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Near-inertial internal waves observed in the vicinity of an anticyclonic eddy in the southwestern East Sea (Japan Sea)

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Background

- The local frequency (f) is about 19.8 hour at EC1
- Tides and tidal currents are weak in the interior of the East Sea (Japan Sea)
- Energetic NIWs have been observed in the deep water of the East Sea (Japan Sea), especially they has an annual cycle with winter intensification corresponding to seasonal wind (Mori et al., 2005)
- Byun et al. (2010) revealed near-inertial motions observed at EC1 and their interactions with a mesoscale anticyclonic eddy
- Whitt and Thomas (2015) and Jing et al. (2017) analyzed the energy exchange between mesoscale eddies and wind-forced near-inertial waves using modified damped slab model including the geostrophic flow

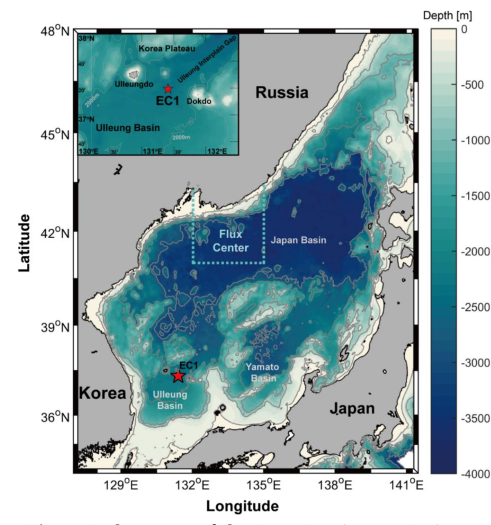

Fig 1. Bathymetry of the East Sea (Japan Sea). Pentagram (red) indicates OceanSITES EC1

Data and Method

Data

- Long-term mooring at EC1 (Mar. 2011 ~ Feb. 2012)
  - Currents – 75 kHz upward-looking ADCP (8m bin, 30 min interval)
  - Temperature – Total 7 depths between 100 and 400 m from SBE39
- 1.5° x 1.5° ECMWF Wind (6 hour interval)
- HYCOM + NCODA Global 1/12° analysis (GLBa0.08/expt 90.8)
  - MLD, temperature, salinity, horizontal velocity (daily)
- AVISO SLA + MDT (Choi et al., 2008)

Method

- NIWs extracted by 4th Butterworth band-pass filter with cut-off frequency [0.85f, 1.15f]
- The effective Coriolis frequency

$$f_{eff} \approx f + \frac{1}{2}\zeta = f + \frac{1}{2}\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right)$$

- Slab model is applied with amplifying factor suggested by Niwa and Hibiya (1999)
- Modified slab model including geostrophic flow (Main assumption: $R_0 \ll B_u$)

$$\frac{\partial u}{\partial t} + u\frac{\partial U}{\partial x} + v\frac{\partial U}{\partial y} = fv + \frac{1}{\rho_0}\frac{\partial \tau_x}{\partial z} - ru$$

$$\frac{\partial v}{\partial t} + u\frac{\partial V}{\partial x} + v\frac{\partial V}{\partial y} = -fu + \frac{1}{\rho_0}\frac{\partial \tau_y}{\partial z} - rv$$

(U, V) geostrophic flow, (u, v) near-inertial current in mixed layer, (τ_x, τ_y) wind stress, r damping parameter

Results

Observed near-inertial kinetic energy in Oct 2011

- **High near-inertial kinetic energy** is observed
  → Target period: Oct 2011
- Persisted about 10 days
- Penetrate down to 250 m
- Estimated $C_{gz} = 18\ m/day$

