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Correction to "Low-frequency variability in the Southern Ocean region in a simplified coupled model"

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1. Introduction

[1] In the paper "Low-frequency variability in the Southern Ocean region in a simplified coupled model" by Guillaume Maze, Fabio D'Andrea, and Alain Colin de Verdière (*Journal of Geophysical Research*, *111*, C05010, doi:10.1029/2005JC003181, 2006), the composite feedback on the ocean induced by the atmospheric response to a SST anomaly (SSTa) shown in Figure 12 is incorrect. Given the slab mixed layer ocean that we used in our coupled model, the SST interacts with the atmosphere through surface air-sea (SHF) and Ekman (EKF) heat fluxes:

$$\mathrm{SHF} = \lambda_1 |U_s| (T - T_s) \tag{1}$$

$$\mathrm{EKF} = \lambda_2\, U_E \cdot \nabla T \tag{2}$$

where λ_1, $\lambda_2 < 0$, U_s is the surface wind vector and $|U_s|$ is its amplitude, T is the sea surface temperature, T_s is the atmospheric surface temperature, and U_E is the Ekman velocity ($\lambda_1 = -\rho_a C_D C_{pa}(1 + B^{-1})$ and $\lambda_2 = -\rho_{oc} c_{poc} H$, where where ρ_a and ρ_{oc} are the atmospheric and oceanic densities, C_D is the surface drag coefficient, B is the Bowen ratio, c_{poc} is the specific heat of seawater, and H is the mixed layer depth). Note that $|\lambda_2|$ is simply the heat capacity of the mixed layer. Coefficients λ_i are unconventionally chosen to be negative here in order to associate a positive heat flux to a positive feedback on the ocean. Both heat fluxes are then positive when warming the ocean, according to the mixed layer temperature tendency: $\partial_t T = -\lambda_2^{-1}$(SHF + EKF), see equation (3) of the original paper (hereinafter referred to as M06). This is the opposite sign convention compared to the initial study; see the equation (2) in M06.

[2] The equilibrium atmospheric response to a positive SSTa is obtained as the long-term mean difference between an anomalous and control simulations performed with and without the SSTa added to the climatological field. Heat fluxes responses are then

$$\Delta\mathrm{SHF} = \lambda_1\, |\overline{U_s^A}| \left(\overline{T^A} - \overline{T_s^A}\right) - \lambda_1\, |\overline{U_s^C}| \left(\overline{T^C} - \overline{T_s^C}\right) \tag{3}$$

$$\Delta\mathrm{EKF} = \lambda_2\, \overline{U_E^A} \cdot \nabla \overline{T^A} - \lambda_2 \overline{U_E^C} \cdot \nabla \overline{T^C} \tag{4}$$

where overbars denote the long-term mean and superscripts A and C stand for perturbed and control simulations, respectively. A careful examination of these heat flux differences needs to be conducted in order to isolate the atmospheric feedback on the ocean from the unperturbed climatology impact on the SSTa. We introduce the temperatures and wind decompositions:

$$\overline{T^A} = \overline{T^C} + T' \;;\; \overline{T_s^A} = \overline{T_s^C} + T_s' \tag{5}$$

$$\overline{u_s^A} = \overline{u_s^C} + u_s' \;;\; \overline{v_s^A} = \overline{v_s^C} + v_s' \tag{6}$$

$$|\overline{U_s^A}| = |\overline{U_s^C}| + U_s' \tag{7}$$

where primes stand for the difference between perturbed and control simulations, associated with the atmospheric response to SSTa. Note that the wind amplitude perturbation U_s' may be either positive or negative.

[3] The decomposition leads to

$$\Delta\mathrm{SHF} = \lambda_1\, U_s' \left(\overline{T^C} - \overline{T_s^C}\right) - \lambda_1\, |\overline{U_s^A}| T_s' + \lambda_1\, |\overline{U_s^A}| T' \tag{8}$$

$$\Delta\mathrm{EKF} = \lambda_2 \left(\overline{U_E^A} - \overline{U_E^C}\right) \cdot \nabla \overline{T^C} + \lambda_2\, \overline{U_E^A} \cdot \nabla T' \tag{9}$$

