What are the origins of the Antarctic Intermediate Waters transported by the North Caledonian

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What are the origins of the Antarctic Intermediate Waters transported by the North Caledonian Jet?

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[1] The trajectories of several Argo floats are studied to investigate the mid-depth circulation in the southwest Pacific that coincides with the spreading of the Antarctic Intermediate Waters (AAIW). Before entering the Coral Sea, the floats converge and join the North Caledonian Jet (NCJ) south of 15°S. These observations suggest that the waters transported by this jet do not have a unique source. Hydrologic parameters and oxygen concentration confirm that the characteristics of the AAIW in the NCJ result from a convergence and a mixing of waters from the northern limb of the subtropical gyre and from the south-eastern New Caledonian region. The northern contribution is associated with the water masses transported by the North Vanuatu jet that re-circulate in the region between the D'Entrecasteaux reefs and the Vanuatu archipelago. It is shown that such complex dynamical features could be reproduced by numerical models when their horizontal resolution is sufficiently high. **Citation:** Maes, C., L. Gourdeau, X. Couvelard, and A. Ganachaud (2007), What are the origins of the Antarctic Intermediate Waters transported by the North Caledonian Jet?, *Geophys. Res. Lett.*, *34*, L21608, doi:10.1029/2007GL031546.

1. Introduction

[2] Intermediate ocean waters from about 500 to 2000 meters depth play a primary role in regulating long-term ocean climate variations. The circulation of intermediate waters represents a substantial component of the poleward oceanic heat transport [*Talley*, 2003; *Ganachaud*, 2003]. These water masses are also involved in the penetration of nutrients into the lower thermocline affecting the biological productivity at low latitudes [*Sarmiento et al.*, 2003] and in the transport of anthropogenic CO_2 into the deep ocean [*Sabine et al.*, 2004].

[3] In the South Pacific Ocean, the most important component of the intermediate waters is the Antarctic Intermediate Waters (AAIW), which is the result of the confluence of waters formed near the Antarctic convergence and near the southeast corner of the Pacific basin. These waters are characterized by a minimum in salinity and a high concentration of oxygen. Once formed these waters spread throughout the subtropical gyre toward the southwestern Pacific Ocean [*Reid*, 1997; *Qu and Lindstrom*, 2002, 2004]. They reach the equatorial band and the North Pacific Ocean mainly through the Solomon Sea and the Coral Sea [*Zenk et al.*, 2005]. This broad picture of the AAIW, spreading into the South Pacific, is well established from the analysis of hydrological profiles.

[4] It is well known that the South Equatorial Current (SEC) divides into jets when it encounters the complex topography of the southwest Pacific [*Sokolov and Rintoul*, 2000; *Webb*, 2000] and, recently, direct velocity measurements deduced from the displacements of an autonomous glider have provided the basis for a regional description of the jets and meso-scale eddies between Guadalcanal and New Caledonia in the top 600 m depth [*Gourdeau et al.*, 2007a]. These observations have also shown that the mass transports of the North Vanuatu Jet (NVJ), near 14°S, and of the North Caledonian Jet (NCJ), near 17°S are stronger than the climatological estimates derived from geostrophy. There is also recent evidence that the NCJ could extend downward as deep as 1000 m. In this case the evidence comes from the trajectory of one neutrally buoyant float that was deployed at 165°E a few months before the passage of the glider and that was subsequently carried by the NCJ into the Coral Sea. These recent observations suggest that the NCJ plays a role well below the thermocline and is involved in the spreading of the AAIW.

[5] As part of the international Argo program, ten autonomous floats have been deployed during the Frontalis-3 oceanographic cruise in April–May 2005 along 165°E between 19°S and 10°S [*Maes et al.*, 2006]. The study of the trajectory of these floats at their parking depth of 1000 m is particularly revealing of the mid-depth circulation that coincides with the AAIW entering the Coral Sea. South of 15°S all of floats are caught up in the NCJ before reaching the Coral Sea. It shows that the origin of the waters transported by the NCJ does not have a unique source in the southeast New Caledonian region. To investigate the origins of the water masses that feed this jet, the trajectory of all Argo floats in the southwest Pacific region will be also used. A goal of this study is to extend the scale of the work of *Gourdeau et al.* [2007a] both in the vertical and over the wider region between New Caledonia and the Vanuatu archipelago. The focus will be on the multiple pathways of the AAIW as it feeds the NCJ and, ultimately, the Coral Sea.

