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# Estimated Cloud-Top Entrainment Index Explains Positive Low-Cloud-Cover Feedback

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## Introduction

Kawai, H., T. Koshiro, and M. J. Webb, 2017: Interpretation of factors controlling low cloud cover and low cloud feedback using a unified predictive index. *J. Climate*, 30, 9119–9131, https://doi.org/10.1175/JCLI-D-16-0825.1.

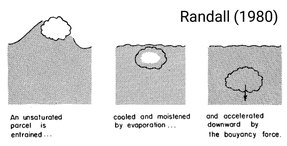
### ★ Estimated Cloud-Top Entrainment Index (ECTEI) Kawai *et al.* (2017)

**Deduced from the inequality in the cloud-top entrainment (CTE) criterion**

$$\Delta_{\mathrm{inv}}\theta_e < k(L/c_p)\Delta_{\mathrm{inv}}q_t$$

$k$ = 0.70 (MacVean and Mason 1990)

Randall (1980)



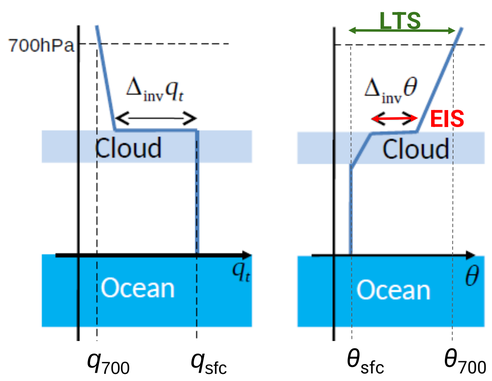

using $\theta$ instead of $\theta_e$, and applying some simplifications for the $q_t$ profile,

$$\Delta_{\mathrm{inv}}\theta - (1-k)(L/c_p)(q_{\mathrm{sfc}} - q_{700})C_{\mathrm{qgap}} < 0$$

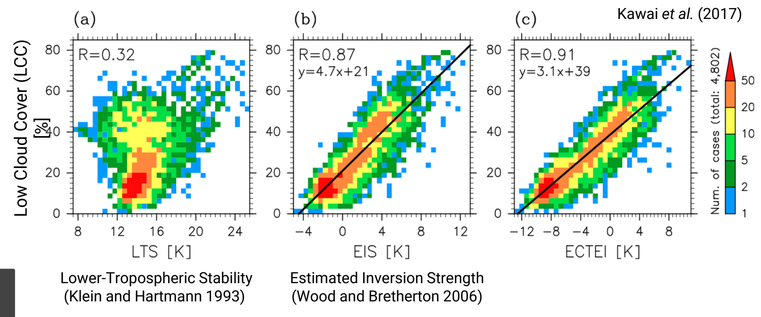
using EIS as the $\theta$ gap in the l.h.s.,

$$\mathrm{ECTEI} \equiv \mathrm{EIS} - \beta(L/c_p)(q_{\mathrm{sfc}} - q_{700})$$

$\beta = (1-k)C_{\mathrm{qgap}}$ = 0.23 ($C_{\mathrm{qgap}}$ = 0.76, based on the observations)




**Comparable to EIS, ECTEI shows a high correlation with low cloud cover (LCC) over the global ocean**




Lower-Tropospheric Stability (Klein and Hartmann 1993)

Estimated Inversion Strength (Wood and Bretherton 2006)

### ★ Previous studies

EIS is strongly correlated with LCC over the global ocean, showing a positive linear relationship

- Responses of temperature and water vapor profiles to warming in the large-scale environment are relatively more reliable than that of LCC actually simulated by GCMs
- **Would the response of EIS allow a more robust prediction of the LCC response?**
  → ***No. While LCC decreases with warming in many GCMs, EIS increases with warming.***

e.g., Webb *et al.* (2013), Qu *et al.* (2015)

Qu *et al.* (2014) Framework of cloud-controlling factors (CCFs) reviewed in Klein *et al.* (2017)

$$\Delta\mathrm{LCC} \approx \left(\frac{\partial\mathrm{LCC}}{\partial\mathrm{EIS}}\right)_{\mathrm{SST}}\Delta\mathrm{EIS} + \left(\frac{\partial\mathrm{LCC}}{\partial\mathrm{SST}}\right)_{\mathrm{EIS}}\Delta\mathrm{SST}$$

