**Technical Report**

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**A dataset of the wind-driven global ocean circulation for climate research**

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Abstract

Some 40 years after Sverdrup (1947) developed his fundamental wind-driven circulation theory, Australian scientist Dr. Stuart Godfrey, advanced it in an elegant and provoking way (Godfrey, 1989). He proposed an “Island Rule” and used it in conjunction with the Sverdrup relationship such that given a set of surface wind-stress field, global wind-driven circulation can be determined. We have applied this Island Rule model to monthly surface wind stress fields from NCEP (Kalnay et al., 1996) reanalysis and ERA40 (Uppala, et al., 2005) reanalysis to generate the wind-driven circulation history in terms of barotropic stream function and steric height. This dataset is now available to serve the global Earth system research community for climate model validation purposes and for description of variations and trends of the wind-driven ocean circulation.

# 1. Introduction: A brief description of the Island Rule models

For the interior ocean, the stream function  is determined by the Sverdrup relationship:

, (1)

Where,  is the Coriolis coefficient, and  is the surface wind stress. The flow along the western boundary, where the Sverdrup relationship breaks down, is calculated using the “Island Rule” for flows around an island, such as Australasia, New Zealand, and Madagascar (see upper panel, Fig. 1). The total flow is determined by the pressure head between each island’s northern and southern extremities, and is the integral of wind along the red loop, i.e.,

. (2)

We have calculated both the stream function and the steric heights for NCEP and ERA40 wind products, with the Indonesian Throughflow Passage open in a quasi-realistic topographic setting. The data provides monthly, annual mean and seasonal outputs of both variables in NetCDF format. These data are now available from the Tasmania Partnership of Advanced Computing (http://digitallibrary.tpac.org.au). The Indonesian Throughflow, which is the path integral of the wind stress around the red loop QRST (upper panel, Fig. 1, based on that calculated using NCEP winds), shows a realistic seasonal cycle, strongest in southern winter and weaker in southern summer (lower panel, Fig. 1).

# 2. Application caveat

One primary application is to calculate ocean climate trends. One of the primary assumptions of the Island Rule is that the wind forcing has acted on the ocean for a timescale longer than that of the oceanic adjustment, i.e., Rossby wave process, long enough such that the ocean can be assumed to be at a steady state. In other words, the timescale for Rossby wave to traverse from the eastern boundary to the western boundary, which is longer as latitude increases, must be shorter than the time duration within which a trend is to be determined. These time scales have been calculated by previous studies for the South Pacific (e.g., Qiu and Chen, 2006, Fig. 2). For example, at 45oS, it would take 22 years to compete the full Rossby wave adjustment process from the South Pacific's eastern boundary to its western boundary. To determine the wind-driven South Pacific circulation trend at this latitude from 1978-2003 (e.g., Cai, 2006), which is 25 years, the Island Rule can be applied. At any latitudes north of 45oS, e.g., in the tropics, where the Rossby wave adjustment time scale is much shorter, the Island Rule is applicable. For the same time duration (1978-2003) discussed above, one can use the Island Rule to calculate maps of the wind-driven circulation trends. We will discuss this further in section 3.4.

# 3. Examples of climate applications

## 3.1 Steady state

Due to lack of observations in the Southern Hemisphere, we have very little understanding of the seasonality of the ocean circulation. The Island Rule model can be used to reveal the seasonality of the wind-driven component. Fig. 3 displays such circulation for two seasons, the southern summer (upper panel) and the southern winter (lower panel). It shows a strong influence of the midlatitude westerly jet on the ocean. In summer, the subtropical ridge is at latitude furthest to the south. As a result, the associated wind stress curl, which determines the ocean circulation, moves furthest to the south, and the zero-curl line, which defines the southern-most boundary of the subtropical gyres, stretches across the three oceans, intersecting the South American coast (Fig. 2, Cai, 2006). This generates the so-called super-gyre circulation, linking the subtropical circulation of the South Pacific, South Indian, and South Atlantic. The flow of the East Australian Current (EAC) through Tasman Sea (Tasman leakage) veers into the Indian Ocean and to the South Atlantic. The super-gyre circulation is thought to be involved in the global thermohaline circulation, with the Tasman leakage contributing 3.2 Sv of the total 20 Sv of the North Atlantic Deep Water formation (Speich et al., 2006). In winter, as the wind system moves northwards, the gyre circulation in the South Pacific is isolated from the Indian and Atlantic circulation. The EAC separates from the coast at about 32oS. These wind-driven features are consistent with what is revealed by limited observations.

## 3.2 Decadal difference in the Pacific discharge/recharge via Sverdrup transport

The Pacific Ocean climate experienced a shift towards a warm state in the late 1970s, with marked changes in the ENSO properties and in many other circulation fields. During the post-1980 period, El Niños are stronger than La Niñas contributing to significant difference in the mean circulation between the pre- and post-1980 periods. In the post-1980 periods, the equal Pacific circulation features weaker equatorial easterlies, stronger positive curls from the equator to 5oN and negative curl in the 5oS – 15oS (Fig. 4a). The curls, through Sverdrup balance promotes a greater discharge of heat from the equatorial region and hence a shallower equatorial Pacific thermocline in the post-1980 period (Fig. 4b) (Jin, 1997; Meinen and McPhaden, 2000), consistent with an El Niño-like multidecadal-long condition for the post-1980 period. On interannual time scales, the discharge signal is transmitted into the WA coast and radiates into the Indian Ocean, leading to a shallower mean thermocline off the WA coast and throughout the southern tropical Indian Ocean (Fig. 4b).

