Decadal Spinup of the South Pacific Subtropical Gyre

D. ROEMMICH, J. GILSON, AND R. DAVIS

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California

P. SUTTON

National Institute of Water and Atmospheric Research, Wellington, New Zealand

S. WIJFFELS

CSIRO Marine Research, Hobart, Tasmania, Australia

S. RISER

School of Oceanography, University of Washington, Seattle, Washington

(Manuscript received 17 May 2005, in final form 15 November 2005)

ABSTRACT

An increase in the circulation of the South Pacific Ocean subtropical gyre, extending from the sea surface to middepth, is observed over 12 years. Datasets used to quantify the decadal gyre spinup include satellite altimetric height, the World Ocean Circulation Experiment (WOCE) hydrographic and float survey of the South Pacific, a repeated hydrographic transect along 170°W, and profiling float data from the global Argo array. The signal in sea surface height is a 12-cm increase between 1993 and 2004, on large spatial scale centered at about 40°S, 170°W. The subsurface datasets show that this signal is predominantly due to density variations in the water column, that is, to deepening of isopycnal surfaces, extending to depths of at least 1800 m. The maximum increase in dynamic height is collocated with the deep center of the subtropical gyre, and the signal represents an increase in the total counterclockwise geostrophic circulation of the gyre, by at least 20% at 1000 m. A comparison of WOCE and Argo float trajectories at 1000 m confirms the gyre spinup during the 1990s. The signals in sea surface height, dynamic height, and velocity all peaked around 2003 and subsequently began to decline. The 1990s increase in wind-driven circulation resulted from decadal intensification of wind stress curl east of New Zealand—variability associated with an increase in the atmosphere’s Southern Hemisphere annular mode. It is suggested (based on altimetric height) that mid-latitude gyres in all of the oceans have been affected by variability in the atmospheric annular modes on decadal time scales.

1. Introduction

Prior to the World Ocean Circulation Experiment (WOCE) experiment of the 1990s, there was no systematic collection of global subsurface ocean data. The long-running expendable bathythermograph networks have a strong Northern Hemisphere bias and only follow shipping routes. Except for a few locations where repeated surveys were carried out, the pre-WOCE large-scale ocean circulation could be viewed only as a static or time-invariant entity because of limited data. This has now changed with the WOCE survey, followed by repeat hydrographic transects of the Climate Variability and Predictability (CLIVAR) program, sustained satellite altimetric height measurements, and the global Argo array of profiling floats. The ocean’s role in climate variability can now be observed. The present work was stimulated by a study of global ocean heat storage from 1993 to 2003 (Willis et al. 2004). An intriguing finding was that the maximum in zonally integrated warming over the past decade occurred at 40°S, where the 4 W m⁻² of warming in the upper 750 m was more than 4 times the global average. In the present
work, this spatial inhomogeneity in ocean warming is explained by the deepening of isopycnal surfaces that signal the spinup of deep ocean gyres.

The most energetic patterns of extratropical variability in the lower atmosphere are the annular modes—the Northern Hemisphere annular mode (NAM), or Arctic Oscillation, and its counterpart, the Southern Hemisphere annular mode (SAM), or Antarctic Oscillation. Positive values of these indices correspond to strengthened subpolar westerly winds and weakened subtropical westerlies and, therefore, to increased wind stress curl over the midlatitude ocean gyres. Positive trends in the amplitude of both annular modes over two or more decades have been described, beginning about 1970 in the case of the NAM (Thompson et al. 2000) and 1979 or earlier in the case of the SAM (Thompson et al. 2000; Marshall 2003; Renwick 2004). The decadal trends, plus large interannual variability represented in the northern and southern annular modes, have provided a substantial fraction of the low-frequency wind forcing for subtropical and subpolar ocean circulation variability.

In the North Atlantic, Curry and McCartney (2001) described an increase of about 30% in the Gulf Stream and North Atlantic Current transport between 1970 and 1995, forced by increases in wind stress and buoyancy fluxes. They showed a similarity between this transport variability and the North Atlantic Oscillation, which is closely related to the NAM. The North Atlantic has had relatively intensive hydrographic and meteorological sampling, and sustained time series ocean records exist at a few locations. Similar studies of long-term ocean variability have not been possible elsewhere.