2. Observations and Numerical Model

[6] Both the trajectories and the temperature and salinity profiles of the Argo floats are used hereafter. The region of interest is the southwest Pacific Ocean between 10°–25°S and 150°–175°E. These data have been obtained from the CORIOLIS global data assembly centre (www.coriolis.eu.org). Only the positions at the time of submergence

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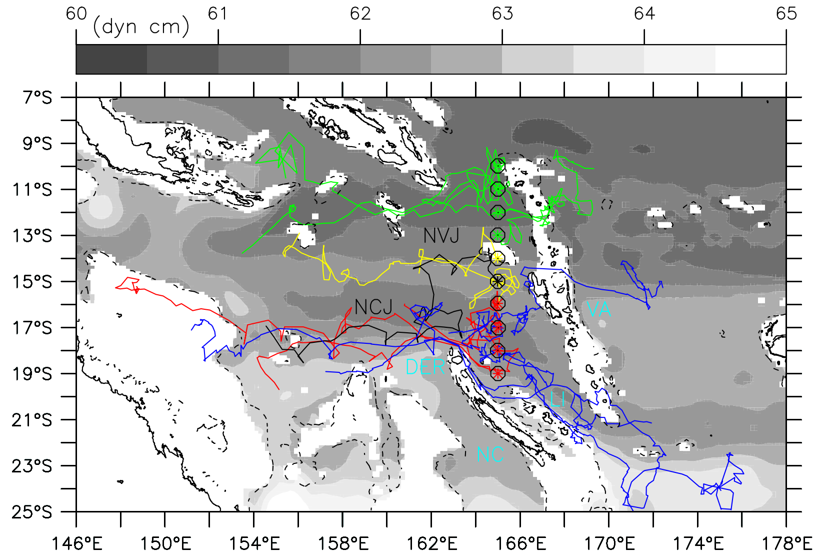

Figure 1. Trajectories of the Argo autonomous floats at their parking depth, i.e., near the 1000 m depth. The stars circled in black indicate the initial positions of the floats deployed during the Frontalis-3 oceanographic cruise in April 2005. The other floats considered in this study are represented by the blue lines (released in the eastern part of the region). The background field represents the mean dynamic height (in dyn. cm.) between 1000 db and the 2000 db reference as simulated by the 1/12° horizontal resolution OCCAM model. The dashed line represents the 2000 m isobath. NC, LI, VA, and DER stand for New Caledonia, Loyauté Islands, Vanuatu Archipelago and D'Entrecasteaux Reefs. The averaged positions of the NCJ and NVJ are also indicated.

and the time of resurfacing of the floats are used to compute trajectories at the parking depth near 1000 m. The data from any float that could not achieve this parking depth are simply discarded. Due to the small number of floats in this region (less than 20), an estimate of an absolute current reference level as described by *Davis* [2005] was not attempted. Only a qualitative description of the raw trajectories at the regional scale will be made. The accuracy of the temperature and salinity profiles from the Argo floats is better than 0.05°C in temperature and 0.02 in salinity between the 900 and 1100 m depth when comparing them with the few available Conductivity-Temperature-Depth profiles compiled by *Boyer et al.* [2006]. We also use observations of the dissolved oxygen concentration as reported from two oceanographic cruises. The first cruise followed the P21 WOCE track [*Tsimplis et al.*, 1998] which crosses the region between 20°S–164.5°E and 18°S–169°E. The second cruise was the third of a series to document the circulation of the region as part of the Secalis program of the IRD centre of Nouméa [*Gourdeau et al.*, 2007b]. The accuracy of the oxygen data is found to be of 1.5 umol/kg or better.

