Absolute Geostrophic Velocity Inverted from World Ocean Atlas 2013 (WOAV13) with the P-Vector Method

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The WOAV13 dataset comprises 3D global gridded climatological fields of absolute geostrophic velocity inverted from World Ocean Atlas-2013 (WOA13) temperature and salinity fields using the P-vector method. It provides a climatological velocity field that is dynamically compatible to the WOA13 (T, S) fields. The WOAV13 has the same spatial resolution and temporal variation (annual, monthly, seasonal) as WOA13 (T, S) fields, but does not cover the equatorial zone (5^oS – 5^oN) due to the geostrophic balance being the theoretical basis for the P-vector inverse method.

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Dataset

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Introduction

World Ocean Atlas 2013 (WOA13), published by the NOAA National Centers for Environmental Information (NCEI) (US), contains annual, seasonal, and monthly means of temperature (*T*), salinity (*S*), dissolved oxygen, apparent oxygen utilization, percent oxygen saturation, phosphate, silicate, and nitrate for the World Oceans with horizontal resolution of 1°×1° at standard 102 depth levels from the surface to the sea floor (5500 m depth) (Boyer et al. 2005; Locarnini et al., 2013; Zweng et al. 2013). It also includes associated statistical fields of observed oceanographic profile data interpolated to standard depth levels on 5°, 1°, and 0.25° grids (http://www.nodc.noaa.gov/OC5/woa13/).

However, an important variable, ocean current velocity vector (*u*, *v*), is not included in the WOA13 dataset. This is primary due to the lack of velocity observations, which are difficult and costly to make. Physical oceanographers usually have a relatively frequent (*T*, *S*). For example, the NOAA NCEI World Ocean Database (WOD)-2013 contains nearly 13 million temperature profiles and almost 6 million salinity measurements, but does not contain any ocean current velocity data.

Inclusion of ocean current velocity data into the WOA13 becomes important for climatic and oceanographic studies. Absolute geostrophic velocity, representing the large-scale ocean circulation, is calculated from the WOA13 (T, S) data using the P-vector inverse method (Chu, 1995, 2006) with the same spatial and temporal resolutions as the (*T*, *S*) data. This velocity dataset is called the WOAV13 (i.e., WOA13-Velocity).

1. Data production method

The P-vector inverse method was first proposed by Chu (1995) and described in detail in a book by Chu (2006). It can be outlined as follows. Let (x, y, z) be the coordinates with x-axis in the zonal direction (eastward positive), y-axis in the latitudinal direction (northward positive), and z-axis in the vertical (upward positive); and **V** the velocity vector with (u, v, w) the components in the three coordinate axes. The large-scale motions in the ocean interior are geostrophic and hydrostatic balanced, continuous, and density (ρ) conserved,

$$\mathbf{V} \bullet \nabla \rho = 0. \tag{1}$$

These conditions lead to the conservation of the potential vorticity ($q = f \partial \rho / \partial z$),

$$\mathbf{V} \bullet \nabla q = 0 \tag{2}$$

where f is the Coriolis parameter. Therefore, the streamline must be along the intersection of the two surfaces of (ρ, q) (Figure 1), and thus the velocity vector **V** should satisfy the following form,

$$\mathbf{V} = \gamma(x, y, z)\mathbf{P}, \quad \mathbf{P} = \frac{\nabla \rho \times \nabla q}{|\nabla \rho \times \nabla q|}, \tag{3}$$

where **P** is calculated from hydrographic data; γ is the speed parameter with $|\gamma|$ the speed.

A two-step method was proposed by Chu (1995) (i.e., the P-vector inverse method): (a) determination of the unit vector **P**, and (b) determination of the scalar γ from the thermal wind relation,

$$\gamma^{(k)} P_x^{(k)} - \gamma^{(m)} P_x^{(m)} = \Delta u_{km}, \tag{4}$$

$$\gamma^{(k)} P_y^{(k)} - \gamma^{(m)} P_y^{(m)} = \Delta v_{km}, \tag{5}$$

where

$$\Delta u_{km} \equiv \frac{g}{f \rho_0} \int_{z_m}^{z_k} \frac{\partial \rho}{\partial y} dz', \tag{6}$$

$$\Delta v_{km} \equiv -\frac{g}{f\rho_0}\int_{z_m}^{z_k}\frac{\partial \rho}{\partial x}dz', \quad (7)$$

are geostrophic shear at depth z_k relative to z_m. If the determinant of the two linear algebraic equations (4) and (5) is non-zero (Figure 2),

$$\sin(\Delta\alpha_{km}) = \begin{vmatrix} P_x^{(k)} & P_x^{(m)} \\ P_y^{(k)} & P_y^{(m)} \end{vmatrix} \neq 0, \quad (8)$$

i.e., the **P** vector spiral exists (Chu 2000), the speed parameter γ at these two levels $\gamma^{(k)}$ and $\gamma^{(m)}$ can be determined after solving the linear algebraic equations (4) and (5), and in turn the horizontal velocity.

