The role of tropical interocean exchange of the Indonesian Throughflow in climate variability

Janet Sprintall
Scripps Institution of Oceanography, USA

Collaborators: Adèle Révelard (Ecole Normale Superieure de Paris); Susan E. Wijffels (CSIRO); Robert Molcard (L’Ocean, France); Arnold L. Gordon (LDEO); Henrik van Aken (NIO, Netherlands)
the Indonesian Throughflow (ITF)

- the only tropical inter-ocean exchange site (~15 Sv)
- transports heat and freshwater from Pacific into Indian Ocean
- pressure gradient between Pacific (high) and Indian Ocean (low) (Wyrtki, 1987)
- complex bathymetric region with strong mixing
- closely coupled to the Australasian Monsoon system; El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD)

Gordon et al., 2008
The ITF warms the Indian Ocean and cools the Pacific (relative to no ITF condition) causing the tropical deep precipitation to shift west and affect the global atmospheric circulation. (e.g. coupled GCM, Schneider, 1987).

The ITF is a net transport of freshwater from the Pacific into the Indian Ocean. Changes in P (mm/d) due to closure of ITF. Solid (dash) lines are increased (decreased) rainfall. Shading is significant at 95% c.i. (See also Hirst and Godfrey (1993); Lee et al., 2002)

Closed ITF -> ENSO more energetic, shorter time scale, more warm events (Song, Vecchi and Rosati, 2007)
• Yes/No ITF experiments ignore impact of circulation changes (both air and sea) so difficult to separate out impact of ITF or atmospheric forcing or both.
• Open ITF experiments show impact on stratification, circulation, surface heat fluxes and SST in Indian Ocean (Song and Gordon, 2004; Potemra and Schneider, 2007; etc)

ITF10 – 10Sv ITF
ITF10TH – thermocline intensified ITF

Cooler SST in ITF10TH than in ITF10 in most of Indian Ocean north of 20S, particularly along NW Australia. -> net heat gain from atmosphere is 0.02 pW more in IT10TH than ITF10
• Pacific: Wind stress curl variability drives upwelling/downwelling Rossby waves that convert to coastal Kelvin waves that propagate along the NW Australian shelf
• Indian: equatorial wind bursts generate upwelling/downwelling Kelvin waves that become coastally trapped along the Sumatra/Java coast to enter Indonesian seas

Dispersion relationship show ray paths (i.e. curves along which energy propagates) travel vertically and horizontally such that high-frequency energy dives deeper than low frequency energy (i.e. interannual signals confined near main thermocline)

Drushka et al (2009)
ITF and Climate Modes

- ITF: pressure gradient between Pacific (high) and Indian Ocean (monsoonal low)

El Niño -> trades reverse ->
pressure gradient lower ->
ITF low (v.v. La Niña)?

IOD+ -> easterly wind anomalies
-> upwelling KW -> ITF stronger
(v.v. with westerly wind anomalies)

SST: red warm/blue cold
White: convective activity
Arrows: Wind anomalies
**INSTANT Interannual Transport Anomalies**

- **2004 El Nino**
  - reversed in surface
  - stronger at depth

- **2006 El Nino/IOD+**
  - stronger surface
  - reversed at depth

Similar in all passages over same depth ranges: phase break at 150m -> upper and lower layer opposed.

- ENSO variability unclear with only 3-year time series!

(Sprintall et al., JGR, 2009)
Partition the ITF transport through each outflow passage: vertical structure of the ITF profile different in each strait

Each outflow strait transports water with different properties at different depth levels -> different impact on tropical Indian Ocean heat/freshwater export and SST patterns

(Sprintall et al., 2009)
Transport and SSHa Lagged Correlations

Positive correlation -> positive SSHa and weaker ITF

(see also Potemra, 1997; 2005; Wijffels and Meyers, 2003)
Best fit of lagged partial linear regression of regional SSHa ($\eta$) boxes and INSTANT transport ($Q$) over 0-150 m and 150-sill depths. Lags varied from 0 - 140 days.

Coefficients statistically tested for difference from zero and comparison of the complete and reduced model. Bootstrapping test for robustness.

Negative into Indian Ocean (i.e. ITF)
Observed and Predicted Transport: Ombai Strait

- Reasonable agreement in upper 150 m
- Stronger predicted transport > 150 m especially at beginning of time series which corresponds to seasonal maximum in deep ITF transport

INSTANT Seasonal Mean Transport
Observed and Predicted: Seasonal Transport

General good agreement between 3-year INSTANT (dashed) and predicted (solid) seasonal transport over depth layers and total ITF.

Phase differences in Timor and Ombai transport.

