On the Indonesian Throughflow in the OCCAM Model

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Introduction

This poster reports on the Indonesian Throughflow as seen in the 1/4-degree version of the OCCAM Global Ocean Model when it is forced by climatological winds, based on the period January 1986 to December 1988, and by six-hourly winds from the period January 1992 to December 2000.

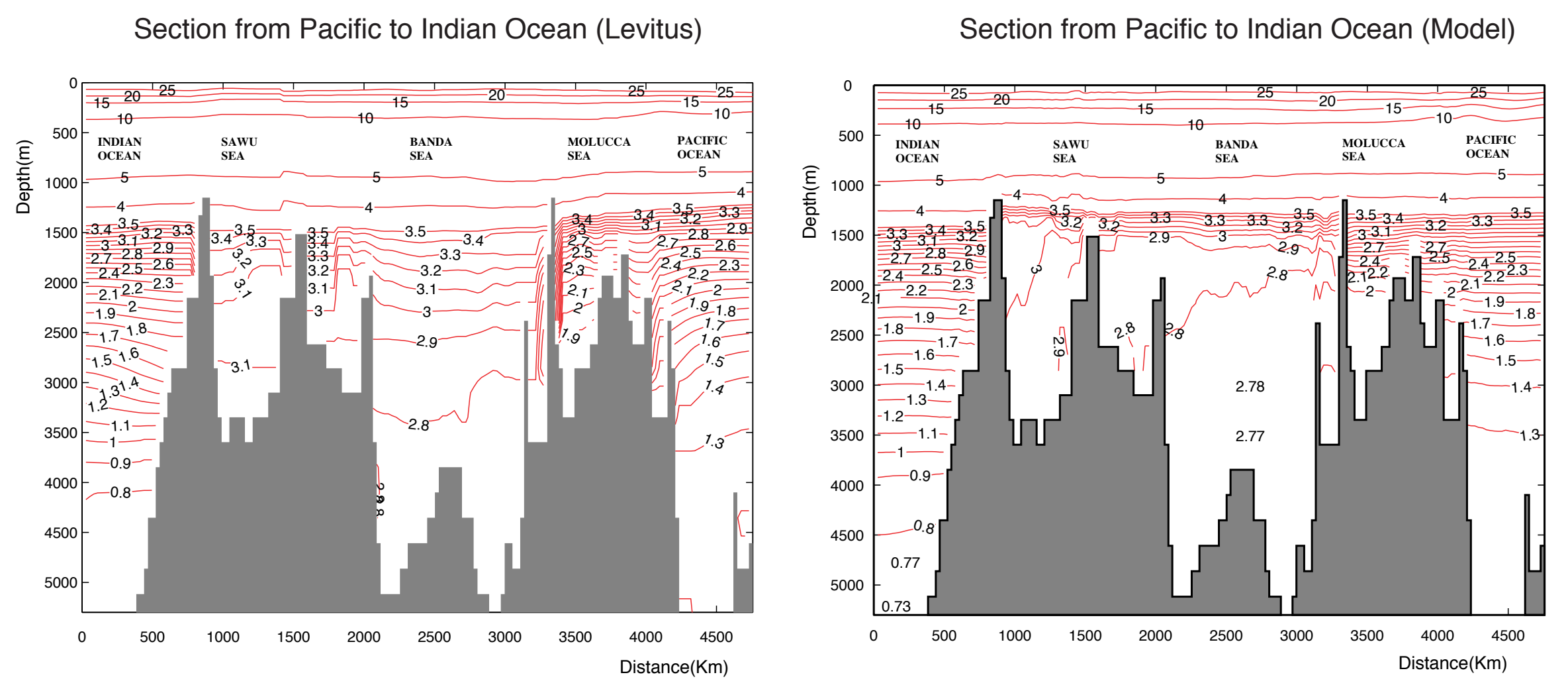
The Indonesian Throughflow is an important part of the large scale circulation of the ocean. Unfortunately it is a difficult place to make good measurements so it is a region for which model results, like these, can be particularly useful for investigating details of the flow and in planning and analysing observational programmes.