Results from a coupled model were used by Hall and Visbeck (2002) to describe the impacts of changes in the SAM on the circulation of the Southern Ocean. Their focus was on high latitudes, where strengthened westerlies resulted in increased northward Ekman transport, divergence of the surface transport near Antarctica, and acceleration of the Antarctic Circumpolar Current. At middle latitudes around 40°S they noted increases in Ekman convergence, SST, and westward flow as effects of an increased SAM. Our description will correspond to this midlatitude part of their domain, and more specifically, in the South Pacific sector.

The present study utilizes a combination of datasets. High-precision altimetric sea surface height (SSH) data have been collected continuously since late 1992. The SSH dataset provides essential space–time context for interpreting sparser in situ datasets. The WOCE hydrographic survey included many transects in the South Pacific between 1991 and 1996, plus middepth velocity measurements from autonomous floats. A key WOCE transect along 170°W in 1996 repeated earlier occupations of that line in 1968 and 1990, and was repeated again in 2001. Last, the Argo profiling float project deployed floats over most of the South Pacific in 2004. As Argo matures and provides denser coverage, it becomes a subsurface counterpart to SSH, measuring time variability in dynamic height on large spatial scales. The floats also provide direct measurements of velocity at 1000-m depth, continuing the WOCE time series. It is the combination of all of these datasets that makes the present study possible. In the following we will first describe the 12-yr variability in SSH and then its relation to subsurface changes in dynamic height and velocity observed in the decade between WOCE and Argo. Last, the decadal change in wind forcing is described.

2. The South Pacific decadal signal in sea surface height

The maximum in zonally integrated ocean warming at 40°S was observed by Willis et al. (2004) in both subsurface temperature, 0–750 m, and in satellite SSH, which is dominated by thermosteric effects on interannual time scales. There are now 12 complete years of high-precision altimetric height data from 1993 to 2004. In Fig. 1 the time mean altimetric height for each 2-yr interval is plotted as the difference from the initial 2-yr mean, 1993–94. These figures use the altimetric height product by the Archiving, Validation and Interpretation of Satellite Oceanographic Data Project (AVISO; Ducet et al. 2000), which merges Ocean Topography Experiment (TOPEX)/Poseidon and European Remote Sensing Satellite (ERS) series altimeter data for improved spatial coverage.

Over the complete 12-yr span of the SSH dataset (Fig. 1), there is both a spatial mean increase in SSH of a few centimeters, corresponding to the global rise over this period, and a much greater increase in the western South Pacific at 40°S. East of New Zealand the increase in SSH is more than 12 cm at 170°W, diminishing eastward to about 5 cm at 120°W. Most of the total SSH rise in this feature occurs in the early years of the record between 1993–94 and 1999–2000 (Figs. 1a–c).

While the increase in SSH east of New Zealand is the most prominent signal in the 12-yr record, there are other substantial interannual anomalies in the South Pacific as well. A high in SSH appears at the northern edge of the domain in Fig. 1 in the early years and then coalesces with the high east of New Zealand in 2001–02.
Another high at about 45°S, 110°W increases in magnitude through most of the record until 2001–02 and then subsides in 2003–04.

In the following section it is seen that the pattern of SSH increase east of New Zealand is aligned more closely with the deep circulation of the subtropical gyre in the South Pacific than with the surface circulation. The decadal SSH signal is indicative of changes extending from the sea surface to depths greater than 1800 m. It also coincides with the decadal change in wind stress forcing.

### 3. Spinup of the deep subtropical gyre

#### a. Argo-minus-WOCE dynamic height change

At the ocean surface, the South Pacific subtropical gyre circulation is centered near 17°S (Reid 1986, Fig. 5). The change in sea surface height from the eastern boundary to the gyre center along 17°S is about 70 cm. As is characteristic of subtropical gyres, the gyre center shifts poleward with increasing depth. At depths of 1000 m and greater, the gyre is split into two parts by New Zealand and the surrounding ocean ridges. A nar-
row recirculation lies in the western Tasman Sea while the main gyre is centered east of New Zealand near Chatham Rise at about 40°S (Reid 1986, Fig. 23). The change in dynamic topography across the gyre at 1000 dbar is about 15 dynamic centimeters, and there are vestiges of the gyre as deep as 3500 dbar.