[7] In order to investigate the mean circulation near the NCJ bifurcation, we also used the results of the OCCAM general circulation model [*Webb*, 2000]. Results from two experiments, one with a horizontal resolution of 1/4° and the other with a resolution of 1/12° are considered. In both case, the model has 66 levels in the vertical with a resolution of 5 m near the surface of the ocean increasing downward to 200 m depth. Details of the model configuration are described by *Lee et al.* [2007]. The 1/4° experiment covered the period 1985–2004 and the 1/12° experiment covered the period 1988–2002.

3. Results

[8] During the Frontalis-3 cruise in April 2005, ten autonomous floats were deployed along 165°E between 19°S and 10°S. Figure 1 shows the trajectory of the floats by the end of May 2007 after two years at sea (only the Argo float 5900918 failed prior to this time in early March, 2007). With one exception, all the floats have been transported into the Coral Sea, while some of the northern floats have gone even farther into the Solomon Sea. While most of the trajectories exhibit some eddy noise and small scale variability, the predominant zonal direction of the flow entering the Coral Sea is obvious. This feature is clearly consistent with the mean circulation patterns that have been previously discussed. It is also interesting to note that the spread of the floats is not uniform but, after a period of approximately 6 months, the floats are concentrated either in the NVJ or in the NCJ. As also depicted by *Gourdeau et al.* [2007a] the latitudinal structure reveals a narrow and intense NCJ in contrast with a broad and weak NVJ. These jets may be clearly associated with the meridional gradients in the mean dynamic height between the 1000 and 2000 db pressure levels as simulated by the OCCAM model at the 1/12° resolution. Another striking point regards the origins of the floats that are transported by the NCJ; between 19°S and 16°S all the floats deployed along 165°E have converged toward the northern tip of the D'Entrecasteaux reefs before entering the Coral Sea via the NCJ. Even the Argo

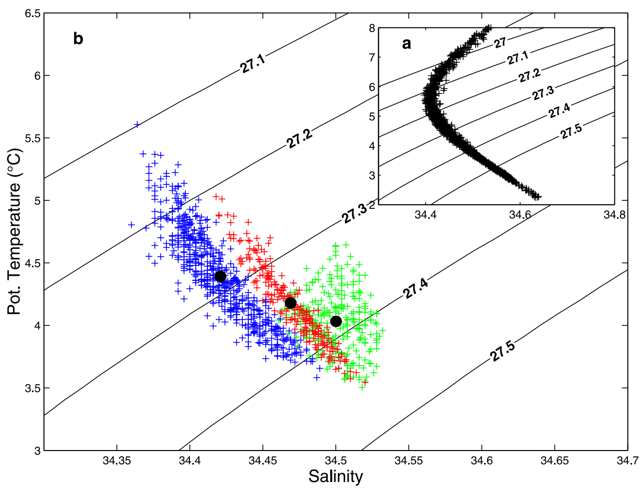

Figure 2. Relation between the potential temperature and salinity of (a) the intermediate water mass transported by the NCJ in the region (17°–18°S; 164°–158°E) and (b) the water masses between the 900 and 1100 m depths for the different regions (see the text for their definitions). The blue symbols represent the data in the southeast region, the green ones are for the region of the NVJ, and the red symbols are for the region of the NCJ. In the middle of each cloud of point, the black circles represent the average conditions, respectively. The solid lines denote the isopycnal surfaces.

float (WMO id 5900915) deployed at 15°S (black line in Figure 1) is finally transported by this jet and this particular case will be discussed later.

[9] The latter point concerning the origins of the water masses transported by the NCJ requires further comment as it is often assumed that the main pathway of the water between the New Caledonia and the Vanuatu archipelago is from the south-east. To complement the set of floats deployed in 2005, we also considered other Argo floats that cross the section along 167°E between 17°S and 18°S. Their trajectories are represented by the blue lines in Figure 1. As expected most of these floats are coming from the south-east corner of the region and they transit into the Coral Sea via the NCJ after either closely rounding the coastal reefs once the Loyauté Islands have been cleared, or crossing the open ocean between New Caledonia and the Vanuatu archipelago. One float suggests, however, a northern pathway that may be extended toward the east, at least to around 15°S–174°E. In this case, the waters following this route to the NCJ could be derived from the bifurcation of the SEC around the northern tip of the Fiji islands.

