

Response letter

We sincerely thank the reviewer for the careful and constructive evaluation of our manuscript. We appreciate the reviewer's recognition of the scope of our analysis and the detailed suggestions regarding scientific contribution, manuscript organization, methodological clarity, and interpretation. In response, we have substantially revised the manuscript, strengthened the comparison with previous studies, clarified the added value and limitations of the Liang–Kleeman information-flow framework, reorganized the Results and Discussion, and improved the figures and supplementary analyses. Our point-by-point responses are provided below.

General Comments:

Comment 1:

The manuscript addresses an interesting topic by applying the Liang–Kleeman information flow framework to investigate soil moisture–temperature coupling at the global scale. The analysis is comprehensive, examining the problem from different angles, including coupling pathways, seasonality, reanalysis vs GCMs, among others. However, several aspects of the manuscript organization and interpretation should be improved before publication.

Response:

We appreciate the reviewer's positive assessment and constructive recommendations. We have carefully revised the manuscript to improve its scientific positioning, organization, methodological transparency, and interpretation. In particular, we have strengthened the literature comparisons and expanded the sensitivity analyses. These revisions are described in detail below.

Comment 2:

The manuscript would benefit from a clearer discussion of its scientific contribution relative to the existing literature. Several findings, such as, the stronger coupling in regions with high soil moisture variability, or the persistence of coupling in deeper soil layers, are generally expected and consistent with well-established knowledge. The authors should better position their results with respect to previous studies (e.g., compare the identified hotspots with previous work) and explicitly state the added value of applying the Liang–Kleeman framework over existing approaches.

Response:

We are grateful for this important observation. We have revised the manuscript to distinguish

these expected characteristics from the additional insights provided by the Liang–Kleeman information-flow framework.

Specifically, we have made the following revisions:

(1) Strengthened the comparison with previous studies.

We have expanded the Introduction and Section 4.1 to discuss previous research on land–atmosphere coupling, including Koster et al. (2004, 2006), Dirmeyer et al. (2006), Notaro (2008), Miralles et al. (2012), and Schwingshackl et al. (2017).

We also discuss regional differences between our results and previous studies. For example, the relatively weak annual SSM→T signal over India contrasts with the strong coupling reported in warm-season studies. Our seasonal analysis shows that significant SSM→T information flow becomes more pronounced over India during the local warm season (Figs. S13–S14), helping explain the differences among studies.

(2) Clarified the added value of the Liang–Kleeman framework.

We have revised the Introduction and Section 4.1 to explain how our analysis complements existing coupling assessments. Previous approaches commonly quantify covariability, sensitivity, or surface-energy responses, whereas LKIF provides a directional measure of information transfer from soil moisture to temperature.

Within this common framework, we examine direct SSM→T information flow, associated ET- and SH-related linkages, and their variations across hydroclimatic conditions, soil depths, seasons, and lag times. We also use the same directional measure to evaluate how CMIP6 models represent these relationships.

These revisions are reflected in the Introduction, Sections 4.1–4.2, and Conclusions.

Comment 3:

The organization of Sections 3–5 is somewhat inadequate. Subsections 4.1 and 4.2 primarily present results and would fit better within Section 3 (Results) rather than in Section 4 (Discussion). The actual discussion starts in Sections 4.3 and 4.4, which could either remain as the Discussion section or be merged with Section 5 into a combined Discussion and Conclusions. Moreover, the current Conclusion section is rather limited and does not address the gaps identified in the introduction (e.g. L38–41).

Response:

We appreciate this helpful recommendation regarding manuscript organization. We have reorganized Sections 3–5 to separate the presentation of results from their interpretation and to

establish a clearer connection between the research questions and conclusions.

The main revisions are as follows:

(1) Reorganized the Results section.

We have moved the relevant analyses and findings previously presented in the Discussion into Section 3. The revised Results section now follows a clearer sequence:

- Section 3.1: Global patterns of soil moisture–temperature causality.
- Section 3.2: Pathways underlying soil moisture–temperature causality.
- Section 3.3: Dependence of SSM–T causality on soil moisture variability.
- Section 3.4: Widespread causal coupling across seasons and soil depths.
- Section 3.5: Comparison with CMIP6 simulations.

This organization presents the spatial patterns, pathway relationships, hydroclimatic dependence, multiscale characteristics, and model comparisons before discussing their broader implications.

(2) Restructured the Discussion section.

We have revised Section 4 to focus on interpretation and comparison with previous studies rather than repeating the results. The revised Discussion includes:

- Section 4.1: Global characteristics and causal pathways of SSM–T coupling.
- Section 4.2: Hydroclimatic and multiscale variations.
- Section 4.3: Model–reanalysis differences in SSM–T causality.
- Section 4.4: Limitations and outlook.