**Negative contribution of EIS** (an increase in LCC) < **Positive contribution of SST** (a decrease in LCC)

### ★ Expectation from Kawai *et al.* (2017)

$$\mathrm{ECTEI} = \mathrm{EIS} - \beta\frac{L}{c_p}(q_{\mathrm{sfc}} - q_{700})$$

**δ*q* term**

- Surface specific humidity $q_{\mathrm{sfc}}$ is mainly controlled by the saturation specific humidity at the surface
- and is much greater than the specific humidity in the free troposphere (i.e., $q_{700}$) in most cases

**The δ*q* term in ECTEI depends strongly on SST**

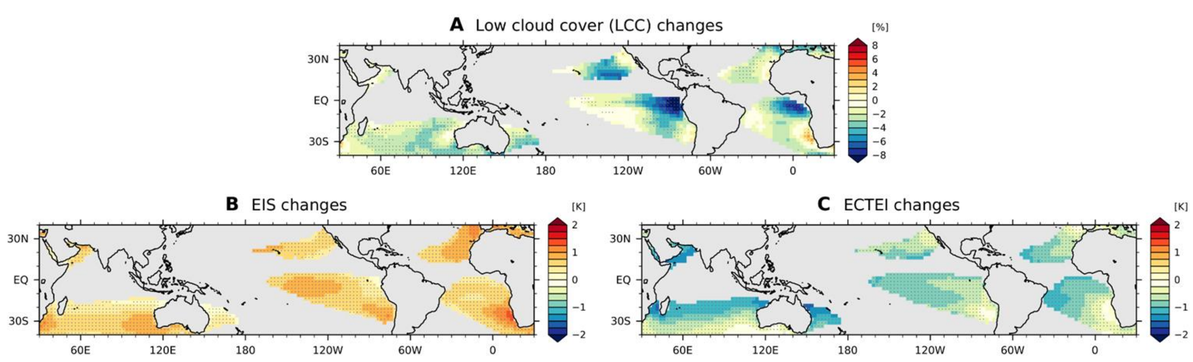
**→ The LCC sensitivity to EIS and SST variations emerges naturally from ECTEI.**

**ECTEI can explain LCC reduction in warmer climates**

**In this work, we confirm this expectation.**

## Results

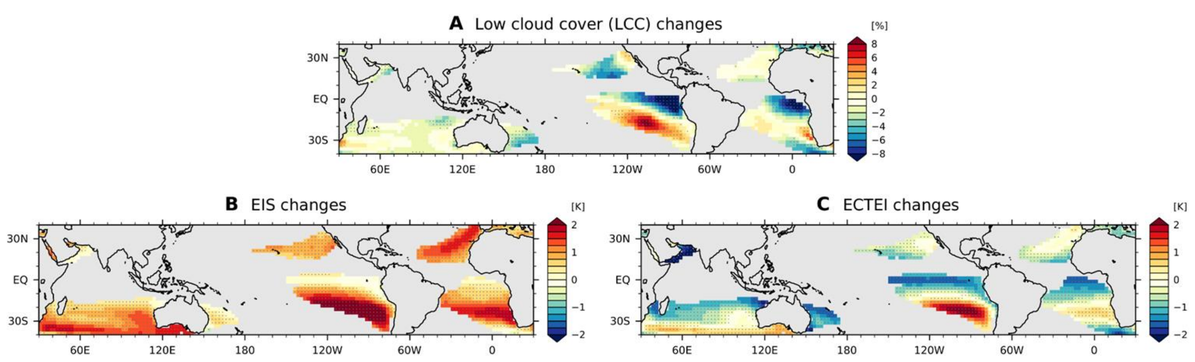
### ★ LCC, EIS, and ECTEI changes to uniform SST warming (amip-p4K)




- A reduction of LCC with a decrease in ECTEI and an increase in EIS are all robust
- The geographical distribution of the LCC changes does not closely match that of the ECTEI changes

➢ Ensemble annual means of five CMIP5 and 10 CMIP6 models (Jul 1998–Jun 2008)
➢ Only ocean areas where at least 12 models of 15 are identified as the domain for analysis (climatological high cloud fraction < 20%)
➢ Stippling indicates the regions where at least 12 models are in agreement about the sign of the field plotted