This method was evaluated (Chu et al., 1998) and applied to calculate the absolute velocity from hydrographic data for the South China Sea (Chu and Li, 2000), Japan Sea (2001a), and Northwest Pacific (Chu et al. 2002, 2003). In conjunction with the wind forcing, the P-vector method is also used to calculate the global volume transport (Chu and Fan 2007). To reduce error, a variational P-vector method was developed (Chu et al., 2001b).

2. Data

The WOAV13 dataset is in the Network Common Data Form (netCDF) (see the website: http://www.unidata.ucar.edu/software/netcdf/), which is an interface for array-oriented data access, a library for implementation of interface, and a machine-independent format for representing data. The netCDF software was developed at the Unidata (http://www.unidata.ucar.edu) Program Center in Boulder, Colorado. Each element is stored at a disk address which is a linear function of the array indices (subscripts) by which it is identified. Hence, these indices need not be stored separately (as in a relational database). This provides a fast and compact storage method. The external types supported by the netCDF interface are listed in Table 1. These types are chosen to provide a reasonably wide range of trade-offs between data precision and number of bits required for each value. The external data types are independent from whatever internal data types are supported by a particular machine and language combination. These types of extracted data are called "external", because they correspond to the portable external representation for netCDF data. Figure 3 shows the global annual mean, January, and July volume transport stream function (unit: Sv, 1 Sv = 10^6 m^3 s^{-1}) with the absolute geostrophic velocity for the extra-equatorial region (north of 8^oN and south of 8^oS) calculated by the P-vector method (Chu and Fan 2007) as examples. The combined WOA13 and WOAV13 provide global 3D annual and monthly (T, S, u, v) data.