Figure 5: Decadal difference in wind-driven circulation (1981-2000 average minus the 1960-1980 average). Unit in Sv. The post-1980 period features stronger ENSO, with greater discharge of heat from the equatorial Pacific to the extra-tropics.

Using the Island Rule calculation, we examine ways in which the discharge process operates. In the tropics, where Rossby wave time scale is short, the model is particularly applicable. The difference in the wind driven circulation (Fig. 5) features broad interior poleward flows. These are important pathways for discharging heat from the equatorial Pacific. Another way is the equatorward flows along the boundaries, replacing the discharged warm equatorial warm water with the off-equatorial colder water. These processes also operate in the southern tropical Indian Ocean, and are supported by negative wind stress curl (Fig. 4a).

## 3.3 South Pacific circulation trend over the past 15 years: comparison of other observations

Large-scale sea surface height (SSH) changes in the extratropical South Pacific Ocean have been investigated using satellite altimetry data (Qiu and Chen, 2006) and available hydrographic and Argo observations (Roemmich et al., 2006). In the midlatitude region south of 30oS, the decadal SSH signals are dominated by an increasing trend in both the western basin around New Zealand and the eastern basin centered around 45oS and 105oW. The change suggests a spin-up of the subtropical Pacific gyre circulation.

Roemmich et al. (2006) estimate that increase in SSH at 40oS 170oW over the period is about 10 cm. They also show that the spin-up penetrates into a depth as deep as 1800m. The extent to which changes in winds contribute to this spin-up can be investigated by the Island Rule model. Wind changes over the period are dominated by an upward trend of the Southern Annular Mode, with decreasing midlatitude westerlies and increasing westerlies at the polar latitudes (Thompson and Solomon, 2002).

Fig. 6a shows the trend in wind-driven steric height during1992-1994 in the unit of m2 per year. At the location of 45oS and 170oW steric height increases as much as 20 m2  per year. If we divide this value by 1800 m, we arrive at an increase of some 1 cm per year, or some 12 cm over the period, consistent with the Roemmich et al. (2006) result. It should be pointed out that the duration of 15 years in which our trend is calculated is marginally comparable to the Rossby wave time scale; as such we might have overestimated the impact of wind changes. However, a comparison with other studies suggests that within the timescale of Rossby wave, the Island Rule performs reasonably well. Fig. 6b shows the trend pattern Qiu and Chen (2006) obtained using a time dependent Rossby wave model for the period of 1992-2004. The two patterns resemble each other.

Figure 6: (a) Linear trend in steric height (m2 per year) obtained using the Island Rule model driven by NCEP wind, which compares well with the SSH trend map (mm per year) shown in (b) for the period October 1992 to December 2004 and obtained using a Rossby wave model (Qiu and Chen, 2006). In (b) black contours denote the climatological sea surface dynamic height.

## 3.4 Linking ozone depletion to ocean circulation changes

Recent climate trends over the Southern Hemisphere summer feature a strengthening of the circumpolar westerly and a weakening of the midlatitude westerly extending from the stratosphere to Earth’s surface (Fig. 7a). Much of the change is attributable to Antarctic ozone depletion (Thompson and Solomon, 2002; Gillett and Thompson, 2003). Although the maximum change of zonal wind stress is located far to the south at approximately 60oS, the maximum change of the wind stress curl, which is dominated by the meridional gradient of zonal wind stress, is located at approximately 45oS–50oS. According to (1) it is the wind stress curl, not the wind stress itself, that drives the large-scale ocean circulation. The consequential circulation resulting from the wind change is determined using the Island Rule model as shown in Fig. 7b (Cai, 2006).

Figure 7: (a) Trends of southern hemispheric summer NCEP surface winds over 1978-2002 (maximum vector 3 m per second), and (b) the associated ocean circulation trend calculated using the Island Rule model (Sv).

The result shows that the observed surface wind changes have forced a southward shift and spin-up of the super gyre, including a strengthening of the EAC flow passing through the Tasman Sea. The increase in the flow reaches approximately 20%. The result is consistent with the trend since 1992 as discussed above. This provides a good example of using the Island Rule model to link atmospheric circulation changes with those of oceanic circulation.

# 4. Summary

Over the past decades, reanalyses of both the atmosphere and the ocean have been generated and commonly used for research on climate variability and climate change. These include the NCEP/NCAR atmospheric circulation reanalysis, SODA, and the thermal reanalysis of the CSIRO and BMRC of the upper Pacific and Indian Ocean. Separately, there have been several other efforts that focused on a specific field of the coupled climate system, such as the sea level data set (Church et al., 2004) and the global rainfall dataset (Xie and Arkin, 1996). Here we provide a global wind-driven barotropic circulation dataset as part of the global reanalysis effort. The data sets include depth-integrated stream-function and steric heights calculated for ERA40 and NCEP monthly winds using Stuart Godfrey’s Island Rule Sverdrup model (Godfrey, 1989). The data is available to the Australian research community. In this report, we have provided a description of the dataset, caveats in using them, and examples of its applications. These include an examination of the temporal behaviour of the Indonesian Throughflow, trends of the ENSO discharge/recharge process in the Indo-Pacific system, and subtropical gyre spin-up associated with the Southern Annular Mode. A natural progression of the work would be a development of a time dependent Island Rule model, which explicitly incorporates the transient wave processes. This is currently being investigated (Godfrey, personal communication). In the ocean interior, this is relatively simple; however, flows around islands and approaching a western boundary would need to adjust to Kelvin-Munk waves as detailed in Godfrey (1975). We plan to generate a new data set once the time-dependent version is completed.

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