Effects of large-scale wind variation on the Kuroshio path south of Japan in a 60-year historical GCM simulation

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1. Introduction

Kuroshio:

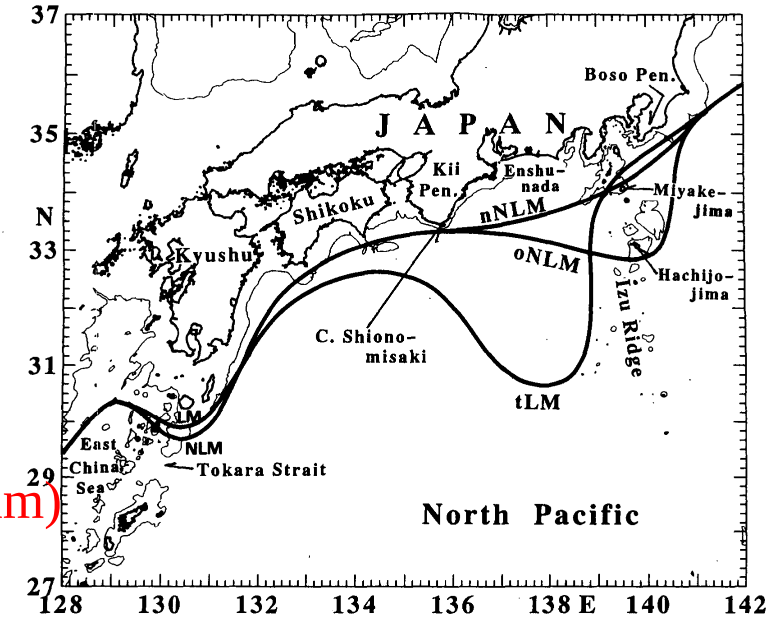
- Western boundary current of the subtropical North Pacific Ocean
- Non-trivial impacts on the atmosphere (Xu et al. 2010, Nakamura et al. 2012)
- Remarkable Bimodality (Large Meander (LM) and Non Large Meander (NLM))

Issue: Are transitions completely intrinsic? or forced to some extent?

Bimodality and Kuroshio transport (large scale wind variation):

- Observations:
  - Large transport in the East China Sea (ECS)
    → LM (Kawabe 1995)
  - Low-latitude (< 21°N) positive SSHA
    → the transport increase in the ECS
    by self-advection (Akitomo et al 1996)

- Numerical Experiments (idealized settings):
  Small (south of Japan) → NLM
  Medium → LM and NLM (multiple equilibrium)
  Large → NLM
  (Kurogi and Akitomo 2006)



Kawabe (1995)

Local vorticity balance of the stationary large meander:

Cushman-Roisin (1993):
equivalent barotropic thin jets

eastward speed of a meander on a jet

$$c = -\beta R_d^2 + \frac{2R_d^2 U}{3RY}$$

R_d : deformation radius
U : jet speed
R : radius of curvature
Y : meridional displacement