3. Data Download

The data can be downloaded directly from the NCEI website: http://www.nodc.noaa.gov/cgi-bin/OAS/prd/accession/download/121576. Please contact NCEI Customer Service if you need further assistance (http://www.nodc.noaa.gov/about/contact.html). To read the data, the free ncdf package needs to be downloaded from the website: https://www.image.ucar.edu/GSP/Software/Netcdf/. The MATLAB (version 2008b and later) provides access to more than 30 functions in the netCDF interface. This interface provides an application program interface (API) that you can use to enable reading data from and writing data to netCDF files (known as *datasets* in netCDF terminology). The MATLAB code is listed as follows to read the WOAV13 data in netCDF.

```
% open netcdf data
ncid=netcdf.open('WOA13pv.nc','nowrite');

% get the year-month-season data
yms_id=netcdf.inqVarID(ncid,'year-month-season');
yms=netcdf.getVar(ncid,yms_id)';

% get the logitude data
lon_id=netcdf.inqVarID(ncid,'lon');
lon=netcdf.getVar(ncid,lon_id);

% get the lattitude data
```

```
lat_id=netcdf.inqVarID(ncid,'lat');
lat=netcdf.getVar(ncid,lat_id);

% get data z
z_id=netcdf.inqVarID(ncid,'z');
z=netcdf.getVar(ncid,z_id);

% get Zonal and Meridional geostrophic Velocity data
ug_id=netcdf.inqVarID(ncid,'ug');
vg_id=netcdf.inqVarID(ncid,'vg');
% get the units
units=netcdf.getAtt(ncid,ug_id,'units');
% get all data (this is easy but it is too big may caused outoff Memory
ug=netcdf.getVar(ncid,ug_id);
vg=netcdf.getVar(ncid,vg_id);
% get part of the data
% Example: Anual level k data
ug=netcdf.getVar(ncid,ug_id,[0,0,k-1,0],[179,360,1,1]);
vg=netcdf.getVar(ncid,vg_id,[0,0,k-1,0],[179,360,1,1]);
ug(ug>1e30)=NaN; vg(vg>1e30)=NaN;   % set the garbage number to NaN.
% Example: Month m level k data
ug=netcdf.getVar(ncid,ug_id,[0,0,k-1,m],[179,360,1,1]);
vg=netcdf.getVar(ncid,vg_id,[0,0,k-1,m],[179,360,1,1]);
ug(ug>1e30)=NaN; vg(vg>1e30)=NaN;   % set the garbage number to NaN.
% Example: Winter level k data
ug=netcdf.getVar(ncid,ug_id,[0,0,k-1,13],[179,360,1,1]);
vg=netcdf.getVar(ncid,vg_id,[0,0,k-1,13],[179,360,1,1]);
ug(ug>1e30)=NaN; vg(vg>1e30)=NaN;   % set the garbage number to NaN.

% get Zonal and Meridional Velocity data
u_id=netcdf.inqVarID(ncid,'u');
v_id=netcdf.inqVarID(ncid,'v');\
% get the units
units=netcdf.getAtt(ncid,u_id,'units');
% get all data (this is easy but it is too big may caused outoff Memory
u=netcdf.getVar(ncid,u_id);
v=netcdf.getVar(ncid,v_id);
u(u>1e30)=NaN; v(v>1e30)=NaN;   % set the garbage number to NaN.
% get part of the data
% Example: Anual level k data
u=netcdf.getVar(ncid,u_id,[0,0,k-1,0],[179,360,1,1]);
v=netcdf.getVar(ncid,v_id,[0,0,k-1,0],[179,360,1,1]);
u(u>1e30)=NaN; v(v>1e30)=NaN;   % set the garbage number to NaN.
% Example: Month m level k data
u=netcdf.getVar(ncid,u_id,[0,0,k-1,m],[179,360,1,1]);
v=netcdf.getVar(ncid,v_id,[0,0,k-1,m],[179,360,1,1]);
```

```
u(u>1e30)=NaN; v(v>1e30)=NaN;   % set the garbage number to NaN.
% Example: Fall level k data
u=netcdf.getVar(ncid,ug_id,[0,0,k-1,16],[179,360,1,1]);
v=netcdf.getVar(ncid,vg_id,[0,0,k-1,16],[179,360,1,1]);
u(u>1e30)=NaN; v(v>1e30)=NaN;   % set the garbage number to NaN.

% close the data file
netcdf.close(ncid);
```

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Table 1. Extracted data type and characteristics.

Data Type	Characteristics
char	8-bit characters intended for representing text
byte	8-bit signed or unsigned integers
short	16-bit signed integers
int	32-bit signed integers.
Float/ real	32-bit IEEE floating-point
double	64-bit IEEE floating-point

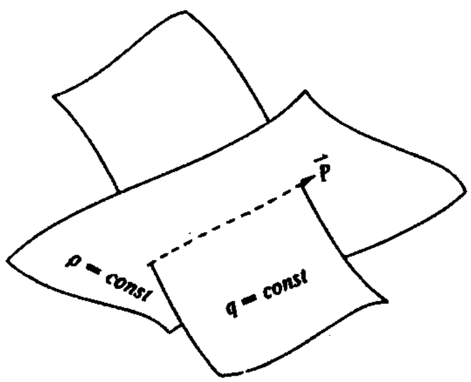

Figure 1. Intersection of surfaces of ρ and q (from Chu 1995, Marine Technology Society Journal).

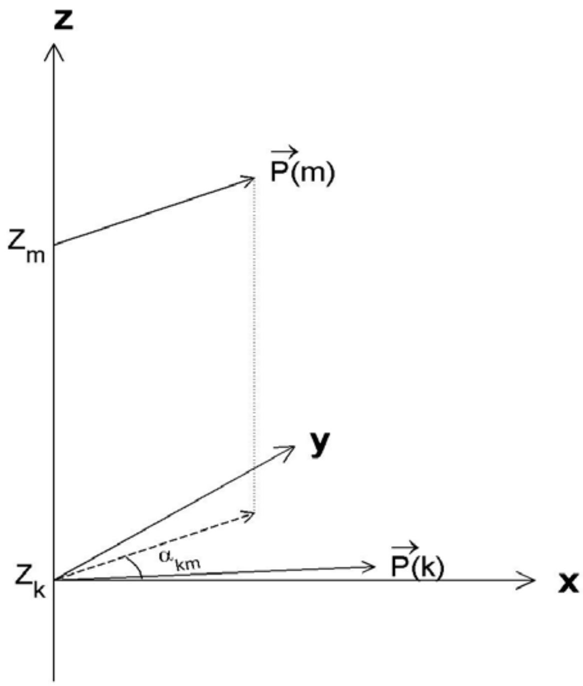

Figure 2. Illustration of **P**-spiral (left panel) and turning angle (right panel) α_{km} between two levels.