These subsections discuss the findings in the context of existing coupling research, soil moisture memory, seasonal energy availability, model structural differences, and the limitations of the LKIF framework.

(3) Revised the Conclusions.

We have rewritten Section 5 to directly address the questions raised in the Introduction. The revised Conclusions summarize the global patterns of directed SSM→T information flow, the coexistence of ET- and SH-related linkages, hydroclimatic and multiscale variations, and differences between CMIP6 simulations and ERA5-Land.

We also clarify that the principal contribution is the integrated assessment of these relationships within a consistent directional framework.

Specific Comments:

Comment 4:

Section 2.1: Please report the spatial resolution of ERA5.

Response:

Thank you for requesting greater precision in the dataset description. We have revised Section 2.1 to provide additional information on the spatial resolution of the primary reanalysis data. We now state that ERA5-Land has a native spatial resolution of approximately 9 km, while the ERA5-Land data used in this study were obtained on the 0.1° regular latitude–longitude grid provided by the Copernicus Climate Data Store (CDS).

These clarifications are included in Section 2.1.

Comment 5:

Please include Table S1 (list of GCMs) in the main manuscript. It would also be useful to report the native resolution of each GCM and the soil depth represented by “mrsos”.

Response:

We appreciate the suggestion to make the model information more accessible. We have revised the CMIP6 dataset description and moved the model information into the main manuscript.

The specific changes are as follows:

(1) Moved the model information to the main manuscript.

The original supplementary model table has been replaced by Table 1 in Section 2.1. The revised table provides the model names, ensemble members, native grid dimensions, and nominal spatial resolutions, allowing readers to directly compare the characteristics of the CMIP6 models.

(2) Expanded the CMIP6 model dataset.

The analysis now includes 29 CMIP6 models with continuous monthly records of the required variables during 1984–2014. The model-selection criteria have been clarified in Section 2.1.

(3) Clarified the soil depth represented by mrsos.

We now explicitly identify *mrsos* as surface soil moisture representing the upper 0–10 cm soil layer.

These revisions are presented in Section 2.1 and Table 1.

Comment 6:

L72: Please clarify what is meant by “model structural diversity”.

Response:

Thank you for identifying this ambiguity in the model-selection criteria.

We have made the following revisions:

- (1) We have removed "model structural diversity" as a selection criterion because it was not based on an explicitly defined quantitative measure.
- (2) We now state the operational selection criteria directly. Specifically, the revised analysis includes all CMIP6 models available through CDS that provide continuous monthly records of surface soil moisture (*mrsos*) and near-surface air temperature (*tas*) throughout 1984–2014.
- (3) We have expanded the model information in Table 1 to include 29 models and their ensemble members and spatial resolutions, making the selection more transparent and reproducible.

The revised description is provided in Section 2.1.

Comment 7:

The manuscript should explain how the different soil depths among ERA5, GLEAM, and the CMIP models are handled to perform a fair comparison.

Response:

We thank the reviewer for raising this important comparability issue. We have clarified the dataset definitions and added a depth-harmonization sensitivity analysis.

Specifically:

- (1) Clarified the soil moisture depths of the datasets.

Section 2.1 now explicitly states that ERA5-Land provides four soil moisture layers (0–7, 7–28, 28–100, and 100–289 cm), whereas GLEAM v4.2a and the CMIP6 *mrsos* variable represent near-surface soil moisture over 0–10 cm.

- (2) Added an ERA5-Land 0–10 cm soil moisture reconstruction.

To provide a depth-consistent comparison with CMIP6, we constructed an ERA5-Land 0–10 cm soil moisture series using a thickness-weighted combination of the first two soil layers:

$$SSM_{0-10} = 0.7 \times SSM_{0-7} + 0.3 \times SSM_{7-28}$$

We then applied the same preprocessing and information-flow estimation procedures to the reconstructed series.

(3) Added a depth-harmonized CMIP6 comparison.

The depth-harmonized comparison is presented in Fig. S17. The main model–reanalysis differences, particularly the generally higher probability and spatial extent of significant SSM→T information flow in CMIP6, remain evident after harmonizing the soil moisture depth.

These changes are described in Sections 2.1 and 2.2.5, with results in Fig. S17.

Comment 8:

L93–101: The description of the Liang–Kleeman information flow framework should be revised for clarity. There are several grammatical and notation inconsistencies (e.g., incorrect capitalization after equations and indentation). In addition, using (T) for both temperature and the information flow (Eq. 1) is potentially confusing and should be clarified or replaced with less ambiguous notation. Lastly, it would be helpful to briefly explain the physical interpretation of each term of Eq. 1 and the possible range of the index.