### ★ LCC, EIS, and ECTEI changes to patterned SST warming (amip-future4K)

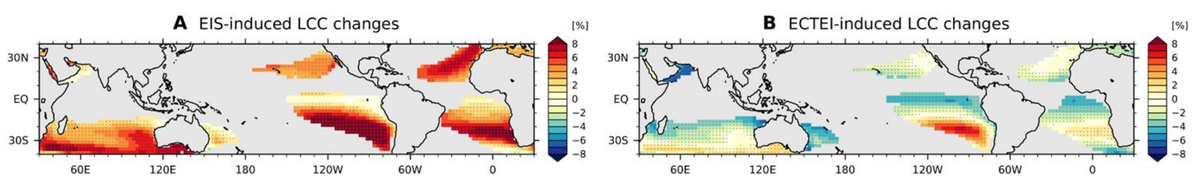



- EIS increases everywhere
- The distribution of the ECTEI changes is in good agreement with that of the LCC changes

**High predictability of ECTEI for LCC changes to SST warming**

The necessity of SST warming pattern for more reliable prediction of the LCC changes

### ★ LCC changes predicted by indices to patterned SST warming




Index-induced LCC changes can be estimated:

$$\Delta\mathrm{LCC}_{\mathrm{EIS}} = \frac{d\mathrm{LCC}}{d\mathrm{EIS}}\Delta\mathrm{EIS}$$

**= 4.7 % K$^{-1}$**

**(Koshiro and Shiotani, 2014)**

$$\Delta\mathrm{LCC}_{\mathrm{ECTEI}} = \frac{d\mathrm{LCC}}{d\mathrm{ECTEI}}\Delta\mathrm{ECTEI}$$

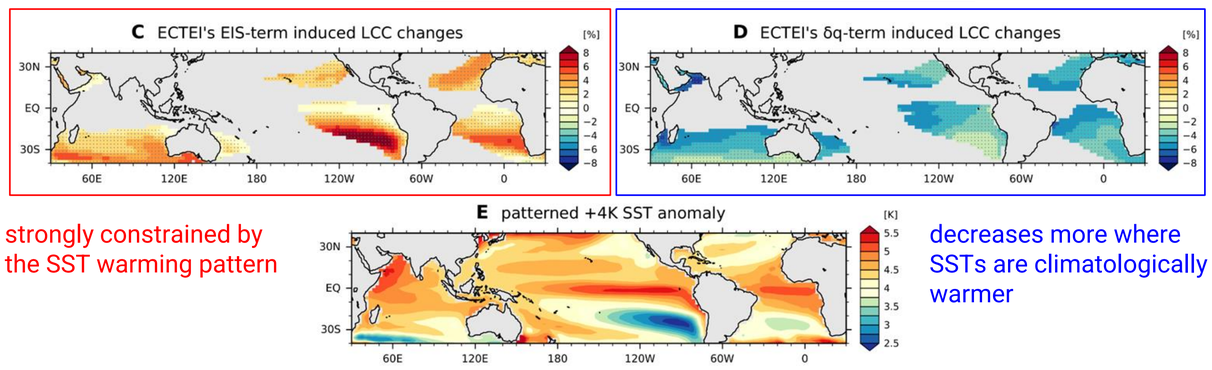
**= 3.1 % K$^{-1}$**

**(Kawai *et al.*, 2017)**

Linear regression coefficients based on the ship-board observations

$\Delta\mathrm{LCC}_{\mathrm{ECTEI}}$ can be divided into the contributions of **the EIS term** and **the δ*q* term**:

$$\Delta\mathrm{LCC}_{\mathrm{ECTEI}} = \frac{d\mathrm{LCC}}{d\mathrm{ECTEI}}\Delta\mathrm{EIS} - \beta\frac{L}{c_p}\frac{d\mathrm{LCC}}{d\mathrm{ECTEI}}\Delta(q_{\mathrm{sfc}} - q_{700})$$