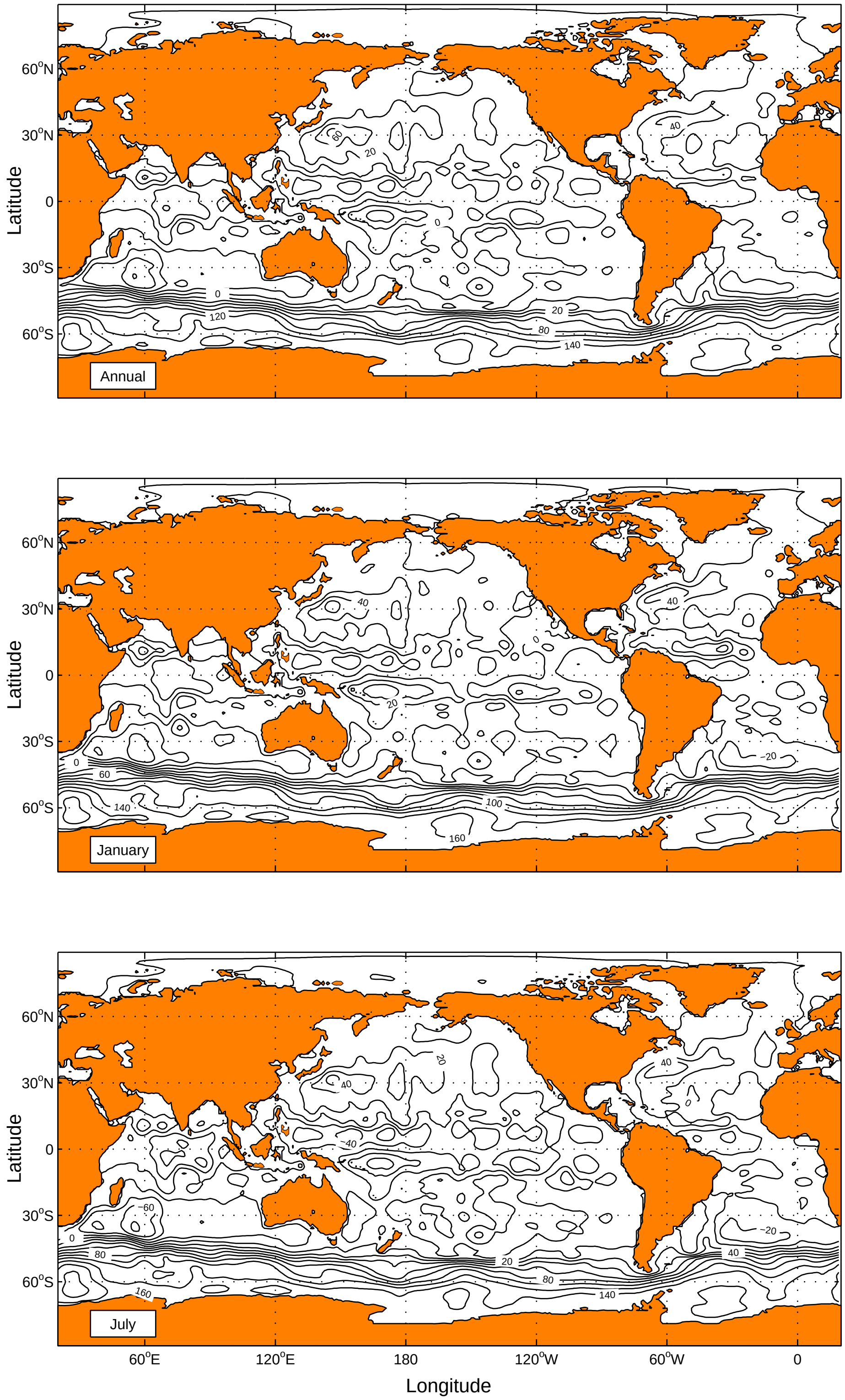

Figure 3. Inverted global volume transport stream function (unit: Sv): (a) annual mean, (b) January, and (c) July (from Chu and Fan 2007, Journal of Marine Systems).