Response:

We appreciate the reviewer's careful examination of the mathematical formulation. We have revised Section 2.2.1 to improve the notation, clarify the interpretation of information flow, and distinguish the dimensional and normalized measures.

The main revisions are as follows:

(1) Standardized the mathematical notation.

We now use (Y_1) and (Y_2) to represent air temperature and soil moisture, respectively. We use $(IF_{2\rightarrow 1})$ to denote dimensional information flow and $(NIF_{2\rightarrow 1})$ for normalized information flow. This avoids using the same symbol for temperature and information flow.

We have also corrected grammatical inconsistencies and improved the presentation of the equations and their accompanying descriptions.

(2) Clarified the terms in the information-flow estimator.

We have revised the description of Eq. (1) to define the sample variances and covariance of the two variables, as well as their covariances with the forward-difference approximation of the temperature derivative. We have also clarified how these covariance terms are used to estimate the directional contribution of soil moisture to the rate of entropy evolution of temperature. We have also introduced normalized information flow, which is dimensionless and ranges from -1

to 1, to facilitate comparisons among different directed relationships.

These revisions are presented in Section 2.2.1.

Comment 9:

L165 and L259: Although significant coupling persists in the second soil layer, Fig. S1 shows a marked reduction in both spatial extent and strength with increasing depth. The discussion should better reflect this overall weakening rather than support that “deeper soil moisture layers continue to exert significant control on temperature...”.

Response:

Thank you for pointing out the need for a more balanced interpretation of soil-depth dependence. We have revised the relevant descriptions as follows:

(1) Emphasized the overall decrease with soil depth.

In Section 3.1, we now explicitly state that both the spatial extent and magnitude of significant SSM→T information flow decrease markedly with increasing soil depth (Fig. S2). We have removed the overly strong interpretation that deeper soil moisture continues to exert substantial control over temperature across extensive regions.

(2) Clarified the difference between spatial extent and temporal persistence.

In Sections 3.4 and 4.2, we distinguish the reduced spatial extent of significant deeper-layer information flow from its slower decay with increasing lag time. Although fewer grid cells show strong signals at greater depths, the remaining significant signals generally exhibit slower temporal decay.

(3) Revised the physical interpretation.

We now explain that the overall weakening with depth is consistent with reduced short-term variability in deeper soil moisture, whereas its relatively longer persistence is consistent with the established longer memory of deep soil water (Seneviratne et al., 2006; Rahmati et al., 2024).

These changes are reflected in Sections 3.1, 3.4, and 4.2.

Comment 10:

L182: The discussion highlights Australia as presenting a strong SSM->SH relationship, whereas Fig. 2b shows relatively weak coupling there. Other regions seem to exhibit much stronger signals.

Response:

We are grateful for identifying this inaccurate regional interpretation. We have revised the description of the SSM→SH relationship to better reflect its spatial distribution in Fig. 2b. We have removed the emphasis on Australia as a major region of particularly strong SSM→SH information flow. We now describe the stronger SSM→SH signals more generally as occurring mainly in semi-arid and mid-latitude regions, consistent with the mapped distribution.

The revised interpretation is provided in Sections 3.2 and 4.1.

Comment 11:

Fig. 2: Please clarify whether the analysis corresponds to the top soil layer.

Response:

Thank you for requesting this clarification. We have revised the caption of Fig. 2 to explicitly identify the soil moisture layer used in the pathway analysis.

Specifically:

- (1) The caption now states that all panels are based on ERA5-Land Layer 1 soil moisture (0–7 cm).
- (2) We have also clarified that the pathway analysis uses ERA5-Land temperature, evapotranspiration, and sensible heat flux, maintaining consistency with the primary SSM→T analysis.

These details are now specified in the caption of Fig. 2.

Comment 12:

The spatial patterns in Figs. 1 and 2 are difficult to reconcile. Figure 1 indicates that significant SSM→T coupling is confined to relatively limited regions, whereas the individual pathways in Fig. 2 appear significant over much larger areas. In particular, the terrestrial legs (SSM→ET and SSM→SH) are broadly consistent with Fig. 1, whereas the atmospheric legs (ET→T and SH→T) extend across most continents. Since Fig. 2 is intended to explain the mechanisms behind Fig. 1, I would expect greater spatial consistency. Would masking the atmospheric maps to regions with significant terrestrial coupling, or using a different color scale or class intervals, improve the interpretation?

Response:

We appreciate this careful comparison of Figs. 1 and 2.

We have revised the pathway analysis and figure presentation as follows:

(1) Restricted the component-link maps to significant SSM→T regions.