To show the decadal change in the deep subtropical gyre circulation, data from WOCE and the Argo float project (Fig. 2) are used. WOCE hydrographic transects were carried out in the southern Pacific during 1991–96 along the tracks shown in Fig. 2. Most of the Argo float deployments in the southern Pacific took place in 2004, and the 8751 Argo profiles used here span the period from July 2003 to June 2005. Locations of Argo profiles are shown in Fig. 2 (gray dots). Argo delayed-mode quality control procedures (Wong et al. 2003) were used to detect and adjust the slow salinity drift that occurred in some floats. Results of the present analysis are not sensitive to those adjustments.

Dynamic height (DH) maps were drawn from WOCE and Argo data using an objective mapping procedure (Bretherton et al. 1975). For both sets of maps, the gridded World Ocean Atlas 2001 (WOA01; Conkright et al. 2002) was used as an initial estimate. The WOCE and Argo data were objectively mapped as differences from the WOA01 initial estimate, using a correlation function that was subjectively fit to the spatial correlation of differences between WOA01 and the later datasets. The correlation function includes an exponential with a 500-km decay scale plus a smaller-scale Gaussian with a 100-km decay scale:

\[ C = 0.5e^{-d/(500)} + 0.5e^{-d/(100)^2}, \]

where \( d \) is the distance in kilometers. This function is similar in form to the one used by Willis et al. (2004) to approximate the spatial correlation of altimetric height anomalies. It elevates the level of the large-scale component, consistent with the fact that the Argo and WOCE differences are relative to historical hydrographic data in WOA01 rather than to contemporaneous data. In other words, the long time-scale variability of Argo minus WOA01 differences has a clear large spatial-scale component.

The objective maps are not very sensitive to the specific choice of a functional representation of the spatial correlation (e.g., Davis 1998). What is important is that the functional form provides a positive definite correlation matrix, and that sensible choices are made of the signal decay scales and the signal-to-noise ratio. Here, we have chosen the parameters so that the functional representation approximates correlation estimates based on the data pairs. Testing with a range of parameters shows little sensitivity to moderate variations. Nevertheless, one should keep in mind the wide gaps between WOCE transects (Fig. 2). An even greater concern is the temporal spread of the WOCE survey, as discussed below.

The dynamic height at 1000 dbar relative to 1800 dbar (1000/1800 dbar) from the WOCE and Argo datasets is shown in Figs. 3a and 3b, and 200/1800 dbar is shown in Figs. 3d and 3e. An increase in dynamic height between the WOCE and Argo eras is evident near the center of the gyre over a broad region east of New Zealand (Figs. 3c and 3f). The DH increase east of New Zealand, extending from 170°W to beyond 150°W, is about 3 dynamic cm at 1000 dbar and more than 5 dynamic cm at 200 dbar, with these increases
tapering off to zero toward the north, south, and east. There is thus an increase in the slope of the dynamic topography of the gyre. In terms of the dynamic height difference between the rim and center of the gyre, say from 28° to 44°S along 170°W, this corresponds to a spinup of the geostrophic circulation by more than 20% at 1000 dbar. The Argo-minus-WOCE differences (Figs. 3c and 3f) are noisy because mesoscale variability...
affects the mapping of both datasets, especially the more sparsely sampled WOCE data.

Maps of Argo-minus-WOCE temperature change (Fig. 4) further illustrate the depth structure of the spinup signal and its intensity in terms of temperature anomaly. Large-scale temperature anomalies near the gyre center are greater than 0.25°C at 1000 dbar (Fig. 4, top) and 0.05°C at 1800 dbar (Fig. 4, bottom), the deepest level consistently sampled by the floats. The deep signal is predominantly one of isopycnal heave rather than $T-S$ change, although there is some $T-S$ change as well. The substantial temperature anomalies at 1000 and 1800 dbar demonstrate that the spinup signal extends deep into the water column. For comparison, in the study of Willis et al. (2004), the global zonally averaged temperature increase in the upper 400 m from 1993 to 2003 was greater than 0.3°C at the 40°S maximum.

There are several notable differences between the patterns of 12-yr SSH increase (Fig. 1) and the Argo-minus-WOCE dynamic height increase at 200 dbar (Fig. 3f). These are largely attributable to sampling limitations.

1) The ~12 cm SSH increase has about 2 times the magnitude of the DH increase at 200 dbar. Since about half of the SSH increase had occurred by 1995–96 (Fig. 1a), and the WOCE P15S transect along 170°W was obtained in 1996, the Argo-minus-WOCE difference map (Fig. 3f) shows proportionately less increase along 170°W.