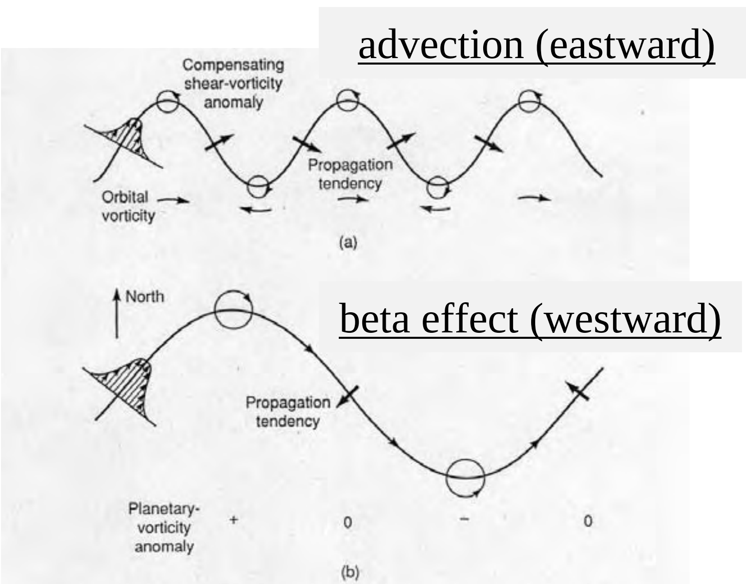


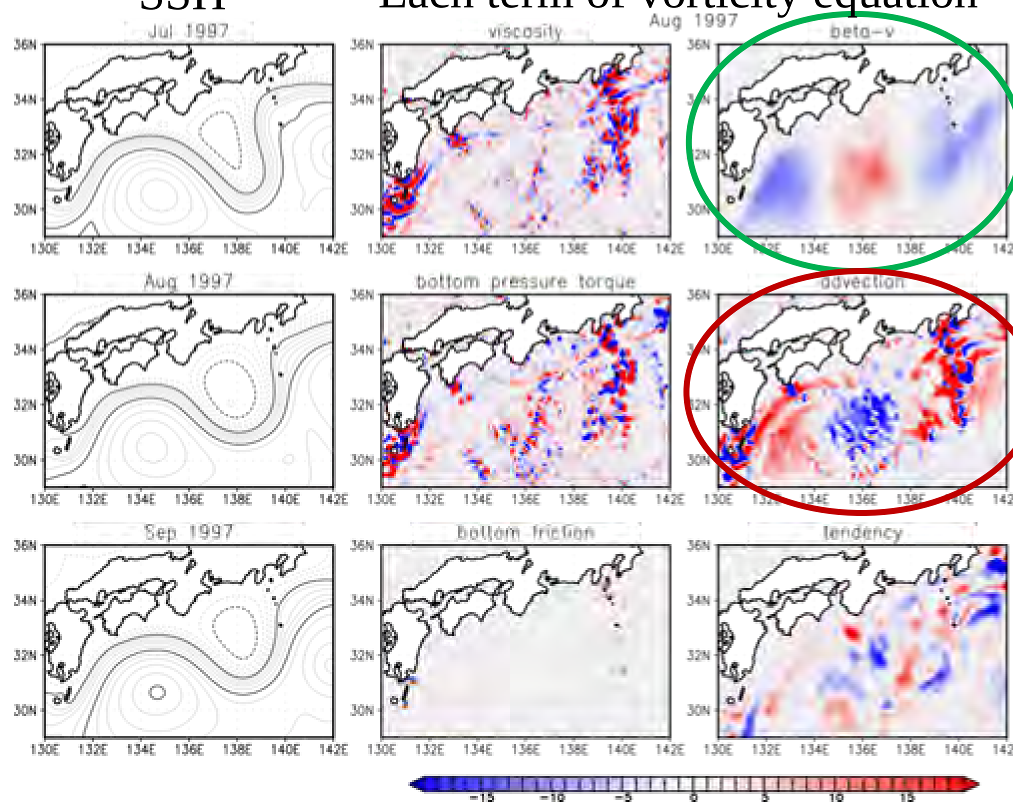
Figure 17-5 Schematic descriptions explaining why (a) curvature and (b) beta effects on an eastward jet induce meander-propagation tendencies that are, respectively, downstream and upstream.

Cushman-Roisin (1994)

Tsujino et al. (2006): vorticity balance of depth-integrated momentum eq.

$$\overbrace{\frac{\partial\overline{\zeta}}{\partial t}}^{\text{tendency}} = \overbrace{-\beta\int_{-H}^{\eta} v\,dz}^{\text{beta}} + \overbrace{\frac{1}{\rho_0}J(p_b,H)}^{\text{bottom torque}} - \overbrace{\text{curl}\left(\int_{-H}^{\eta}(\mathcal{A}(u),\mathcal{A}(v))dz\right)}^{\text{advection}} + \overbrace{\text{curl}\left(\int_{-H}^{\eta}(\mathcal{V}_h(u),\mathcal{V}_h(v))dz\right)}^{\text{viscosity}} + \overbrace{\text{curl}\left[\frac{\tau_s}{\rho_0}\right]}^{\text{wind stress}} - \overbrace{\text{curl}\left[\frac{\tau_b}{\rho_0}\right]}^{\text{botom friction}}$$

SSH | Each term of vorticity equation



It may be hypothesized that the bimodality has "Forced" aspects, but only one LM has occurred in the modern observing system.
→ GCM simulations are expected to be useful.

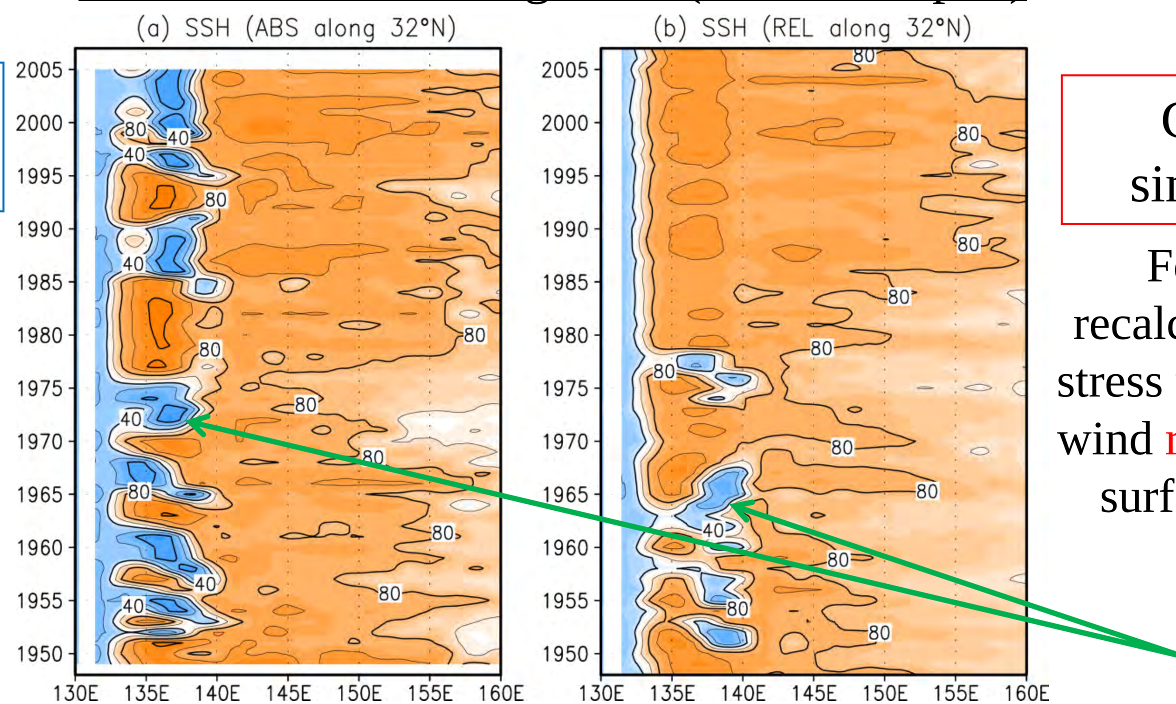
Current simulation:

- Use of "relative" wind → moderate EKE level (Zhai and Greatbatch 2007)
- Kuroshio spends less time in the LM state compared to conventional runs
- Discussion about the bimodality under natural variations of the forcing fields is possible for the first time (to our knowledge) → objective of this study

SSH time series along 32°N (south of Japan)

Conventional simulation

Forced by reanalysis wind stress (calculated using absolute surface wind)



Current simulation

Forced by recalculated wind stress using surface wind relative to the surface current

LM

2. Model and Experiment

Model:

Meteorological Research Institute Community Ocean Model (MRI.COM; Tsujino et al. 2010)

A set of nested Global - Western North Pacific models.

