ANDRO: An Argo-based deep displacement atlas

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Introduction

During the first decade of the 21st century, more than 6000 Argo floats have been launched in the World Ocean, gathering temperature and salinity data from the top 2000 m, at a 10-day or so sampling period. Meanwhile their deep displacements can be used to map the ocean circulation at their drifting depth (mostly around 1000 m). A comprehensive processing of the Argo data collected has been done to produce a world atlas (named ANDRO) of deep displacements fully checked and corrected for possible errors found in the public Argo data files (due to wrong decoding or instrument failure). So far, 75% (to be updated soon) of the world data have been processed to generate the present ANDRO displacements (which are based only on Argos or GPS surface locations). In a future version, improved deep displacement estimates will be based on float surfacing and diving estimated positions.

Float displacements at depth (roughly 8 days and a half over a 10 day total cycle time) provide estimates of absolute velocity (averaged over the displacement times) all over the world with an approximate 10-day sampling period. Although such a velocity field is mainly restricted to one depth (1000 m), if the estimates are accurate enough, it may solve the long-standing problem of the reference level (Wunsch, 2008 e.g.) for the first time. As far as the mean circulation is concerned the accuracy of the velocity estimates is quite sufficient (Ollitrault et al., 2006, e.g.) but may be questionable for studies focusing on monthly variations and in specific areas (as the equatorial band). It may seem strange to question the accuracy of Argo floats since ALACEs had already proven excellent (Davis, 2005 e.g.). But Argo floats go deeper (2000 m) and spend generally less time at their park pressures.

Yoshinari, Maximenko & Hacker (2006) first produced an atlas of velocity estimates (YoMaHa'05) by using the then available Argo data. YoMaHa'07 (Lebedev et al., 2007) is a regularly updated version (available at http://apdrc.soest.hawaii.edu/projects/Argo/data/trjctry/). This atlas uses Argo data from the public NetCDF files found on the Global Data Assembly Center (GDAC) web sites (http://www.coriolis.eu.org/ or http://www.usgodae.org/argo/). Generally float displacements from YoMaHa'07 look quite realistic. But a few percent show high speed or have drifting depth obviously wrong (i.e., some are found drifting over the continental shelf while their drifting depth is given as 1000 m).

This convinced us to look more closely into the Argo data (and if possible to start anew from the very first Argos or Iridium raw data received at the different Data Assembly Centers (DAC)) for checking and (if necessary) correcting the various parameters measured by the floats and used to estimate the float displacements.

We present here what we have done so far with the data sets from AOML (USA), Coriolis (France) , JMA (Japan), CSIRO (Australia), MEDS (Canada) and INCOIS (India) DACs (90% of the world data).

First the various floats used are presented: functioning, parking data measurement and transmission. Then the processing done on DAC NetCDF files and (available) Argos raw ASCII files is explained. In the third part, we present our deep displacement (velocity) atlas named ANDRO (for Argo New Displacements Rannou and Ollitrault, or because it is the name of a traditional dance of Brittany meaning a round or a swirl), resulting from our processing of Argo data. A last section explains what could be done to improve the deep displacement estimates.

The various Argo floats

There are three main types of Argo floats: APEX, SOLO and PROVOR contributing 61%, 26% and 11% respectively to the total number of Argo floats used since 1999. A few other float designs have been developed (for example NEMO in Germany, PALACE in USA or NINJA in Japan) but contribute only 2%.

APEX float

The APEX float is designed and manufactured by Teledyne Webb Research (USA). It uses an aluminum pressure case (16.5 cm diameter and 130 cm long) and a hydraulic mechanism to stabilize it at a prescribed depth. Each instrument is tailored and its mission programmed by the manufacturer, depending on the final user desires.

Four parameters are essential for the APEX mission: DOWN TIME which comprises the descent from the surface, the float drift at its park pressure and the (possible) descent to its deepest profile pressure, UP TIME which comprises the ascent from the deepest profile pressure and the surface drift with the ARGOS (or Iridium) transmission, PARK PRESSURE and DEEPEST (profile) PRESSURE. Thus APEX cycles are DOWN TIME + UP TIME long.