2) Part of the SSH signal is due to warming in the upper 200 m (see Willis et al. 2004, Fig. 13). A warming of the upper 200 m by 0.5°C raises sea level by about 2 cm. However, since the WOCE data are single realizations rather than annual averages, we have not extended the DH maps into the seasonally varying surface layer.

3) The maximum in SSH increase is fairly narrow from west to east (falling off east of 165°W), while the maximum in DH increase extends beyond 150°W. The P16S transect along 150°W was performed in 1991. Thus, the Argo-minus-WOCE DH maps represent the relatively smaller change over the shorter period from 1996 to 2004 along 170°W and the larger change over the longer period from 1991 to 2004 along 150°W.

4) The SSH anomalies are centered at about 40°S while the DH anomalies near Chatham Rise are centered at about 44°S. The offset in the DH anomaly is probably an artifact of mesoscale variability in the 1996 WOCE P15S transect along 170°W.

WOCE was intended conceptually to produce a “snapshot” of global ocean circulation, but the 6-yr time span of the southern Pacific WOCE survey complicates its interpretation. The substantial large-scale variability on interannual scales during the 6 years, plus the mesoscale variability along transects and large separations between them, limit the ability to characterize the basin as a whole for the WOCE period.

b. The hydrographic time series along 170°W

Further insight into the 170°W signal and the sampling issues is obtained from considering a number of hydrographic transects that have been occupied along that longitude. These include the Southern Cross expedition in 1968, a pre-WOCE transect in 1990, the 1996 WOCE P15S line used in our objective mapping, and another repeat transect obtained by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 2001. The 1968 line followed 170°W. The 1996 and 2001 occupations followed the westward jog shown in Fig. 2, to Chatham Rise at about 44°S. The
1990 transect took a similar but reduced jog to the west. Hence, differences include spatial ones as well as temporal variability on a range of scales. For each of these transects, the dynamic heights at 200/1800 and 1000/1800 dbar are shown in Fig. 5. Also shown are the corresponding dynamic heights from the Argo objective map (i.e., from Figs. 3b and 3e), along the same track followed by the 170°W hydrographic transects from 1996 and 2001. Argo profiles are plentiful near that track (Fig. 2).

What is most clear in Fig. 5 is that a large dynamic height increase, 200/1800 dbar, occurred between the 1968 Southern Cross transect and the 2003–05 Argo data, over a broad latitude interval between 36° and 48°S along 170°W. At 40°S the increase was more than 12 dynamic cm. There is substantial eddy noise as well as interannual variability. The 2001 transect was comparable to Argo at 40°S. The 1990 and 1996 transects were similar to one another but with values less than both the 2001 transect and Argo at 40°S.

A summary version of the 170°W time series is made by averaging DH (200/1800 dbar) and SSH over a latitude band representing the decadal anomaly. Figure 6 shows the result of averaging along the 170°W meridian between 38° and 42°S, and the figure is little changed if averaged from 38° and 46°S. Here, the Argo DH is displayed as a time series, calculated by including an additional temporal correlation (Gaussian, 3-month decay) in the objective mapping procedure, and then smoothing with a 12-month running mean, as with the SSH data. An equivalent result is obtained if the 2-yr Argo dataset is broken into two 1-yr pieces with a single DH estimate from each. The DH increase from the 1996 transect to the 2001 transect to the 2003–05 Argo time series is consistent with the continuous SSH dataset. Unfortunately, the SSH series does not cover 1990, when the hydrographic transect indicated high values. It is therefore not clear whether the high in 1990 represents large-scale variability or mesoscale eddies along the hydrographic transect. Based on both SSH and Argo DH (Fig. 6), the gyre center appears to have reached its maximum height at about the end of 2003, subsequently decreasing in 2004–05.