- Global-model: global tri-pole model developed for CMIP5
- Western North Pacific regional model: embedded within the global model, two-way transfer

Experiment:

•Forced by the Coordinated Ocean-sea ice Reference Experiments (CORE) interannual forcing (Large and Yeager 2008)

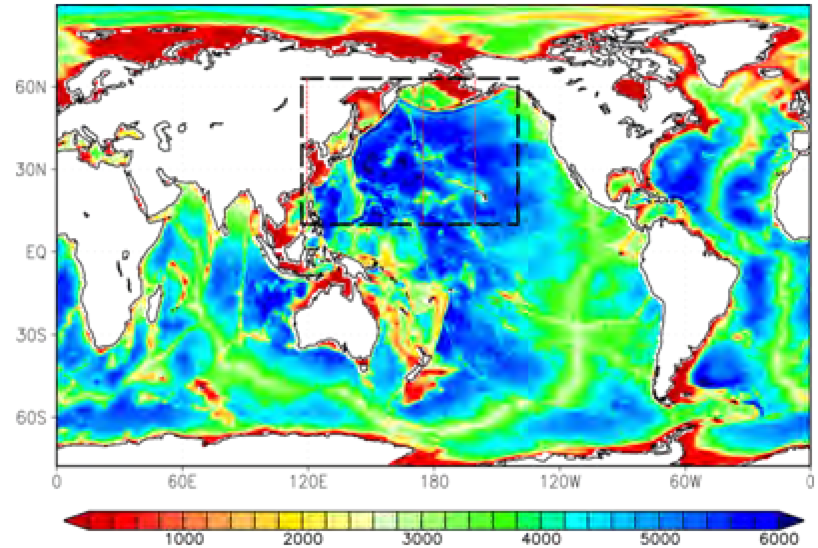
•Long-term spin-up of the global model (3000yrs)

•24 yr (1983-2006) spin-up of Western North Pacific model

(initial: end of 1982 of global model)

•60-yr historical simulation (1948-2007)

(initial: end of 2006 of the spin-up)



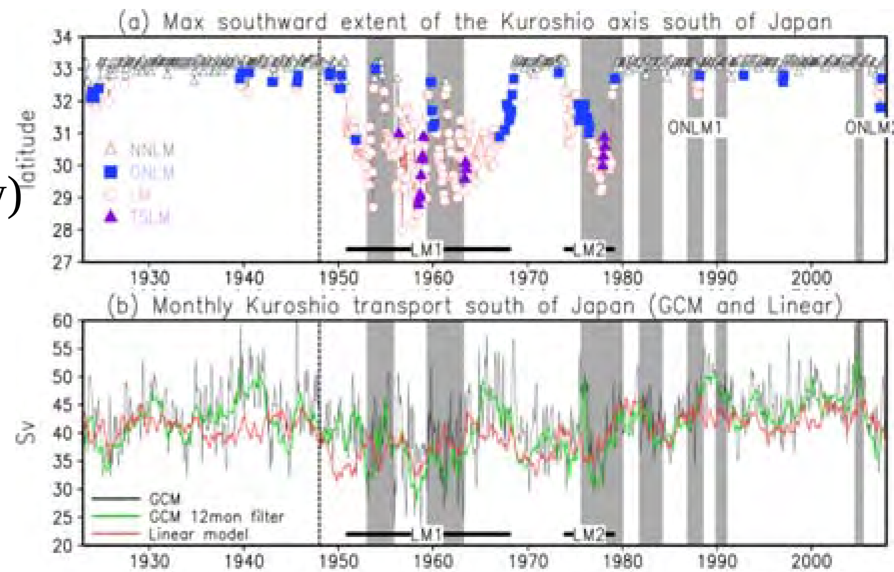
3. General feature of the simulated fields