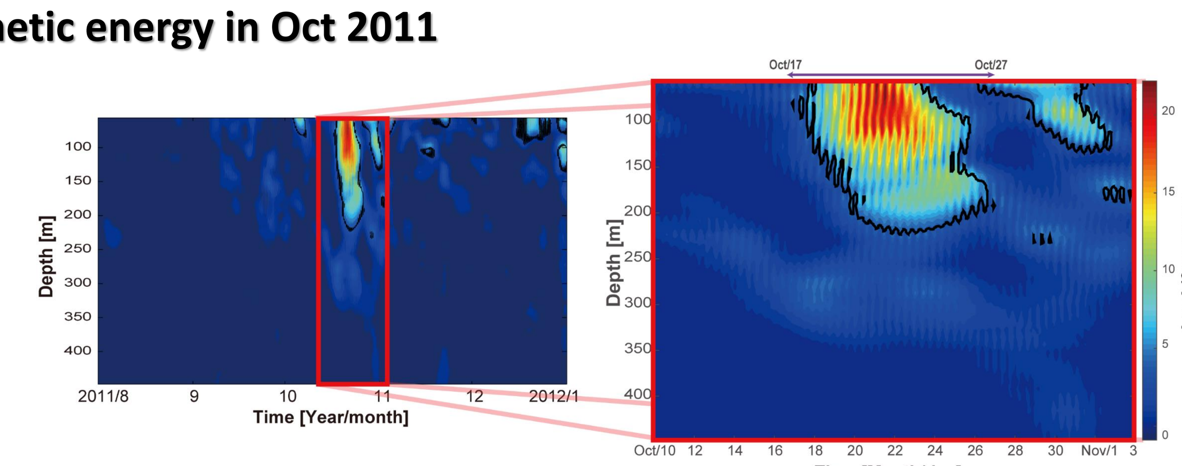

Fig 2. Time-depth contour of observed near-inertial kinetic energy (shading). Black solid line indicates criteria over 0.1 m/s

Predominant downward propagating near-inertial energy

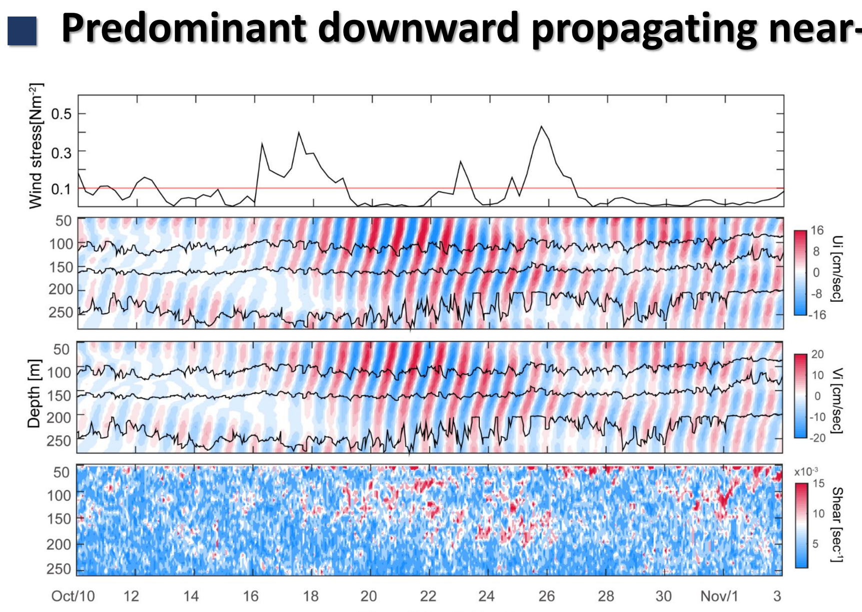

Fig 3. Time series of (a) Wind stress, (b) zonal component of near-inertial oscillation, (c) meridional component of near-inertial oscillation, and (d) shear during NIWs event in Oct 2011. Mean wind stress is represented by red line in (a). In (b) and (c), black lines indicate isotherms (10, 6, 2°C)