A more detailed comparison of Argo DH and SSH, retaining the annual variability, is shown in Fig. 7. Here, Argo DH is shown for the sea surface, that is, 0/1800 dbar rather than 200/1800 dbar, and the 12-month running mean filter is omitted from both datasets. Al-
though the temporal overlap of SSH and Argo DH is only 2 yr, the excellent agreement of the datasets demonstrates the potential of Argo to provide a subsurface analog to satellite altimeters.

c. Float velocity data

During WOCE, floats were deployed about every 250 km along the hydrographic transects (Fig. 2), drifting at about 900 m. These instruments provided trajectory data, but not profiles, from the endpoints of each 25-day drift cycle. Because of their long cycle time and lack of CTD, the WOCE floats had long battery life, and some instruments spanned the interval prior to the early Argo deployments in 2003. The circulation of the tropical and South Pacific, based on 300 WOCE floats providing 1332 float years of velocity observations through 2003, is described by Davis (2005). Argo floats have a 10-day cycle time, and were deployed in large numbers in the South Pacific beginning in 2004. The Argo dataset includes 240 float years between July 2003 and January 2005.

Because geostrophic velocity is proportional to the horizontal gradient of pressure, its spectrum is less red than that of dynamic height, making velocity a noisier measurement. This and the nonuniform float coverage between 1997 and 2002 preclude accurate year-by-year velocity mapping. Instead, the time-varying strengths of two specified circulation patterns were estimated by least squares, maximum likelihood fitting of the patterns to the velocity observations. The two patterns were the geostrophic velocity fields associated with DH (1000/1800 dbar) from WOA01 and from Argo (Fig. 3b). The fitted time-varying amplitudes minimize the sum (over 1-yr time periods and the region 26°–56°S and 150°E–70°W) of the squares of the observed velocity minus the fitted pattern velocity, normalized by the expected noise variance. The noise variance was estimated from the Taylor eddy diffusivity and observation record length as in Davis (2005). In fact, noise in the fitting context is the velocity from mesoscale eddies (described by the diffusivity) as well as all circulation patterns other than the one being fitted. The estimated amplitude errors resulting from mesoscale variability are 10%–20%, but this is unrealistically small because other large-scale sources of error are neglected. Experiments fitting data over different time periods suggest that errors in 1-yr amplitudes are nearer 40% and approximately serially uncorrelated.

Figure 8 shows the time series of amplitudes based on the WOA01 and Argo DH patterns. Both amplitude time series show the gyre strength increasing substantially during the mid-1990s, followed by a decrease in 2003–04. That the variability in the two patterns is similar shows the method’s robustness to reasonable changes in gyre pattern. The velocity amplitudes fitted to the Argo DH pattern are smaller than to WOA01 because the Argo circulation pattern is itself stronger than the one based on earlier data. That is, the offset of the solid line from the dashed one in Fig. 8 is itself evidence that the Argo-era circulation was stronger than in historical WOA01 data. The increase in strength
during the 1990s is consistent with the DH variability near 40°S, 170°W (Fig. 6). The downturn in circulation seen in 2003 and 2004 in the velocity data is also consistent with the SSH and Argo DH data, albeit with a suggestion that it occurs first in the velocity data.

Differences between velocity and dynamic height can be rationalized by differences in the nature of the measured quantities as well as the noise and sampling issues. Dynamic height anomalies are due entirely to changes in the density field—baroclinic variability—while velocity anomalies are due to a combination of barotropic and baroclinic effects. The fact that a downturn is seen first in the velocity data may be indicative of the faster time scale of the barotropic response to diminished wind stress curl (next section). A well-sampled continuous time series of both velocity and dynamic height is necessary for a complete description.

Each of the datasets described here has limitations, but together they provide a consistent interpretation of the variability in the midlatitude South Pacific between 1993 and 2005. The altimetric height maps (Fig. 1) show that SSH east of New Zealand increased by about 12 cm, with most of the increase occurring in the first half of the record. The pattern of SSH anomaly indicates an increasing anticlockwise geostrophic circulation centered near 40°S, 170°W. This location is near the center of the deep portion of the subtropical gyre, and the height anomaly therefore represents an acceleration of the deep gyre. Argo profile data from 2003–05 in comparison with WOCE hydrographic data from the early 1990s confirm the acceleration (Fig. 3), though sampling issues complicate the direct quantitative comparison of DH and SSH. The Argo-minus-WOCE temperature comparison (Fig. 4) shows that the signal penetrated deep into the water column, to depths greater than 1800 m, again consistent with changes in the deep portion of the subtropical gyre. Data along 170°W from 1968 suggest that the gyre acceleration described here has a multidecadal time scale, although unresolved interannual and mesoscale variabilities are substantial. The SSH and DH near the gyre center along 170°W (Fig. 6) peaked in late 2003 and dropped during 2004–05. Further confirmation of the 1990s spinup is found in float trajectory data (Fig. 8), which also reinforce the finding that the circulation at 1000 m began to drop near the end of the record.