Prior to the first dive, APEX stays for 6 hours at the surface and continually transmits a test message, which contains the mission parameters. Then the float begins its mission proper, cycling until battery exhaustion. At the end of each cycle, a number of data messages (approximately proportional to the profile size) are sent repeatedly for several hours (usually 12h).

During the drifting phase, APEX regularly measures P, T & S triplets but only the last one (sampled at parking phase end) is transmitted. Newer APEX versions, however, also transmit statistics for P, T and S regularly sampled during the parking phase.

Because APEX floats have evolved since the beginning of Argo, there are many firmware versions. Presently we have developed 73 APEX decoders (all with Argos transmission).

SOLO floats

The SOLO floats come in two models: the WHOI SOLO developed at the Woods Hole Oceanographic Institution on the East coast of the USA and the SIO SOLO developed at the Scripps Institution of Oceanography in California (both models contributing equally to the Argo fleet). These floats share the same pressure case with the APEX. However each float mission must be programmed by the user.

For the WHOI SOLO, each cycle is exactly N days long (10 days generally) and the time reference is at the beginning of the parking phase which is always at 0h (or midnight), when the float is supposed to have reached its park pressure.

The drift phase is usually 8 days and 5 hours long, then the float descents to its DEEPEST (profile) PRESSURE, usually reached within 4 hours. Thus, with these figures, the start of ascent is 8 d 9 h after the descent end, whether or not the deepest profile pressure was reached. The time to reach the surface is similar to that for APEX floats and also with APEX floats is not known a priori. The time for Argos transmission is typically 12 h.

During the drift phase, the float acquires 6 P, T and C (or S) triplets, if equipped with FSI (or SBE) sensors. The first and last triplets are taken at the beginning and end of the parking phase (thus 8 days and 5 h apart in our example). The four other triplets are measured 1day 1h, 3days 1h, 5days 1h and 7days 1h after the reference time. These are averages over the previous intervals.

There are three types of Argos messages: one for profile data, one for drift data and one for engineering data. The engineering message contains P, T and C (or S) at beginning and end of the drift phase, given in full range.

In the drift message, the four other P, T and C (or S) triplets are given as remainders modulo 409.6 dbar, 4.096° C and 1.024 PSU (or mS cm^{-1}) respectively. With each of these four triplets, a very useful parameter is also given modulo 4096: the variation of volume of the float DV counted as number of turns of the piston driver. Actually, ΔPark Pres = 0.75 *DV to a high accuracy, and this enables to solve the modulo uncertainties on the pressures measured during the drift phase.

The SIO SOLO functioning is rather different from the WHOI SOLO. All times except the rise time (for profiling) are fixed. For example with a mission at 1000 dbar (parking depth), the fall time is generally 500 min, followed always by two repositioning phases 5 h each (to get closer to the prescribed depth). The park time proper lasts 20 times a sampling interval (generally 20 times 557 min). Descent to deepest profile pressure is always 5h long, after which the float ascends as fast as it can by moving out its piston completely (a 1000 m rise takes roughly 2 h but this is slightly variable). Then the float transmits to Argos for a fixed duration (e.g. 18 h). While drifting at its parking depth, 20 measurements of P, T and S are acquired but only the averages for the first and second halves are transmitted.

There are two different message types: Data message for P, T and S measurements taken either during the parking or the profiling phases, and Engineering message for various parameters of the float functioning.

Presently we have developed 2 WHOI SOLO and 3 SIO SOLO decoders (all with Argos transmission).

PROVOR float

This float is designed and manufactured by NKE (previously TEKELEC then MARTEC) in partnership with IFREMER. It is slightly taller (1.60 m) than its American counterparts. Each instrument mission must be programmed by the user.

Each cycle (except the first one) is N days long and the reference time is at the beginning of the ascending profile (the day and hour of the reference time is programmable). PROVOR is controlled hydraulically to follow its park pressure within 30 dbar and does P, T and S measurements every H hours (generally every 12 h) while drifting. All these measurements are transmitted and many are dated by the float clock. PROVOR ascent velocity is of the order of 10 cm s^{-1}.