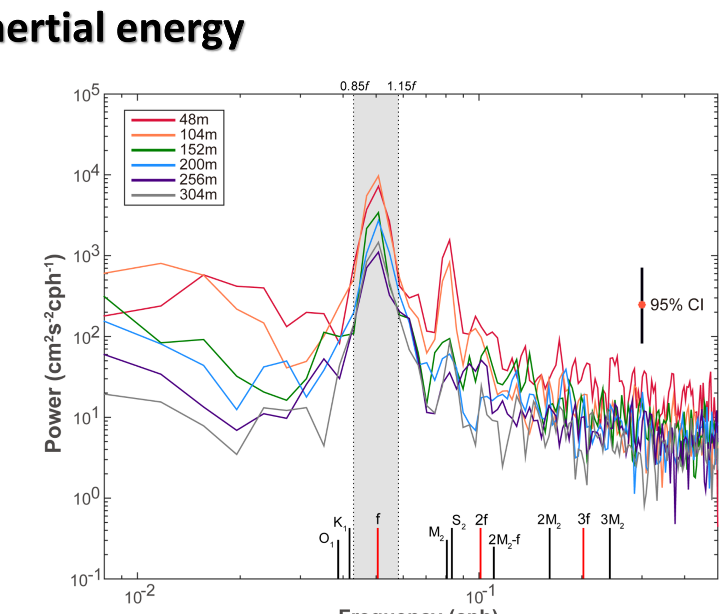

Fig 4. Power spectra of meridional current velocity during Oct.2011. Shaded area represents near inertial band [0.85f, 1.15f]. Primary tidal constituents and inertial frequencies are represented by minor ticks in x-axis. Confidence interval is 95%

- Predominant upward phase (downward energy) propagation
- Deepening of 2°C isotherm when the amplitude of NIWs are enhanced
- Significant NIWs above 300 m and weak semidiurnal and diurnal currents below 100 m

