusion - Discussion

A new scheme has been presented for the interpolation of an atmospheric model variables onto a finer surface grid, which takes into account the different underlying surface types. As demonstrated by simple 1D experiments, the interpolated fields are continuous at the atmospheric mesh boundaries, but may be discontinuous where the surface conditions are, yielding more realistic profiles.

This new scheme has then been successfully tested for the temperature and specific humidity on a coupled atmosphere-Pacific ocean general circulation model using the delocalized physics method. Important discrepancies near the eastern Pacific coast in sensible and latent heat flux have been corrected. Both the temperature and humidity difference in the lowest layer, and the changes in the drag coefficient due to differences in the vertical stability were involved. This is quite important, as the near-equatorial Pacific is a very sensitive area. Indeed, significant differences in the SST were also observed far off the coast in the equatorial cold tongue area, showing that the consequences are not only local.

Discontinuous interpolation versus extrapolation A solution used by several current coupled models to avoid unrealistic air temperatures and heat fluxes over the ocean near the coasts is to extrapolate the values from neighboring AG oceanic points. This may prevent the most obvious problems, but appears quite crude: to calculate a profile over an oceanic SG point, either only or no information from AG land points must be used. The discontinuous interpolation scheme can be reduced to an extrapolation by taking $\mathcal{H}$ and $\mathcal{Z}$ equal to 1, but the use of these two functions provides additional flexibility.

The $\mathcal{H}$ function enables to keep some information from the AG land points, and to change the strength of the contrast for different variables and different surface types transitions. For example, the temperature or water content contrast should be greater at an ocean/desert coastline than for an ocean/swamp like transition. The altitude difference between two adjacent points is also included in $\mathcal{H}$, which can be quite important. Schneider *et al* (1997) for example find that an extrapolation of the wind near the eastern coasts of equatorial oceans significantly improves their coupled model; however this extrapolation should be stronger near steep orography where there is more physical justification to do it.

The function $\mathcal{Z}$ is also important for models which use flux aggregation on whole atmospheric columns and not only on the first layer. Here, the vertical fluxes and radiative transfers are calculated in columns covering the SG meshes, then integrated to the AG grid. Extrapolating atmospheric profiles over the problematic SG points supposes that the influence of the surface conditions fully extends to the top of the atmosphere. This is obviously not true, so the extrapolation will yield wrong vertical profiles, and thus wrong fluxes. On the other hand, $\mathcal{Z}$ allows a more realistic modulation of this influence with the altitude: it can for example decrease above a prescribed or calculated mixed layer top.

Special cases Some coupled models compute the atmospheric physical parameterizations separately over land and ocean at the coast, where an AG mesh covers both surface types, but use averaged surface conditions elsewhere. This is the case for example in the Double Physics method tested at CERFACS (Lagarde, 1996). They encountered the same type of problems: too high air temperatures over the sea near the coast leading to a lack of evaporation through increased stability. The solution would be to attribute different coordinates to the two columns constructed from one AG mesh point, which should be approximately those of the barycenter of the oceanic and continental parts. The discontinuous interpolation scheme can then be used to calculate appropriate values for the atmospheric fields over each column.

An extreme case is an island smaller than an AG mesh. For the scheme to work, this island must be represented by one point in the AG grid. The fluxes can then be calculated separately over the island and the neighboring ocean using the method described above. It is necessary that the island is represented in the AG grid, so that the interpolation scheme can use the difference in surface conditions. The case of a big lake or inner sea is exactly similar, but reversed: it must exist in the AG grid for the scheme to work.

The discontinuous interpolation scheme can thus be introduced in models using a great variety of coupling methods and will improve the interfacial fluxes calculation near water-land boundaries and steep orography, with almost no additional computational cost. There remain however some problems: first, the scheme cannot represent non-monotonous horizontal profiles, like a succession of hills, but this is not essential for actual coupled models. The main difficulty is when different surface types are defined as fractional areas of a mesh with no specific location, as with the sea ice/open sea difference. The air should be warmer over open water than over sea ice, but all AG meshes in a given area can have similar sea ice proportions, making the discontinuous scheme ineffective as there is no surface type difference among the AG points. Another solution will have to be found, perhaps by keeping in memory different vertical profiles over different surface types.