We now restrict the four component-link maps (SSM→ET, SSM→SH, ET→T, and SH→T) to grid cells where direct SSM→T information flow is statistically significant ($p < 0.05$). Each component-link map additionally requires statistical significance of the corresponding individual link.

(2) Clarified the pathway-identification criteria.

We have revised Section 2.2.3 to specify that the SSM→ET→T pathway is identified only when SSM→ET and ET→T are both significant, together with a significant direct SSM→T relationship. The same criterion is applied to SSM→SH→T.

Regions where both sets of component links are significant are classified as dual-pathway regions.

(3) Revised the interpretation and presentation of Fig. 2.

We have clarified these restrictions in the figure caption and revised the accompanying discussion. We also use normalized information-flow magnitudes to facilitate comparisons among component links.

These revisions are provided in Sections 2.2.3, 3.2, and 4.1, and in the revised Fig. 2.

Comment 13:

Fig. 3: Panel (c) This is an interesting figure, but the probability values are difficult to distinguish. The meaning of the circle sizes should be explained in the caption, and a discrete color scale (e.g., 5% intervals) would facilitate interpretation. Similar suggestions apply to Figs. S6–S7 and Fig. 7. Panel (d): Why are the soil moisture variability percentile bins defined using unequal intervals?

Response:

We thank the reviewer for these detailed suggestions on figure readability and bin definition. We have revised Fig. 3 and the corresponding supplementary figures to improve their presentation and clarify the grouping procedures.

Specifically:

(1) Improved the probability visualization in Fig. 3c.

We have revised Fig. 3c to use a stepped color scale for the probability of significant SSM→T information flow, making differences among probability classes easier to distinguish.

We have also clarified the meaning of the visual encoding in the figure caption. Both circle size and color represent the probability of significant SSM→T information flow, defined as the fraction of significant grid cells relative to the total number of grid cells within each bin.

(2) Revised the corresponding supplementary figures.

We have updated the related probability diagrams, now presented as Figs. S5–S6, to use a consistent bin-based graphical presentation.

(3) Standardized the percentile groups in Fig. 3d.

We have replaced the original unequal percentile intervals with five equal-width percentile groups: 0–20%, 20–40%, 40–60%, 60–80%, and 80–100%.

The revised grouping allows the probability of significant information flow to be compared consistently across increasing levels of soil moisture variability.

These modifications are reflected in Fig. 3, its caption, and the revised supplementary figures.

Comment 14:

L216: The relationship between soil moisture variability and coupling strength is largely expected, since temporal variability is a prerequisite for soil moisture to influence temperature. This result therefore seems to reinforce the existing understanding rather than represent a novel finding and should be discussed in the context of previous literature. In addition, the manuscript repeatedly refers to land-atmosphere “feedbacks”, although only the directed influence of soil moisture on temperature is evaluated; but the reciprocal atmospheric influence required to characterize a feedback is not analyzed.

Response:

Thank you for encouraging a more cautious interpretation of these findings. We have addressed these concerns through the following revisions:

(1) We have revised the Introduction and Section 4.2 to discuss the relationship between soil moisture variability and coupling in the context of previous research (Dirmeyer, 2011; Hsu and Dirmeyer, 2023; Nouri and Homaei, 2021). Our analysis examines whether this established relationship also appears in the occurrence of statistically significant directional SSM→T information flow and its associated ET- and SH-related links.

(2) The revised discussion explains that mean soil moisture conditions define the broader

hydroclimatic background, whereas temporal variability characterizes fluctuations in soil water availability. These properties provide complementary information rather than mutually exclusive explanations.

(3) Added an analysis of the reverse direction. To provide additional information on the reciprocal relationship, we have calculated the normalized information flow from temperature to soil moisture ($T \rightarrow SSM$). The spatial distribution and longitudinal and latitudinal characteristics of this reverse direction are now presented in Fig. S19.

(4) We have carefully reviewed and revised the use of the term “feedback” throughout the manuscript, replacing it with more precise expressions such as “coupling”, “interaction”, or “directed influence” where appropriate. These changes ensure that the terminology accurately reflects the directional $SSM \rightarrow T$ relationships evaluated under the LKIF framework.

These revisions are included in the Introduction, Sections 4.1–4.2 and 4.4, and Fig. S19.

Comment 15:

Fig. 4: It would be helpful to include the global ERA5-Land map as a visual reference.