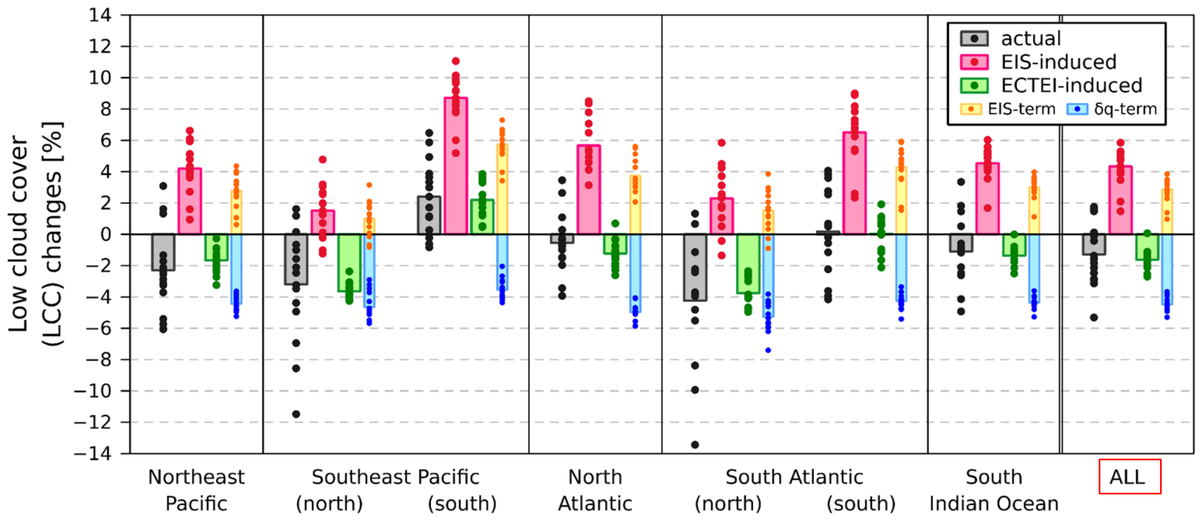



strongly constrained by the SST warming pattern

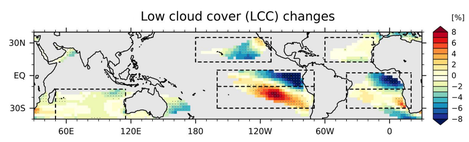
decreases more where SSTs are climatologically warmer

ECTEI gives a physical interpretation of the EIS and SST dependencies, which were heuristically indicated in the previous studies, as being due to the effects of CTE processes

### ★ Regional-averaged LCC changes to patterned SST warming




- ECTEI-induced LCC changes are in very good agreement with the actual LCC changes in the multimodel mean
- The intermodel spread of the ECTEI-induced LCC changes is much narrower than that of the actual LCC changes

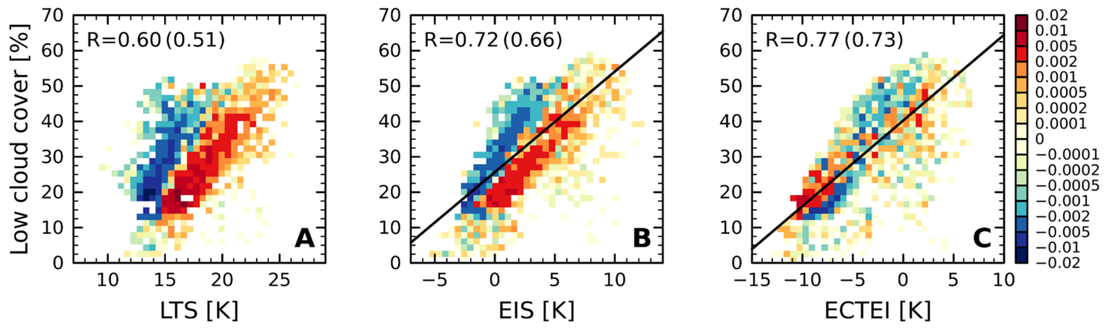



actually simulated by GCMs: −0.32 ± 0.83 % K$^{-1}$ → **predicted by ECTEI: −0.41 ± 0.28 % K$^{-1}$** (90% CI)

**virtually certain positive feedback** (<1% chance of negative feedback)

### ★ Changes in LCC–index relationships to patterned SST warming

To confirm the assumption that the linear relationship between LCC and ECTEI does not change between the present and warmer climates:




***changed***

Because of the behavior of the moist adiabat (Wood and Bretherton 2006)

***changed***

Free tropospheric temperature warming is generally greater than that predicted by the moist adiabat (Qu *et al.* 2014, 2015)

***not changed***

**The main changes in the distribution largely follow the regression line for the amip case: High LCC and ECTEI → Low LCC and ECTEI**

## Conclusions

Koshiro, T., H. Kawai, and A. T. Noda, 2022: Estimated cloud-top entrainment index explains positive low-cloud-cover feedback. *Proc. Natl. Acad. Sci. USA*, 119, e2200635119, https://doi.org/10.1073/pnas.2200635119.

**We have clearly demonstrated the expectation from Kawai *et al.* (2017)**

- ECTEI can explain the sign of the LCC changes
- even reproduce their geographical distribution for patterned SST warming
- and make it possible to understand the LCC changes by decomposing the contributions of EIS and SST

**These advantages of ECTEI significantly reduce the uncertainty in LCC feedback**

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