In equations (8) and (9), the first right-hand side term is the perturbation of the mean heat flux by the anomalous wind, and it vanishes if the atmosphere does not respond to the SSTa and is part of the feedback on the ocean. The second term of equation (8) is the anomalous heat flux induced by the atmospheric thermal response. The last right-hand side terms in equations (8)–(9) need further decomposition to isolate the unperturbed control state influence on the SSTa. Let us rewrite the air-sea heat flux term as

$$\lambda_1 |\overline{U_s^A}| T' = \lambda_1 |\overline{U_s^C}| T' + \lambda_1 U_s' T' \tag{10}$$

The initial SSTa forcing is now isolated (first term) from the feedback component (second term). The Ekman heat

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flux term is more complicated because Ekman currents are related to both the amplitude and the direction of the surface wind through: $U_E = \alpha|U_S|\ k \times U_s$ where $\alpha = -\rho_a C_D(\rho_{oc} f_0 H)^{-1} > 0$ and k is a vertical unit vector. Introducing the Ekman currents expression and the decomposition of the wind into the last right-hand side term of equation (9) leads to

$$\begin{aligned} \lambda_2 \overline{U_E^A} \cdot \nabla T' &= \lambda_2 \alpha |U_S^A| \left(k \times U_S^A\right) \cdot \nabla T' \\ \lambda_2 \overline{U_E^A} \cdot \nabla T' &= \lambda_2 \overline{U_E^C} \cdot \nabla T' + \alpha \lambda_2 U_s' \left(k \times \overline{U_s^C}\right) \cdot \nabla T' \\ &\quad + \alpha \lambda_2 |\overline{U_s^A}| \left(k \times U_s'\right) \cdot \nabla T' \end{aligned} \tag{11}$$

where the first right-hand side term is the effect of the unperturbed control state onto the SSTa and the second and third terms are the multicomponents wind response onto the SSTa. Introducing decompositions of equations (10)–(11) into heat flux differences of equations (8)–(9) finally leads to

$$\Delta \mathrm{SHF} = \lambda_1 |\overline{U_s^C}| T' + \mathrm{SHF}^f \tag{12}$$

$$\Delta \mathrm{EKF} = \lambda_2 \overline{U_E^C} \cdot \nabla T' + \mathrm{EKF}^f \tag{13}$$

where we introduced the explicit atmospheric feedback terms:

$$\mathrm{SHF}^f = \lambda_1 U_s' T' + \lambda_1\, U' \left(\overline{T^C} - \overline{T_s^C}\right) - \lambda_1\, |\overline{U_s^A}| T_s' \tag{14}$$

$$\begin{aligned} \mathrm{EKF}^f &= \lambda_2 \left(\overline{U_E^A} - \overline{U_E^C}\right) \cdot \nabla \overline{T^C} \\ &\quad + \alpha \lambda_2 \left[U_s' \left(k \times \overline{U_s^C}\right) + |\overline{U_s^A}| \left(k \times U_s'\right)\right] \cdot \nabla T' \end{aligned} \tag{15}$$

On one hand, air-sea heat fluxes on the right-hand side of equation (14) are the modulation by the wind amplitude response of the direct SSTa forcing (first term) and the climatological flux (second term), and the one induced by the atmospheric temperature response (third term). On the other hand, Ekman heat fluxes on the right-hand side of equation (15) are the impact of the Ekman current response on the climatological flux (first term) and the SSTa (second term).

[4] What was plotted in Figures 12c and 12d of M06 was only the first term on the right-hand side of equation (14) for SHF^f and all terms on the right-hand side of equation (15) but added to $\lambda_2 \overline{U_E} \cdot \nabla T'$ (mean Ekman advection of the SST anomaly, which cannot be considered as a feedback) for EKF^f. Both errors led to a misinterpretation of the relative importance of air-sea and Ekman heat flux feedbacks. This correction aims to rectify it.

2. Results

[5] The total net air-sea heat flux feedback SHF^f is shown in Figure 1a. Remember that the prescribed SSTa had an approximately gaussian shape centered at 46S with a zonal extension of 80 degrees and a meridional extension of 10 degrees (see Figure 12 of M06).