Interannual Anomalies: Remove seasonal cycle and apply 180-day low pass filter.
Predicted Anomalous Transport: Trends

0-150 m:
- 18-year trends increased transport in Lombok (-0.04±0.003 Sv/yr -> -0.7Sv) and Timor (-0.04±0.003 Sv/yr -> -0.7Sv) and reduced in Ombai (0.03±0.001 Sv/yr -> 0.6Sv)
- Stronger Lombok 2006-2010

150-sill depth:
- opposing trends
Timor (-0.042±0.003 Sv/yr -> -0.75Sv)
Ombai (0.135±0.003 Sv/yr -> 2.4 Sv)

Full Depth:
- opposing trends mean little long term trend in TOTAL ITF (0.05±0.005 Sv/yr -> 0.8Sv)
Increased and shoaling **Makassar Strait** velocity: upper layer flow toward Indian Ocean (reds) (Gordon et al., GRL, 2012)

2006-10 increased Lombok Transport (Response to changed ENSO variability)
Trends: ITF Response to Pacific TradeWinds

- Pacific trade wind intensification since 1990s -> higher sea level -> models show increased ITF (Lee and McPhaden, 2008; Merrifield, 2011; Merrifield and Maltrud, 2011; Feng et al., 2011 etc)
- 18-year ITF transport increases in Lombok and Timor (both layers)

1993-2010: Colors: Linear trend in SSHa
Vectors: ECMWF wind stress trend
(Merrifield and Maltrud, 2011)
Longer Term: Decadal Pacific Wind Changes

Multi-decadal weakening of the Pacific trade winds over the past 6 decades is associated with a slowdown of the Walker Circulation

Tokinaga et al., Nature, 2012
(see also Vecchi et al., 2006; Held and Soden, 2006)
Observed ITF Response to Decadal Pacific Wind Change

Weaker Pacific winds -> SEC (ITF) diminished in size and strength
-> ITF decrease by 2.5 Sv (25%)
Observed ITF Response to Decadal Pacific Wind Change

Cooling thermocline

Wainwright et al., GRL, 2008
Tropical I.O. at ITF latitude range -> subsurface cooling corresponding to shoaling of thermocline and increased vertical stratification at base of MLD

1960-1999: T-trends IPCC AR4 Models

Alory et al., GRL, 2007
Mechanism: Shoaling of Pacific thermocline associated with the weakening Pacific trade winds propagate RW into the Indian Ocean that shoal the I.O. thermocline (i.e. remotely driven and oceanic transmission by ITF)

R=-0.78 between subsurface I.O temperature trend and Pacific tropical wind trend

Alory et al.. GRL, 2007
ITF plays an important role in the heat and freshwater of both the Pacific and Indian Ocean on time scales of relevance to climate — feeds back to regional precipitation patterns.

Trends:
- increased Timor Strait transport due to increased west Pacific sea level from early 90s through present
- long-term trends suggest a weakening of the Walker Cell in response to a warming climate and this acts to decrease ITF and shoal the thermocline in the Indian Ocean.

Both responses are consistent with the idea that ENSO (Pacific) response is stronger in Timor Passage through transmission via Rossby and coastal Kelvin Waves.
Interannual Variability: ENSO and IOD

IOD$^+$: 94, 97, 06, 07, 08
IOD$^-$: 96, 98, 10

Typically begins ~April, peaks Aug-Sep, decays Nov-Dec

El Niño: 94, 97, 02, 04, 06, 09
La Niña: 95, 98, 99, 00, 07, 10

Typically peaks Nov-Jan
Interannual Variability: ENSO and IOD

IOD+: 94, 97, 06, 07, 08

El Niño: 94, 97, 02, 04, 06, 09

Form composites (Apr-Jan) of El Nino solo and El Nino/IOD+

El Niño Expectation: Reduced ITF
Interannual Variability: ENSO and IOD

IOD-: 96, 98, 10

La Niña: 95, 98, 99, 00, 07, 10

Form composites (Apr-Jan) of La Nina solo and La Nina/IOD-

La Niña Expectation: Stronger ITF
Solo El Niño:
- decrease in upper layer Lombok and Timor
- increase in deep Ombai

Concurrent El Niño and IOD+:
- strong ITF in upper layer Lombok and Ombai
- reversed at depth

Timor and Lombok behave as expected during El Niño
La Niña Variability: Average Transports (Sv)

Solo La Niña:
- increase in both shallow and deep Timor

Concurrent La Niña/IOD-:
- weak in upper layer Ombai and Timor
- strong deep Ombai
- small sample!

Only Timor behaves as expected during La Niña
Equatorial Zonal Wind Stress Anomalies

- Concurrent El Nino and IOD+ events: equatorial Pacific and Indian Ocean zonal wind stress correlated & out of phase (modulation of the Walker Cell) -> partial cancellation of wind effect that drives the ITF.
- but larger wind response in Indian Ocean ...
Outline

- Develop proxy Indonesian ThroughFlow (ITF) transports for the outflow passages using INSTANT transport and the 18-year altimeter time series
- Examine long-term trends and variability
- Investigate relationship of ITF transport to IOD and ENSO phase
- Conclusions
Ombai Strait Deployment (Molcard et al., 2001):
- Single year mooring deployment (1996)
- Single mooring at INSTANT Ombai South location
- Vertical resolution of velocity instrumentation poor
  >150 m with effective sill depth of 1250 m
El Niño and El Niño/IOD+ Anomalies

- El Niño solo -> reduced upper layer flow in Lombok and Timor as expected (Pacific RW influence?). Similar result to Pacific driven long-term trends.