4. Atmospheric forcing

What is the variability in wind forcing that drives the changes in circulation of the subtropical gyre? Thompson and Wallace (2000) defined the Antarctic Oscillation (a.k.a. SAM) as the leading principal component of the 850-hPa height anomaly in the region south of 20°S. It accounts for 27% of the variance in monthly mean sea level pressure fields (Thompson and Wallace 2000), and positive values of the SAM project onto stronger westerly winds at about 55°S and onto easterly anomalies (weaker westerlies) in subtropical latitudes. The SAM had a positive trend in recent decades (Thompson et al. 2000), though Marshall (2002, 2003) found that it was exaggerated in the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis in comparison with the data. Renwick (2004) showed that the SAM trends in NCEP–NCAR and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses came into good agreement after the advent of satellite observations in 1979. Other modes of variability are also important on interannual scales (e.g., White 2004).

A time series of the SAM, smoothed with both a 1- and a 5-yr running mean, is shown in Fig. 9. This figure uses the time series of the monthly SAM index provided by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center based on the 700-hPa height from the NCEP–NCAR reanalysis (Kalnay et al. 1996). A pronounced increase in the 5-yr running mean is seen from 1990 to 1999. Here, the SAM index (Fig. 9) is used only to suggest appropriate times for examining the 1990s decadal change in the wind forcing east of New Zealand. The full sea level pressure (SLP) and wind stress fields from the NCEP–NCAR reanalysis are then examined for differences...
in this interval. Figure 10 shows the difference between 5-yr running means of SLP centered on 1999 and 1990. It also shows the anomaly in Ekman pumping resulting from the mean wind stress difference between these two 5-yr periods. The decadal increase in wind stress curl centered east of New Zealand is evident. The anomalous gradient in SLP amounts to several hecto-pascals between the deep ocean gyre’s center and its edges, and the wind stress change produces 10 m yr$^{-1}$ or more of increased (downward) Ekman pumping over a broad region.

The pattern of change in SLP (Fig. 10) coincides remarkably well with the deep gyre’s structure and its pattern of acceleration (Figs. 3a–c). The wind pattern gives rise to anomalous Ekman convergence at 40$^\circ$–45$^\circ$S and divergence at high latitude. As described by Hall and Visbeck (2002), this pattern leads to acceleration of the zonal flows extending to great depth—in the eastward-flowing Antarctic Circumpolar Current (ACC) and southern limb of the subtropical gyre and in the westward northern limb of the gyre. As they note, the convergence at 40$^\circ$S depresses the thermocline and causes elevated sea surface temperature (Fig. 10, bottom), especially on the northern, warm-water side of the anomaly.

Following its 1999 peak, the 5-yr smoothed SAM has decreased (Fig. 9). For a decreasing SAM, the effects of the decadal increase should begin to diminish. In the previous sections (Figs. 6 and 8) a decrease during 2003–04 was noted in the float velocity field and in 2004–05 in the SSH and DH. Thus, there is a lag of about 4–5 years between the peak forcing and the peak response. This is consistent with a part of the signal being due to the propagation of baroclinic waves, as described by Qiu and Chen (2006). The shortness of the lag indicates that most of the forcing occurred in the west, since propagation across the basin requires a much longer time (e.g., Qiu and Chen’s Fig. 4). Further work is needed to separate the locally forced and propagating responses.

5. Discussion

A spinup of the deep subtropical gyre in the South Pacific during the 1990s, due to an increased wind stress curl as part of a decadal or longer increase in the SAM, has been described. The decadal circulation signal in the South Pacific is clear, based on SSH, dynamic height, and float velocity datasets. The gyre spinup is revealed by downward displacement of isopycnal surfaces and increased SSH at the gyre center, along with increased counterclockwise circulation in the middepth.

Fig. 10. (top) The change in SLP (contours, hPa) and the change in Ekman pumping (m yr$^{-1}$) between an initial 5-yr period centered on 1990 and another centered on 1999, from the NCEP–NCAR reanalysis. Note the anomaly in the wind stress curl and Ekman pumping east of New Zealand. (bottom) The change in sea surface temperature (°C) for the same period.
velocity measurements. These changes in the gyre were also responsible for the maximum in zonally integrated ocean warming at 40°S observed by Willis et al. (2004). In the pre-Argo era, the subsurface datasets were not continuous in time or in space, and the intermittent sampling results in uncertainties in the spinup signal’s magnitude and timing. An objective for future work is to describe the evolution of both the barotropic and baroclinic components of the gyre-scale circulation, and to fully account for the relationship of the SSH with the subsurface density and velocity fields.

