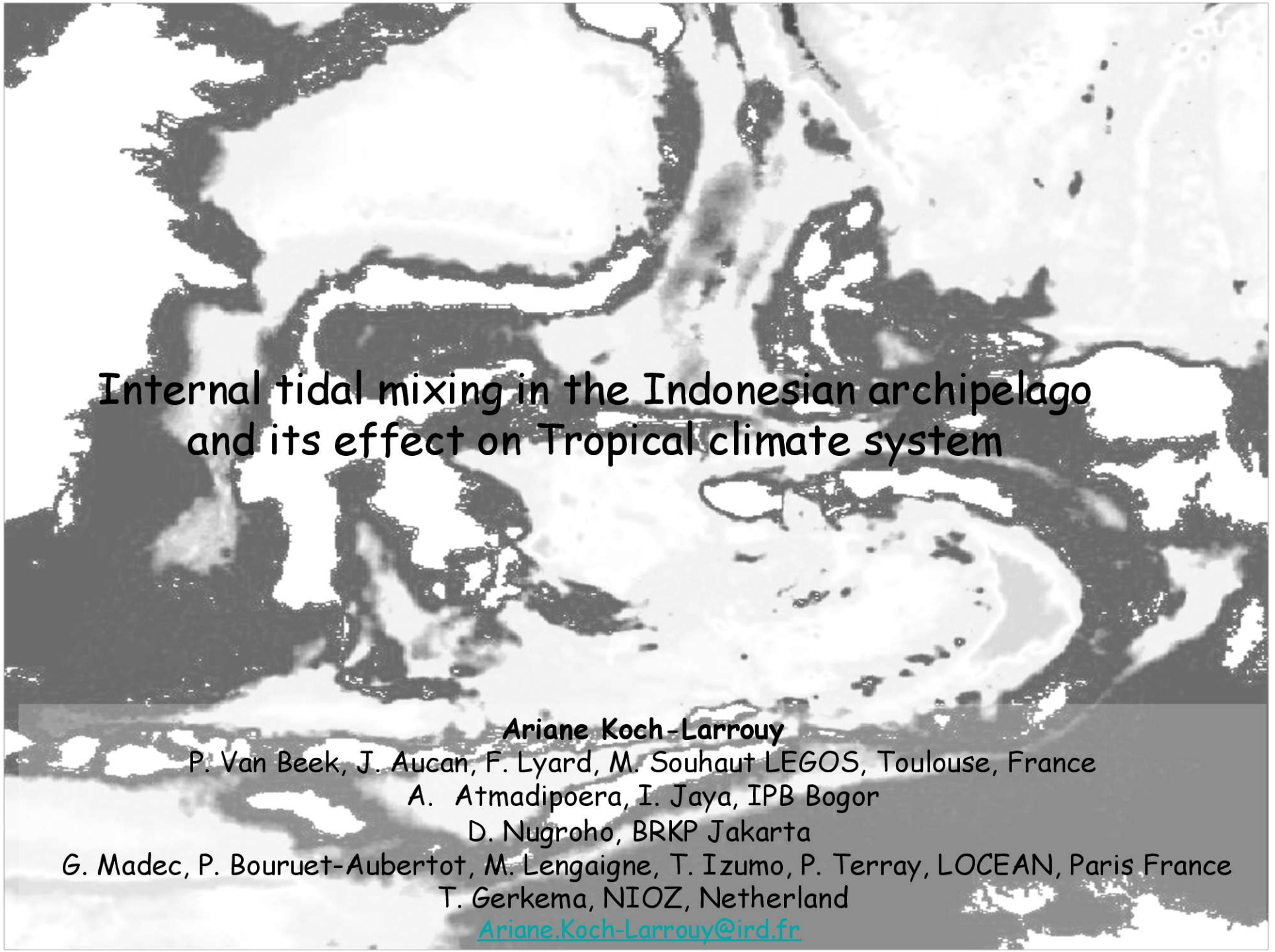
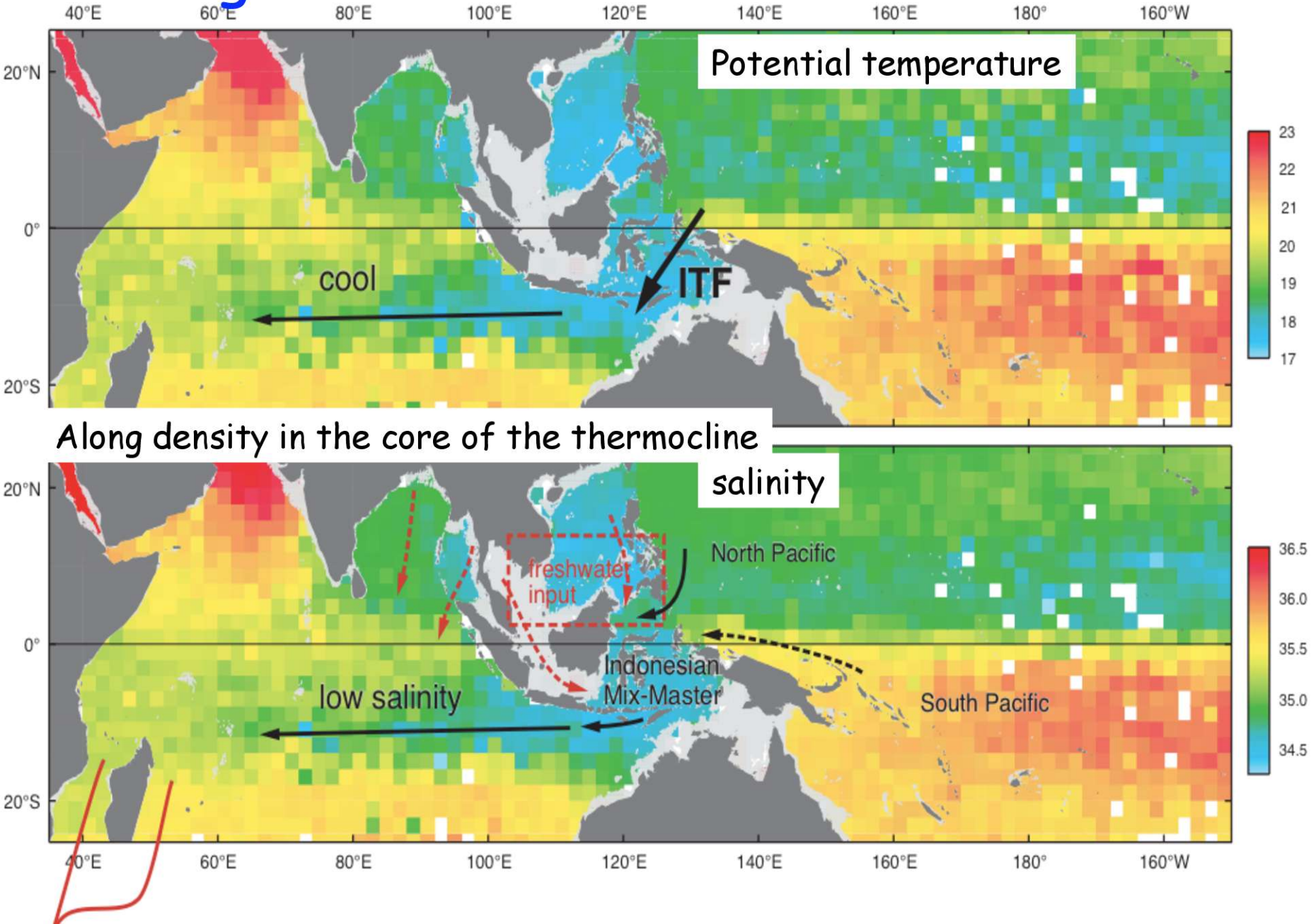


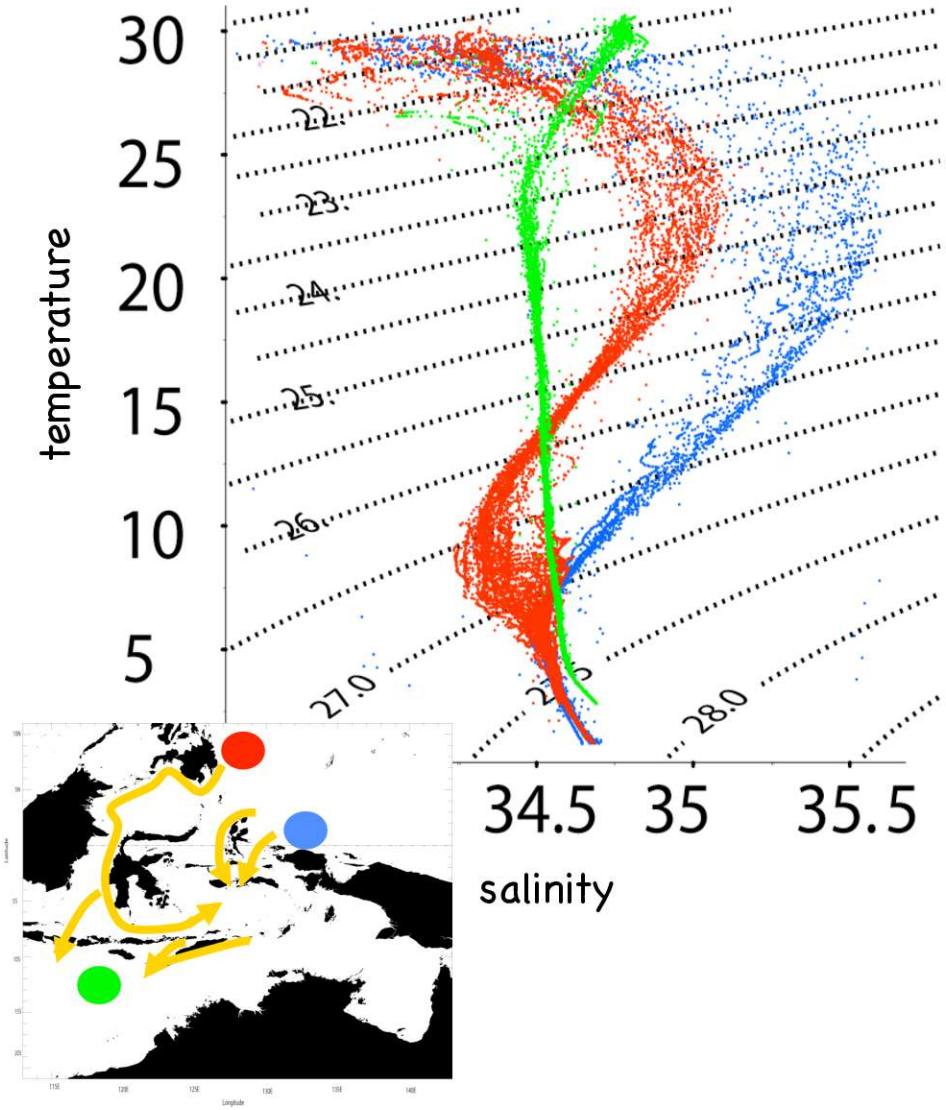
Internal tidal mixing in the Indonesian archipelago and its effect on Tropical climate system

Ariane Koch-Larrouy
P. Van Beek, J. Aucan, F. Lyard, M. Souhaut LEGOS, Toulouse, France
A. Atmadipoera, I. Jaya, IPB Bogor
D. Nugroho, BRKP Jakarta
G. Madec, P. Bouruet-Aubertot, M. Lengaigne, T. Izumo, P. Terray, LOCEAN, Paris France
T. Gerkema, NIOZ, Netherland
Ariane.Koch-Larrouy@ird.fr

Indonesian archipelago
= strong water mass transformation



Indonesian archipelago
= strong water mass transformation



Advection diffusion model

-> strong vertical mixing
Kz ~ 1-2 cm^2/s

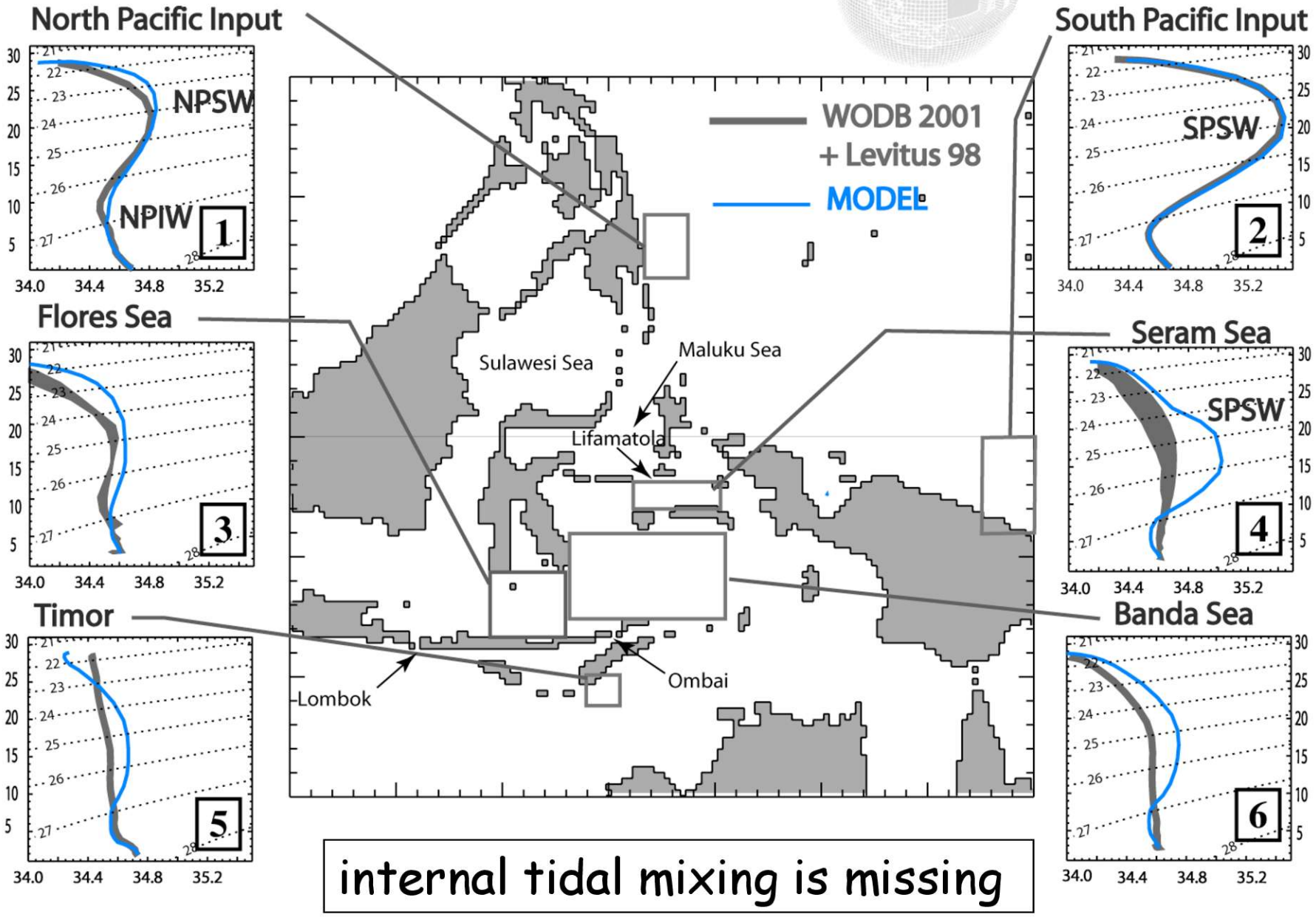
Hautala et al 1996, Ffield et Gordon 1996

= 10 times > open ocean

best candidate

Internal Tides ?

What about in the model ?