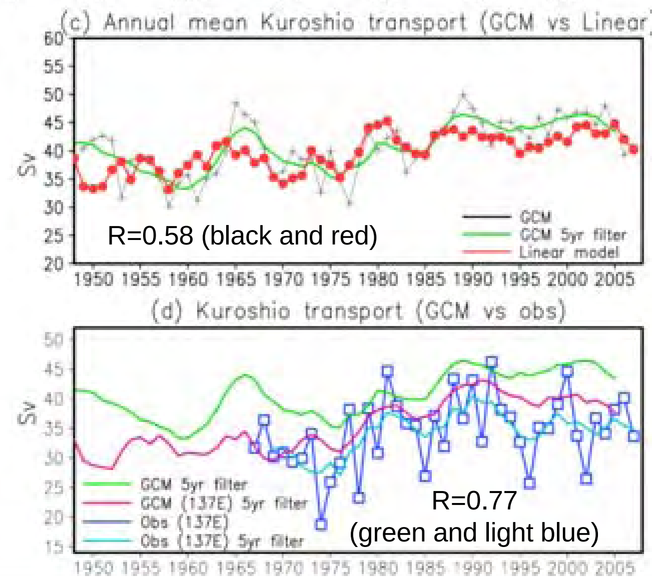
Observed LMs

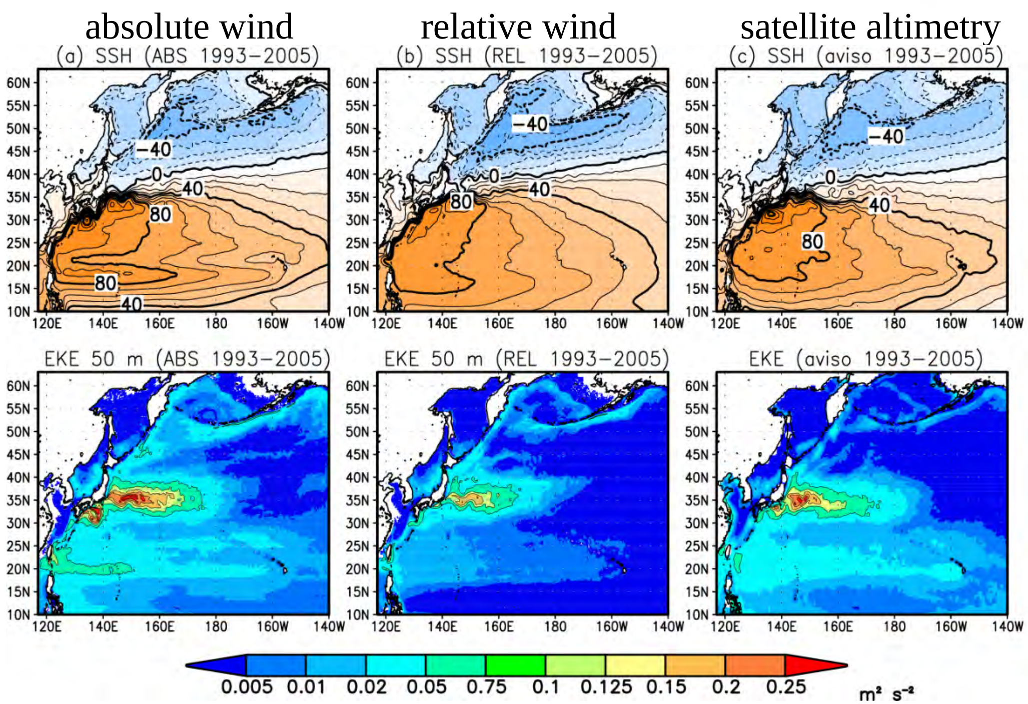
- Two major LM periods (LM1 and LM2)
- NLM in recent decades (especially in 1990s)

  … related to the moderate level of EKE (below)

- Modeled Kuroshio transport south of Japan (black and green) is largely explained by linear baroclinic vorticity model (red) (b and c)
- Long-term observed transport variation south of Japan (light blue) is reproduced (d)





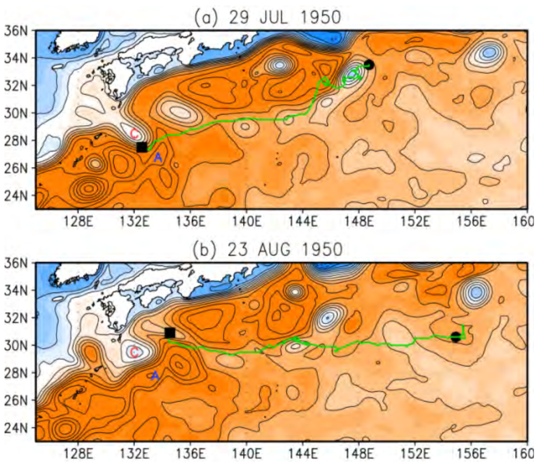


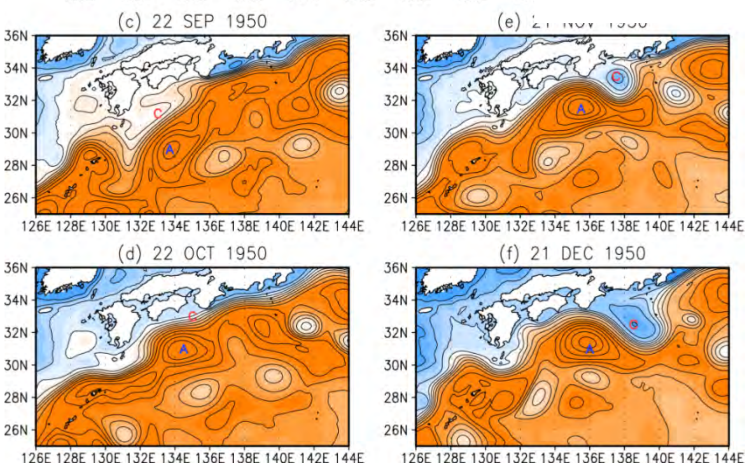
4. Relation between each stage of the LM and the large scale wind forcing

4.1 Formation

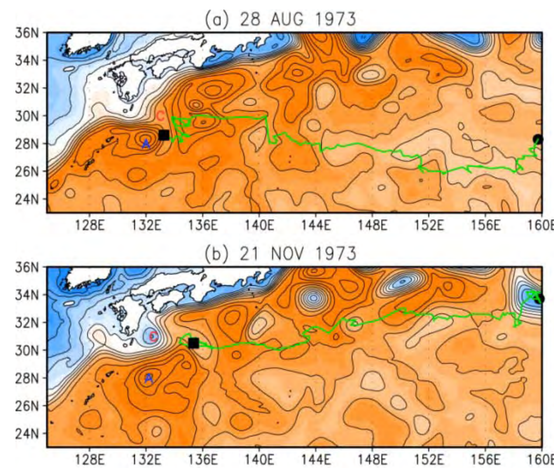
The two LMs follow a very similar formation sequence:

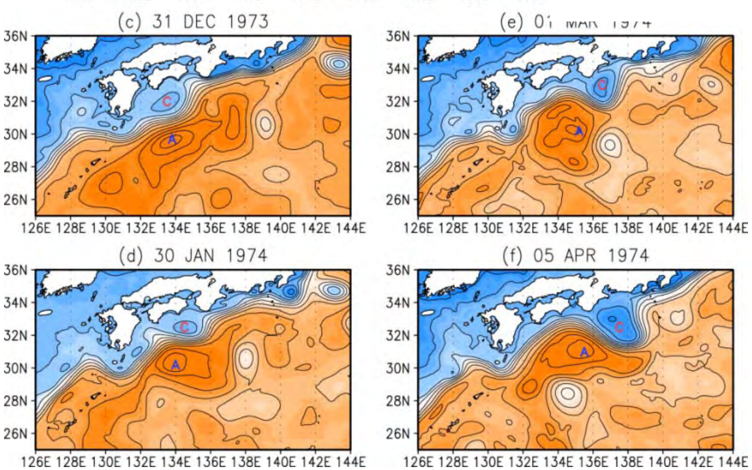
trigger meander (C), enlarged by offshore cyclonic eddies (green lines), followed by a sizable anti-cyclonic eddy (A)





SSH evolution (CI=10cm) during the formation of LM1





SSH evolution (CI=10cm) during the formation of LM2

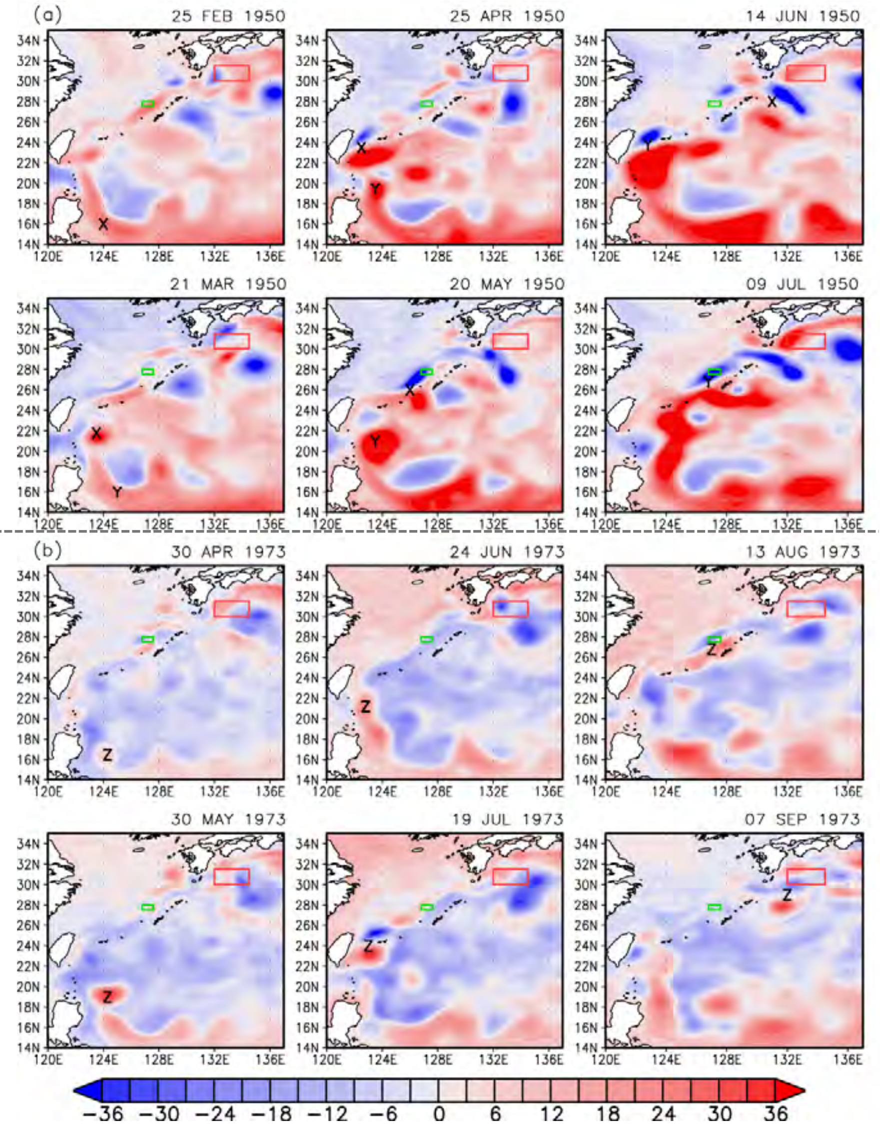
What is the cause of the trigger meander southeast of Kyushu?