- El Niño/IOD+ -> easterly wind response in Indian Ocean -> lower SSHa due to:
  1. Upwelling KW
  2. Offshore Ekman transport
Both act to enhance upper layer transport

- El Niño/IOD+ -> weaker ITF at depth -> intermittent downwelling KWs (as in 2006)??
La Niña and La Niña/IOD− Anomalies

- **La Niña Solo:** marginal impact on SSH in west Pacific. Slightly higher SSH in off-equatorial Pacific region could be RW signal (McClean et al., 2005). Only Timor has stronger ITF.

- **La Niña/IOD−:** Stronger SSH response in both Pacific and Indian with higher SSH. In Indian, westerly winds force downwelling KW that reverse flow in outflow passages.

**Sea Surface Height Anomalies**

**Wind Stress Anomalies**
SUMMARY

• Long term trends -> increased Timor Strait transport due to increased west Pacific sealevel -> consistent with the idea that ENSO response is stronger in Timor

• Concurrent IOD+/El Nino events: surface stronger but reversals at depth “consistent” with expected Pacific ENSO response but IOD+ wind forcing likely more influential.

• Continue to explore relationships with wind stress

• Caveat: Full-depth velocity and property measurements still needed to verify proxy transports and to obtain the climatically meaningful direct estimates of the heat and freshwater transport profiles.
The INSTANT Field Program

- Mooring and shallow pressure gauge array in Indonesian Throughflow (ITF)
- December 2003 - June 2005 - December 2006
Indian Ocean Dipole (IOD)

SST: red warm/blue cold
White: convective activity
Arrows: Wind anomalies

Easterly wind anomalies (blue) -> lower SSHA -> upwelling KW -> shoal thermocline -> (stronger ITF?)
Westerly wind anomalies (red) -> higher SSHA -> downwelling KW -> depress thermocline -> (weaker ITF?)

Horii et al., 2008
• Pacific: Wind stress curl variability drives upwelling/downwelling Rossby waves that convert to coastal Kelvin waves that propagate along the NW Australian shelf
• Indian: equatorial wind bursts generate upwelling/downwelling Kelvin waves that become coastally trapped along the Sumatra/Java coast to enter Indonesian seas

Dispersion relationship gives slopes of ray paths (i.e. curves along which energy propagates)
• Free KWs disperse eastward along vertical ray paths with slopes $\sigma/N$
• Long RW energy dives westward with slopes $(2l+1)\sigma/N$ where $N$ is Brunt-Vaisala buoyancy frequency, $\sigma$ is wave frequency $l$ is meridional wave number.

Hence high-frequency energy dives deeper than low frequency energy (i.e. interannual signals confined near main thermocline)

ITF and ENSO

- ITF: pressure gradient between Pacific (high) and Indian Ocean (monsoonal low)
- El Niño -> trades reverse -> pressure gradient lower -> ITF low (v.v. La Niña)?

Average thermocline temperature and volume transport from Makassar mooring shows high correlation with SOI. e.g. 97-98 El Niño -> lower transport & shallower thermocline (Gordon et al., 1999)
Kelvin Waves and the ITF

IO westerly wind
Downwelling (reverse ITF)

IO easterly wind
Upwelling (enhance ITF)

Composite Transport Anomalies (Sv/m)
from INSTANT 2003-2006
Drushka et al., 2011
La Niña Zonal Wind Stress Anomalies

- La Nina solo: stronger easterlies in West Pacific

- El Nino/IOD- strong westerlies in region due west of Sumatra, not so much impact on wind round outflow straits
El Niño Zonal Wind Stress Anomalies

- Larger easterly wind response in Indian Ocean -> IOD+ strong easterlies drive upwelling Kelvin wave that acts to enhance upper layer ITF (Lombok and Ombai) -> enhance heat transport
Observed and Predicted Transport: Ombai Strait

Subinertial Transport (Sv/m: 2004-2006)

Seasonal Transport (Sv/m)

(Sprintall et al., 2009)
Interannual Variability: ENSO and IOD

No significant IOD event:

1999 - 2001: “cold” phase
2002 - 2005: “warm” phase
Composite of full depth transports show stronger transport in **Timor Passage** during “cold” phase.
Composite of full depth transports show weaker transport in **Lombok Strait** during “warm” phase.

Near normal full depth transports in **Ombai** and **Timor**
• La Nina/cold phase: Pacific and Indian Ocean cancellation of wind effect?
• Pacific response only in Timor deep layer?
La Nina Variability: Average Transports (Sv)

As in “cold” phase: main response in Timor Passage during sole La Nina episodes

Small sample size: weaker surface layer and stronger deep in Ombai (opposite to IOD+)
ENSO Variability: Average Transports

Cold Phase

0-150 m: Lombok and Timor response “as expected”

150 m - sill: Timor response same in cold and warm phase

Full Depth: Timor response as expected in cold phase and “cancelled” in warm phase
ITF Transport and Climate Variability: Correlation

NINO3 correlation significant in Timor and Ombai (shallow/deep layers out of phase)

Modoki correlation significant in Timor and Lombok in surface layer

Indian Ocean Dipole significantly correlated in Lombok and Ombai -> out of phase with deep layer