PROVOR messages are of two types: technical and data messages. Technical messages contain information about the float functioning. Data messages come in three types: one for descending profile (if required), another one for the parking phase and a last one for ascending profile data. In each data message, there are between 4 and 16 P, T and S triplets with the first triplet dated.

Presently we have developed 19 different PROVOR versions using Argos transmission and 4 versions using Iridium transmission.

Data processing

From the NetCDF public Argo files, we first generate a data set (henceforth called DEP) comprising all the useful information given by the various floats. Then the data are checked, corrected and improved with information gathered outside or through a decoding of the original Argos or Iridium raw data files. Some complementary estimated data are also added. The final data set is then used to generate our ANDRO deep displacements atlas.

DEP data set creation

ASCII DEP files (there is one file for each float) are created from the public NetCDF (meta.nc, traj.nc, prof.nc and tech.nc) files. Argos (or GPS) positions, dates and location classes come from the traj.nc files together with the (real time) P, T and S measurements during the parking phase. Real time P, T and S values sampled during profile come from prof.nc files. A few other measurements or data are recovered from the meta.nc and tech.nc files, to be used in the future (for an improved version of ANDRO, discussed at the end of the paper).

Argos raw data pre-processing

In order to check and improve the DEP data set, we asked the DACs to provide the original Argos raw data. All Argos data from each DAC are first concatenated to be sorted afterwards by Argos PTT number. Then WMO float numbers are attributed to the data (sometimes one Argos PTT may have been consecutively shared by two or more different WMO numbers). Finally, the data are split into different cycles (there is one Argos raw data file for one received float cycle).

Additional Argos (or GPS) locations

Examination of the Argos (or GPS) raw data files revealed that some Argos (or GPS) locations are not found in the traj.nc files. Missing positions were added in the DEP files (sometimes improving the accuracy of existing ones because of a better location class).

Argos Data decoding

At the beginning of our work (in 2007) we discovered several errors on physical parameters given in the NetCDF files possibly due to unreliable decoding (for example roll-over errors for P, T and S parking values). Thus, we decided to decode anew the Argos (or Iridium) raw data (the DACs provided roughly 95% of the whole Argo dataset). Newly decoded park and profile P, T and S values are then added to the DEP files (they replace existing ones).

All floats (except SIO SOLO) have an error detection code imbedded in the Argos messages (called CRC for Cyclic Redundancy Check) that we have used to reject possibly corrupted messages. Furthermore among all the received copies of one transmitted message, the most redundant one is preserved.

Meta data check

At this stage, we are able to check the following parameters given in the meta.nc files:

- REPETITION_RATE which gives the number of times the float does the same cycle mission (defined by fixed CYCLE_TIME, PARKING_PRESSURE and DEEPEST_ PRESSURE parameters),
- CYCLE_TIME (theoretical cycle duration),
- PARKING_PRESSURE (theoretical subsurface drifting pressure),
- DEEPEST_PRESSURE (theoretical starting pressure of ascending profile).

These parameters (corrected if necessary) are stored in a separate file to be used in the following steps.

Representative park pressure

For each cycle, we determine a realistic estimate of the float parking depth, which is very important if we want to use Argo float deep displacements to track water motions.

This Representative Park Pressure (RPP) is computed as follows:

- If the float provides regularly sampled park pressure values, RPP is the average value,
- If the float only provides the mean of the (regularly sampled) park pressures, it is RPP,
- If the float provides only one park pressure (generally sampled at the end of the drifting phase), it is RPP,
- If the float provides the minimum and maximum pressures sampled during the drifting phase, RPP is the middle value,
- If no pressure measurement is available during the drifting phase, RPP is given by the theoretical PARKING_PRESSURE value (in this case we need to check if the local bathymetry is not shallower and if the induced deep velocity seems realistic).

Then a systematic visual check on the RPP time-series is done to detect possible errors due to float pressure transducer ill function (mostly on APEX) or transmission error. Existing RPP values are then replaced by: a default value if the RPP is not correctable, 0 dbar if the float is obviously at the surface, the theoretical PARKING_PRESSURE if the float seems to be working nominally.