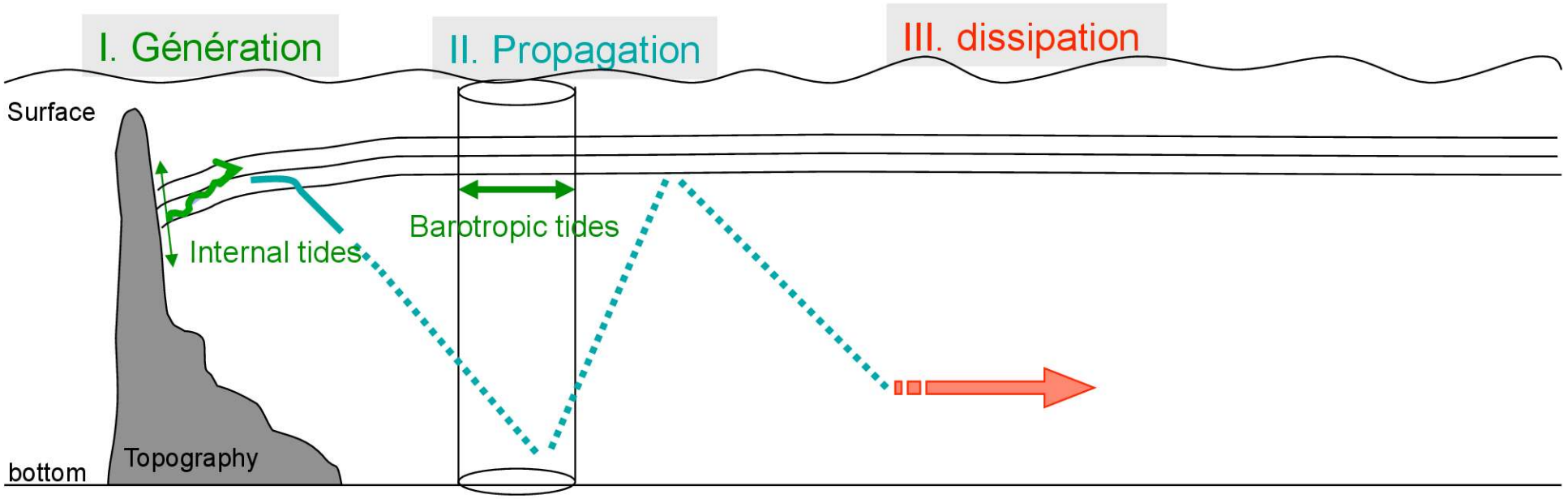


internal tidal mixing is missing

Internal tides mixing in the Indonesian seas

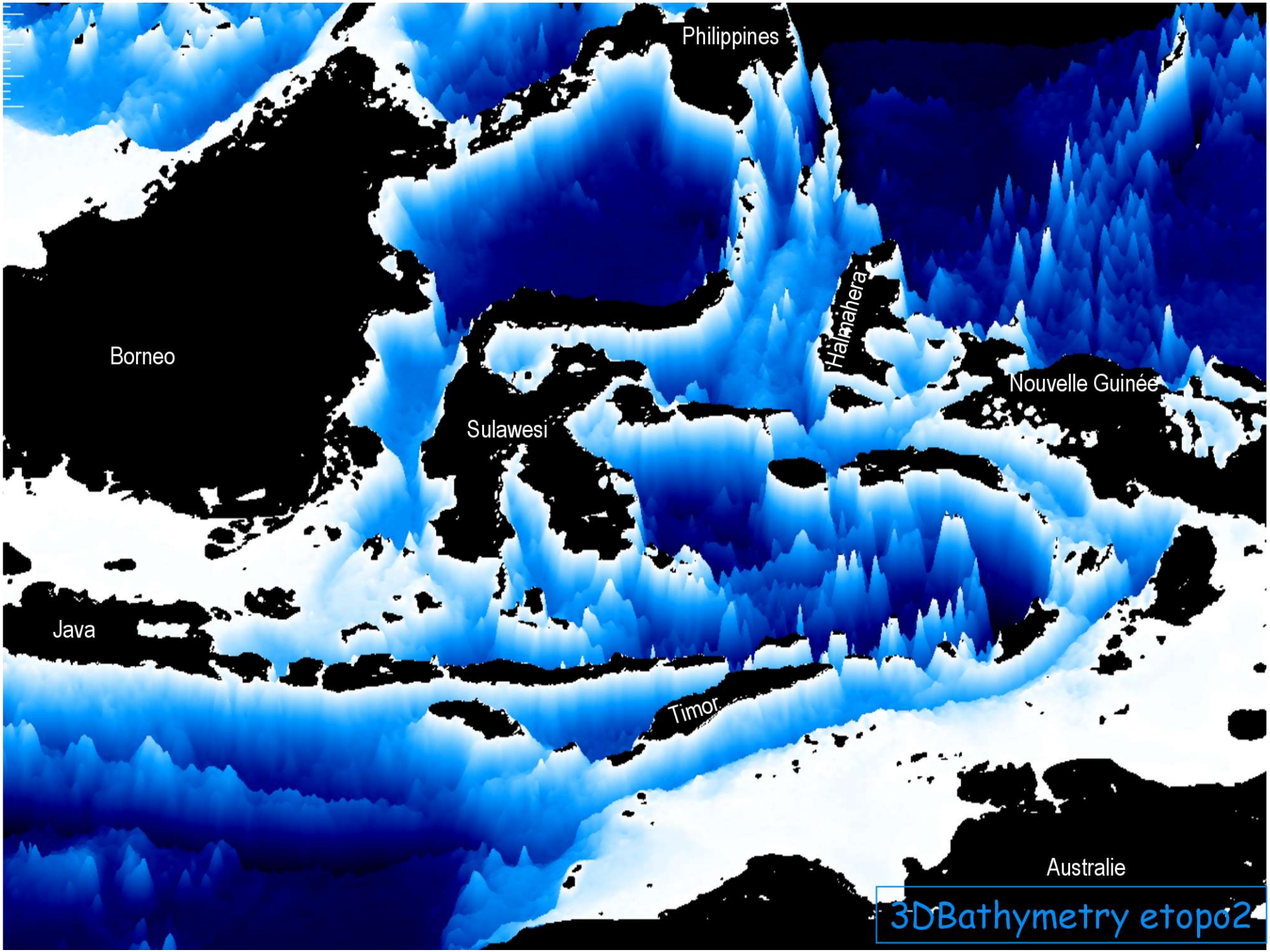
1) Improve the model by taking into account the unresolved internal tides
2) Impact on Climate model ?
3) Verify hypotheses raised with the model with INDOMIX *in-situ* data
4) Explicit tides in an OGCM

Internal Tides

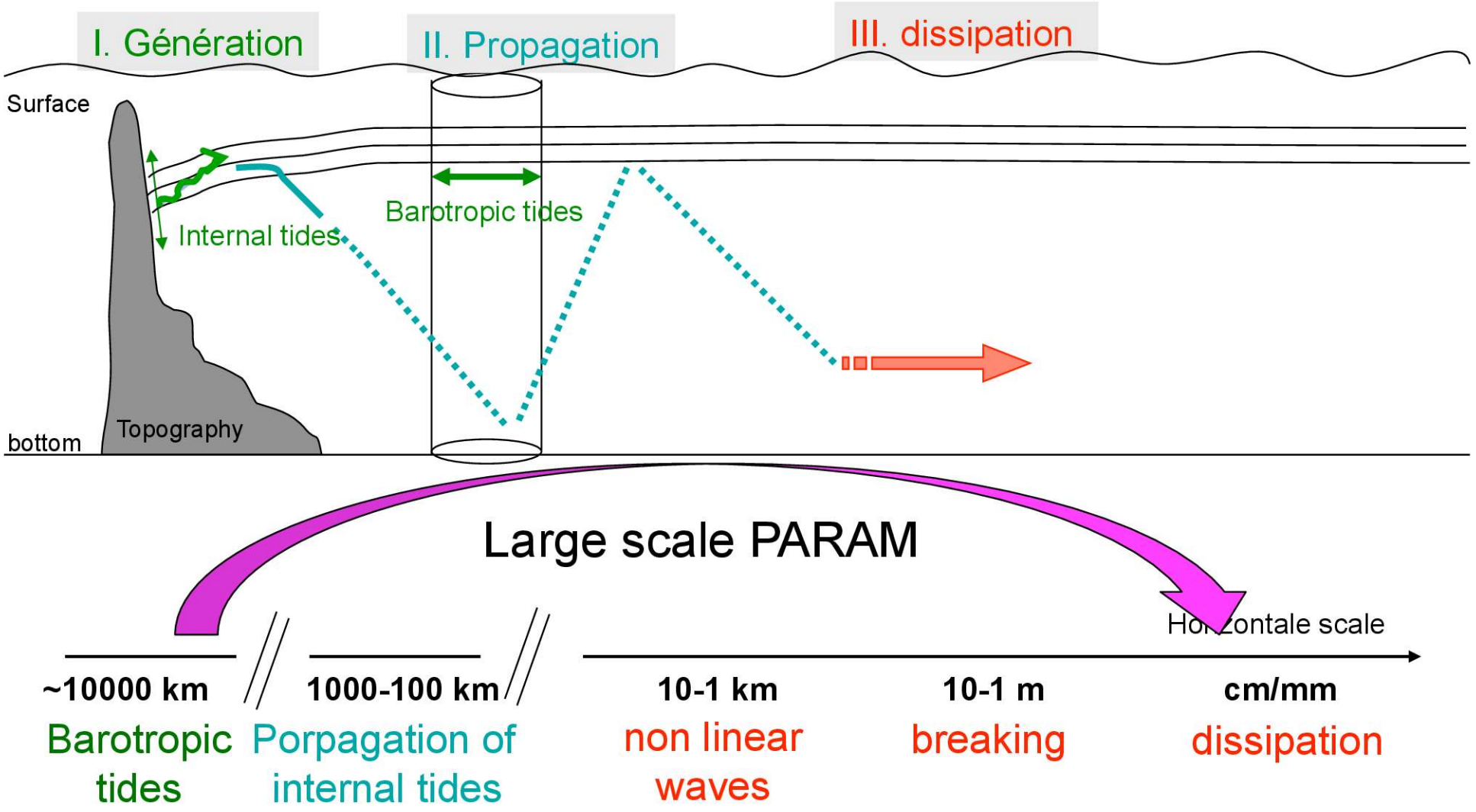


Horizontale scale

~10000 km	1000-100 km	10-1 km	10-1 m	cm/mm
Barotropic tides	Porpagation of internal tides	non linear waves	breaking	dissipation


Philippines
Halmahera
Borneo
Nouvelle Guinée
Sulawesi
Java
Timor
Australie
3DBathymetry etopo2

Internal Tides



1) Improve the model : parameterization

How to take them into account ?

$$k_{z\ tides} = \frac{0.2\ q\ E(x,y)\ F(z)}{\rho\ N^2}$$

$E(x,y)$

St Laurent 2002

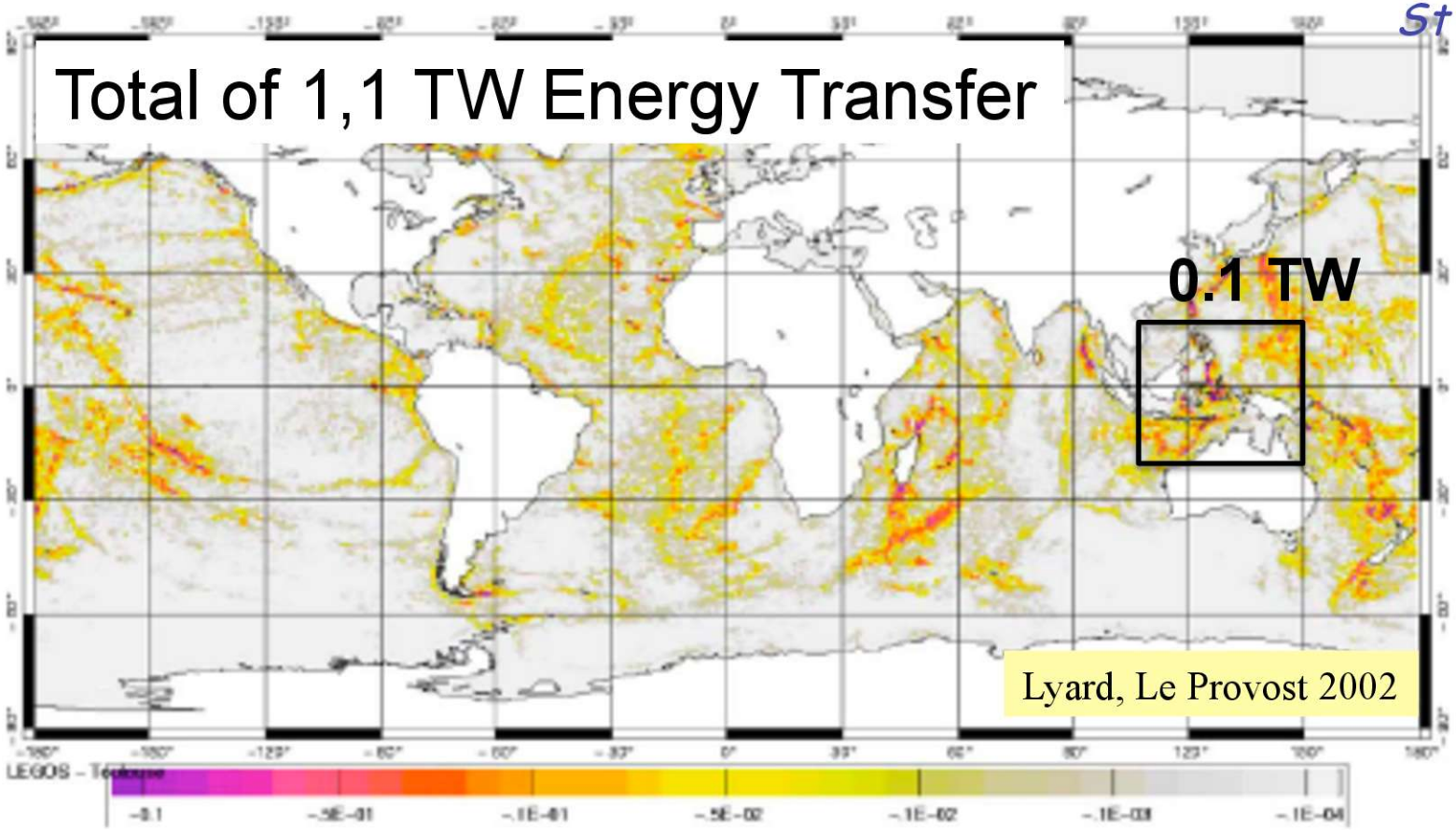
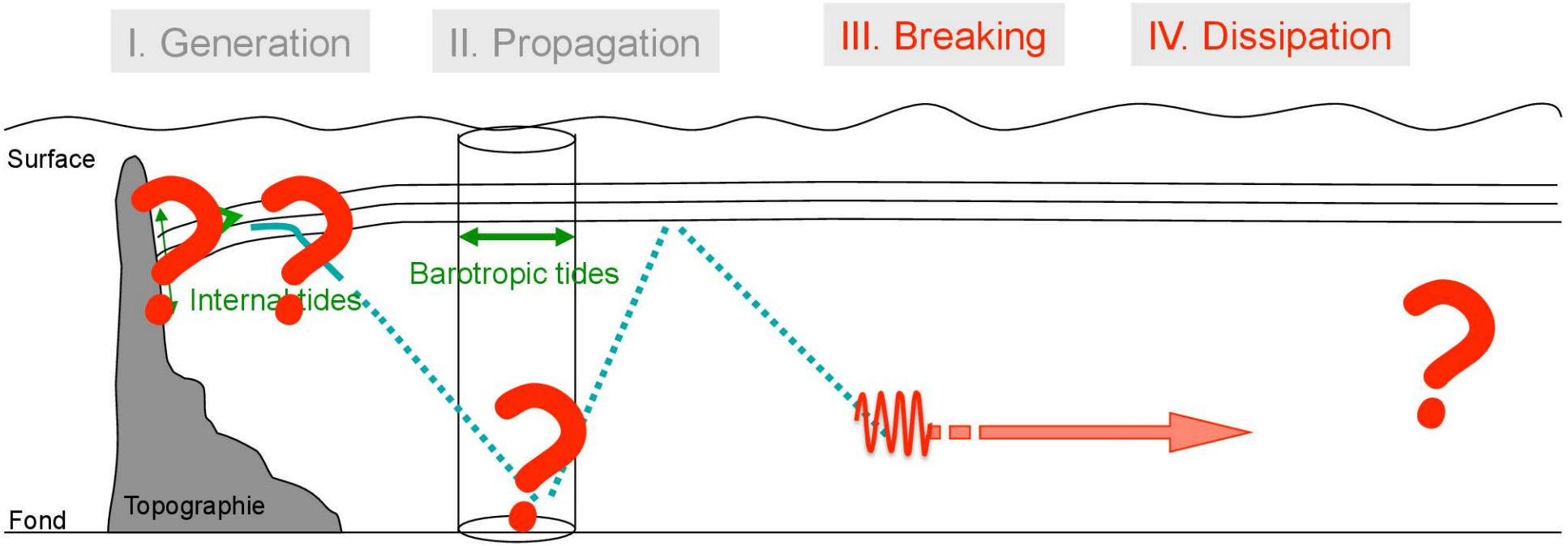


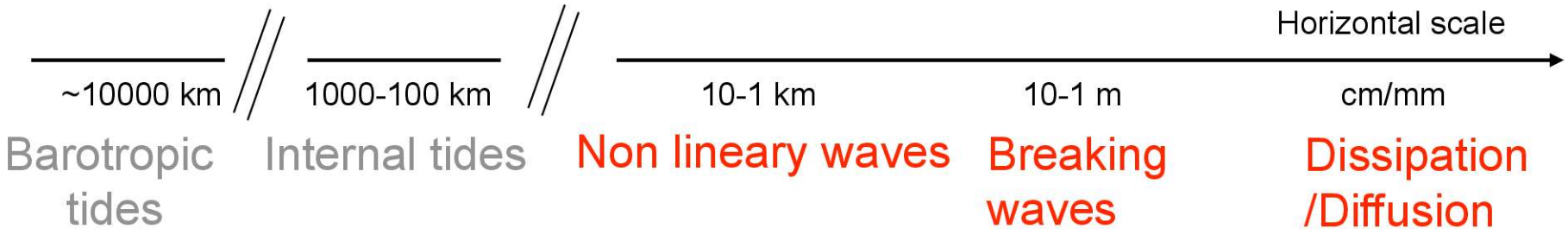
Fig. 7 M_2 wave drag dissipation (W/m^2)

Generation sites well known

1) Improve the model : parameterization

Dissipation big unknown



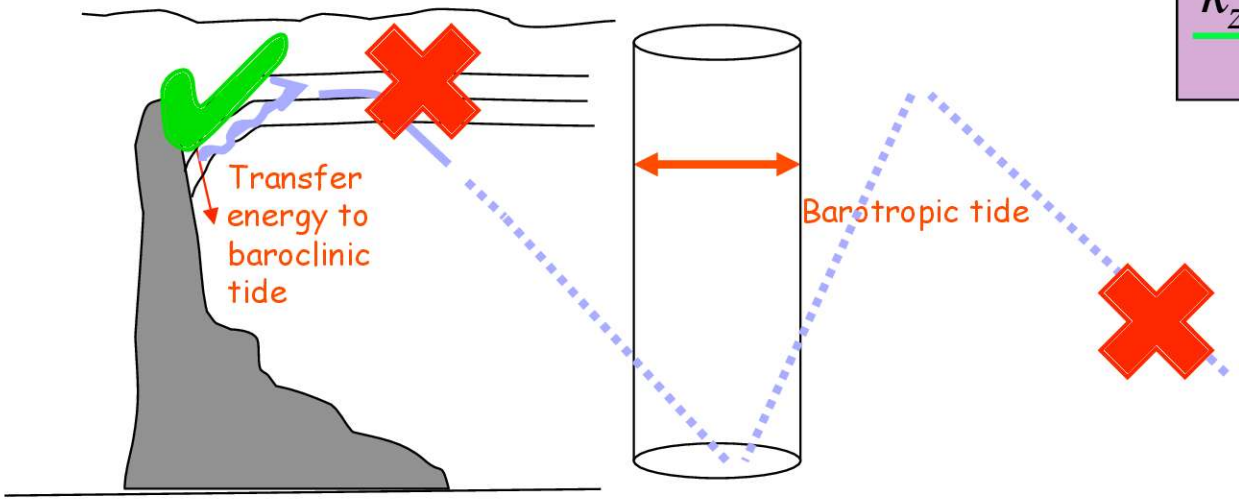


1) Improve the model : parameterization

Classical param in open ocean

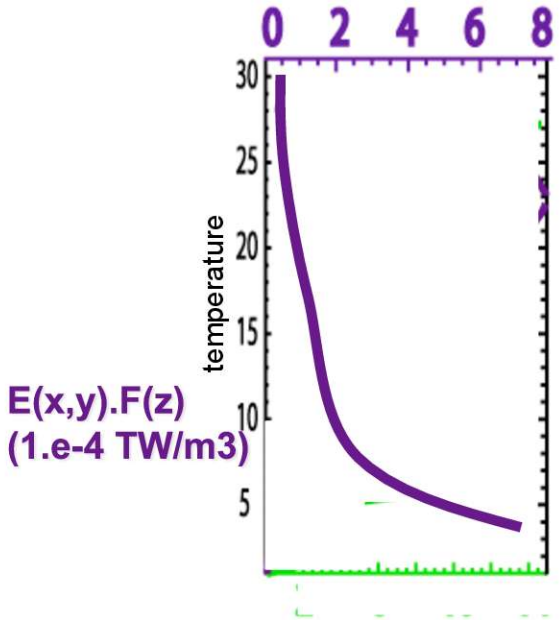
$$k_{z\ tides} = \frac{0.2\ q\ E(x,y)\ F(z)}{\rho\ N^2}$$