Wavenumber-frequency spectra during the Event

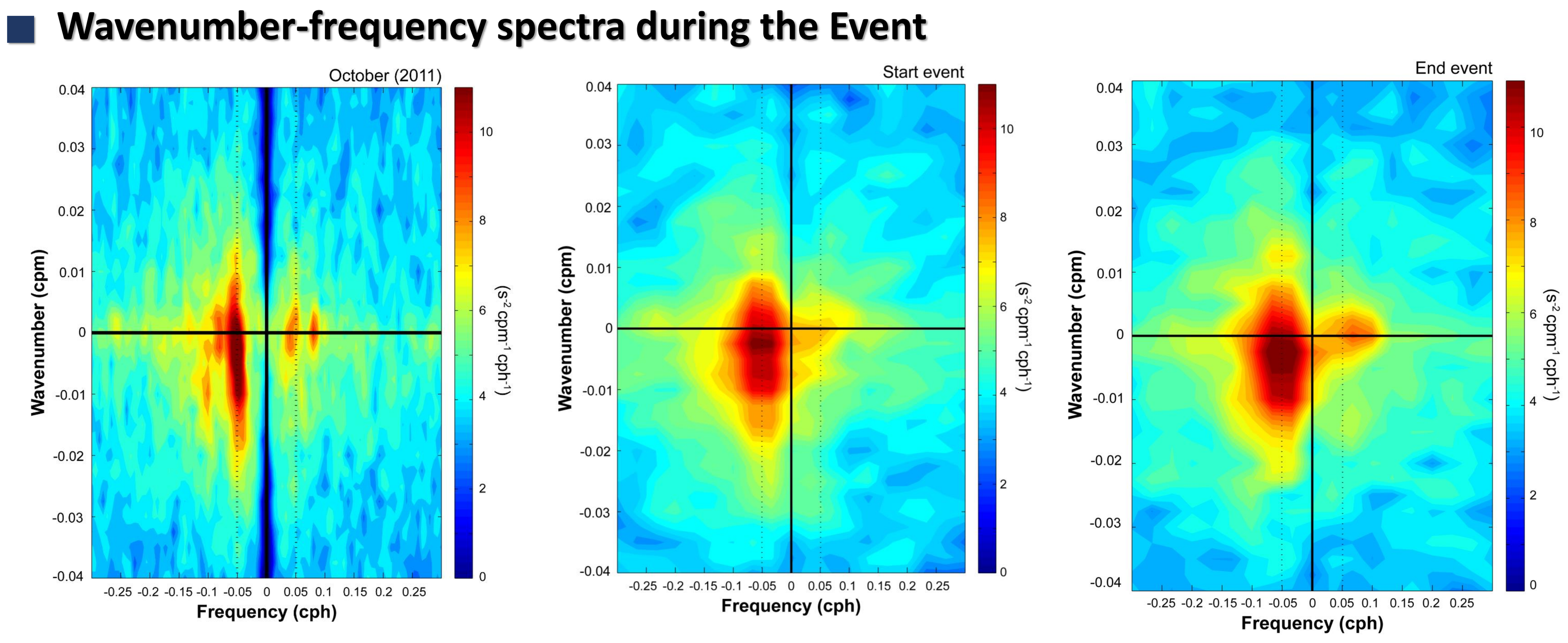

Fig.5. Frequency(σ)-vertical wavenumber (m) spectra of the observed currents (left) in Oct 2011, (middle) front of NIW event from Oct. 14 to Oct. 19 and (right) rear of NIW event from Oct. 23 to Oct. 28. These four-quadrant, two-dimensional spectra : positive (negative) frequencies correspond to counterclockwise (clockwise) rotation and downward (upward) propagating energy correspond to σ /m (-σ/m)

Wind – Causative forcing inducing near-inertial waves

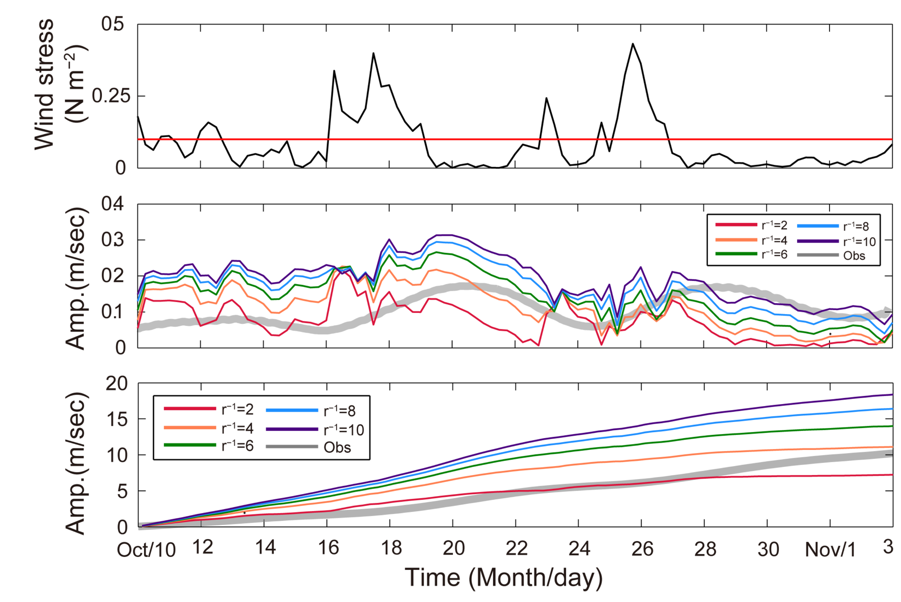

Fig.6. Damped slab model results (not considering geostrophic flow). (Top) Wind stress, used to calculate NIWs in mixed layer, (middle) predicted NIWs in mixed layer by slab model, (bottom) cumulative curve of middle panel. Gray thick line indicates observed NIWs at 48 m. In this slab model, MLD was constant 22 m.

- Similar patterns of predicted and observed NIWs
- Previously, 2-D spectra shows clockwise rotation in near-inertial band during the Event
  → indicating wind-induced NIWs
- The larger the damping parameter, the higher NIWs amplitude in MLD
- Reasonable damping parameter ~ 4 day