Response:

We appreciate this suggestion for improving the model comparison. We have reorganized the CMIP6 evaluation figure and added a global ERA5-Land reference map. The revised model-evaluation figure, now presented as Fig. 7, includes the global spatial distribution of significant $SSM \rightarrow T$ normalized information flow derived from ERA5-Land (Fig. 7c). Five selected CMIP6 model maps are shown alongside ERA5-Land in Fig. 7d–h, while the remaining model maps are provided in Figs. S15–S16. These changes allow the differences between the reanalysis and CMIP6 simulations to be examined more directly.

Comment 16:

L268–277: I disagree with the interpretation because the discussion overlooks the opposite seasons of the two hemispheres. The results indicate stronger coupling during the warm season of each hemisphere, rather than during the boreal warm season alone. A version of Fig. 5 separated by hemisphere could help illustrate this point.

Response:

We thank the reviewer for identifying this important issue in the seasonal interpretation.

We have revised the seasonal analysis and its interpretation as follows:

(1) Introduced hemisphere-specific seasonal definitions.

We now define the local warm season as April–September in the Northern Hemisphere and October–March in the Southern Hemisphere. The local cold season is defined using the opposite months.

These definitions are explicitly stated in Section 2.2.4.

(2) Revised the seasonal figures.

We have updated the seasonal spatial analyses using the local warm- and cold-season definitions for each hemisphere. The revised results are presented in Figs. S13–S14 for all four soil layers.

(3) Corrected the interpretation.

We have revised Sections 3.4 and 4.2 to emphasize that the seasonal enhancement occurs during the local warm season of each hemisphere rather than exclusively during the boreal warm season.

These changes are described in Sections 2.2.4, 3.4, and 4.2, and in Figs. S13–S14.

Comment 17:

Section 5 concludes that deeper soil moisture exerts more persistent influence on temperature. Given that deeper layers generally exhibit longer memory, this conclusion appears expected. The discussion should better distinguish between expected behavior and genuinely new insights.

Response:

We appreciate this distinction between established soil moisture memory and the additional characterization provided by our analysis.

We have revised the relevant sections as follows:

(1) Linked persistence to previous findings.

In Section 4.2, we now explicitly explain that the slower decay of significant SSM→T information flow in deeper layers is consistent with the longer soil moisture memory documented in previous studies (Seneviratne et al., 2006; Rahmati et al., 2024).

(2) Distinguished persistence from coupling strength and spatial extent.

We have clarified that deeper layers exhibit a smaller spatial extent and generally weaker magnitudes of significant information flow, although the remaining significant signals tend to decay more slowly over the examined lag period (Figs. 5–6).

This provides a distinction between the spatial occurrence of significant directed influence and its temporal persistence.

(3) Revised the Conclusions.

We have moderated the emphasis on deeper-layer persistence as a principal finding. Instead, the revised Conclusions focus on the integrated characterization of SSM→T information flow, associated ET- and SH-related structures, multiscale variations, and CMIP6 model representation within a common directional framework.

These revisions are presented in Sections 3.4, 4.2, and 5.

Technical Comments:

Comment 18:

L164: I believe the correct reference is Fig. 1b rather than Fig. 1a.

Response:

Thank you for catching this incorrect figure reference.

We have corrected the reference to Fig. 1b, which presents the spatial distribution of significant SSM→T information flow. We have also checked the figure references in the revised Results section to improve consistency between the text and figures.

Comment 19:

Fig. 1: Please add latitude–longitude gridlines in the map to facilitate the link with panel (a).

Response:

We are grateful for this cartographic suggestion. We have added latitude–longitude gridlines to the global map in Fig. 1b to improve geographic reference and facilitate comparison with the longitudinal and latitudinal profiles in Fig. 1a and c.

Comment 20:

Supplementary figures are not presented in the order in which they are first cited in the manuscript. For example, Fig. S10 is discussed before Figs. S2 and S3.

Response:

Thank you for noticing the inconsistency in the supplementary figure order.

We have reorganized and renumbered the supplementary figures according to the order in which they are first cited in the revised manuscript. We have updated the corresponding references in the main text and figure captions to maintain consistency with the revised numbering.

References

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Table 1. CMIP6 model information

CMIP6 models	Ensemble member	Native grid(lon × lat)	Nominal resolution
ACCESS-CM2	r1ilp1f1	192 × 144	250 km
ACCESS-ESM1-5	r1ilp1f1	192 × 145	250 km
AWI-ESM-1-1-LR	r1ilp1f1	192 × 96	250 km
BCC-CSM2-MR	r1ilp1f1	320 × 160	100 km
BCC-ESM1	r1ilp1f1	128 × 64	250 km
CAMS-CSM1-0	r1ilp1f1	320 × 160	100 km
CanESM5-CanOE	r1ilp2f1	128 × 64	500 km
CESM2-WACCM	r1ilp1f1	288 × 192	100 km
CMCC-CM2-HR4	r1ilp1f1	288 × 192	100 km
CMCC-CM2-SR5	r1ilp1f1	288 × 192	100 km
CMCC-ESM2	r1ilp1f1	288 × 192	100 km
CNRM-CM6-1-HR	r1ilp1f2	720 × 360	50 km
CNRM-ESM2-1	r1ilp1f2	256 × 128	250 km