The South Pacific gyre spinup has a number of broader implications, and raises the following questions that are beyond the scope of the present work.

1) Model studies have suggested that positive changes in the SAM may result from greenhouse warming (e.g., Kushner et al. 2001) and ozone depletion (e.g., Shindell and Schmidt 2004). Distinguishing between anthropogenic climate change and natural decadal variability is important for understanding whether the 40°S ocean warming signal (Willis et al. 2004), and the corresponding ocean circulation changes described here, will continue and intensify or reverse in the coming decades. The decadal South Pacific warming signal has significant regional climate effects, for example in New Zealand air temperature and perhaps rainfall (Sutton et al. 2005).

2) It is plausible that decadal climate variability as described here has effects on fisheries and marine ecosystems. New Zealand’s largest commercial fishery, the hoki, has declined to a present stock that is estimated at 13% of its 1972 biomass (Bradford-Grieve et al. 2004). These authors speculate that a cause of the hoki decline may be ocean warming and a reduced supply of nutrients in the euphotic zone. The enhanced Ekman convergence and downward displacement of isopycnals described in the present work provide a physical mechanism consistent with a reduction in surface-layer nutrient supply.

3) The decadal circulation signal seen in the South Pacific is likely to have a global expression. The pattern of the SAM projects onto all three Southern Hemisphere oceans. The 40°S maximum in zonally integrated ocean heat gain described by Willis et al. (2004) is a global signal, including contributions from the South Atlantic and South Indian Oceans. Preliminary examination of SSH and DH data from the South Atlantic suggests that a similar gyre spinup has occurred there. It is likely that decadal increases in the annular modes of the atmosphere have impacts on the subtropical and subpolar circulation in all ocean basins.

4) There is previous evidence of changes in precipitation minus evaporation at high latitudes in both hemispheres. Decadal freshening of intermediate waters has been observed in all of the oceans (Wong et al. 1999; Wong et al. 2001; Curry et al. 2003). Are the circulation variability described here and the salinity anomalies observed previously both symptoms of the same decadal variability in the atmospheric annular modes? Changes in the midlatitude storm tracks would be expected to have impacts on ocean dynamics through forcing by a wind stress curl and on water mass characteristics through precipitation minus evaporation.

5) The decadal anomaly in SST (Fig. 10) is substantial, about 0.5°C over a large area. The SST anomaly may be the result of anomalous Ekman convergence due to the SAM, as suggested by Hall and Visbeck (2002). The presence of a substantial SST anomaly not only affects the regional air temperature in New Zealand, but also raises the question of whether oceanic feedback might contribute to decadal variability of the midlatitude atmosphere.

The physical description of the oceans needed to address these broader implications will be provided by a completed and long-term sustained Argo array. At present, there are more than 330 active Argo floats south of 20°S in the Pacific, more than the total number of floats deployed there during WOCE. A comparable density of Argo floats is found in the South Atlantic and South Indian Oceans. In the Southern Hemisphere oceans, which constitute two-thirds of the global ocean, the large-scale fields of density, dynamic height, and middepth velocity are now being measured continuously for the first time. A unique contribution of Argo is to open a window on the vast and remote southern oceans for better understanding of climate variability and change.

Acknowledgments. At an MIT “sack lunch” in 1976, upon finding no pointer available, seminar speaker Carl Wunsch picked up his turkey drumstick and began pointing it at the screen, in between bites. Carl has always made the best use of whatever tools, techniques, and datasets are available. The profound contributions of Carl Wunsch in stimulating the era of global ocean observations, in developing original techniques for the analysis and synthesis of the new datasets, and in teaching a generation of oceanographers are gratefully acknowledged.