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Table 1: LMD-5b AGCM characteristics

Horizontal Resolution	64 longitude x 50 sine of latitude
Dynamic Equations	(Sadourny, 1975)
Lateral Diffusion	bi-Laplacian
Vertical coordinate	11 layers in $\sigma = p/p_s$
Thermodynamical variable	Potential Enthalpy $H = C_pT(p_s/p)^\kappa$
shortwave radiation	(Fouquart and Bonnel, 1980)
Longwave radiation	(Morcrette, 1991)
Clouds parameterization	(Le Treut and Li, 1991)
Boundary Layer	Bulk aerodynamic
Convection Schemes	(Manabe and Strickler, 1964) saturated case (Kuo, 1965) unsaturated case

Table 2: 1D surface configurations for each value of the horizontal coordinate x. The number given is the altitude of a land point, "sea" or "land" alone meaning altitude 0.

panel	a	b	c	d	e	f	g	h
$x \leq 50$	sea	sea	sea	$20x$	sea	land	sea	land
$50 < x \leq 75$	land	400	sea	$20x$	200	200	$40\,(x-50)$	$40\,(x-50)$
$75 < x \leq 100$	land	400	400	$20x$	400	400	$40\,(x-50)$	$40\,(x-50)$

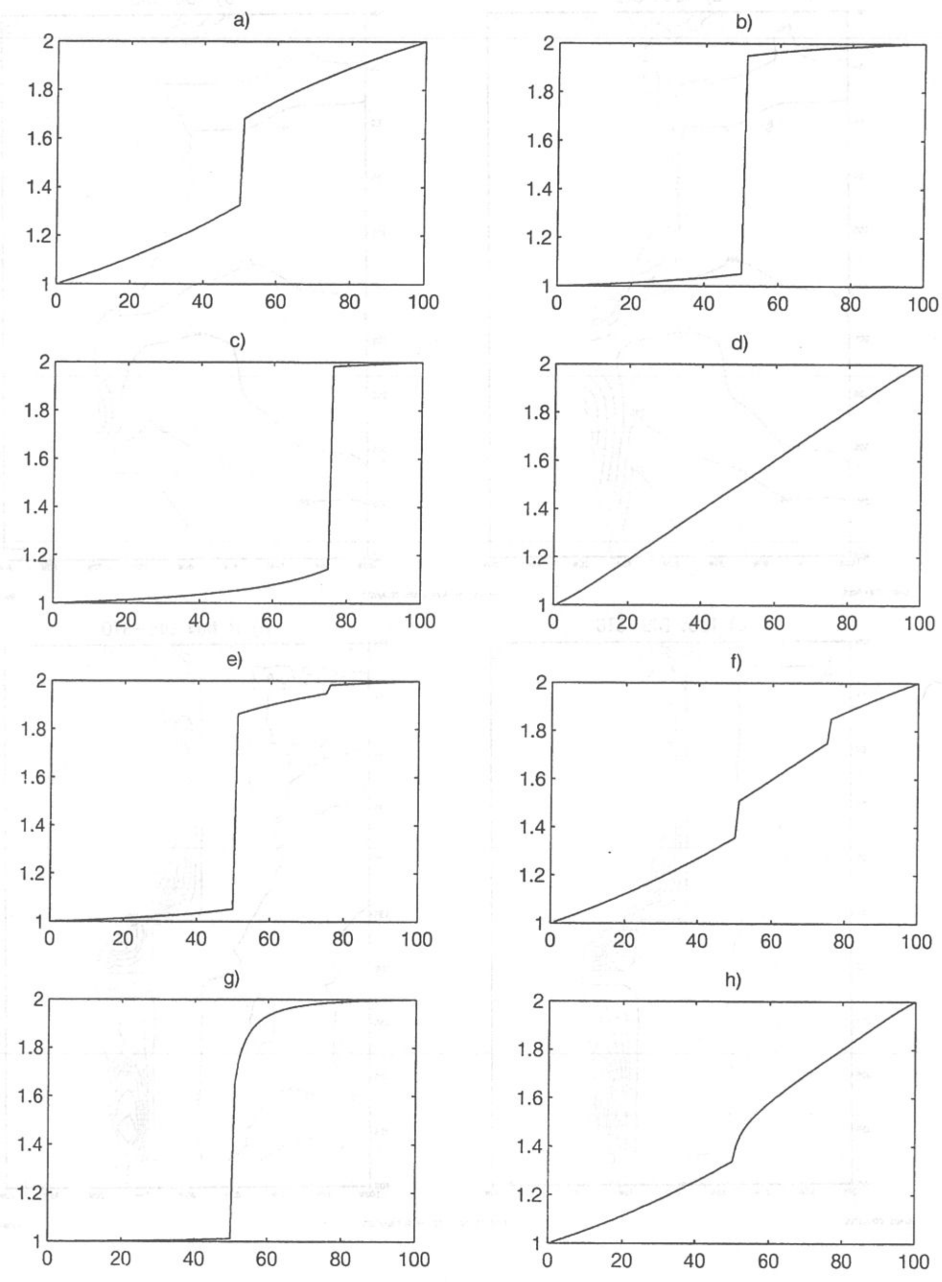


Figure 1: 1D interpolated field F (ordinates). The surface conditions profiles for $1 \leq x \leq 100$ (abscissae) for each panel are given in Table 2.

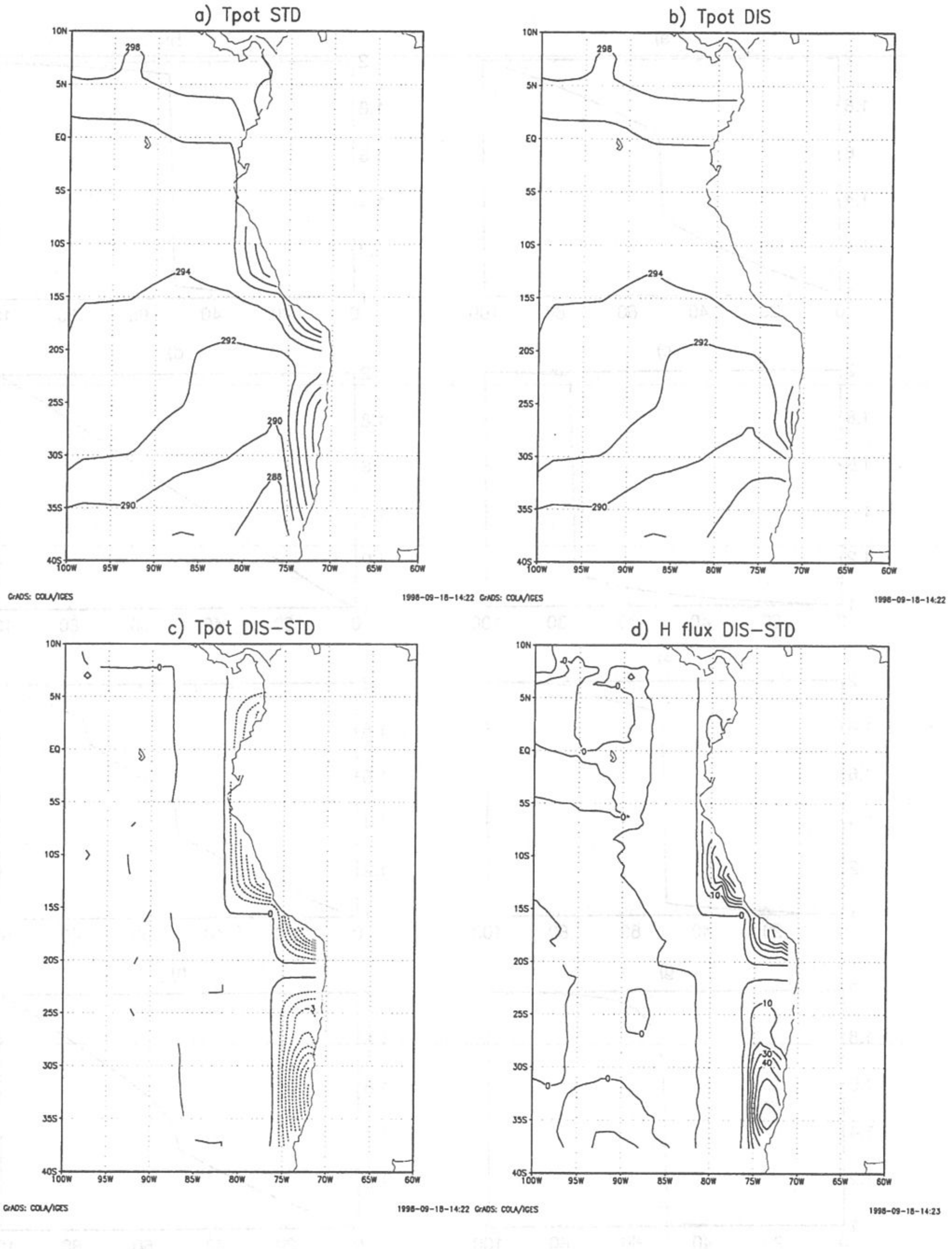


Figure 2: Potential temperature at the first atmospheric level interpolated over the SG grid. a) Standard STD run, b) DIS run with discontinuous scheme at the coast. c) DIS-STD difference. d) DIS-STD ocean to atmosphere sensible heat flux difference in $W.m^{-2}$.