Cycle number

To be reliable for scientific use, a deep displacement must be defined between two consecutive cycles. Thus it is very important to be confident in the cycle number. The check is easy with the APEX floats because they transmit the cycle number in one Argos message. For most of the other floats, we need to cross check the Argos (or GPS) location dates with the CYCLE_TIME parameter.

Unusable cycles

If a float hits the bottom while drifting, it is considered grounded, and this cycle will be excluded from our ANDRO atlas. Grounded cycles are detected by comparing RPP with a precise local bathymetry (SRTM30+

worldwide bathymetric atlas).

Some floats are recovered at sea or after beaching, while still functioning. The corresponding cycles are deleted from the DEP files.

ANDRO generation

From the final DEP files, one then generates the ANDRO atlas, which basically contains the deep displacement estimates defined as the distance between the last Argos (or GPS) fix and the first Argos (or GPS) fix of two consecutive cycles. All GPS locations, but only Argos locations with classes 1, 2 or 3 (i.e. with 1km, 350m or 150m accuracy) are used. Furthermore only those Argos positions that pass the Nakamura et al. (2008) test are preserved.

ANDRO actual contents

ANDRO atlas is available as an ASCII file (containing 28 columns) whose format is identical to YoMaHa'07 (except we use WMO number instead of their float ID). Thus, in ANDRO, one finds float depths, deep and surface displacements, times, deep and surface associated velocities with their estimated errors.

Presently, ANDRO contains data from AOML and JMA until December 31st 2008, from Coriolis, CSIRO, MEDS and INCOIS until December 31st 2009 (later versions of ANDRO will cover the following years). There are a total of 5 258 floats contributing 465 896 displacements (over 481 907 cycles done). Table one and figure one give the displacement depth repartition.

Towards better deep displacement estimates

Actual deep displacement estimation relies only on surface locations. However, contrary to GPS locations, Argos positions are not (generally) available when the floats surface (or dive), but slightly later (or sooner) implying possibly a few km error on the deep displacement estimated (on average there is a delay of one hour or two).

Parking pressure (dbar)	Number of displacements (5,258 floats)	
0 < P ≤ 250	14,566	3.1%
250 < P ≤ 750	22,762	4.9%
750 < P ≤ 1250	332,650	71.4%
1250 < P ≤ 1750	50,095	10.7%
1750 < P ≤ 2250	39,426	8.5%
2250 < P ≤ 2750	82	0.0%
Undefined	6,315	1.4%
Total	465,896	

To estimate the true surfacing or diving positions, one needs to determine first the corresponding times, to then extrapolate the surface float trajectory (sampled by the Argos locations) at these times.

For most of the floats, the surfacing time can be precisely estimated (within a few minutes), contrary to the diving time, for which one can use the envelope method proposed by Park et al. (2005). We have presently estimated these times for all floats except the SOLOs.

The extrapolation can be done, for example, by fitting a uniform velocity and a circular inertial motion to the Argos fixes (Park et al., 2004). We have tested this method on 750 floats, but with partial success (consequently, those estimates have not been saved in the DEP files yet).

Figure 4 gives an example of such an extrapolation (with a good fit), showing a large distance (13 km) between surfacing and the first Argos fix. Fortunately this is not representative of the general case: our study with 750 floats gives an average delay (after surfacing or before diving) of 80 ± 60 min implying an average 1.5 ± 1.5 km error.

A second planned improvement will consist in estimating the current shear between the surface and the parking depth, in order to be able, using a modeled vertical float velocity, to integrate the horizontal motion of the float during descent and ascent.