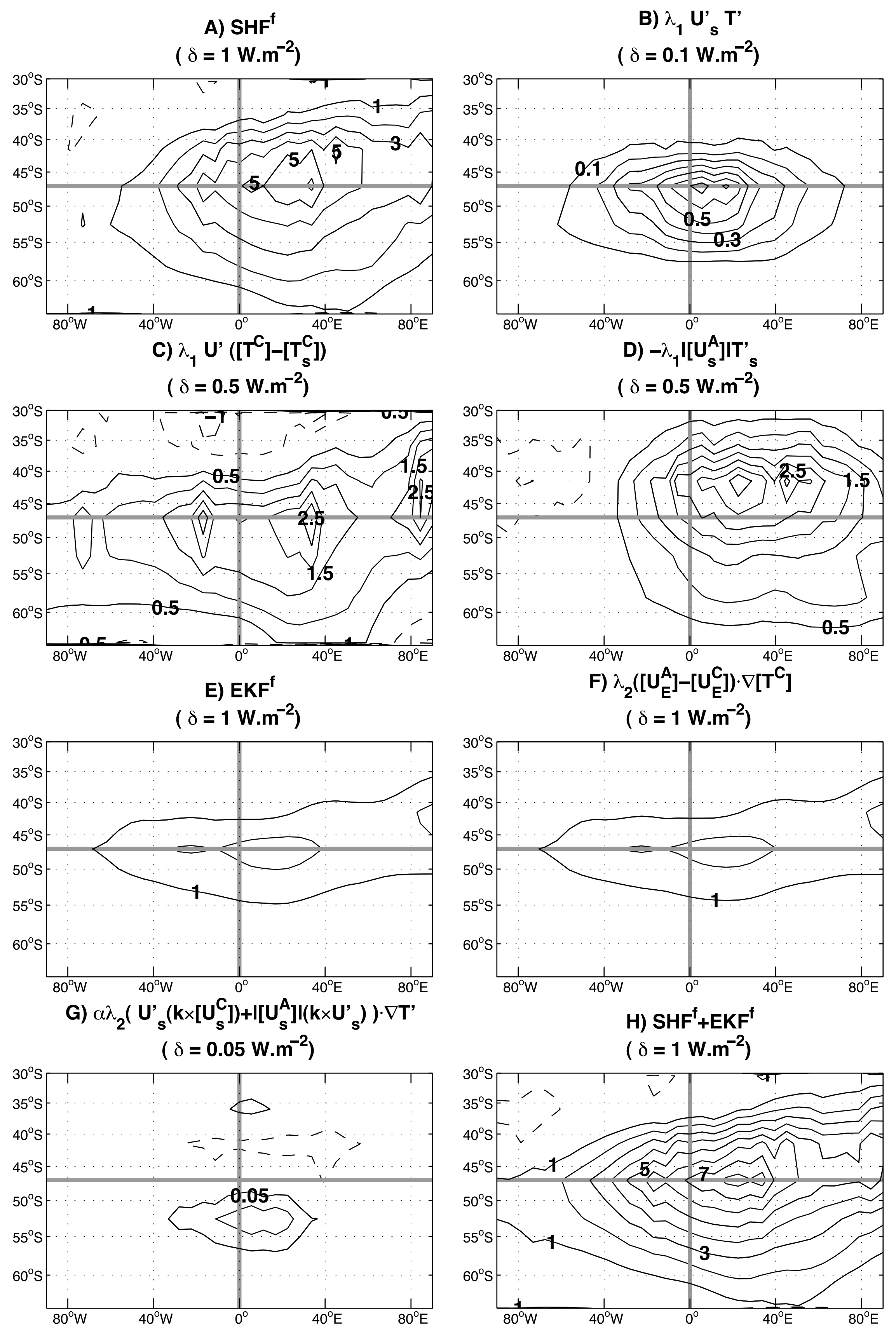
[6] SHF^f exhibits a positive feedback about 5 W m^{-2} east of the SSTa instead of 0.6 W m^{-2} as was originally given by M06. It also shows a small negative -1 W m^{-2} feedback west of the SSTa. Each components of SHF^f (right-hand side terms in equation 14) are shown in Figures 1b, 1c, and 1d.

[7] The modulation from the wind response of the SSTa forcing (Figure 1b) is about 0.6 W m^{-2} centered on the SSTa. It is a positive feedback because anomalous easterlies over the SSTa reduce the mean wind amplitude and so is the systematic SSTa damping by SHF. Next, as the climatological air-sea heat flux is systematically cooling the ocean in this perpetual winter time simulation, the feedback induced by the wind amplitude response through climatological temperature fields is positive everywhere (Figure 1c) with a maximum of 2 W m^{-2}. The dominant component of SHF^f is the one induced by the atmospheric surface temperature response (Figure 1d). As the stationary atmospheric response is locally dominated by its linear baroclinic component, it induces a warm atmospheric temperature anomaly eastward of the SSTa. This atmospheric temperature response drives a positive feedback on the SSTa, centered around 30 degrees eastward and of 3.5 W m^{-2} amplitude.