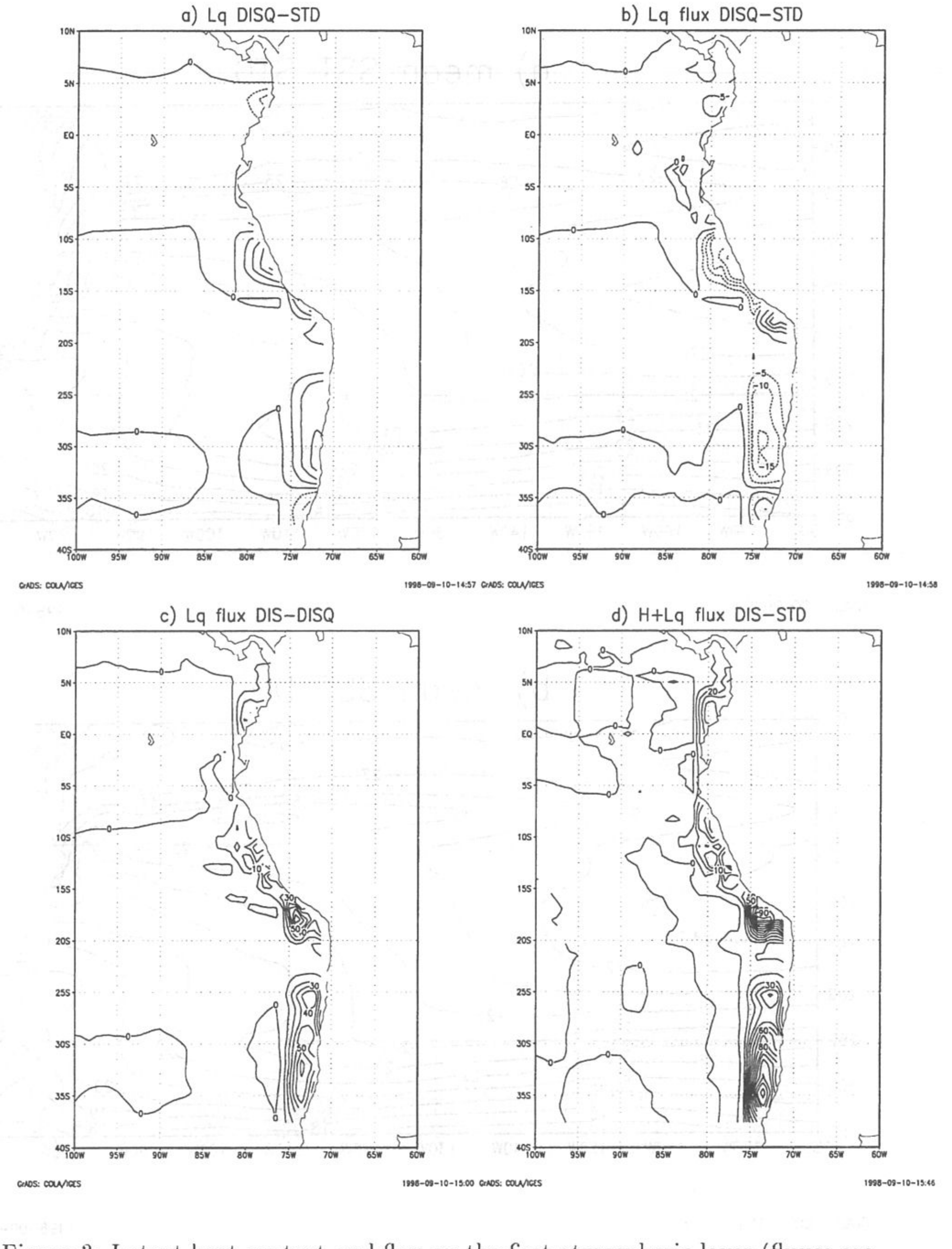
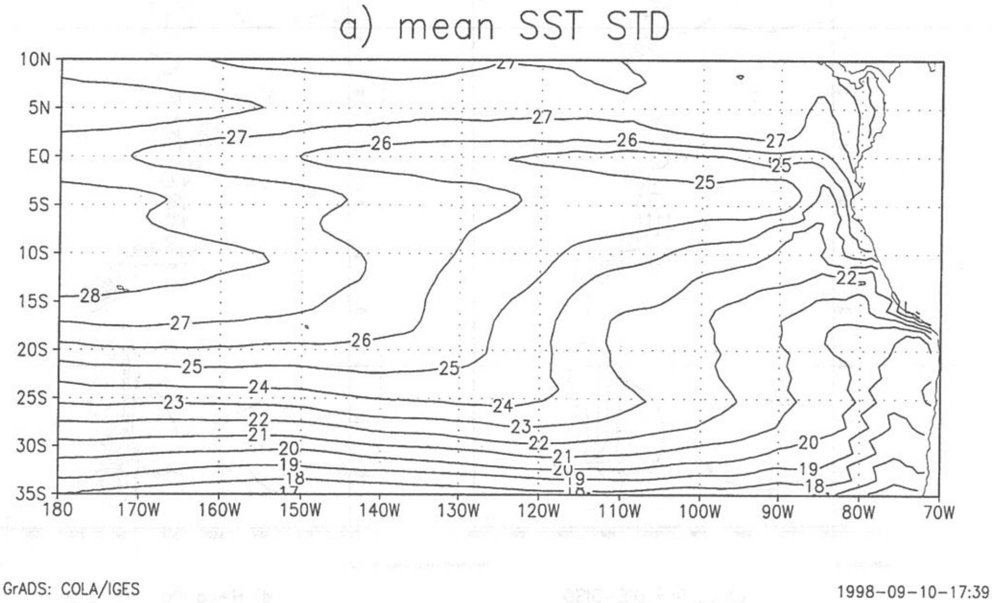