Pacific water flowing into the Indian Ocean can follow a number of routes. In the north there are four distinct passages, a shallow path through the South China Sea and deeper paths through the Makassar and Molucca Straits and the Halmerhera Sea. Further south there are shallow paths through the Malacca and Sunda Straits and deeper paths through the Lombok and Ombai Straits and the Timor Passage.

The actual path used by water at each depth in the ocean depends on both the topography and changes of the Coriolis force with latitude. One consequence of the latter is that steady north-south currents in the deep ocean are usually trapped against the western boundary. In the Indonesian region this means that most of the flow is expected to occur in the most western passage that does not contain a sill to block the flow. Thus in the north much of the flow is via the Macassar Strait and in the south the Lombok and Ombai Straits are important.

Bathymetry and Sills

When developing OCCAM's bathymetry we tried to ensure that all major sills were correctly represented. However we were not always successful. The figure below left shows the temperature field in the Indonesian region in the Levitus dataset. To the right is the model temperature field after eleven years. In the model, bottom temperatures in the Molucca Sea are reasonable but cold water has spilled over the sill into the Banda and Sawu Seas, decreasing the bottom temperatures there.


Section from Pacific to Indian Ocean (Levitus)

Section from Pacific to Indian Ocean (Model)

Total Transports

Transports were calculated through two sections, one through the straits in the north and one through those in the south. When the mean winds from 1986-88 were used, the average throughflow, based on six years model data, was 11.7 Sv. (see Table 1). This increased to 12.9 Sv with the 6-hourly winds when the model data were averaged over the six year period 1993-98. As both wind fields were based on ECMWF data, the difference may be due to differences in the wind climatology for the two periods. Changes in the analysis methods used may also have an effect. The flow through the southern section is 0.1 Sv greater than that in the north, the result of net precipitation in the area between the two sections.

As expected most of the transport through the northern section is via the Makassar Strait (5.7 Sv). There are also significant flows via the South China Sea, the deep Molucca Strait and the Halmahera Sea. Changes between the mean and 6-hourly wind runs are small, except for the Halmahera Sea where the transport more than doubles in the 6-hourly wind run to 3.4 Sv. This result is particularly unexpected because it is the most easterly of the deep passages.

In the south the bulk of the transport is through the relatively shallow Lombok Strait in the west and the deeper Ombai Strait. In the east 1.1 Sv also flows through the Timor Passage with monthly mean winds and this increases to 2.2 Sv with the 6-hourly wind field. Again the behavior is unexpected.

Table 1. The transport through the northern and southern sections. The transport is positive for flows towards the Indian Ocean. ($1\,\mathrm{Sv} = 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$).