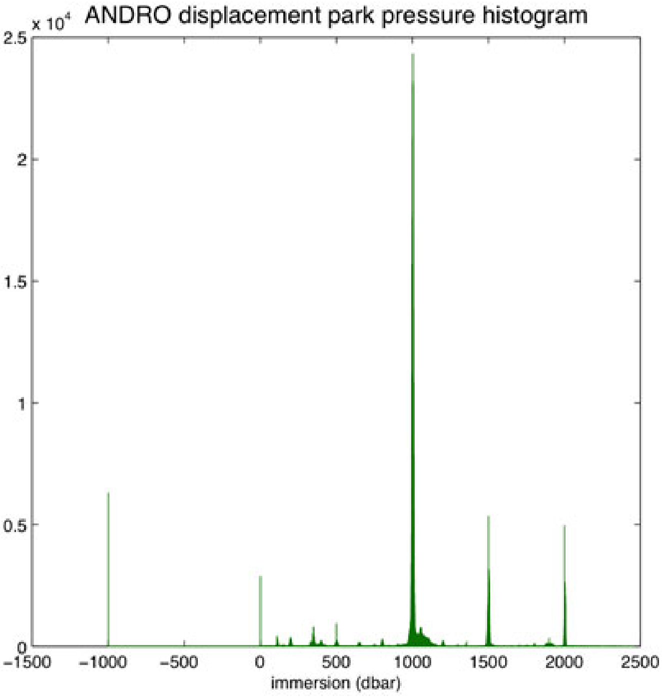

Figure 1: ANDRO displacement depth repartition. Ordinate gives the number of displacements within 1dbar layers. Unknown depths are defaulted to –999.9.

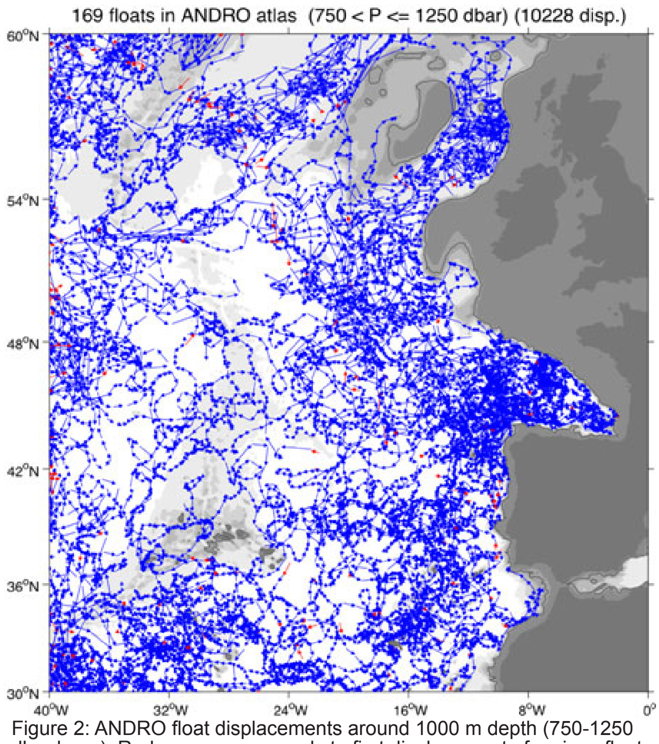

Figure 2: ANDRO float displacements around 1000 m depth (750-1250 dbar layer). Red arrow corresponds to first displacement of a given float.

Conclusion

Almost all ANDRO atlas displacement depths are *insitu* measured values. YoMaHa'07 displacement depths are only copied from the meta.nc files, implying erroneous drifting depths for almost 7% of the displacements (even with perfectly filled meta files, 4% would remain, due to instrument malfunction).

Thanks to the Argos and Iridium raw data provided by the DACs, we have been able to get rid of decoding errors and to concentrate on the float functioning. Furthermore we have slightly enlarged the Argo data set with cycles not publicly available (for reasons unknown to us).

Meanwhile, the DACs progressively update their NetCDF data files, as a result of our work. Since YoMaHa'07 atlas is regenerated periodically, the differences between ANDRO and YoMaHa'07 will tend progressively towards 4% due to instrument malfunction.

Before the end of this year, we shall process the AOML and JMA data for the year 2009, and the rest of the world Argo data (presently lacking in ANDRO) from BODC, KORDI, KMA and CSIO DACs.

After completion, the ANDRO atlas (covering the period July 1999 to December 2009) will be freely available on the Coriolis web site by the end of 2011.