Low latitude, wind-induced positive SSHA → cyclonic/anti-cyclonic pair

SSHA evolution prior to the formation of trigger meanders

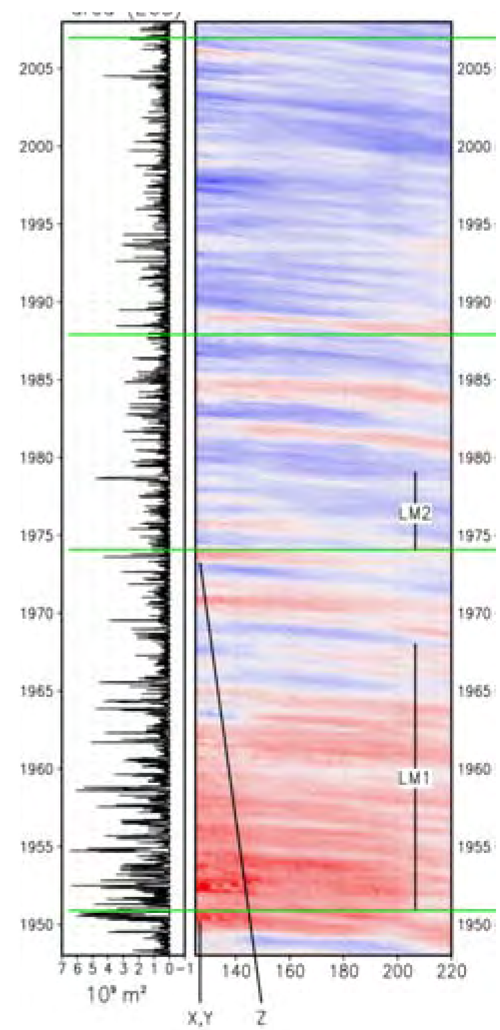
LM1

LM2



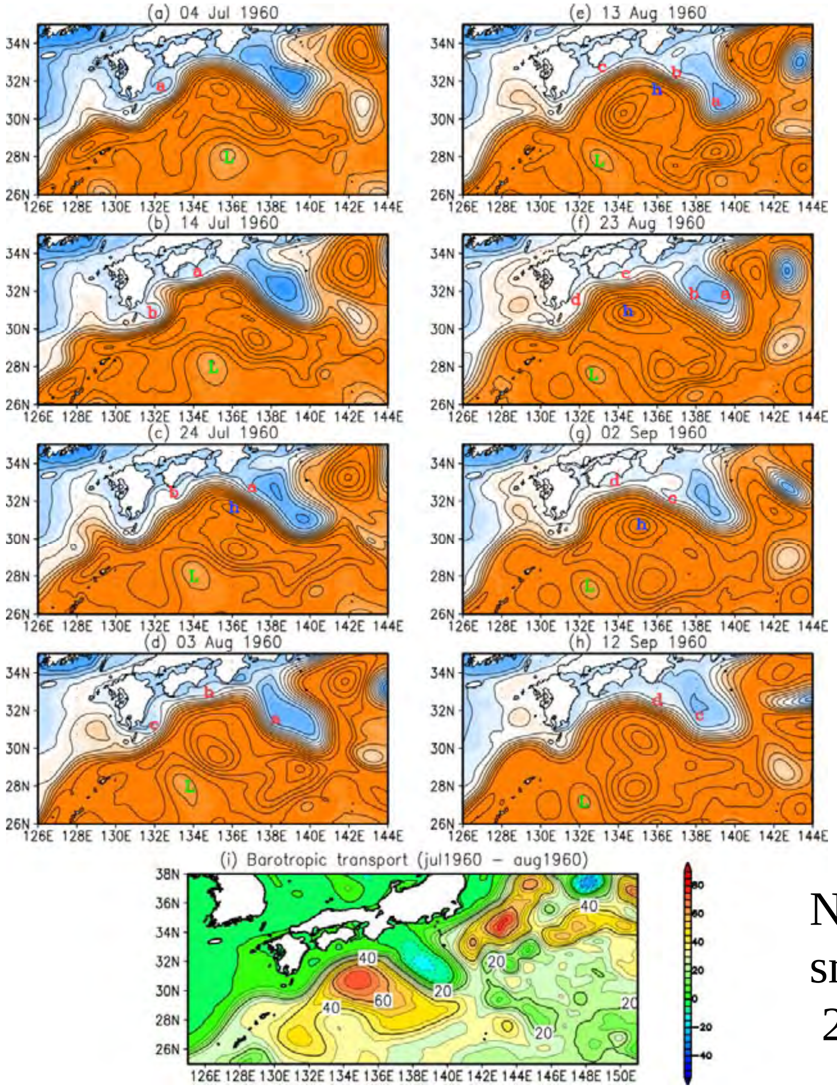
High PV (cyclonic eddy) area in the ECS

SSHA along 15ºN



4.2 Maintenance

Intermittent supply of cyclonic disturbance from the upstream (ECS) is trapped by the pre-existing LM



High PV (cyclonic eddy) area in the ECS

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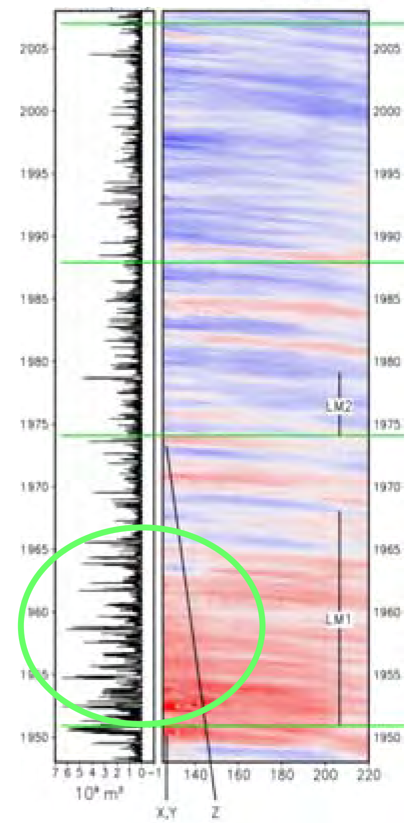