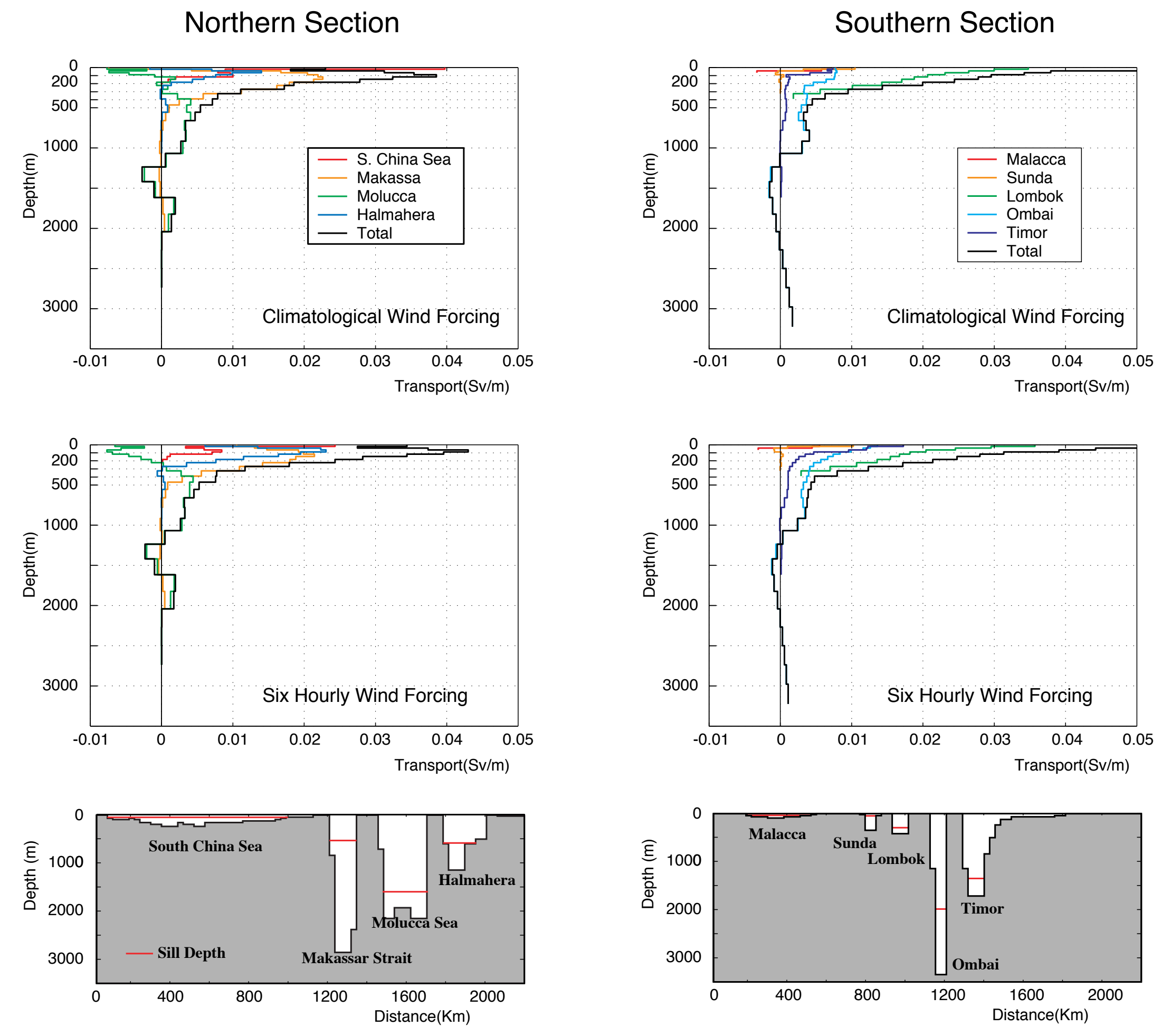
Sections	Width (km)	Depth (m)	Sill Depth (m)	Transport (Sv)	
				Mean Winds	6-hourly Winds
South China Sea.	1,000	240	40	1.7	1.2
Makassar Strait	160	2,800	550	5.7	5.9
Molucca Strait	250	2,200	1,600	2.1	1.8
Halmahera Sea	230	1,150	500	1.6	3.4
Torres Strait	140	20	20	0.6	0.6
			Total for Northern Section	11.7	12.9
Malacca Strait	350	100	20	0.2	0.1
Sunda Strait	100	350	20	0.3	0.2
Lombok Strait	80	430	350	5.7	5.6
Ombai Strait	80	3,400	2,000	4.5	4.9
Timor Passage	520	1,800	1,400	1.1	2.2
			Total for Southern Section	11.8	13.0

The OCCAM Model

The results shown here come from the first run of the OCCAM 1/4 degree global ocean model. The model was developed as part of the Ocean Circulation and Climate Advanced Modelling project (OCCAM). It is a primitive equation model, using level surfaces in the vertical and an Arakawa-B grid in the horizontal. The model differs from the standard Bryan, Cox and Semtner model in that it has a free surface, uses Split-Quick advection in the horizontal and an improved scheme for the vertical advection of momentum.