Influence of mesoscale background flow field on NIWs

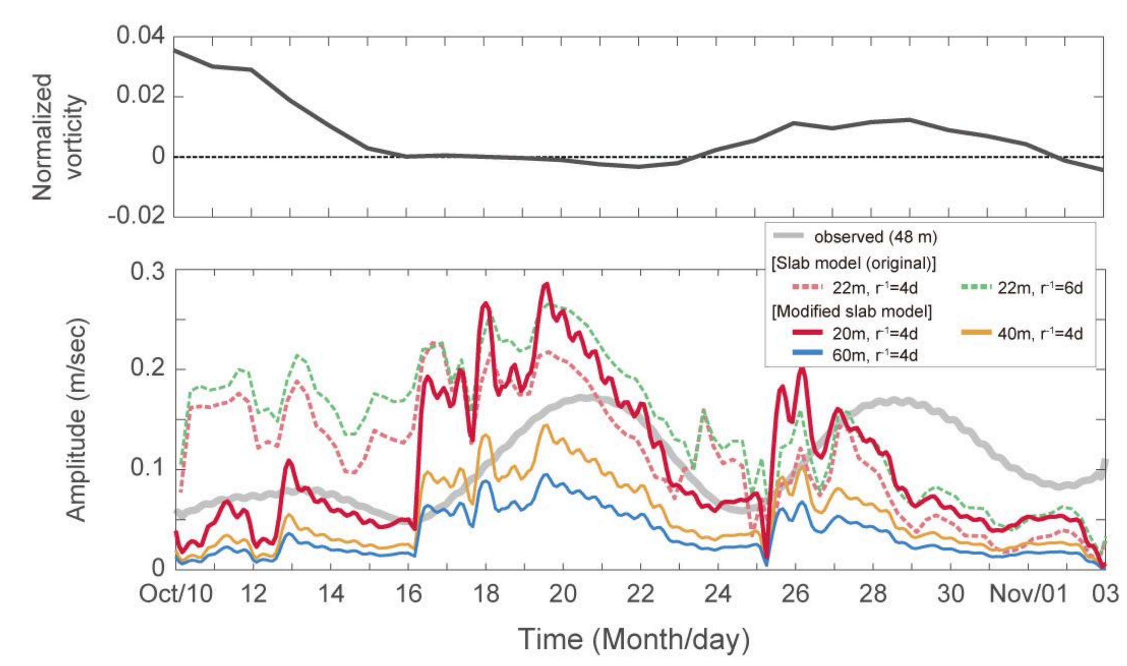

Fig.7. (Top) Normalized relative vorticity obtained from sea surface height, (bottom) predicted and observed near-inertial waves. Dash lines mean original damped slab model (not considering geostrophic flows) and thick lines indicate near-inertial waves predicted by modified damped slab model. Gray thick line is observed near-inertial waves at 48 m.

- Background relative vorticity ▲, predicted NIWs ▼
  (see red dashed and solid line)
- Observed NIWs are well explained by modified slab model from Oct. 10 to Oct. 25 (Event period)
- Unexplainable enhanced NIWs with slab model from Oct. 26
  → other mechanism?

	10/16	10/17	10/18	10/19	10/20	10/21	10/22	10/23	10/24
Obs.	0.0677	0.0669	0.0693	0.0772	0.0902	0.1071	0.1252	0.1373	0.1373
Case 1	0.0523	0.0719	0.0938	0.1183	0.1462	0.1737	0.1941	0.1903	0.1715
Case 2	0.1410	0.1509	0.1515	0.1609	0.1681	0.1822	0.1837	0.1657	0.1572

	10/25	10/26	10/27	10/28	10/29	10/30	10/31	11/01	11/02
Obs.	0.1273	0.1146	0.1064	0.1052	0.1115	0.1238	0.1360	0.1405	0.1350
Case 1	0.1495	0.1298	0.1166	0.1114	0.1070	0.1064	0.1036	0.0922	0.0762
Case 2	0.1399	0.1174	0.1013	0.0985	0.0947	0.0824	0.0737	0.0656	0.0555

Table.1. 6-day moving averaged near-inertial amplitude (unit: m/sec). Obs. means observed near-inertial amplitude at 48 m, Case 1 indicates predicted near-inertial amplitude from modified slab model with 20 m MLD and 4 day damping parameter (red solid line in Fig.7.) and Case 2 indicates predicted near-inertial amplitude from original slab model with 22 m MLD and 4 day damping parameter (red dashed line in Fig.7.)