[10] Figure 2a shows the potential Temperature-Salinity (T-S) diagram at the level of intermediate waters and representative of the waters transported by the NCJ. All the profiles from Argo floats within in the region between 17° and 18°S ranging from 164° to 158°E are shown. The tight distribution of the values indicates that a single water mass has been sampled. These layers are characterized by a salinity minimum around 34.40 on the isopycnal surface $\sigma_\theta = 27.2$ kg/m^3 corresponding to the standard definition of the AAIW in this region [*Qu and Lindstrom*, 2002]. Near the parking depth of the Argo floats, between the 900 and 1100 m, the density is between 27.3 and 27.4 kg/m^3 and, in consequence, the trajectories of the floats shown in Figure 1 are representative of the lower part of the AAIW. At these depths, Figure 2b shows the T-S diagrams for three different regions: the region of the NCJ (17°–18°S: 164°–158°E), the south-eastern Pacific Ocean (20°–23°S; 169°–178°E) and the waters of the NVJ originating east of the Vanuatu archipelago (13°–15°S; 167°–174°E). The two latter regions are crossed by the blue float trajectories before entering the Coral Sea (Figure 1). In each region, there are between 250 and 650 temperature and salinity data points. The potential temperature ranges between 3.5° and 5°C for these three water masses. More interestingly, the water mass from the eastern NVJ-region exhibits the largest salinity values and the least distinct salinity minimum of the three regions. The fresher waters are found to originate in the south-east corner of the region with a minimum that is slightly lower than 34.40 in salinity. This latter value is consistent with the climatology of the region. Figure 2b clearly shows that the T-S characteristics of the NCJ-region lie between those of the NVJ-region and the south-eastern Pacific, suggesting that the waters transported into the Coral Sea by the NCJ result from the mixing of waters from the two other regions. The observed change of density between these waters masses is small, typically less than 0.1, consistent with limited mixing across isopycnal surfaces. If we consider only these two sources of water and if we assume that mixing occurs in T-S space, i.e., along the line passing through the black circles in Figure 2b, then the waters from the NVJ make up a larger proportion of the NCJ waters than waters from the south-east region. This result is not supported by other analyses and climatology using passive tracers such as the oxygen concentration [*Qu and Lindstrom*, 2002, 2004], and prompted us to consider other evidence for the influence of an eastern NVJ source on the NCJ. Looking back at Figure 1, the trajectory of the Argo float 5900915 (in black), originating in the NVJ, shows a complex re-circulation pattern in the region between the New Caledonia and the Vanuatu archipelago before joining the NCJ.

[11] To differentiate between water masses in the region between New Caledonia and the Vanuatu archipelago, we consider variations in the oxygen concentration in the expectation that it is a more sensitive indicator than variations in temperature or salinity. When the intermediate waters are formed in contact with the atmosphere, their concentration in oxygen is high. Once these water masses have been subducted, their O_2 concentration will decrease as they spread toward the western Pacific. Table 1 lists intermediate water characteristics for pairs of stations in the NCJ region for two oceanographic cruises, the P21 and the

Table 1. Positions, Temperature, Salinity, and O_2 Concentrations Between the 900 and 1100 m Depth for Different Stations of the P21 Section and of the Secalis-3 Oceanographic Cruise[a]

	Position, °S/°E	Pot. Temp., °C	Salinity	O_2, umol/kg
Secalis-3 (2)	18.05/163.2	4.31	34.45	169.4
Secalis-3 (28)	20.83/166.9	4.56	34.44	175.8
P21 (249)	19.38/165.7	4.06	34.47	167.2
P21 (254)	19.91/164.4	4.34	34.45	173.0

[a]In the first column, the number in brackets denotes the number of the station.