St Laurent 2002



Dissipation
at the generation sites
close to the bottom

$F(z)$

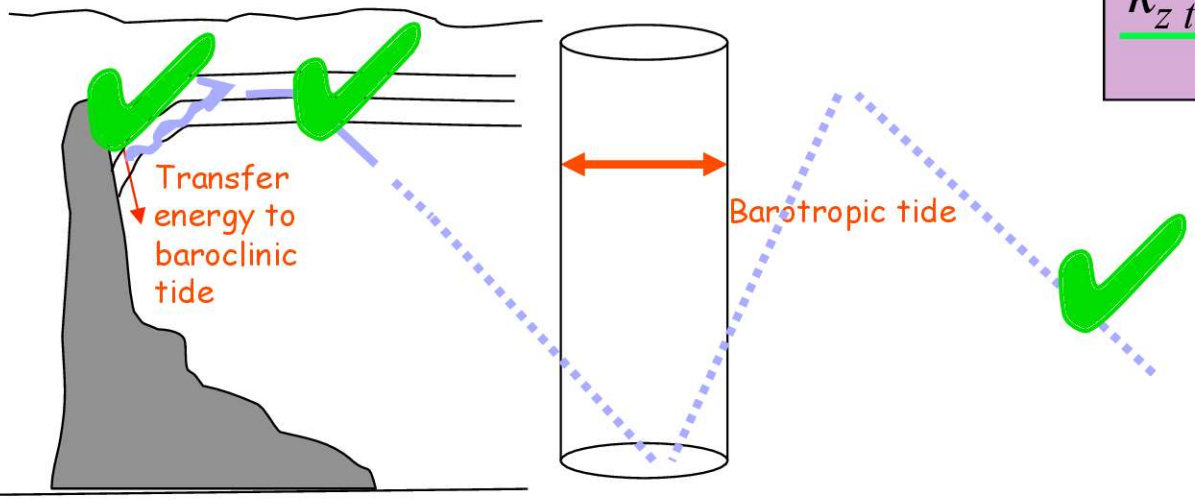


1) Improve the model : parameterization

Indonesian : semi enclosed seas

$$k_{z\ tides} = \frac{0.2\ q\ E(x,y)\ F(z)}{\rho\ N^2}$$

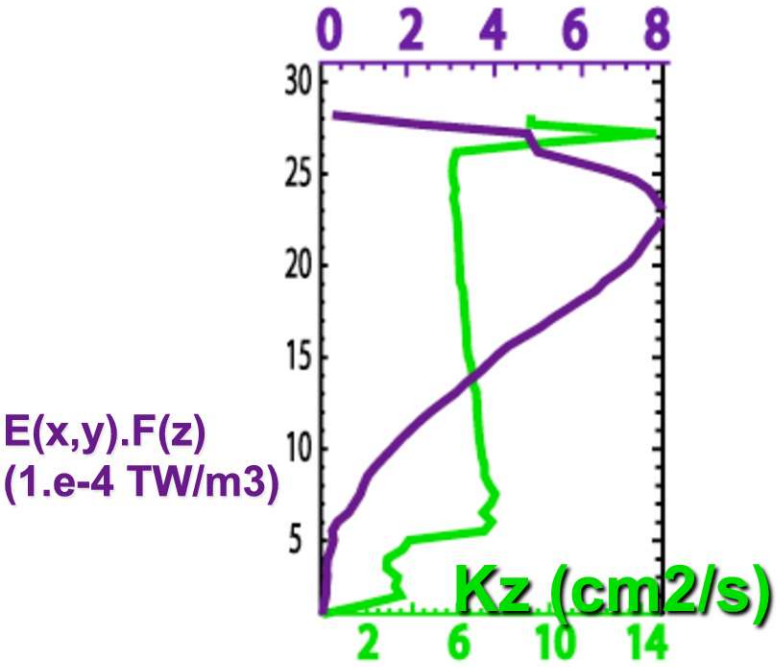
St Laurent 2002



Dissipation
at the generation sites
MAX in the thermocline

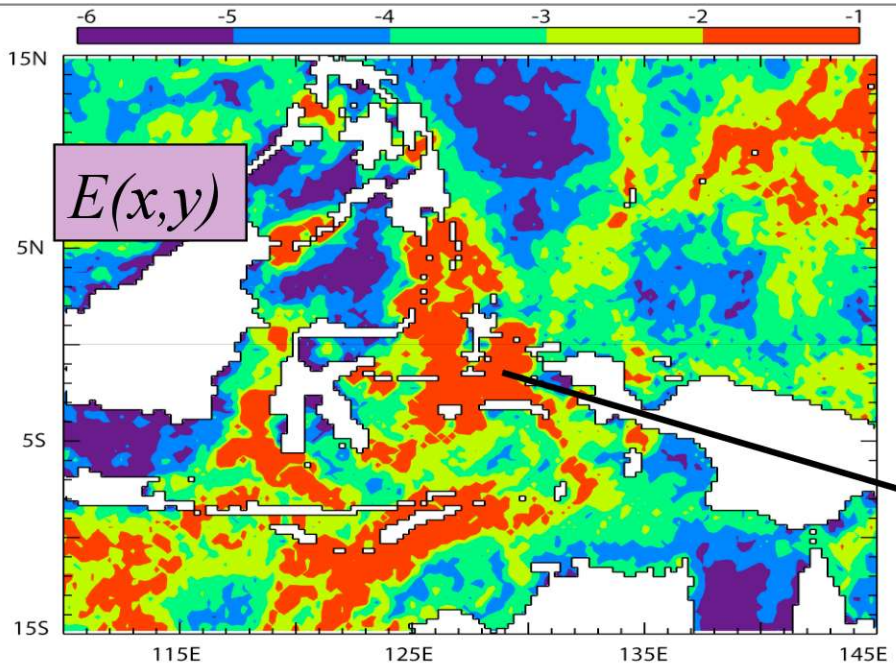
All dissipated locally q=1

$F(z)$



Main Hypotheses !

1) Improve the model : parameterization



$$k_{z\ tides} = \frac{0.2\ q\ E(x,y)\ F(z)}{\rho\ N^2}$$

St Laurent 2002

Halmahera Sea
8 cm²/s

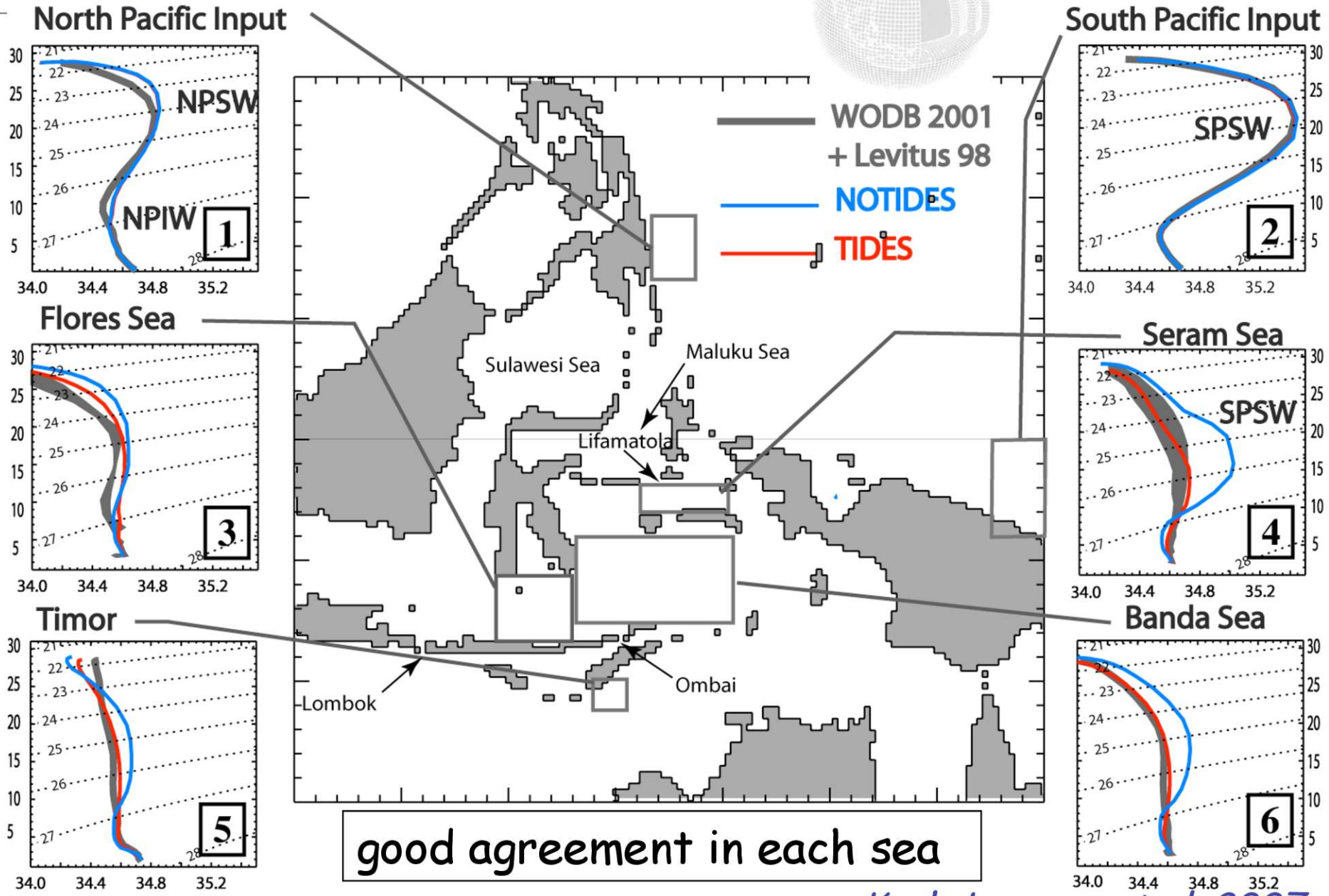
Kz very heterogeneous

Mean Kz of 1.5 cm²/s

very good agreement with independant estimates
inferred from observations 1-2 cm²/s

Koch-Larrouy et al. 2007

1) Improve the model : parameterization

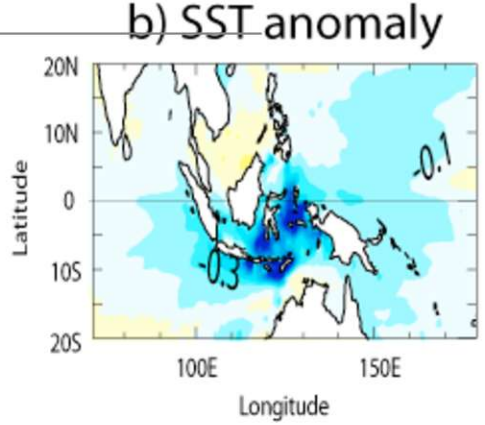


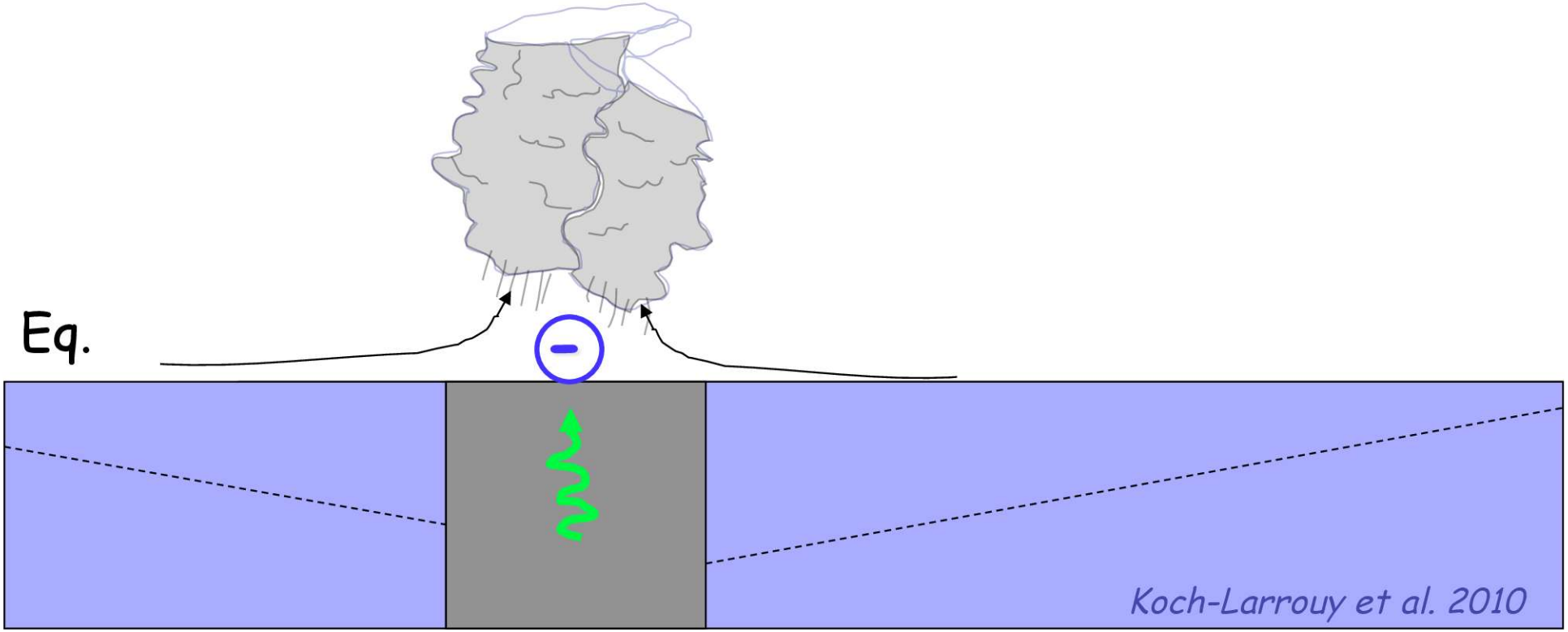
good agreement in each sea

Koch-Larrouy et al. 2007

2) Impact on climate model ?

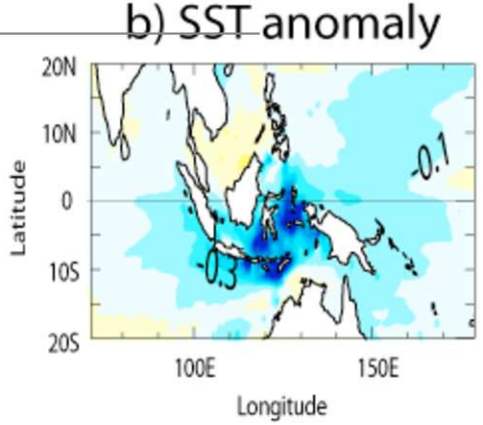
Coupled model :
with param
⇒Reduce SST

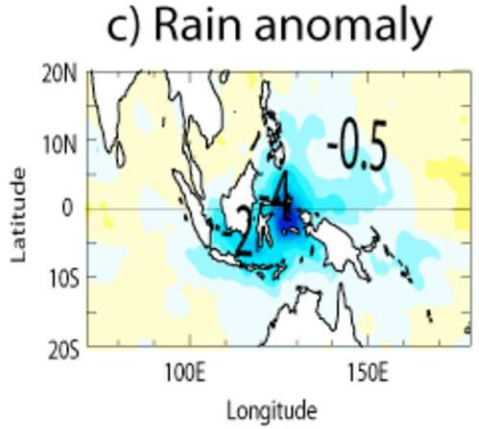


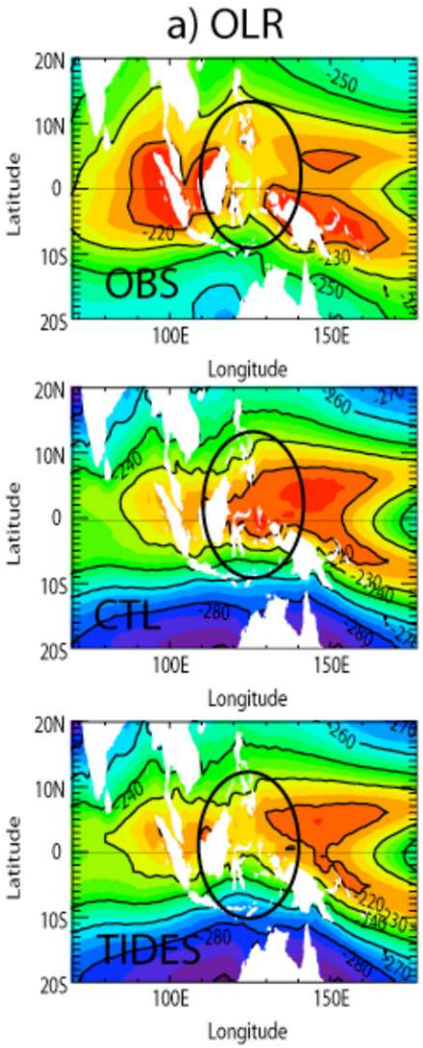


2) Impact on climate model ?