Figure 3: Latent heat content and flux on the first atmospheric layer (fluxes are positive from the ocean to the atmosphere). a) DIS-STD latent heat content difference (in $J.kg^{-1}$). b) DISQ-STD (same drag coefficient) latent heat flux in $W.m^{-2}$. c) DIS-DISQ (same specific humidity) latent heat flux. d) total DIS-STD latent and sensible heat flux.



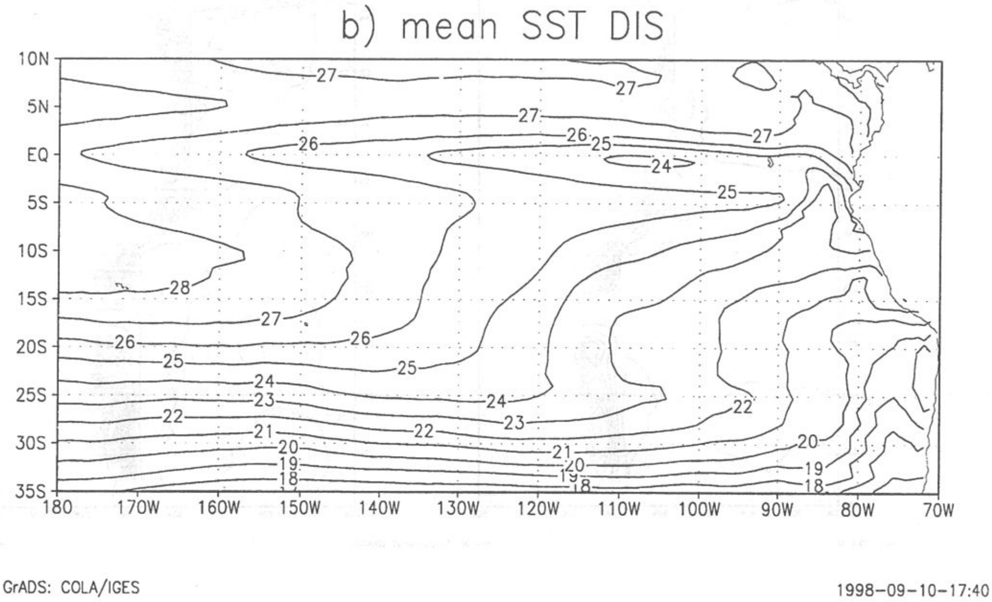


Figure 4: mean SST, 5 years coupled model runs. a) standard STD run, b) DIS run.