Mesoscale background fields – Possible factor influences on NIWs

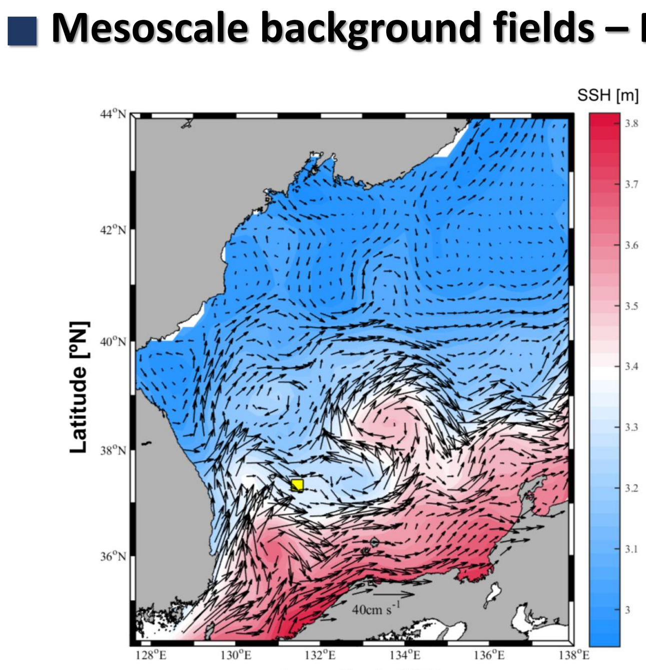

Fig.8. Sea surface height (contour) and geostrophic currents (vector) derived from SSH on Oct. 26. Yellow symbol indicates EC1

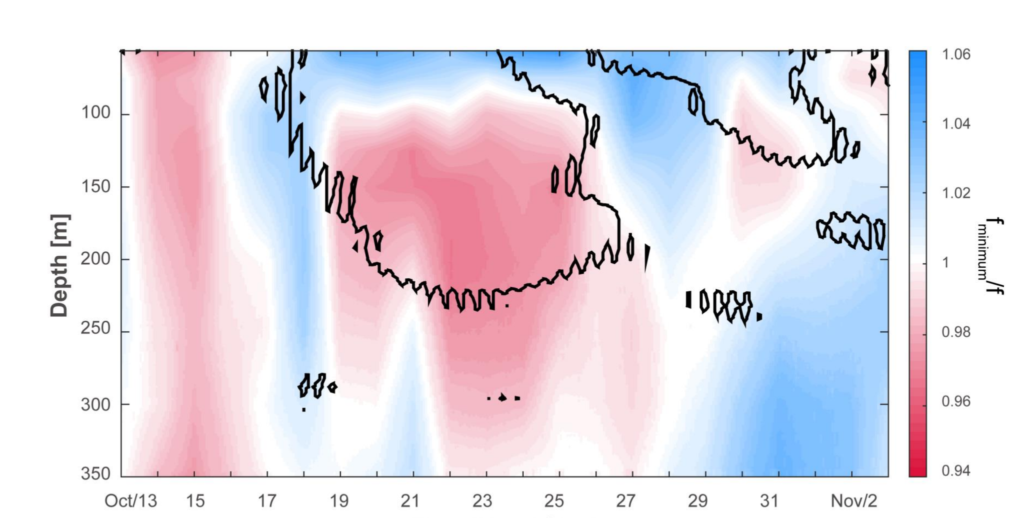

Fig.9. The minimum frequency (color shading) normalized by local inertial frequency. Black contour represents observed near-inertial currents over 0.1 m/s

- NIW favorable condition in interior during the Event

Summary

- This study focused on enhanced NIWs during October in 2011 above 250 m in the East Sea (Japan Sea)
- The observation captured high near-inertial energy, which persisted about 10 days with the maximum currents reached over 22 cm/s and estimated vertical propagation speed is 18 m/day
- Slanted phase line and wavenumber-frequency spectra also confirmed clockwise downward near-inertial currents, which presumably generated by intermittent wind forcing at the surface
- Since the simple damped slab model is only considered MLD and wind stress, modified slab model including geostrophic currents were applied to identify role of mesoscale flow field
- From modified slab model and minimum frequency results, it was confirmed that the mesoscale background field quite contributes to the propagation and energy amplification of NIWs
- However the reason why enhanced near-inertial energies are found after the Oct. 27 is not figured out
- NIWs seem to be involved in the mixing – when NIWs are enhanced, the 2°C isotherm was deepened
- It is necessary to quantify the interaction between the mesoscale background fields and NIWs
  : the ratio of the energy transfer rate (energy efficiency), comparison of each term in momentum equation...

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