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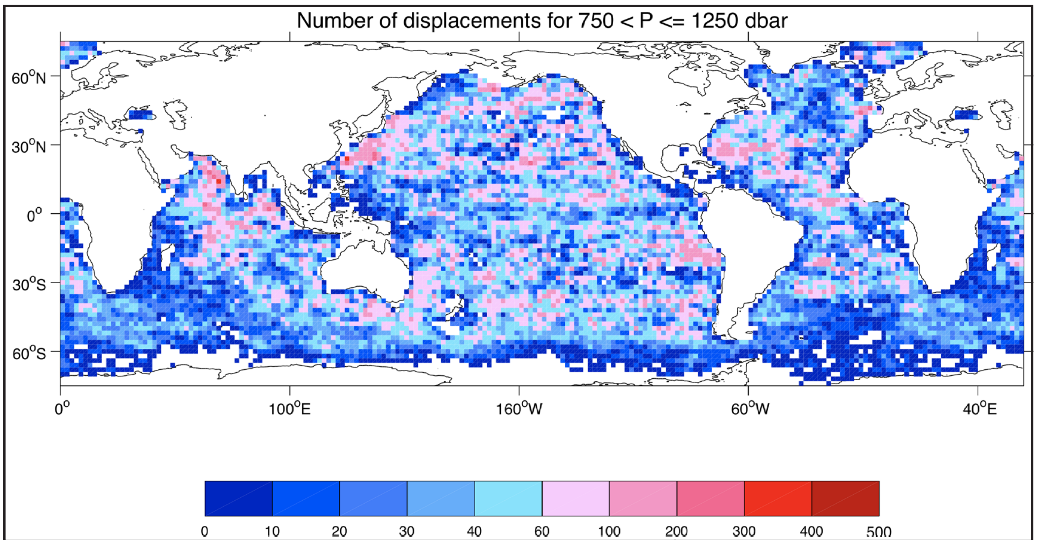

Figure 3: ANDRO world displacement atlas for the 750-1250 dbar layer.

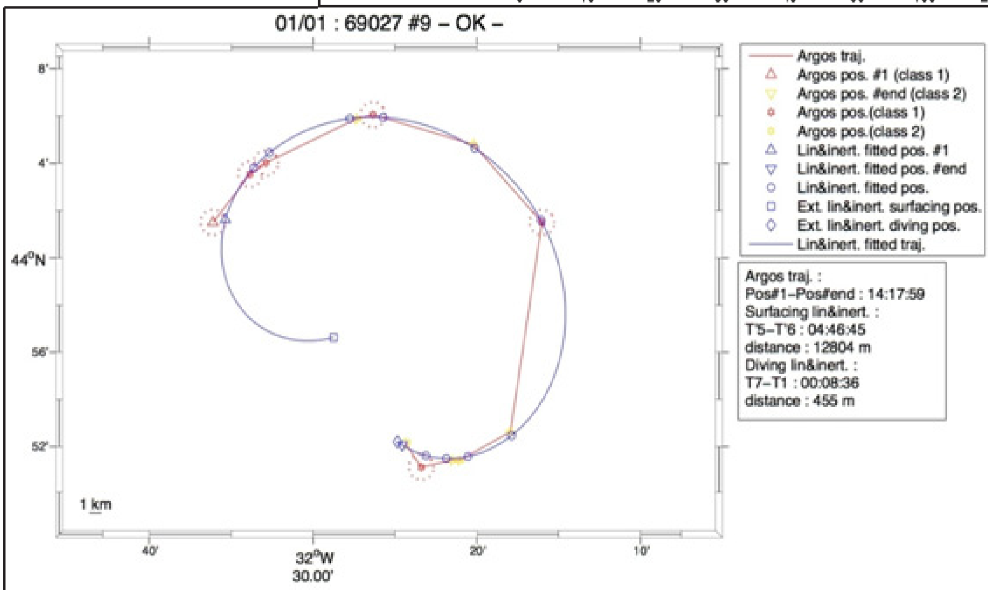

Figure 4: Least square fit of a uniform velocity plus a circular inertial motion on Argos fixes, with extrapolated surfacing and diving positions. Dotted circles are Argos location 1 sigma uncertainty.