Coupled model :
with param
⇒Reduce SST
⇒Reduce precipitation







Conclusions 1/3

- Unique region of the world = strong internal tides generation
  + semi enclosed seas.
- Specific parameterization energy constrained
  mean Kz in good agreement with observation independently
  + water masses in good agreement with observations.
  => give confidence in the simulated solution

  Koch-Larrouy, et al. 2007 GRL
- Tidal mixing in the Indonesian seas reduces SST, local rain
  In good agreement with observations
- Anomalies as strong as closing the ITF !!!
- Impact on INTERANNUAL and INTRASEASONAL variability of the climate system in good agreement observation

  Koch-Larrouy, et al. 2010, Climate Dyn.
  Sprintall, Gordon, Koch-Larrouy et al. 2014, Nature Geo.

BUT STRONG HYPOTHESIS !
MIXING maximum in the thermocline and reach the surface
All energy dissipated locally

Internal tides mixing in the Indonesian seas

1) Improve the model by taking into account the ur
2) Impact on Climate model ?
3) Verify hypotheses raised with the model with INDOMIX in situ data
4) Explicit tides forcing in an OGCM

2010 INDOMIX

First cruise dedicated to mixing

Marion Dufresne

CTD profile with Ra/Ac sampling

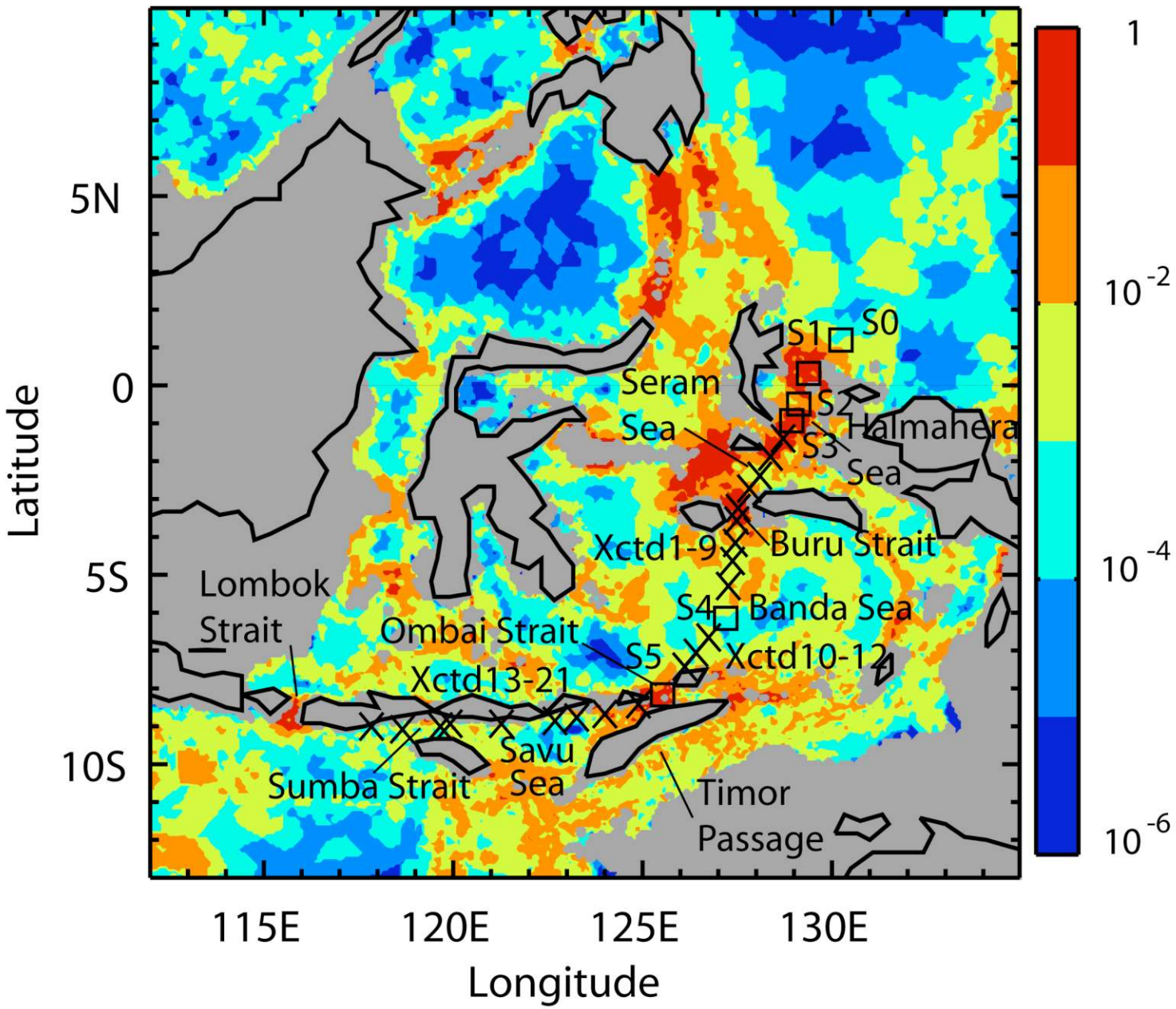
CTD profile with Nd sampling

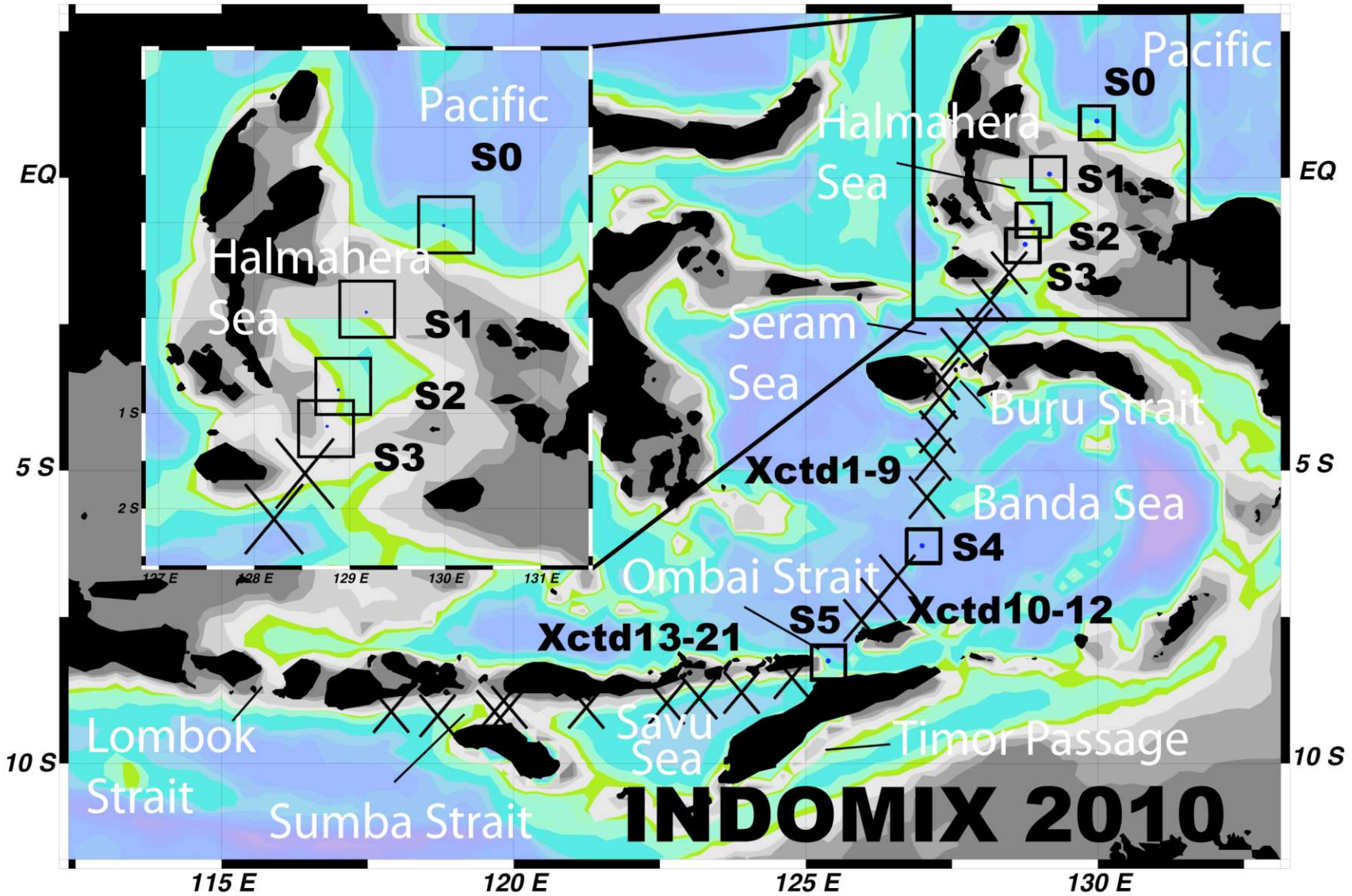
CTD profile and VMP profile

24h Station :
7 to 9 VMP profiles alternated with
7 to 9 CTD profiles (sampling O2, S, Ni, Ph)

XCTD

ADCP
Mooring


5N
0
5S
10S
Latitude
115E
120E
125E
130E
Longitude
S1
S0
S2
S3
Seram
Sea
Halmahera
Sea
Xctd1-9
Buru Strait
S4
Banda Sea
Lombok
Strait
Ombai Strait
S5
Xctd10-12
Xctd13-21
Savu
Sea
Sumba Strait
Timor
Passage
1
10 -2
10 -4
10 -6


Pacific
S0
Halmahera
Sea
S1
S2
S3
1 S
2 S
127 E
128 E
129 E
130 E
131 E
Pacific
S0
Halmahera
Sea
S1
S2
S3
Seram
Sea
Buru Strait
Xctd1-9
Banda Sea
S4
Ombai Strait
S5
Xctd10-12
Xctd13-21
Savu
Sea
Timor Passage
Lombok
Strait
Sumba Strait
INDOMIX 2010
EQ
5 S
10 S
EQ
5 S
10 S
115 E
120 E
125 E
130 E

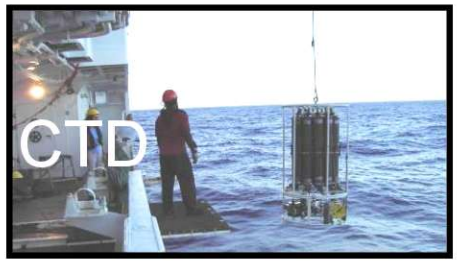
repeated profiles during 24h to catch the diurnal tidal cycle

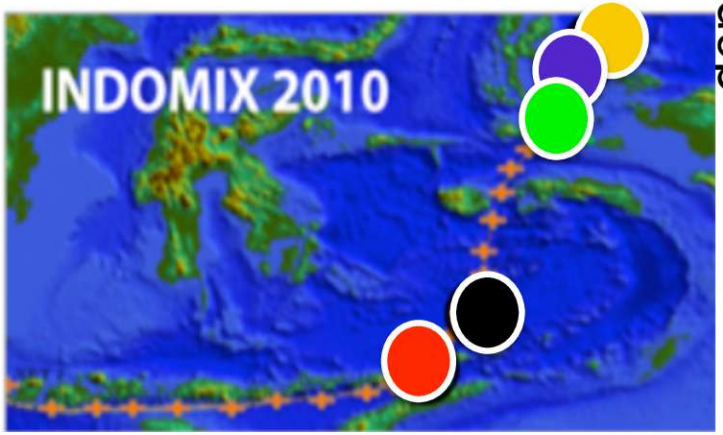
Microstructure
measurements
VMP/CTD
Turbulence + TS profiles

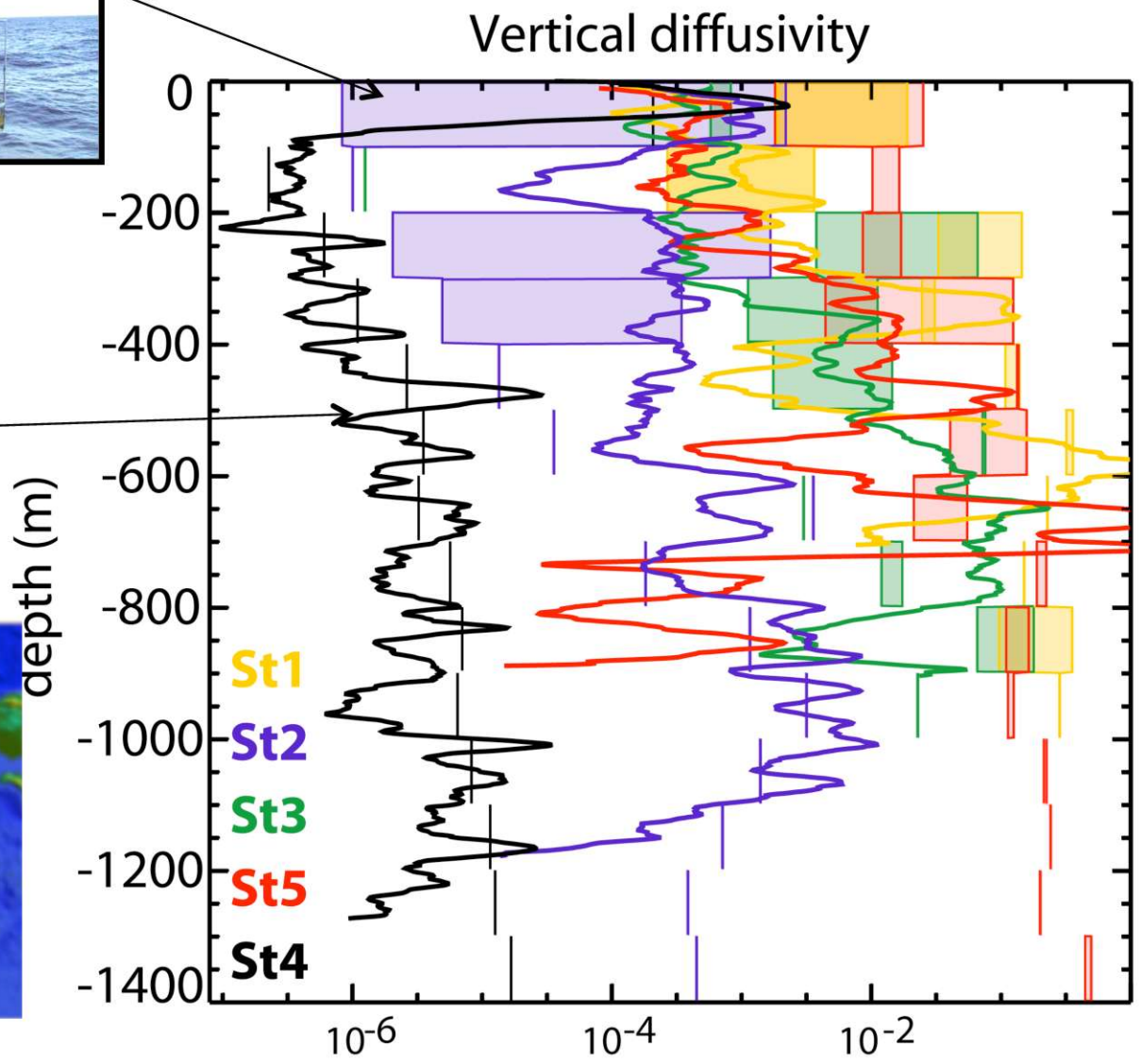
DIRECT

CTD/LADCP
Currents + TS profiles

INDIRECT



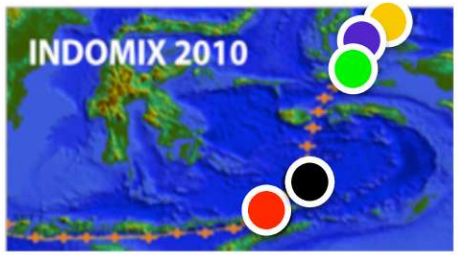


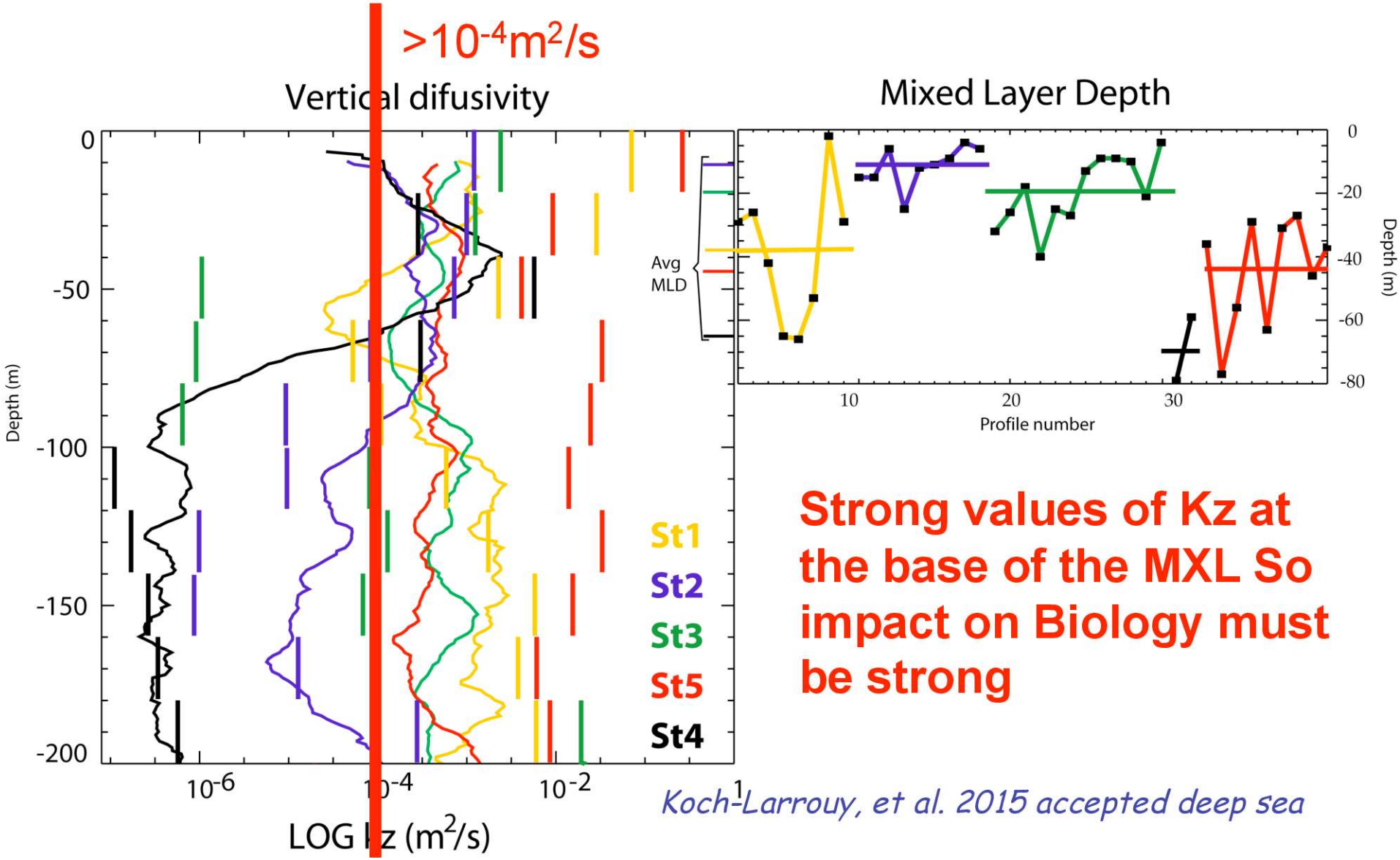


Large uncertainties with CTD, needs VMP

Strong and Heterogeneous vertical mixing

Koch-Larrouy, et al. 2015 accepted deep sea





Strong values of Kz at the base of the MXL So impact on Biology must be strong

Koch-Larrouy, et al. 2015 accepted deep sea

Conclusions 2/3

- Unique region of the world = strong internal tides generation
  + semi enclosed seas.
- Specific parameterization energy constrained

Koch-Larrouy, et al. 2007 GRL

- Tidal mixing in the Indonesian seas reduces SST, local rain
  In good agreement with observations
- Anomalies as strong as closing the ITF !!!
- Impact on INTERANNUAL and INTRASEASONAL variability of the climate system in good agreement observation

Koch-Larrouy, et al. 2010, Climate Dyn.
Sprintall, Gordon, Koch-Larrouy et al. 2014, Nature Geo.