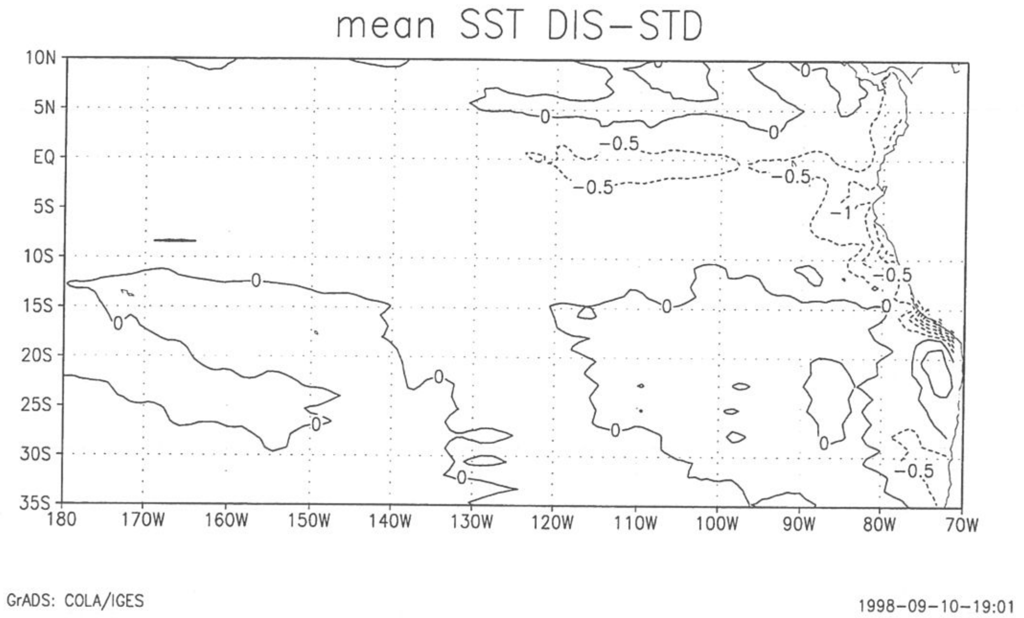


Figure 5: 5-year-mean SST difference in the DIS-STD coupled runs.

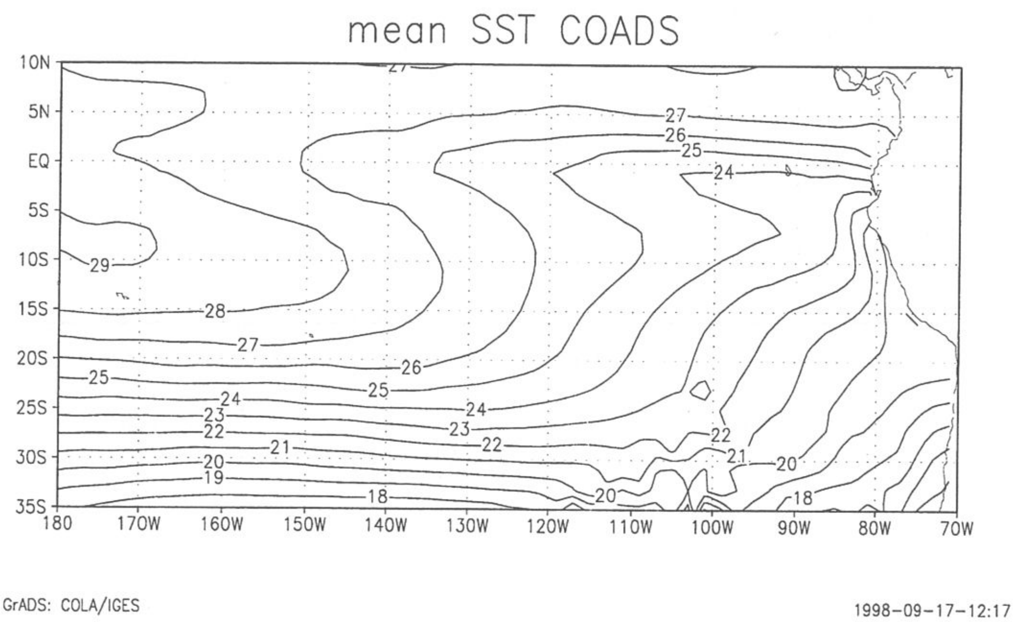


Figure 6: mean SST in the Oberhuber COADS observations data set.

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Déjà paru :

1 : **Janvier 1998** Agnès Ducharne, Katia Laval and Jan Polcher, *Sensitivity of the hydrological cycle to the parameterization of soil hydrology in a GCM*

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