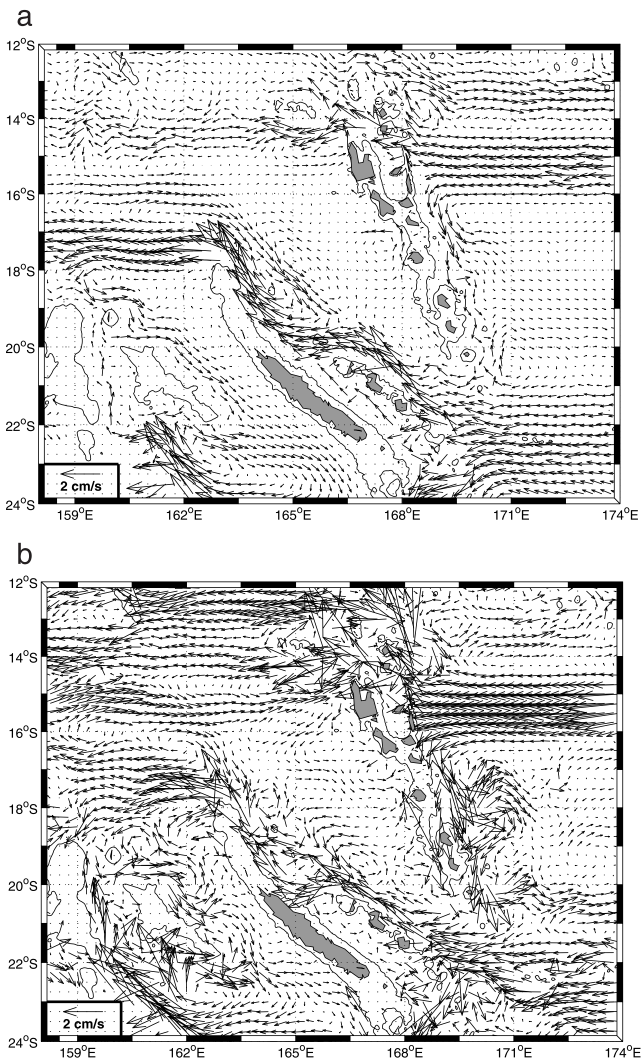

Figure 3. (a) Mean velocity circulation at the 1000 m depth simulated by OCCAM at the 1/4° horizontal resolution. The vector scale is indicated at the lower left. The thin solid line represents the 1000 m isobath. (b) The same as for Figure 3a at the 1/12° horizontal resolution.

Secalis-3. For both cruises the more southerly station has a higher O_2 concentration by about 6 umol/kg, suggesting that the waters sampled at the southern stations have travelled a shorter distance from their source than those at the northern stations. Nevertheless, these stations are not widely separated leading us to suggest that the longer path of the waters at the northern stations enters the region from the east through the Vanuatu archipelago following a trajectory similar to that of Argo float 5900915.

[12] The float trajectories and station data provide strong circumstantial evidence for the idea that it is the complex circulation and the mixing of water masses in the region between New Caledonia and the Vanuatu archipelago that establish characteristics of the NCJ as it enters the Coral Sea. We turn next to a dynamical model for further support of this idea. Figure 3 shows the mean circulation at the 1000 m depth from the OCCAM model at both the 1/4° and the 1/12° horizontal resolution. The main jets are simulated in both experiments and the total mass transport of the jets agrees within a 20% between the two experiments. The T-S characteristics of these two experiments (not shown) are consistent with the Argo data displayed in Figure 2. In both experiments the general layout of the jets is similar: the NVJ results from the splitting of the SEC on the Vanuatu archipelago (between 14° and 16°S) whereas the NCJ is mainly fed by a southern limb of the SEC. Note that, at the 1000 m depth, no current in either experiment crosses the Vanuatu ridge. The simulation at the 1/12° resolution exhibits small scale variability and stronger currents. Another important difference occurs in the re-circulation of the flow in the lee of the Vanuatu archipelago. The 1/4° simulation shows a re-circulation of the NVJ from the Coral Sea (near 16°S) and this flow turns southward near 164°E toward the Loyauté ridge with little or no eastward penetration toward the coasts of the Vanuatu archipelago. In the simulation at the 1/12° resolution this re-circulation cell is stronger and located slightly northward. More importantly, it divides north of New Caledonia with the larger component extending to the east reaching the northern tip of Santo Island before to re-circulating toward the eastern edge of New Caledonia. The re-circulations of the NVJ jets in these model experiments are qualitatively consistent with several trajectories of the Argo floats as shown in Figure 1. These re-circulations also support the idea that water masses transported by the NVJ play a role in determining the water mass characteristics of the NCJ.