Sub-grid scale horizontal mixing is represented using a Laplacian operator, with coefficients of 1x10 $\mathrm{cm}^2\mathrm{s}^{-1}$ for diffusion and 2x10 $\mathrm{cm}^2\mathrm{s}^{-1}$ for kinematic viscosity. In the vertical, the model uses Pakanowski and Philander (1981) mixing for tracers and Laplacian mixing, with a coefficient of 1x10 $\mathrm{cm}^2\mathrm{s}^{-1}$, for velocity. The surface fluxes of heat and fresh water were obtained by relaxing the surface layer of the model to the Levitus monthly average values using linear interpolation to the model grid with a relaxation time scale of 30 days.

The model has 36 levels in the vertical, increasing in thickness from 20 m (plus the sea surface height) at the surface, to 250 m at the maximum depth of 5500 m. The model bathymetry is derived from the DBDB5 dataset. The depths of key sills and channels were checked manually and adjusted where necessary. The model was initialized with the Levitus82 potential temperature and salinity fields and with zero velocity and sea surface height.



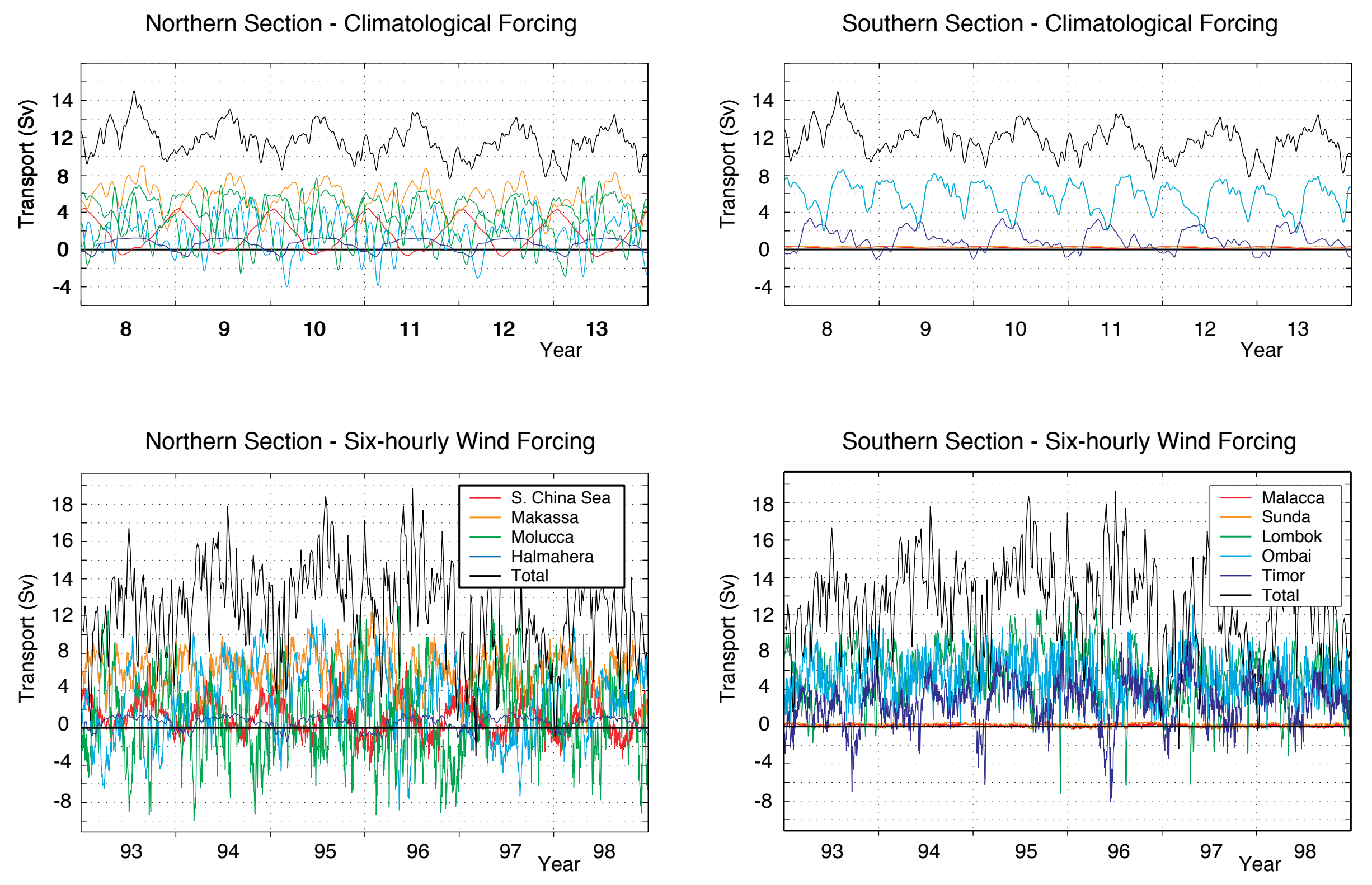
Section Transports

The figures on the left show the mean transport through each section and through each passage as a function of depth. Positive transports correspond to flow from the Pacific into the Indian Ocean. The top row shows the transport from the run forced by climatological winds, the middle row the transports with the six-hourly wind forcing. The topography of the sections is shown in the bottom figure, together with the sill depth for each of the passages.

The results show that over half the throughflow occurs in the top 400 m. In the north, in the climatological run, most of this is due to flow through the Makassar Strait. There is a positive contribution from the Halmahera and South China Seas, but in the surface waters the flow through the Molucca Strait is primarily northward into the Pacific. Below 400 m, flow in the Makassar Strait is blocked and all of the southward flow passes through the Molucca Strait, the passage with the deepest sill depth.

In the south, the climatological run again shows that most of the transport occurs in the top 400m. At these depths most of this transport is through the Lombok Strait in the west. Below 400m, this becomes blocked and most of the the flow switches to the Ombai Strait.

With six-hourly forcing the results are similar for all but two of the channels. The exceptions are the Halmahera Sea in the north and the Timor Passage in the south. In both cases there is a significant increase in the transport - a very unusual result given that they are both the most easterly deep passages in their section.



Time Series

The figures on the left show the transport time series for the northern and southern sections with both monthly climatology and six-hourly wind forcing. The red and orange colours correspond to straits in the west, blues to those in the east and black represents the total transport through the section.

The monthly climatological forcing repeats each year, so if there is no turbulence then once the initial transients have died out, the transports should be identical each year and relatively smooth, reflecting the twelve monthly wind stress values. This is true for the South China Sea (red curve at top left), probably because it is shallow and dominated by bottom friction, but the deep straits show much more variability.

The variability is largest in the northern section, the main signal having a period of about two months. In the south the variability tends to have shorter periods but the total transport through the two sections is similar. The latter result means that the waves causing variability in the north are trapped in the north, flow through one strait being balance by a return flow though another.