[8] The total Ekman feedback EKF^f is shown in Figure 1e. It is driven by the first term in the right-hand side of equation (15), shown in Figure 1f. The low pressure surface response centered northeastward to the SSTa shown in Figure 12b of M06 induces easterlies over the SSTa which in turn trigger poleward Ekman currents. Acting on the climatological SST field, they provide a positive feedback on the SSTa with a maximum of 1 W m^{-2} (Figure 1f), but while acting on the SSTa (Figure 1g), they advect it poleward (driving a small 0.06 W m^{-2} positive feedback to the south of the SSTa and a smaller -0.02 W m^{-2} negative feedback to the north).

[9] The total atmospheric feedback on the ocean induced by both air-sea and Ekman heat fluxes is shown in Figure 1h. It is largely dominated by the SHF^f contribution (Figure 1a) which in turn is driven by the atmospheric temperature response (Figure 1d) modulated by the wind response onto the systematic damping due to perpetual winter conditions

Figure 1. Components of the atmospheric feedback onto the ocean induced by a positive sea surface temperature anomaly. (a) The total feedback due to air-sea heat fluxes (sum of Figures 1b, 1c, and 1d). (b, c, and d) Feedback components of the air-sea heat flux: successive terms on the right-hand side of the equation (14). (e) The total feedback due to Ekman heat flux (sum of Figures 1f and 1g). (f and g) Feedback components of the Ekman heat flux, i.e., both terms on the right-hand side of equation (15). (h) The total feedback, i.e., the sum of contributions from air-sea and Ekman heat fluxes (Figures 1a and 1e). Fluxes are positive into the ocean so that a positive flux is a positive feedback and is warming the ocean. Negative contours dashed and zero contour omitted. Contours level are indicated with δ values on each plot title. Longitudes are relative to the SST anomaly center, marked by horizontal and vertical heavy gray lines.



A) SHF^f ($\delta = 1$ W.m^{-2})

B) $\lambda_1 U'_s T'$ ($\delta = 0.1$ W.m^{-2})

C) $\lambda_1 U' ([T^C]-[T^C_s])$ ($\delta = 0.5$ W.m^{-2})

D) $-\lambda_1 |[U^A_s]| T'_s$ ($\delta = 0.5$ W.m^{-2})

E) EKF^f ($\delta = 1$ W.m^{-2})

F) $\lambda_2([U^A_E]-[U^C_E])\cdot\nabla[T^C]$ ($\delta = 1$ W.m^{-2})

G) $\alpha\lambda_2(U'_s(k\times[U^C_s])+|[U^A_s]|(k\times U'_s))\cdot\nabla T'$ ($\delta = 0.05$ W.m^{-2})

H) $\mathrm{SHF}^f+\mathrm{EKF}^f$ ($\delta = 1$ W.m^{-2})

Figure 1

(Figure 1c). As centered eastward of the SSTa, this pattern may enhance the advection of the SSTa by the Antarctic Circumpolar Current. However, when comparing SSTa propagation speeds between a fully coupled simulation (the CPL experiment of M06) and one where the ocean is passively forced by the atmosphere (which in turn only feels climatological surface boundary conditions, the FR-OC experiment in M06), no significant increase was found. Presumably, such increase is too small to be detected.

[10] As SSTa exhibited a slower decay time and a larger amplitude in the coupled experiment (CPL) than in the uncoupled one (FR-OC), M06 concluded the existence of a positive feedback from the air-sea coupling onto the ocean, driven by the atmospheric response to SSTa. This conclusion remains valid. Additionally, we now argue that this positive feedback is much larger, and it is primarily driven by air-sea heat fluxes rather than by horizontal Ekman heat fluxes. This latter contribution is now 30% the first one. This is qualitatively consistent with the *Colin de Verdière and Blanc* [2001] study showing (in a simple 2 atmospheric and 1.5 oceanic layers coupled model in a one-dimensional zonal channel) a coupled resonant mode where both thermal and mechanical air-sea interactions provide a positive feedback on the ocean, with a dominant role of the former upon the later.

[11] **Acknowledgments.** We wish to thank two anonymous reviewers for suggesting significant improvements to the text.

References

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