Net (throughflow) transport of the Kuroshio is small during the LM period

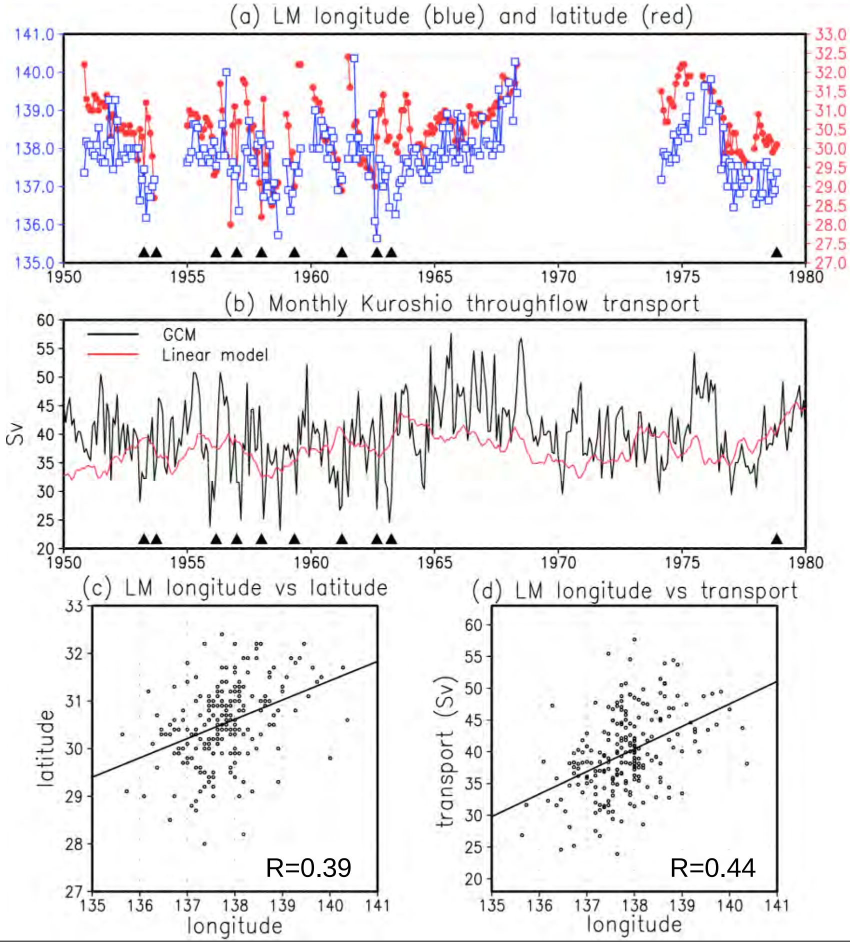
25 ~ 30 Sv in this example (cf. mean 40 ~ 45 Sv)

Eastward speed of a meander on a jet:

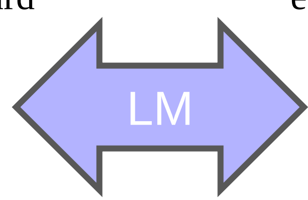
$$c = -\beta R_d^2 + \frac{2R_d^2 U}{3RY}$$