CMIP6 models	Ensemble member	Native grid(lon $\times$ lat)	Nominal resolution
E3SM-1-0	rlilp1fl	360 $\times$ 180	100 km
E3SM-1-1	rlilp1fl	360 $\times$ 180	100 km
E3SM-1-1-ECA	rlilp1fl	360 $\times$ 180	100 km
EC-Earth3-AerChem	rlilp1fl	512 $\times$ 256	100 km
EC-Earth3-CC	rlilp1fl	512 $\times$ 256	100 km
KACE-1-0-G	rlilp1fl	192 $\times$ 144	250 km
MIROC-ES2L	rlilp1f2	128 $\times$ 64	500 km
MIROC6	rlilp1fl	256 $\times$ 128	250 km
MPI-ESM1-2-HR	rlilp1fl	384 $\times$ 192	100 km
MPI-ESM1-2-LR	rlilp1fl	192 $\times$ 96	250 km
MRI-ESM2-0	rlilp1fl	320 $\times$ 160	100 km
NorCPM1	rlilp1fl	144 $\times$ 96	250 km
NorESM2-MM	rlilp1fl	288 $\times$ 192	100 km
SAM0-UNICON	rlilp1fl	288 $\times$ 192	100 km
TaiESM1	rlilp1fl	288 $\times$ 192	100 km
UKESM1-0-LL	rlilp1f2	192 $\times$ 144	250 km

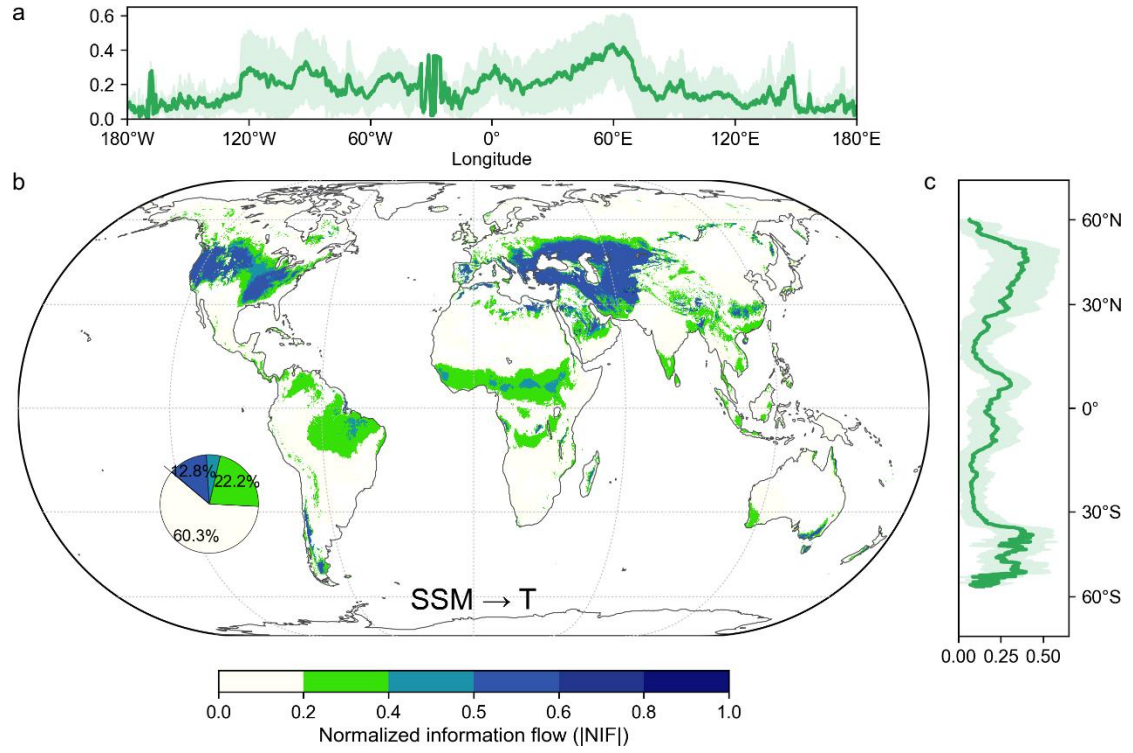


Fig. 1 Significant effects of surface soil moisture on near-surface air temperature based on absolute normalized information flow. (a) Longitudinal mean of |NIF| for SSM→T causality based on ERA5-Land, with shading indicating ± 1 standard deviation. (b) Global distribution of effects of surface (0–7 cm) soil moisture on temperature during 1984–2014. Only statistically significant grid cells are shown ($p < 0.05$). The pie chart shows the proportions of statistically significant grid cells within different absolute normalized information flow strength classes. (c) Same as in (a), but for latitudinal means.