- Need for measurements !!!!
  => INDOMIX 2010

Large uncertainties with CTD, needs VMP
Strong and Heterogeneous vertical mixing,
Show large values even in the thermocline and the surface

Koch-Larrouy, et al. 2015, Deep Sea part II

So impact on Biology must be strong
=> INDESOMix 2016/2017/2018

Internal tides mixing in the Indonesian seas

1) Improve the model by taking into account the unresolved internal tides
2) Impact on Climate model ?
3) Verify hypotheses raised with the model with INDOMIX *in-situ* data
4) Explicit tides in an OGCM

4) INDESO : NEMO explicit tidal forcing at 1/12° (10km)

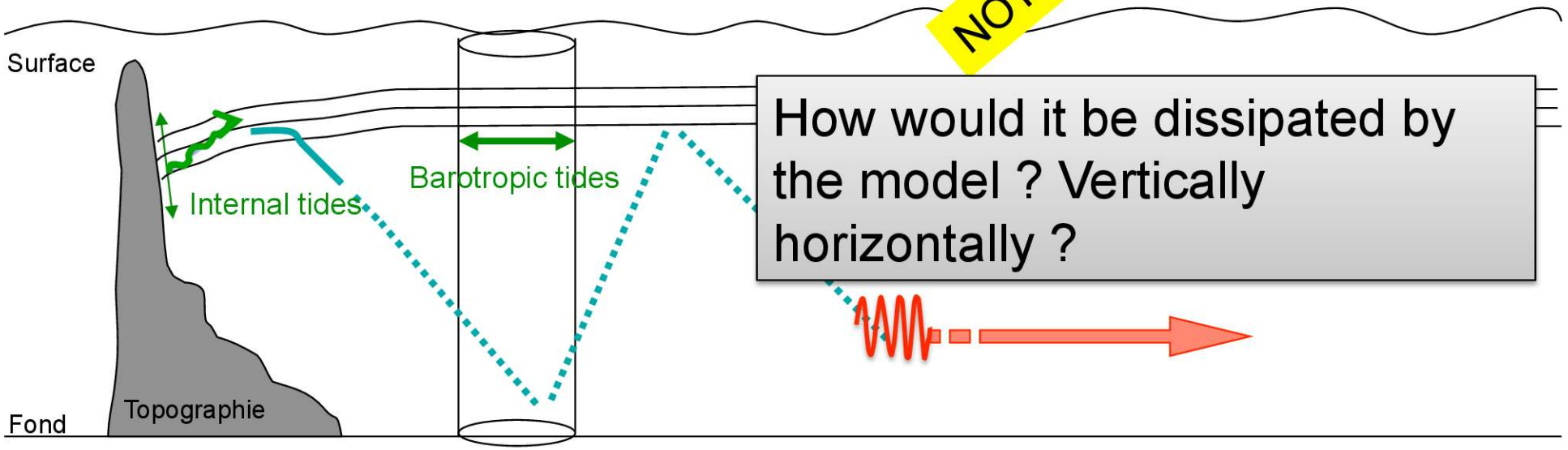
How do we resolve internal tides ?

Partly I. Generation

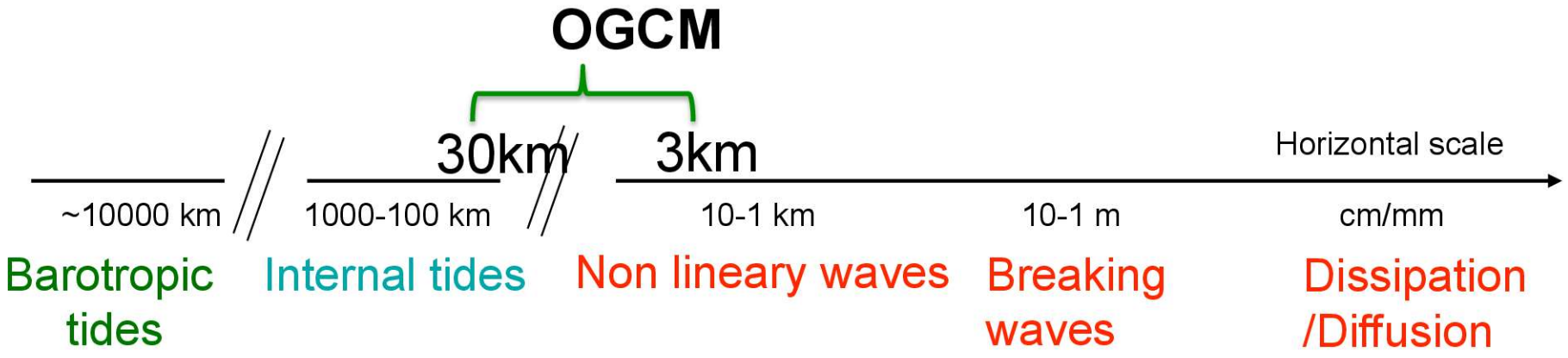
Partly II. Propagation

III. Breaking

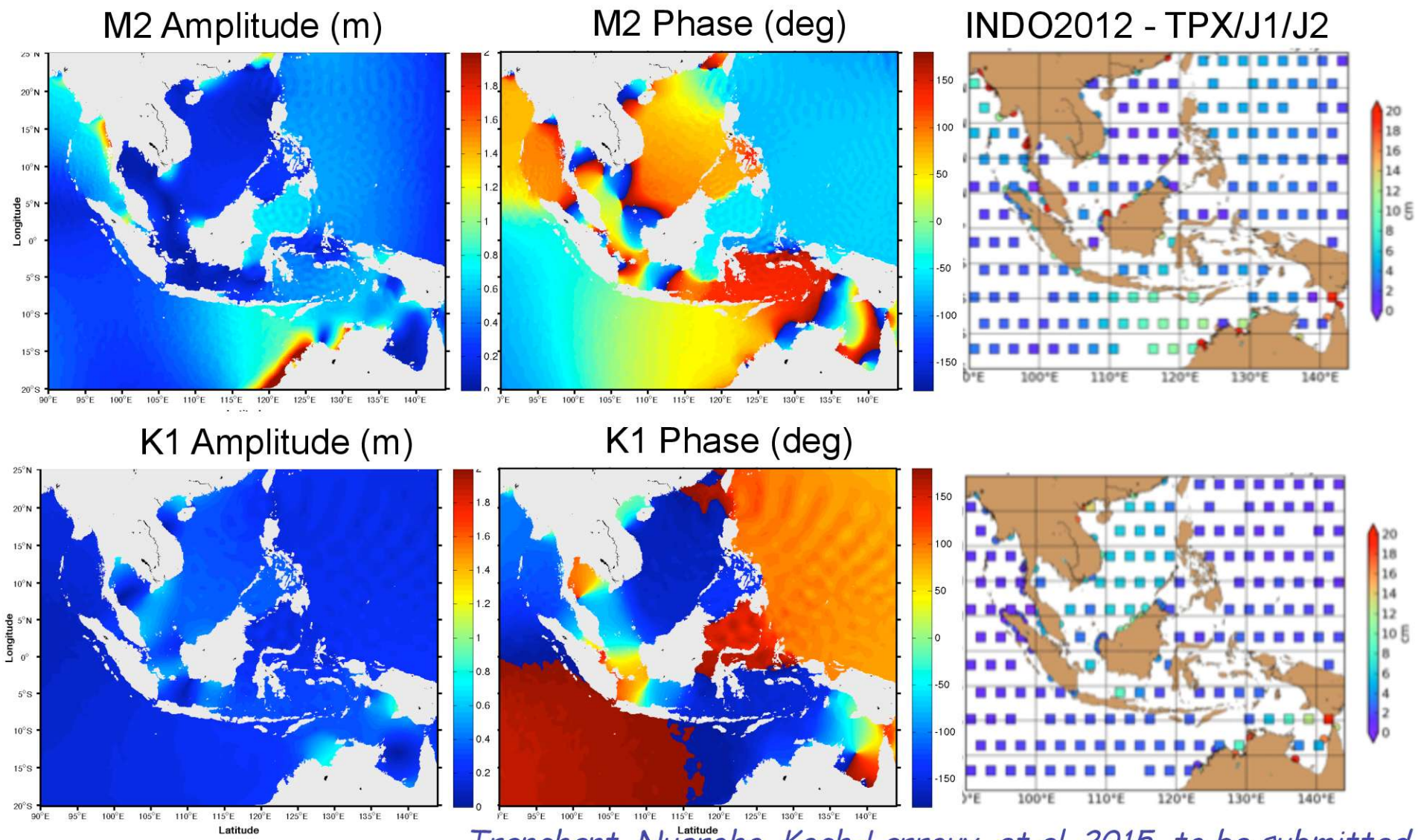
NOT RESOLVED IV. Dissipation



How would it be dissipated by the model ? Vertically horizontally ?



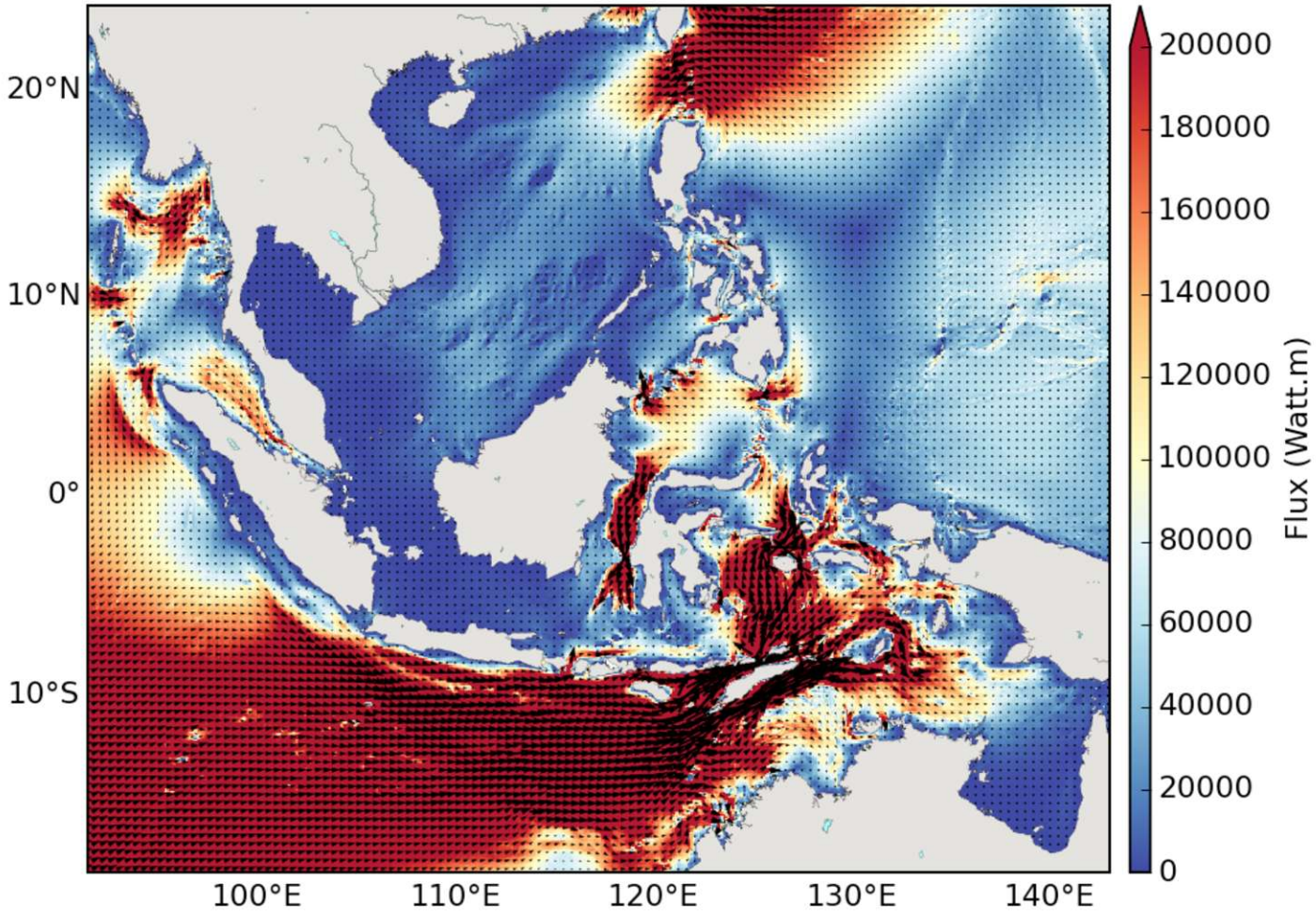
4) INDESO : NEMO explicit tidal forcing



Tranchant, Nugroho, Koch-Larrouy, et al. 2015 to be submitted

4) INDESO : NEMO explicit tidal forcing

F : barotropic flux M2 (W/m)