4. Discussion and Summary

[13] An examination of the mid-depth circulation through the trajectories of several Argo autonomous floats confirms that the NVJ and the NCJ are the main elements of the inflow to the Coral Sea in the southwest Pacific Ocean. The NCJ appears as a narrow flow at the northern tip of the D'Entrecasteaux reefs of New Caledonia transporting different proportions of AAIW. These jets have been associated until now with the main thermocline but the evidence of the trajectories suggests they extend into the lower part of the thermocline. The result extends the recent work of *Gourdeau et al.* [2007a] that depicts the NCJ as a very thin jet characterized by high velocity and little shear in the top 600 m depth of the water column. In the density range of the AAIW, characteristics of the water masses indicate that the NCJ participates in spreading these waters in the deep part of the thermocline toward the southwest Pacific. These results are consistent with the fact that the wind-driven circulation of the subtropical South Pacific Ocean extends relatively deep as compared to the North Pacific [*Huang and Qiu*, 1998].

[14] At the depth of the deep thermocline, the origin of intermediate waters that transit ultimately toward the Solomon Sea through the western boundary currents has been mainly thought to be associated with the circulation of water masses between the Vanuatu archipelago and New Caledonia. For instance, *Sokolov and Rintoul* [2000] estimate the volume of AAIW from this origin at 12 Sv whereas the volume transported by the northern limb is at 3.3 Sv. This partition must remain uncertain as it does not rely on local measurements but results from analyses of climatological data. The different observations analyzed in this study,

which may be considered as independent, show that the water masses transported by the NCJ into the Coral Sea result from the convergence and mixing of waters originating from the northern limb of the subtropical gyre and from the south-eastern New Caledonian region. The contribution from the northern water masses is associated with a complex re-circulation of the NVJ in the lee of the Vanuatu archipelago. The importance of this re-circulation has also been highlighted recently by an inverse calculation of water transports with a box model using as input CTD profiles collected during the Secalis-2 oceanographic cruise (A. Ganachaud et al., Bifurcation of the subtropical south equatorial current against New Caledonia from a hydrographic inverse box model in December 2004, submitted to *Journal of Physical Oceanography*, 2007). These analyses of in situ observations are also supported by the patterns of the mean circulation reproduced by a high 1/12° resolution configuration of the OCCAM model.

[15] The features of the water masses from the thermocline and below, transported into the equatorial band by the subtropical gyre, are of primary importance for decadal and long-term climate variations [*Roemmich et al.*, 2007]. However, the region due to its maritime nature and the circulation remain poorly sampled and understood. These difficulties have led to the organisation of the Southwest Pacific ocean Circulation and Climate Experiment (SPICE), an international program under the auspices of CLIVAR [*Ganachaud et al.*, 2007]. The present study demonstrates that the deployment of autonomous floats represents an unprecedented wealth of in situ observations for programs like SPICE.

[16] **Acknowledgments.** The Argo data are collected and made freely available by the International Argo Project and the national programmes that contribute to it (www.argo.ucsd.edu, http://wo.jcommops.org/cgi-bin/WebObjects/Argo). Comments from David Behringer were greatly appreciated. The UK OCCAM is a Community Research Project supported by the Natural Environmental Research Council. This study has been supported by the LEFE program in France.

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