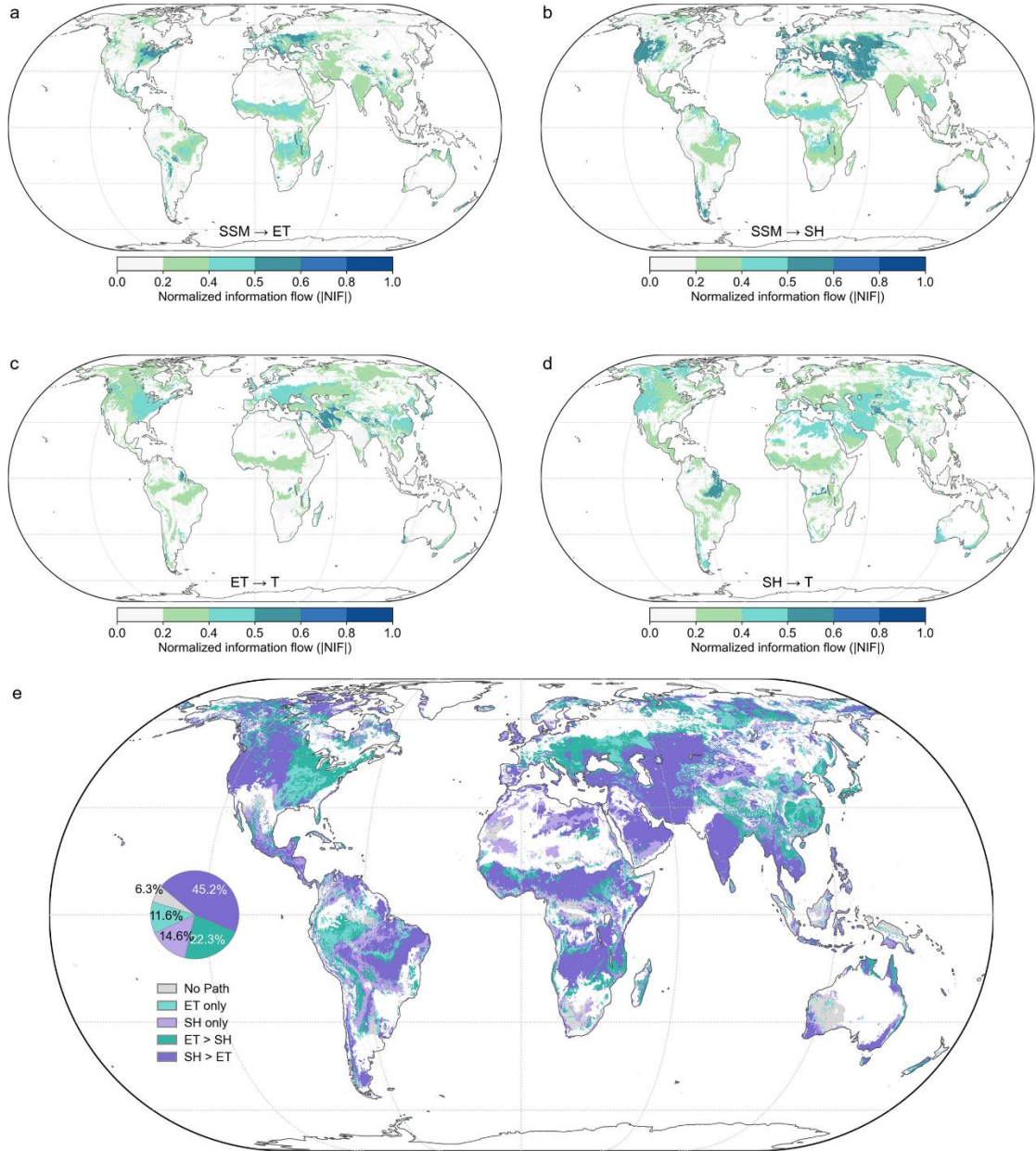


Fig. 2 Causal relationships among the sub-processes linking soil moisture and temperature based on ERA5-Land temperature. (a) Global distribution of the absolute normalized information flow for surface soil moisture (SSM)→evapotranspiration (ET) during 1984–2014 ($p < 0.05$). (b–d) Same as in (a), but for the SSM→sensible heat flux (SH), ET→temperature (T), and SH→T sub-processes, respectively. (e) Global distribution of the causal pathways linking SSM to T. The SSM→ET→T pathway is identified when both SSM→ET and ET→T are significant. The SSM→SH→T pathway is identified when both SSM→SH and SH→T are significant. All panels are restricted to grid cells with significant direct SSM→T information flow ($p < 0.05$), and panels (a–d) additionally require significance