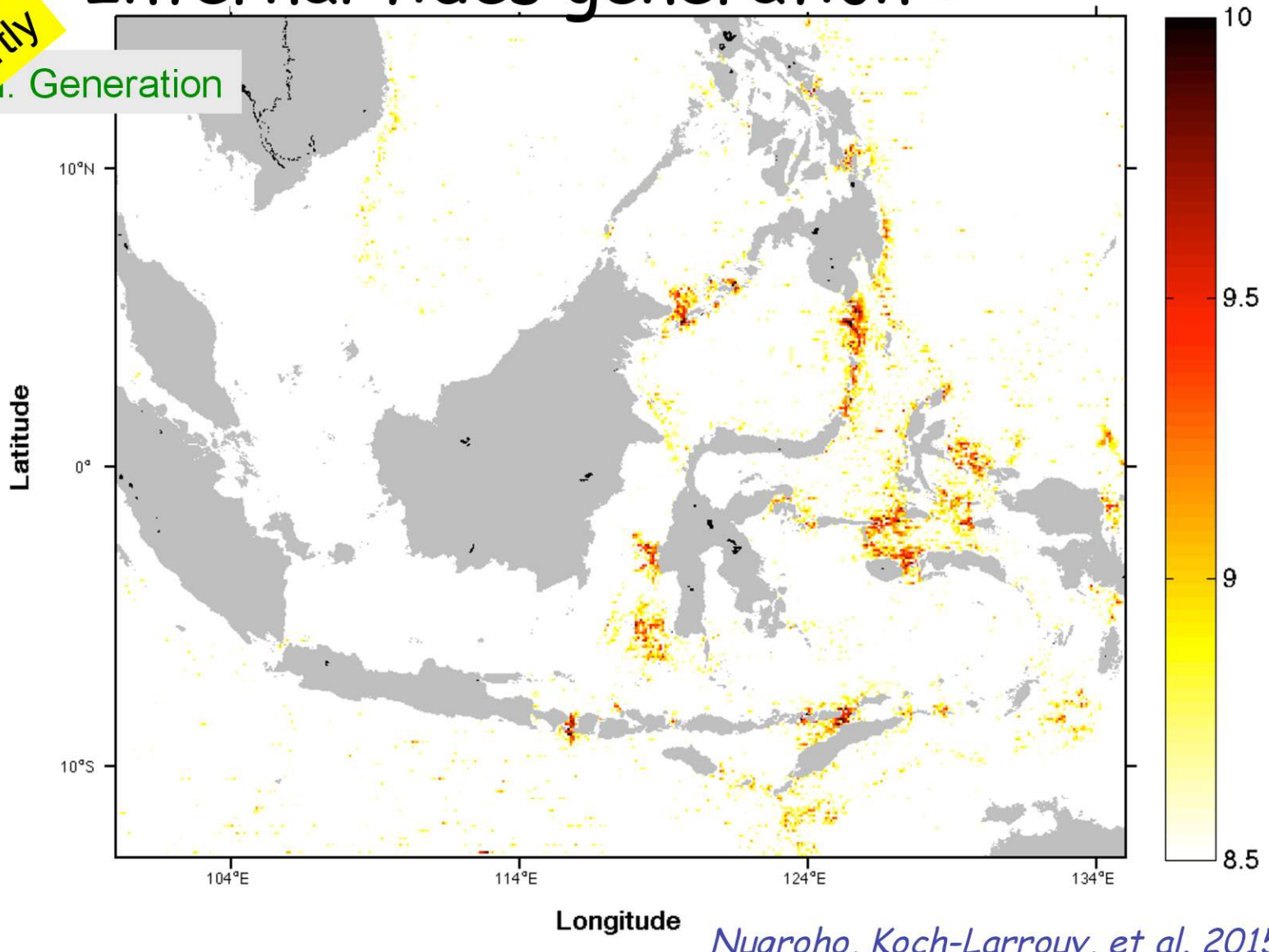


4) INDESO : NEMO explicit tidal forcing

Internal tides generation

Partly

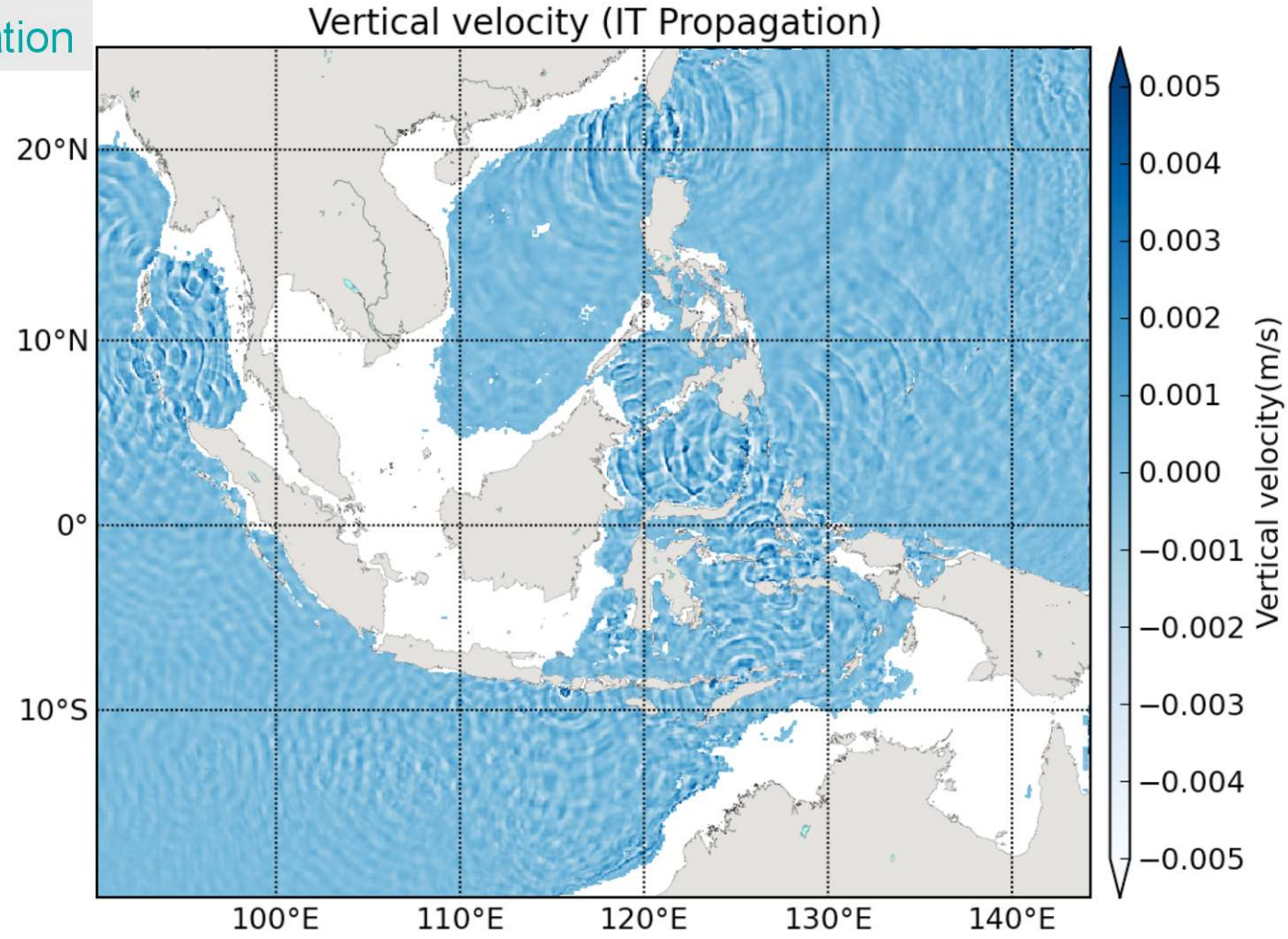
1. Generation



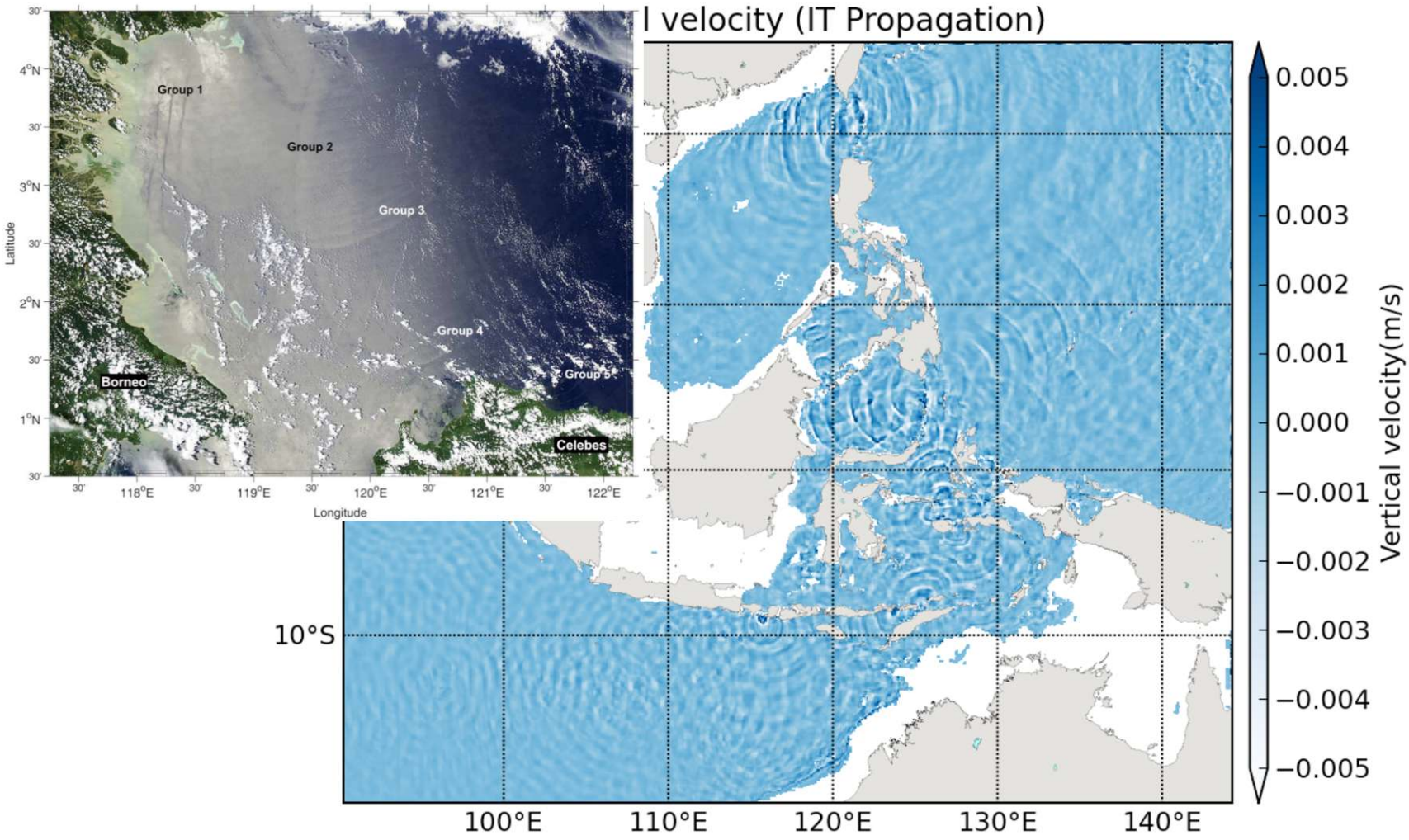
Nugroho, Koch-Larrouy, et al. 2015 in prep

4) INDESO : NEMO explicit tidal forcing

II. Propagation



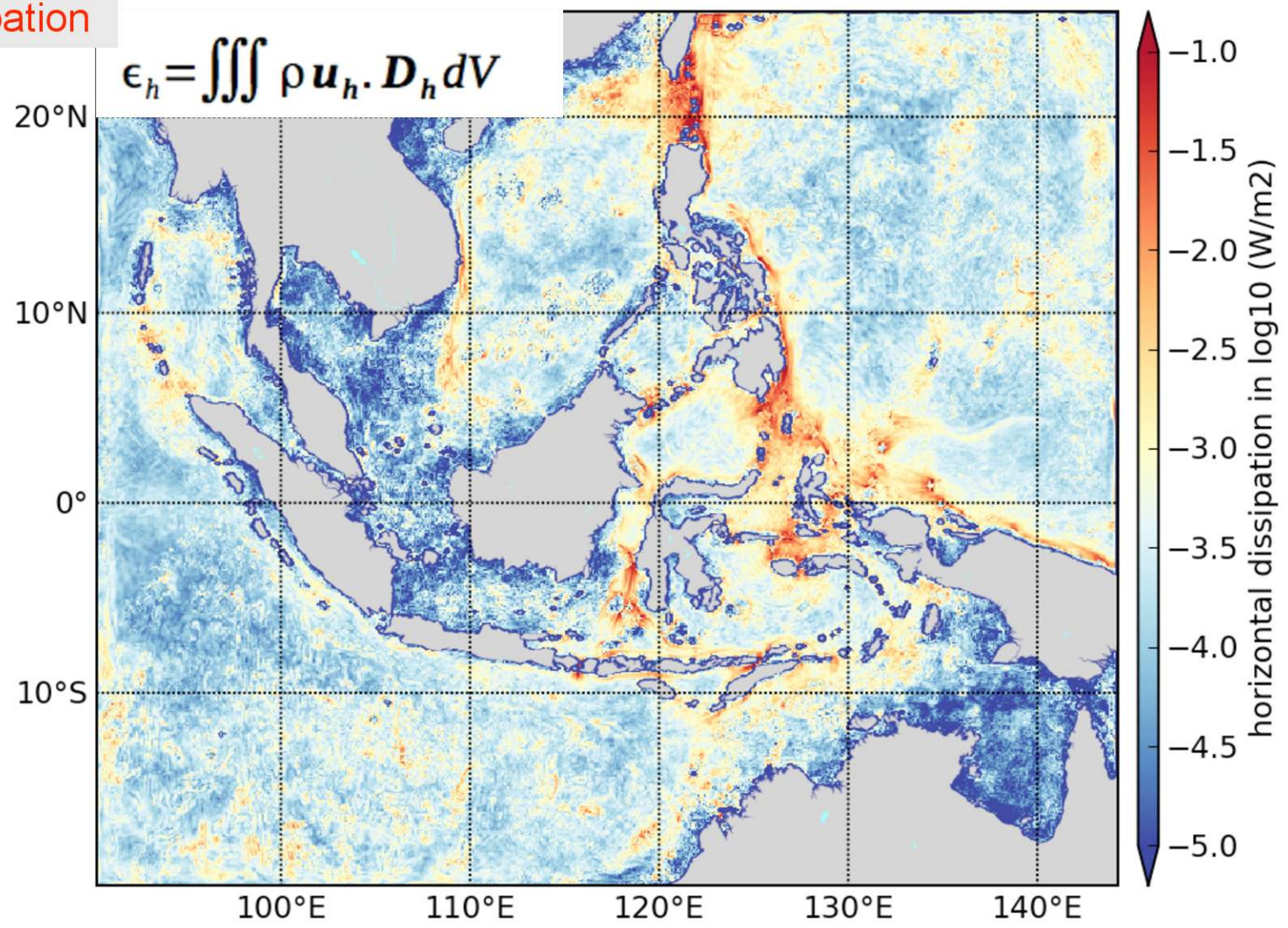
4) INDESO : NEMO explicit tidal forcing



4) INDESO : NEMO explicit tidal forcing

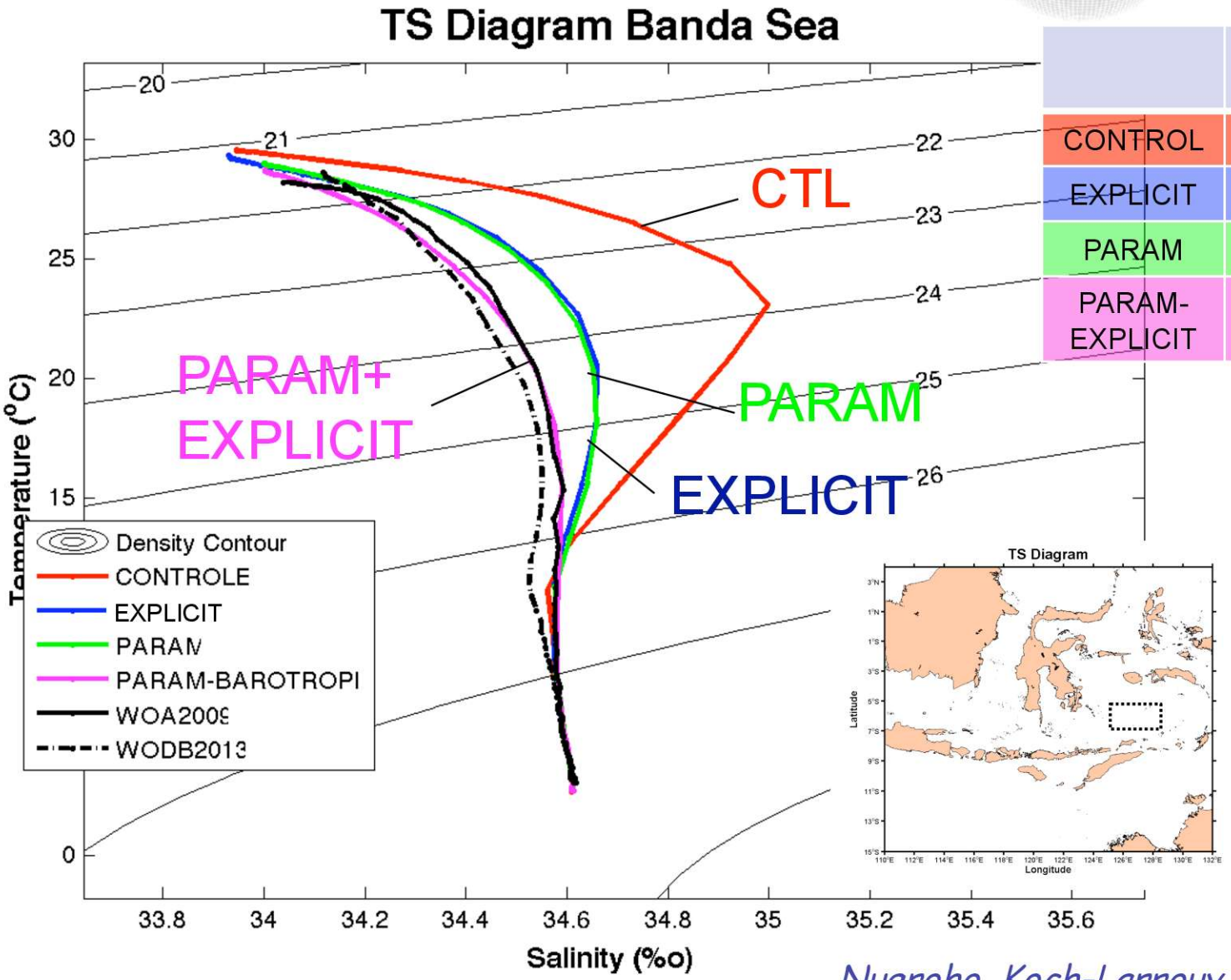
Horizontal Internal Tides dissipation@depth integrated