The Argo data used here were collected and are made freely available by the International Argo Project and by the national programs that contribute to it (in-
formation online at http://www.argo.net. Analysis was
supported in part by the NASA JASON-1 project
through JPL Contract 961424 to SIO. The U.S. authors
and their part of the Argo project were supported by
U.S. Argo through NOAA Grants NA17RJ1231 (SIO–
JIMO) and NA17RJ1232 (UW–JISAO). The state-
ments, findings, conclusions, and recommendations
herein are those of the authors and do not necessarily
reflect the views of the National Oceanic and Atmo-
spheric Administration or the Department of Com-
merce. The deployment of Argo floats in the remotest
regions of the South Pacific was made possible through
a collaborative effort involving many individuals in
the U.S. and New Zealand (NIWA) Argo programs.
NIWA’s R/V Kaharoa (Captain Ron Palmer and crew
and marine science technician John Hunt) has deployed
over 200 floats to date and made an indispensable con-
tribution to Argo. Graphics were produced using Ferret
software, a product of NOAA’s Pacific Marine Envi-
rmental Laboratory. The AVISO altimeter products
were produced by the CLS Space Oceanography
Division as part of the Environment and Climate EU
ENACT project (EVK2-CT2001-00117) and with sup-
port from CNES.

REFERENCES

Bradford-Grieve, J., M. Livingston, P. Sutton, and M. Hadfield,
2004: Ocean variability and hoki decline. Water and Atmo-
sphere, Vol. 12, No. 4, NIWA Science, Wellington, New
Zealand, 20–21.

Bretherton, F. P., R. E. Davis, and C. B. Fandry, 1975: A tech-
nique for objective analysis and design of oceanographic ex-

Conkright, M. E., R. A. Locarnini, H. E. Garcia, T. D. O’Brien,
Ocean Atlas 2001: Objective Analyses, Data Statistics,
and Figures. CD-ROM documentation. National Oceanographic
Data Center, Silver Spring, MD, 17 pp.

Curry, R., and M. McCartney, 2001: Ocean gyre circulation
changes associated with the North Atlantic Oscillation. J.

Dickson, B., and I. Yashayaev, 2003: A change in the fresh-
water balance of the Atlantic Ocean over the past four de-

Davis, R., 1998: Preliminary results from measuring middepth cir-
ulation in the tropical and South Pacific. J. Geophys. Res.,
103, 24 619–24 639.

Davis, R. E., 2005: Intermediate-depth circulation of the Indian
and South Pacific Oceans measured by autonomous floats. J.

resolution mapping of ocean circulation from TOPEX/
19 498.

Hall, A., and M. Visbeck, 2002: Synchronous variability in the
Southern Hemisphere atmosphere, sea ice, and ocean result-
ing from the annular mode. J. Climate, 15, 3043–3057.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Re-

Kushner, P., I. Held, and T. Delworth, 2001: Southern Hemi-
sphere atmospheric circulation response to global warming. J.
Climate, 14, 2238–2249.

Marshall, G. J., 2002: Trends in Antarctic geopotential height and
temperature: A comparison between radiosonde and NCEP–

Qiu, B. and S. Chen, 2006: Decadal variability in the large-scale
sea surface height field of the South Pacific Ocean: Observa-

Reid, J., 1986: On the total geostrophic circulation of the South
Pacific Ocean: Flow patterns, tracers, and transports. Progress


climate response to ozone changes and greenhouse gas in-
2004GL020724.

Sutton, P., M. Bowen, and D. Roemmich, 2005: Decadal tempera-
ture changes in the Tasman Sea. N. Z. J. Mar. Freshwater

the extratropical circulation. Part I: Month-to-month vari-

White, W. B., 2004: Comments on “Synchronous variability in
the Southern Hemisphere atmosphere, sea ice, and ocean result-
ing from the annular mode.” J. Climate, 17, 2249–2254.

Willis, J. K., D. Roemmich, and B. Cornuelle, 2004: Interannual
variability in upper ocean heat content, temperature, and
thermosteric expansion on global scales. J. Geophys. Res.,

Wong, A. P. S., N. Bindoff, and J. Church, 1999: Large-scale freshen-
ing of intermediate waters in the Pacific and Indian

Davis, R. E., and Qiu, B., 2001: Freshwater and heat changes in
the North and South Pacific Oceans between the 1960s and 1985–
94. J. Climate, 14, 1613–1633.

Johnson, G. C., and W. B. Owens, 2003: Delayed-mode calibra-
tion of autonomous CTD profiling float salinity data
by theta-S climatology. J. Atmos. Oceanic Technol., 20, 308–
318.