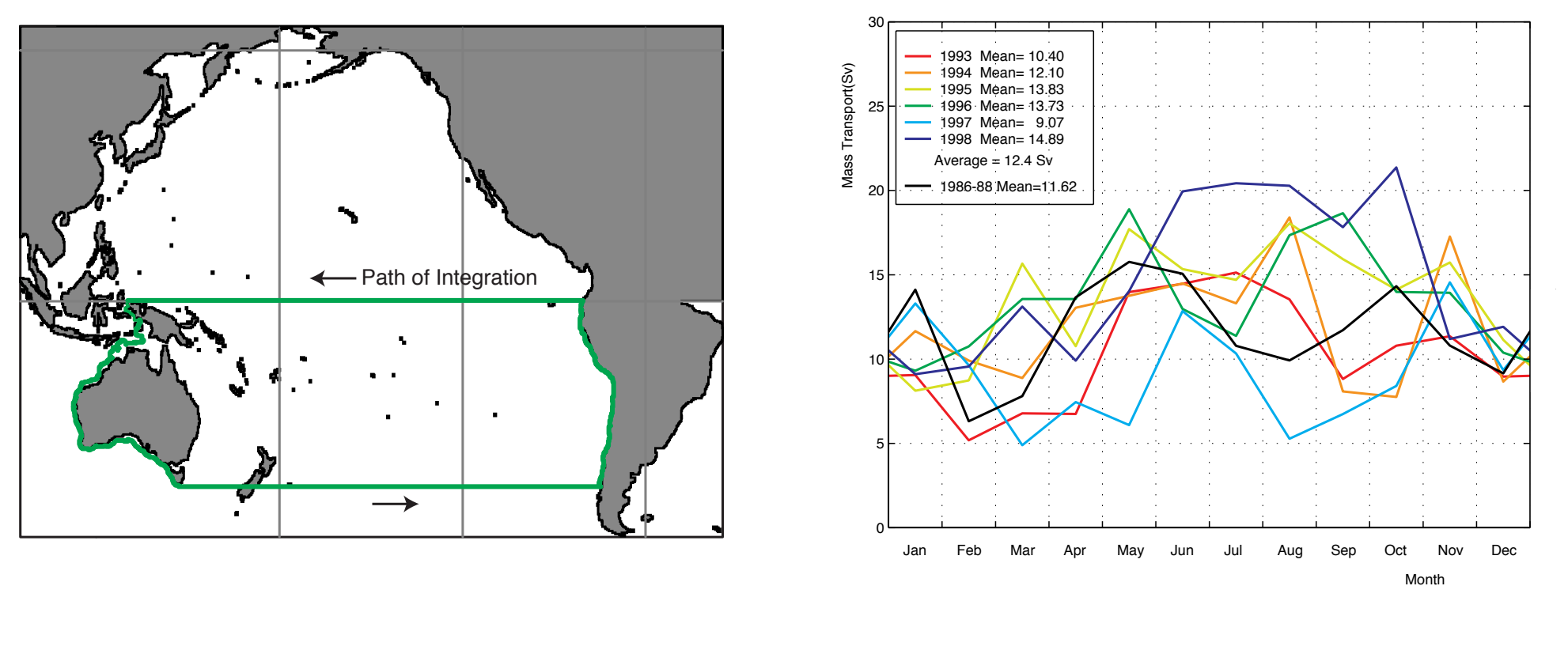
There is a dramatic change with six-hourly forcing, with a large amount of high frequency variability through both the northern and southern straits. At high frequency there is no discernable difference between the northern and southern section, implying that the waves are passing right through the region. However the northern section still has more variability at periods around two months.

Godfrey's Island Rule

Godfrey's Island Rule can be used to predict the mean northward transport in the S. Pacific. As the transport through Bering Strait is small, the result should be a good approximation to the total Indonesian Throughflow. Previous work has shown that the annual throughflow in the OCCAM model is about 90% of that predicted in this way and that at a period of six months there is still a significant correlation.

The figures below show the contour used to calculate the S. Pacific transport and the instantaneous values of the transport estimate with the climatological winds and the six-hourly winds. Godfrey's Rule predicts a significantly higher transport with the six-hourly winds. This is consistent with the present model results. It may indicate an actual change in the transport between the 1986-88 and 1993-98 periods.

Mass Transport across the South Pacific using Godfrey's Rule



Conclusions

The results from the OCCAM model show that:

1. The annual mean transport in the Indonesian Throughflow lies in the range of 12 to 13 Sv.
2. Over half the flow occurs in the top 400m. In the north most of this flow is via the Makassar Strait, but there is also a significant throughflow via the Halmahera Strait. In the south most of the shallow flow is via the Lombok Strait.
3. Below 400, the main flow is via the Molucca Strait in the north and via the Ombai Strait in the south.
4. In the six-houly wind run, which uses winds from the 1990's, there is a significant increase in the transport through the Halmahera Sea and Timor Passage in the east. This may be related to the increased northward flow in the South Pacific predicted by Godfrey's Island Rule.
5. There is considerable variability in the flow. With six-houly winds the total transport can reach 18 Sv. It can also reverse in direction. Variability is seen at seasonal scales and at high frequencies with periods of just a few days. In the northern sections there is also significant energy at periods around two months.