III. dissipation



Nugroho, Koch-Larrouy, et al. 2015 in prep

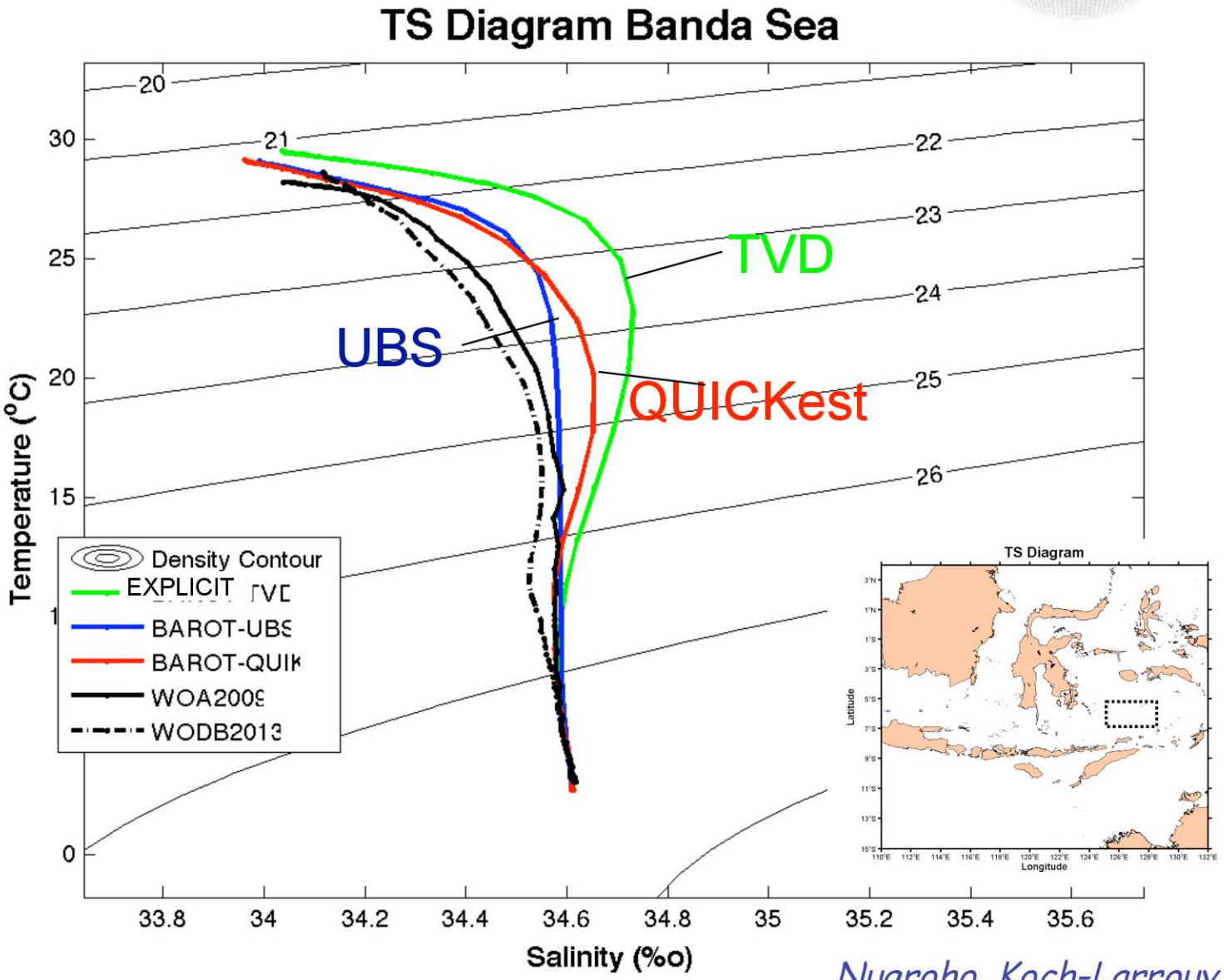
4) INDESO : NEMO explicit tidal forcing



	PARAM	EXPLICIT Tides
CONTROL		
EXPLICIT		X
PARAM	X	
PARAM-EXPLICIT	X	X

Nugroho, Koch-Larrouy, et al. 2015 in prep

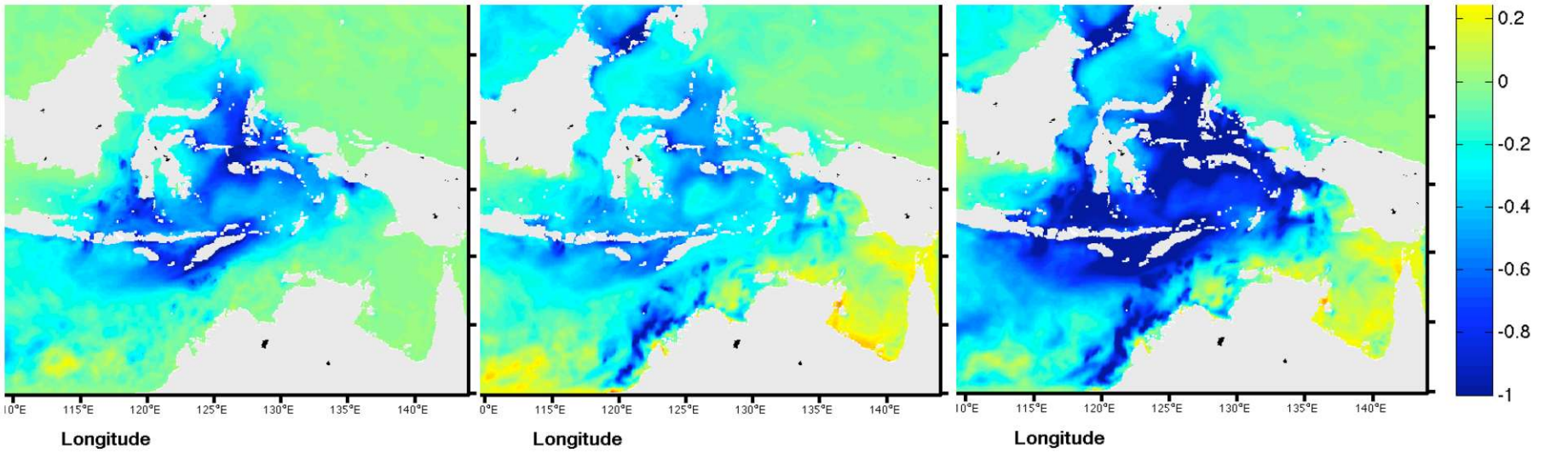
4) INDESO : NEMO explicit tidal forcing

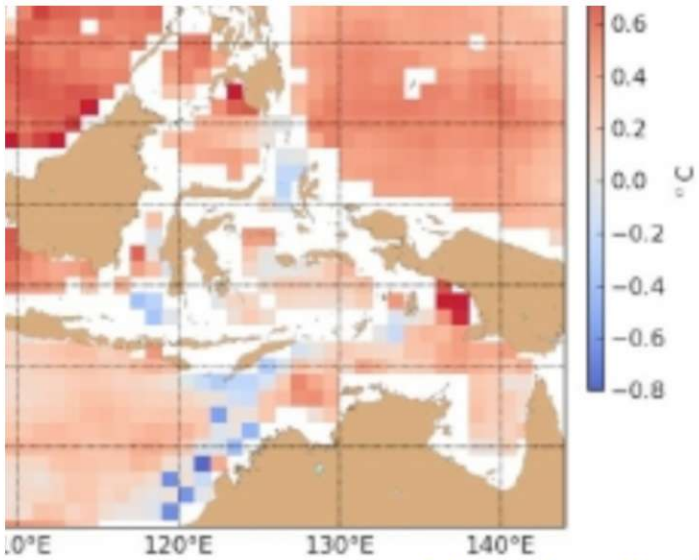


Nugroho, Koch-Larrouy, et al. 2015 in prep

4) INDESO : NEMO explicite tidal forcing

Param-CTRL Explicit-CTRL PARAM&Explicit-CTRL





Bias compare to AMSR-E

Nugroho, Koch-Larrouy, et al. 2015 in prep

4) INDESO : NEMO explicit tidal forcing

How do we resolve internal tides ?

Partly

I. Generation

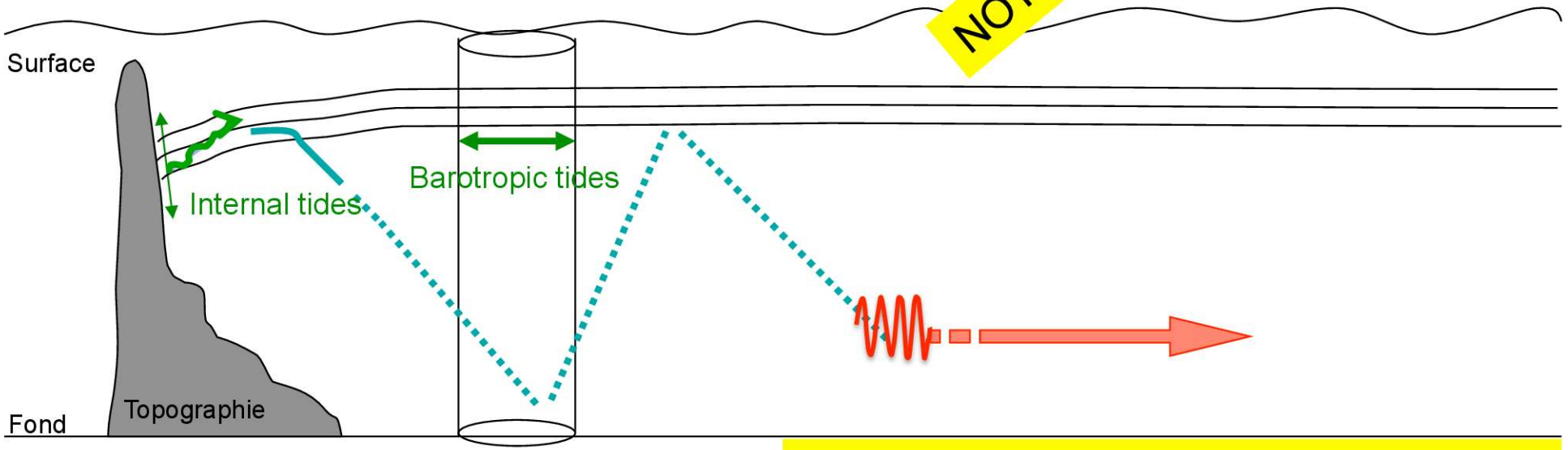
Partly

II. Propagation

III. Breaking

NOT RESOLVED

IV. Dissipation



Is diffused
By horizontal advection diffusion

OGCM

30km 3km

Horizontal scale

~10000 km | 1000-100 km | 10-1 km | 10-1 m | cm/mm

Barotropic tides | Internal tides | Non lineary waves | Breaking waves | Dissipation /Diffusion

Conclusions 3/3

- Specific parameterization energy constrained
  BUT energy dissipated locally
  Koch-Larrouy, et al. 2007 GRL

- Tidal mixing in the Indonesian seas reduces SST, local rain, ENSO
  In good agreement with observations
  Koch-Larrouy, et al. 2010, Climate Dyn.
  Sprintall, Gordon, Koch-Larrouy et al. 2014, Nature Geo.

- Need for measurements **=> INDOMIX 2010**

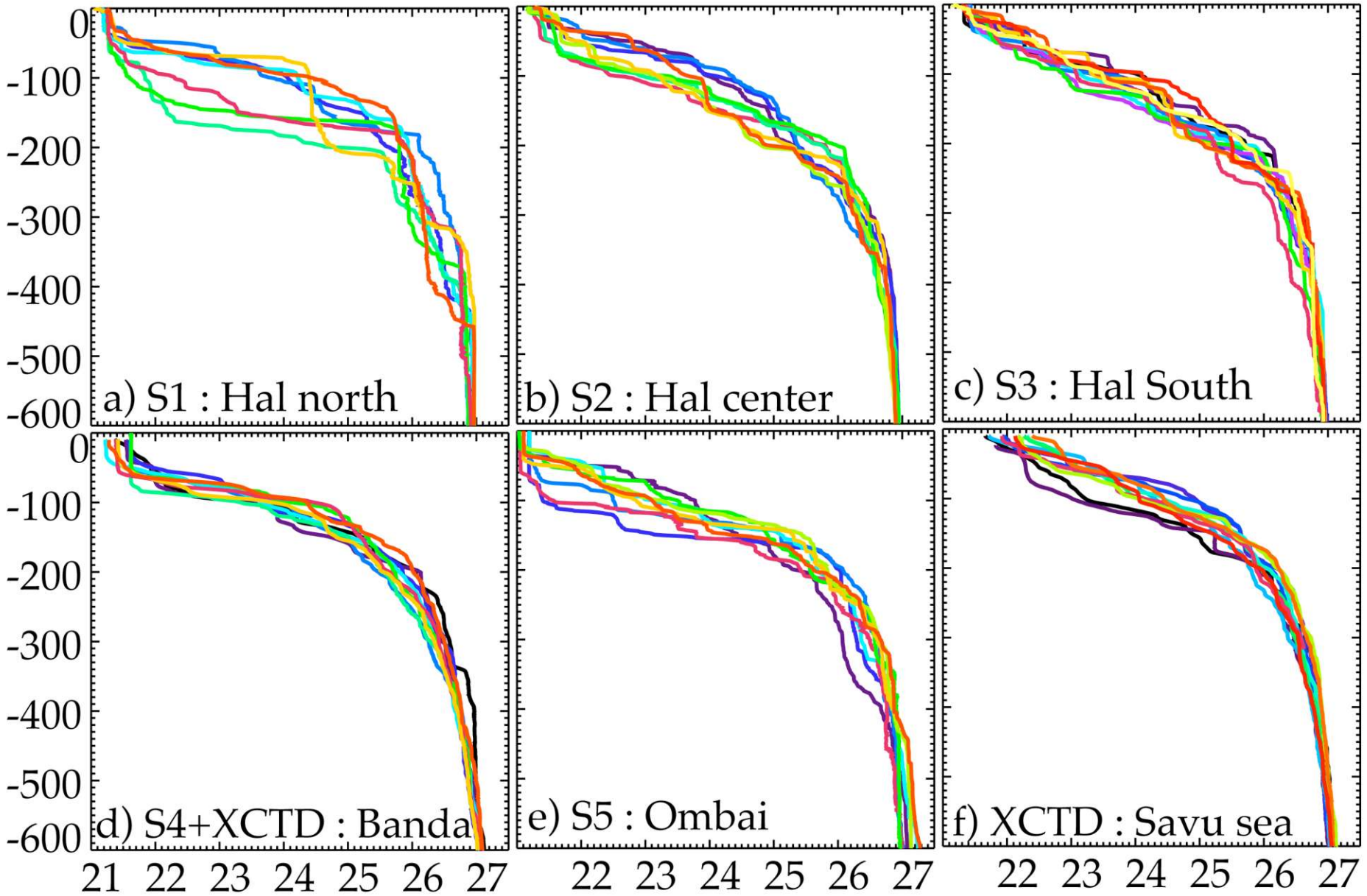
Strong and Heterogeneous vertical mixing, large values even in the thermocline and the surface *Koch-Larrouy, et al. 2015, Deep Sea part II*

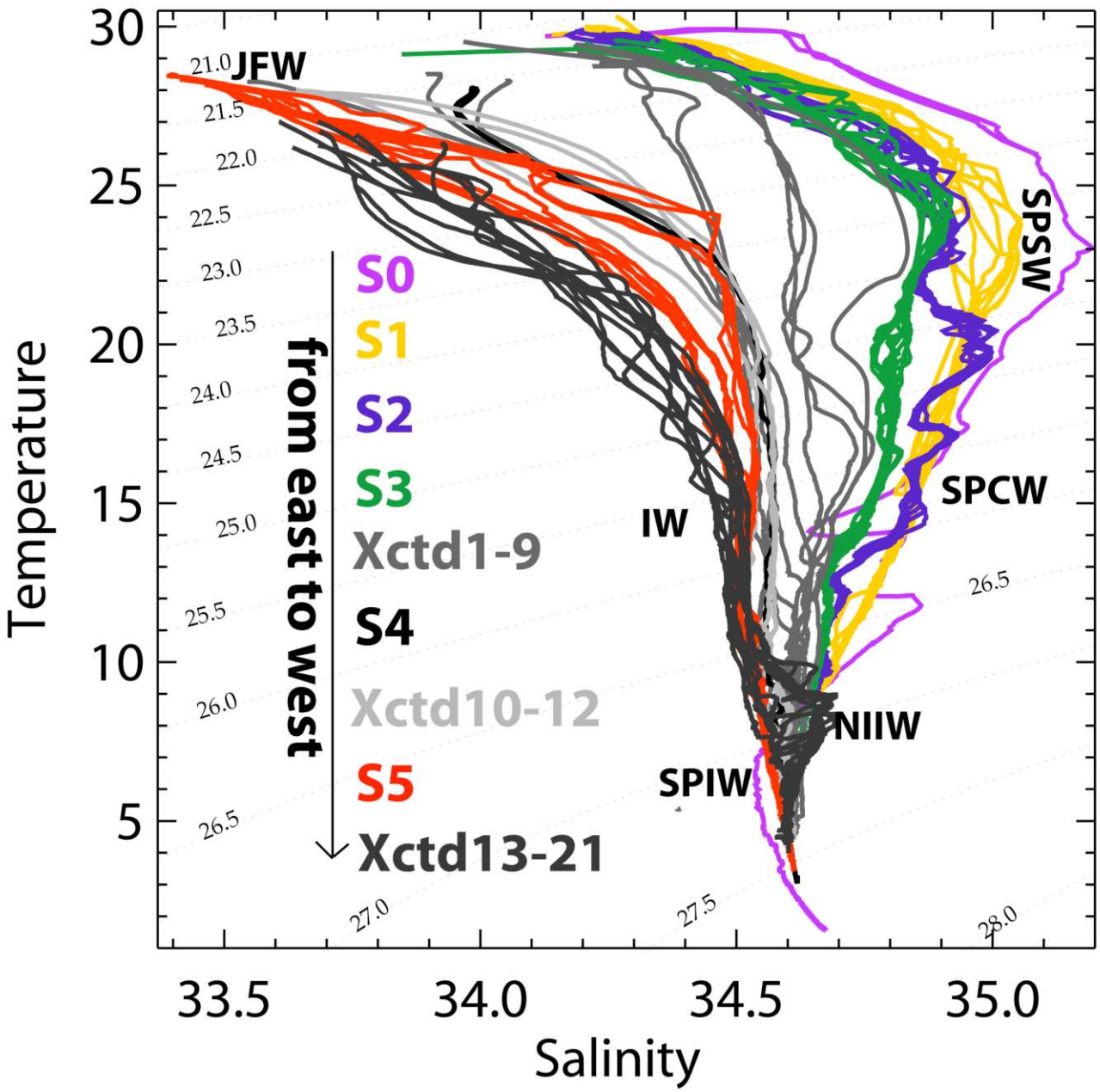
So impact on Biology must be strong **=> INDESOMix 2016/2017/2018**

- Explicit tides in an OGCM
  - Produce large mixing as high as param but further away from generation sites
  - Very sensitive to advection schemes
  - Internal tides are dissipated by numerical horizontal (!) dissipation of the advection scheme