U : jet speed

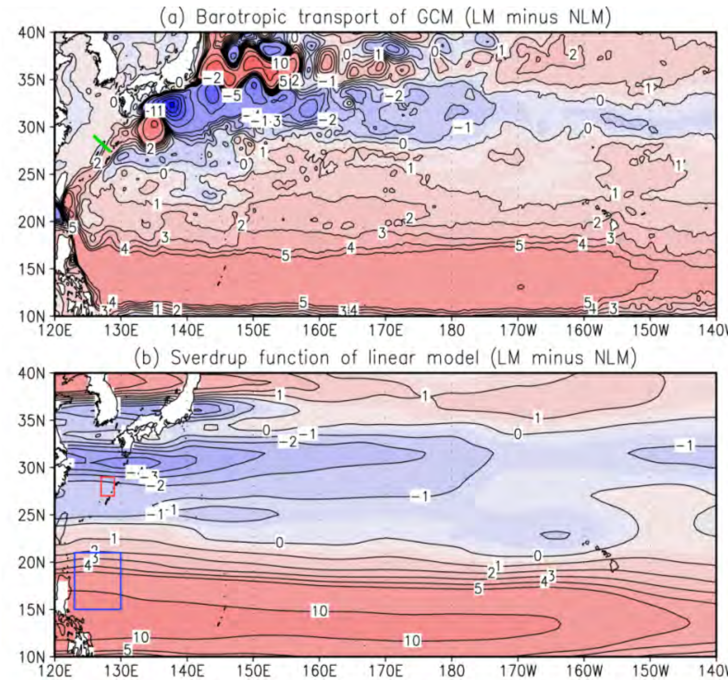
Y : meridional displacement



westward		eastward
enlarged		reduced in size
small transport		large transport



Difference between LM and NLM composite of barotropic transport stream functions



In the LM period,

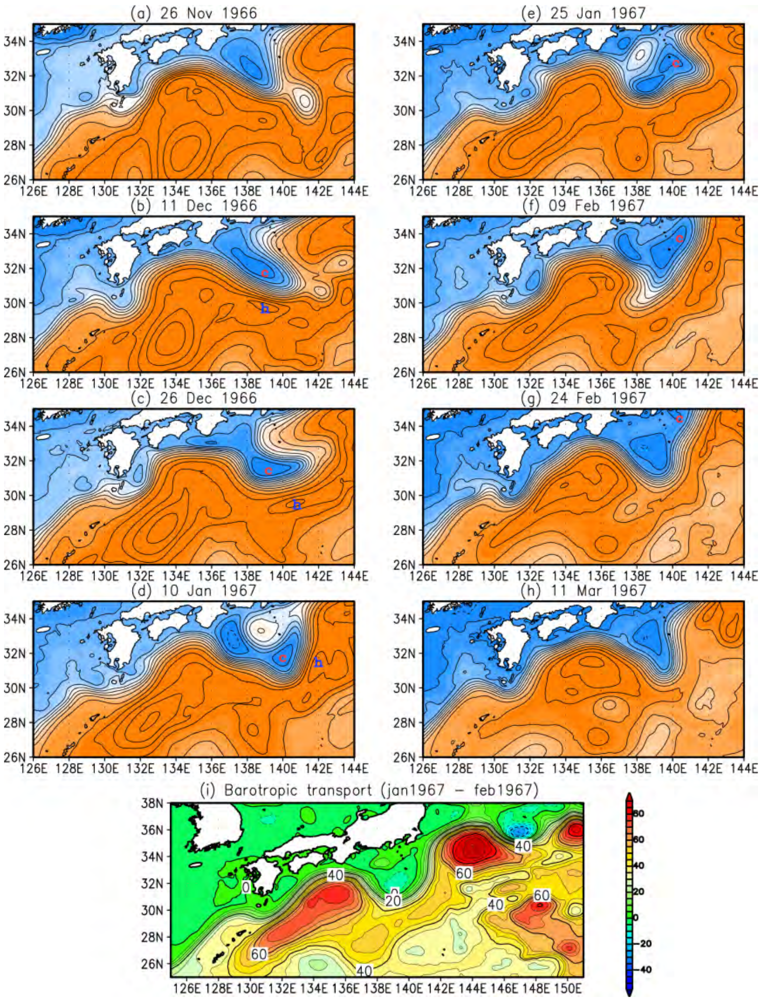
- Low latitude positive stream function anomaly is advected along the ECS
- Kuroshio transport along the southern coast of Japan is small

4.3 Decay

The Kuroshio transport is large in the decay stage

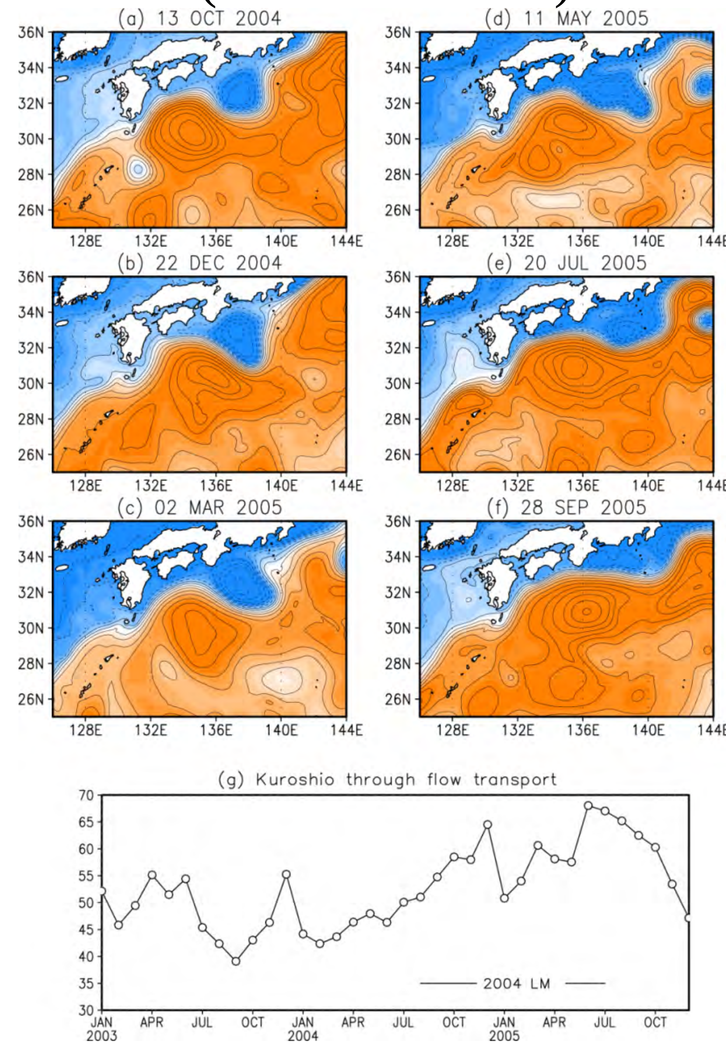
Disturbances from the upstream are not trapped by the LM, but flow away eastward.

LM1



Observed LM in 2004

(Usui et al. 2006)



5. Summary

- The trigger meander for the simulated LM events originates from the wind-induced positive SSHA hitting the upstream Kuroshio (and is enlarged by cyclonic eddies from the recirculation and is followed by a sizable anti-cyclonic eddy).

- A LM tends to be maintained when the Kuroshio transport south of Japan is small.

- The intermittent supply of disturbances from the upstream, which is related to the wind-induced positive SSH variability in low-latitudes, also contributes to the maintenance of a preexisting LM.

- The increased Kuroshio transport promotes decay of a LM.

- Conclusion: Large scale wind variation certainly affects bimodality of the Kuroshio path south of Japan. (It is not the sole mechanism to cause path variations, though.)