=> Need for param to dissipate internal tides vertically in OGCM

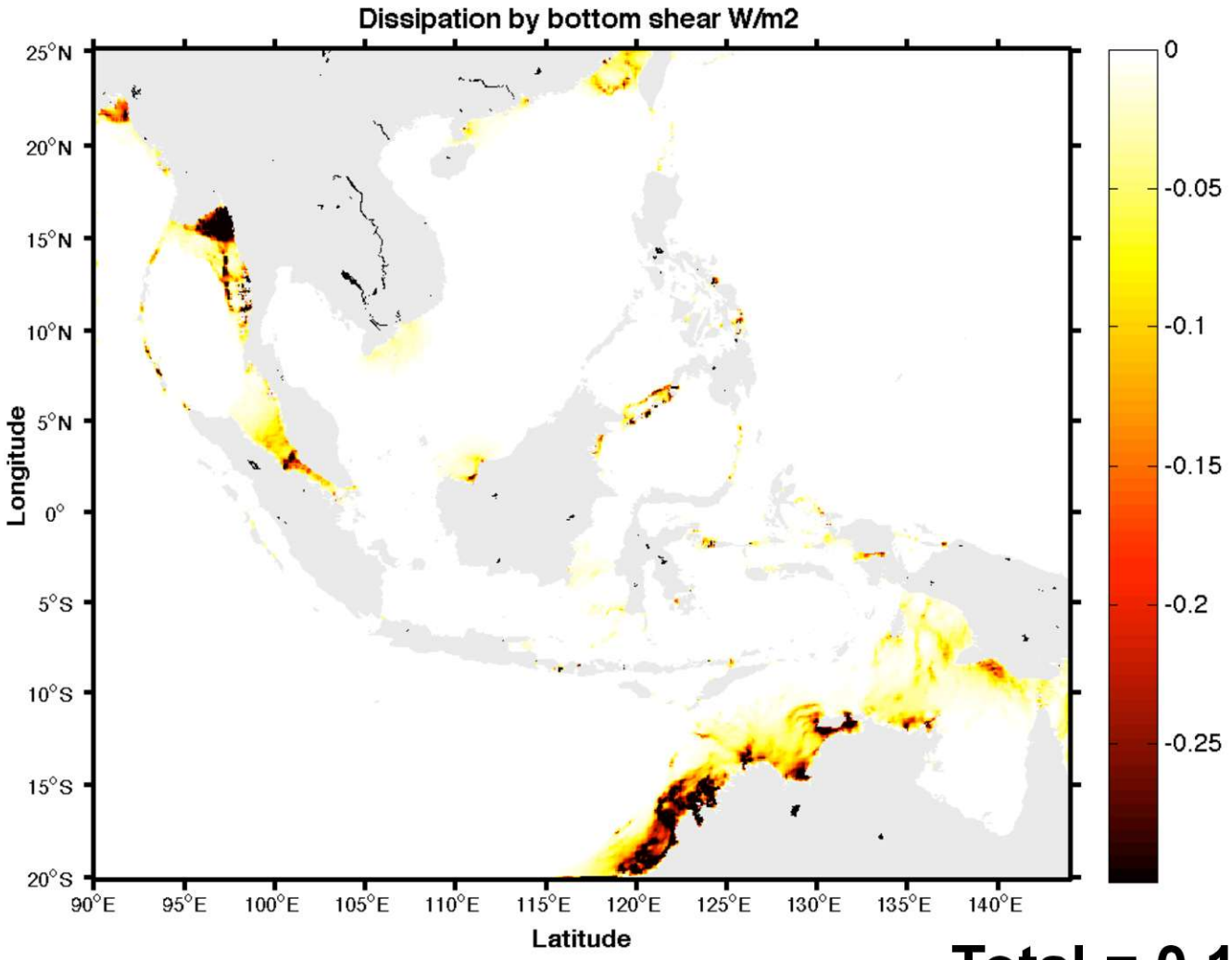

Thanks !
CRONOS
INDOMIX Jul 2010


0
-100
-200
-300
-400
-500
-600
a) S1 : Hal north
b) S2 : Hal center
c) S3 : Hal South
d) S4+XCTD : Banda
e) S5 : Ombai
f) XCTD : Savu sea
21 22 23 24 25 26 27
22 23 24 25 26 27
22 23 24 25 26 27


Temperature
Salinity
30
25
20
15
10
5
33.5
34.0
34.5
35.0
JFW
SPSW
SPCW
IW
NIIW
SPIW
S0
S1
S2
S3
Xctd1-9
S4
Xctd10-12
S5
Xctd13-21
from east to west
21.0
21.5
22.0
22.5
23.0
23.5
24.0
24.5
25.0
25.5
26.0
26.5
26.5
27.0
27.5
28.0

D1 : rate of dissipation by bottom friction Dissipation M2

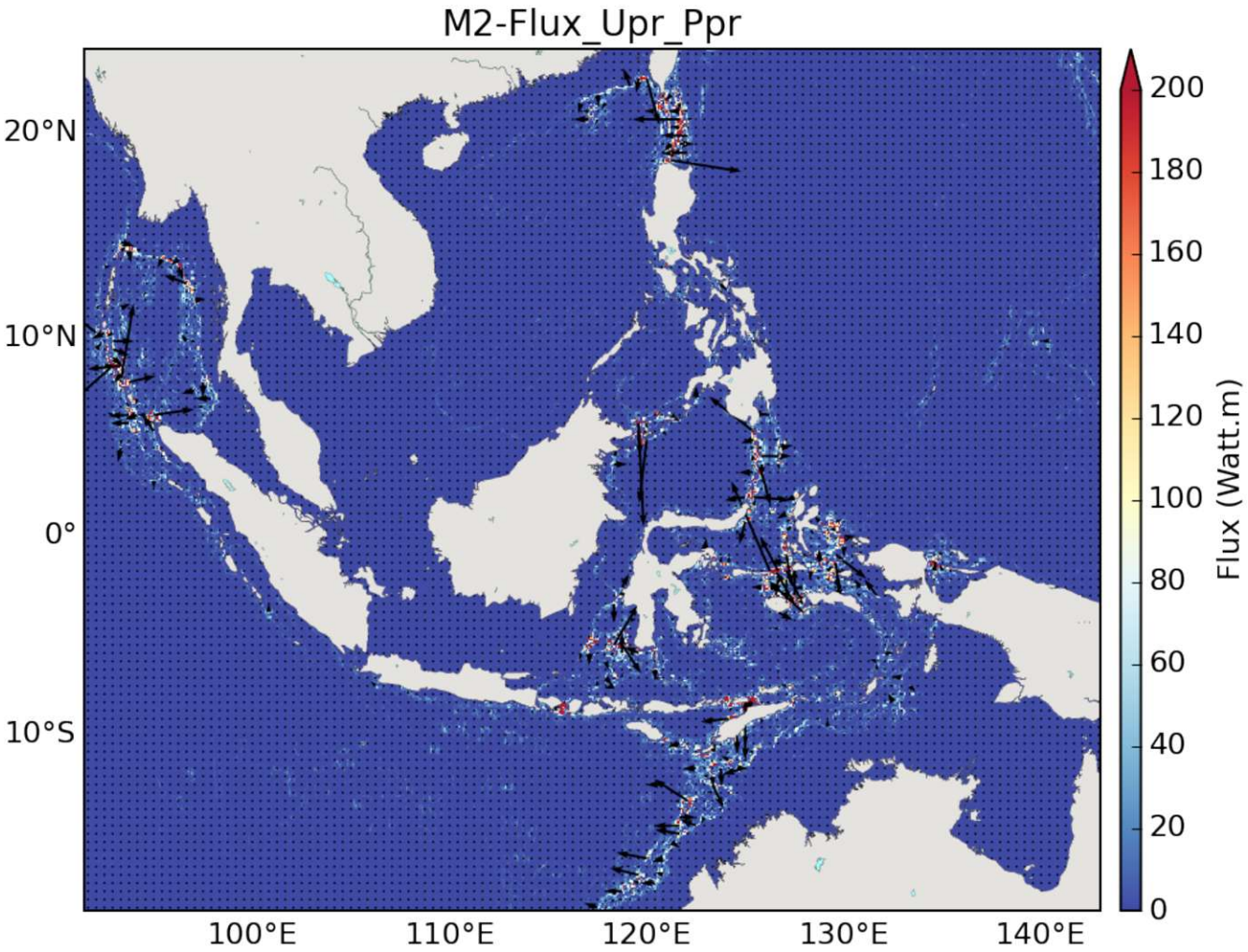
$$W = \rho_0 c_d |u| u^2$$

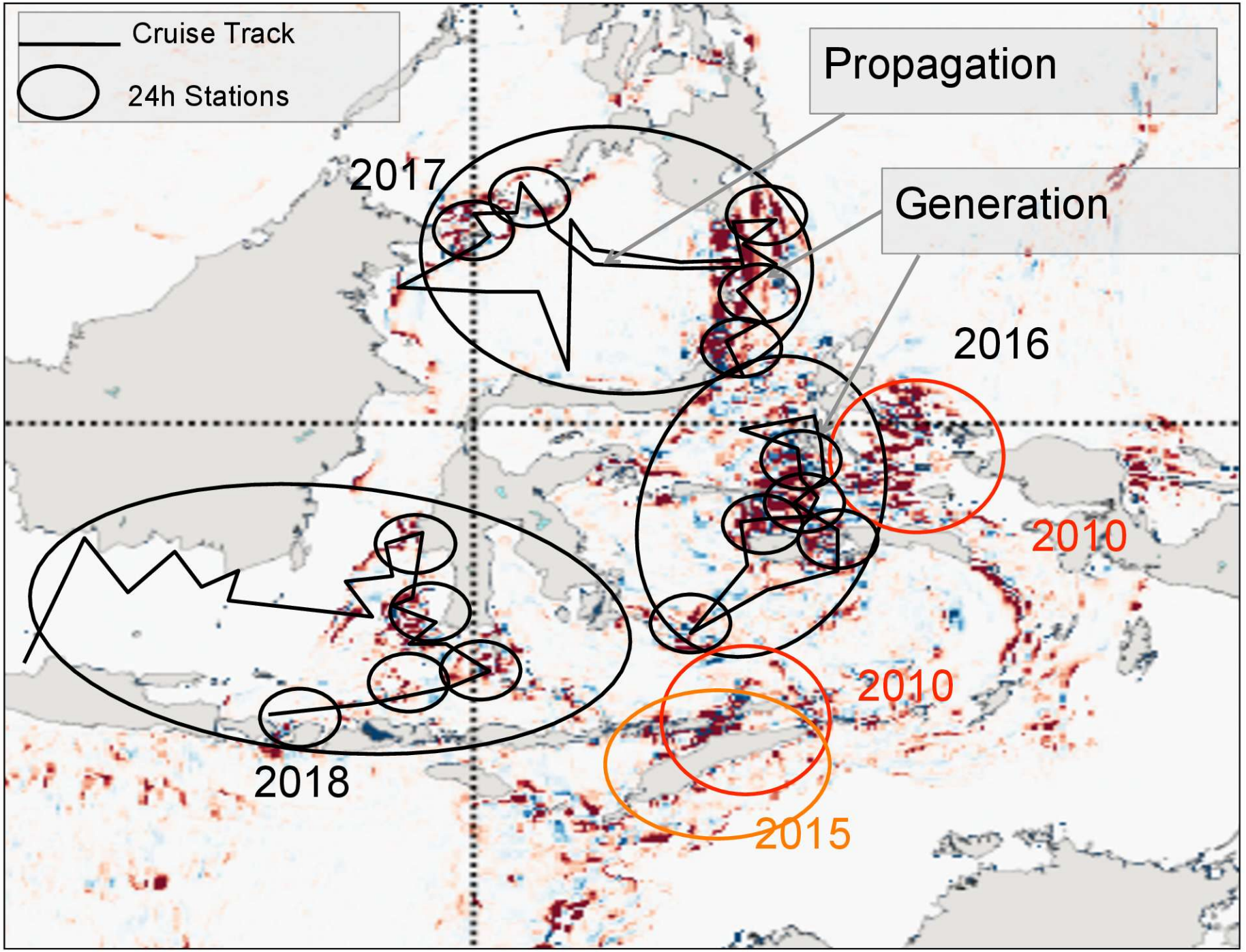


Total = 0,18 TW

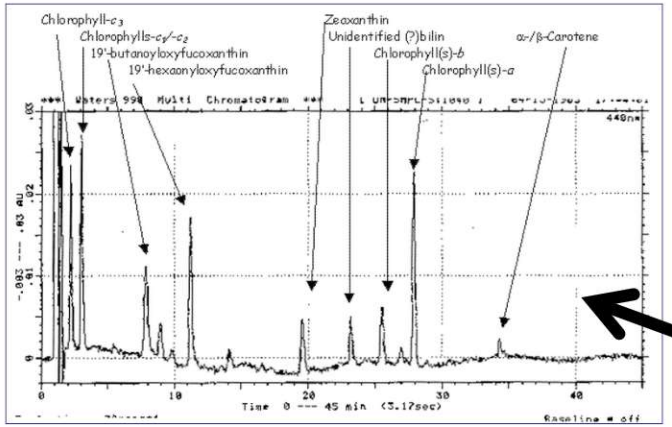
4) INDESO : NEMO explicit tidal forcing

F' : baroclinic flux M2 (W/m)



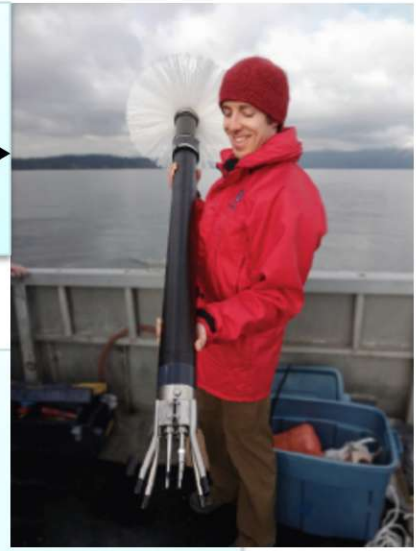

Cruise Track
24h Stations
Propagation
Generation
2017
2016
2010
2010
2015
2018

INDESOMix : measures



Physic

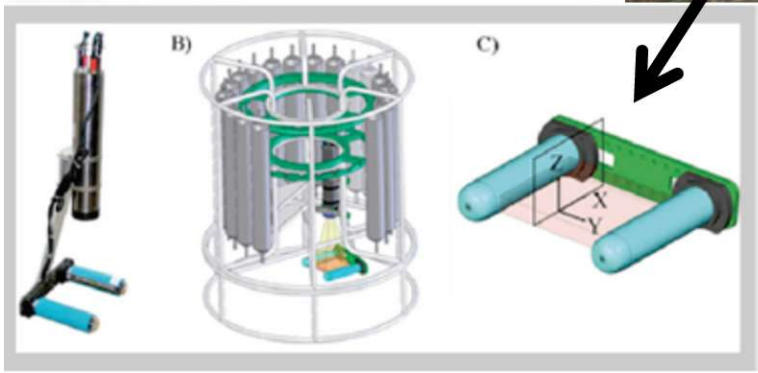
VMP
+ CTD/LADCP

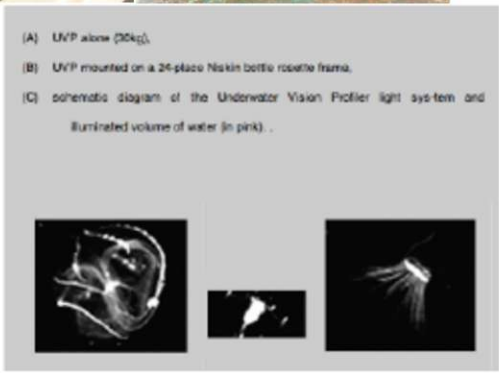


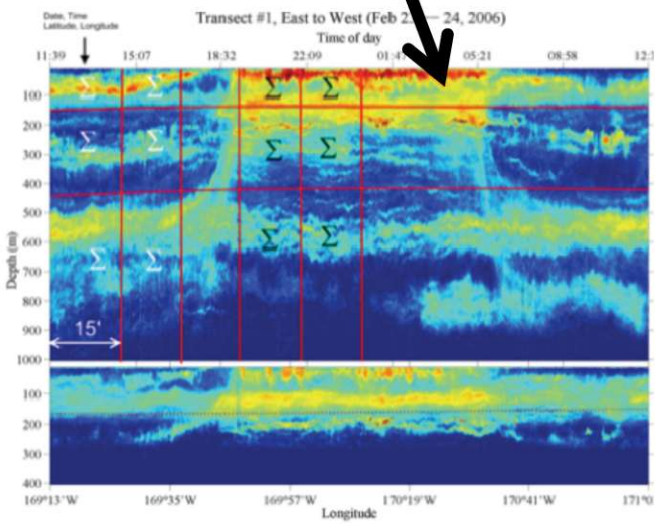
Biology

- CO2 : DIC/Alkalinity, PH
- CHLa : HPLC Chomatography
- Nutrients : ISUS
- LISST/Transmissiometer
- Echo sounder (3 freq EK60,Simrad)

Chomatography
Need Freezer on bord !

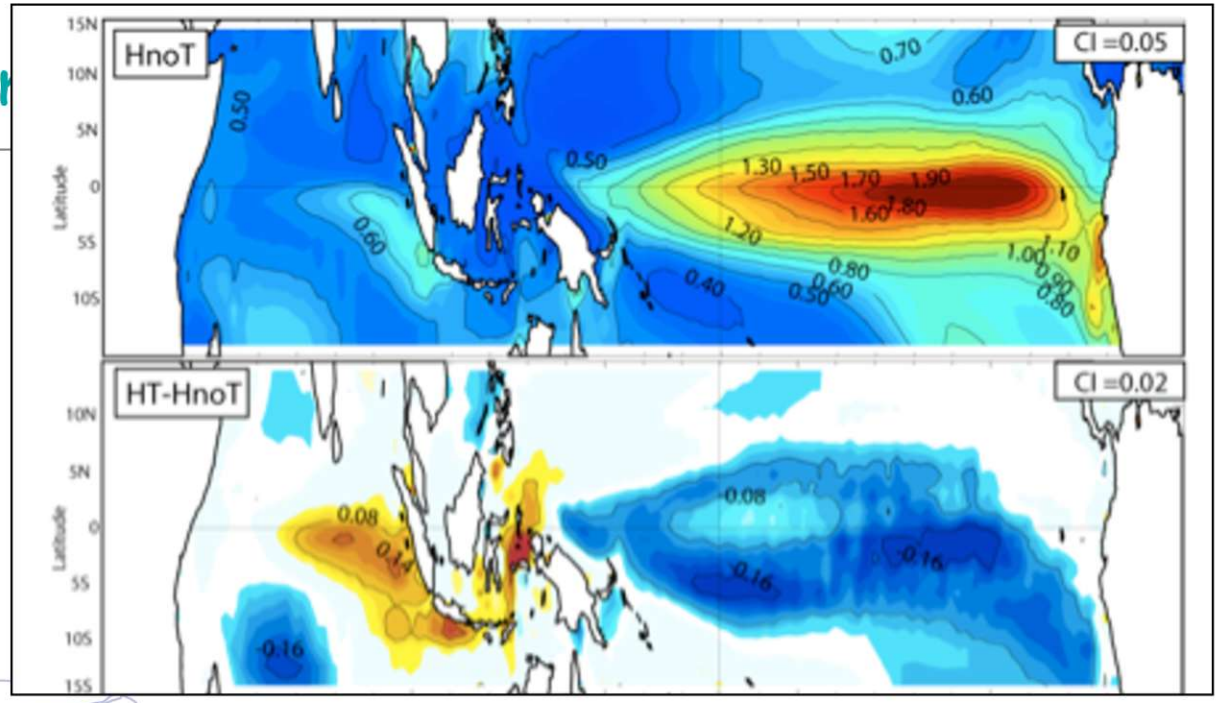






2) Impact on climate r

Coupled model :
with param.
⇒Modify tropical variability



Std of SSTs