in their respective component links. Areas where all four causal links are significant are designated as dual-pathway regions and further classified as $ET > SH$ or $SH > ET$ based on the products of the absolute normalized information flow along the two respective links of each pathway. These indices describe relative information-flow magnitudes rather than independent physical contributions. The inset pie chart shows the proportion of each pathway type among grid cells with significant direct $SSM \rightarrow T$ causality. All panels use ERA5-Land Layer 1 soil moisture (0–7 cm).

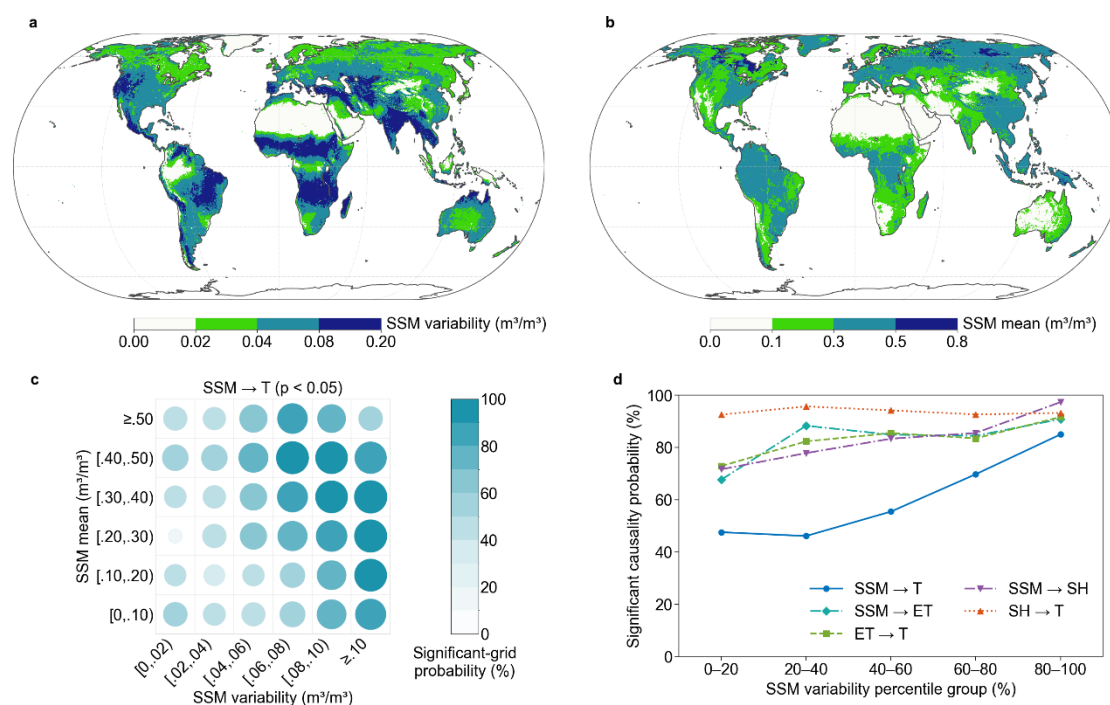


Fig. 3 Hydroclimatic dependence of directed SSM–T influence. (a) Spatial distribution of surface (0–7 cm) SSM variability (m^3/m^3) during 1984–2014, defined as the standard deviation of monthly mean SSM. (b) Spatial distribution of mean surface SSM (m^3/m^3) during 1984–2014. (c) Probability of significant $SSM \rightarrow T$ causality ($p < 0.05$) across two-dimensional bins of SSM variability and mean state. Probability is defined as the fraction of significant grid cells relative to the total number of grid cells within each bin. Both circle size and colour indicate the probability of significant $SSM \rightarrow T$ causality. (d) Probability of significant $SSM \rightarrow T$, $SSM \rightarrow ET$, $ET \rightarrow T$, $SSM \rightarrow SH$, and $SH \rightarrow T$ information flow across different SSM variability percentile groups (0–20%, 20–40%, 40–60%, 60–80%, and 80–100%), where ET denotes evapotranspiration, SH denotes sensible heat flux, and T denotes near-surface air temperature.

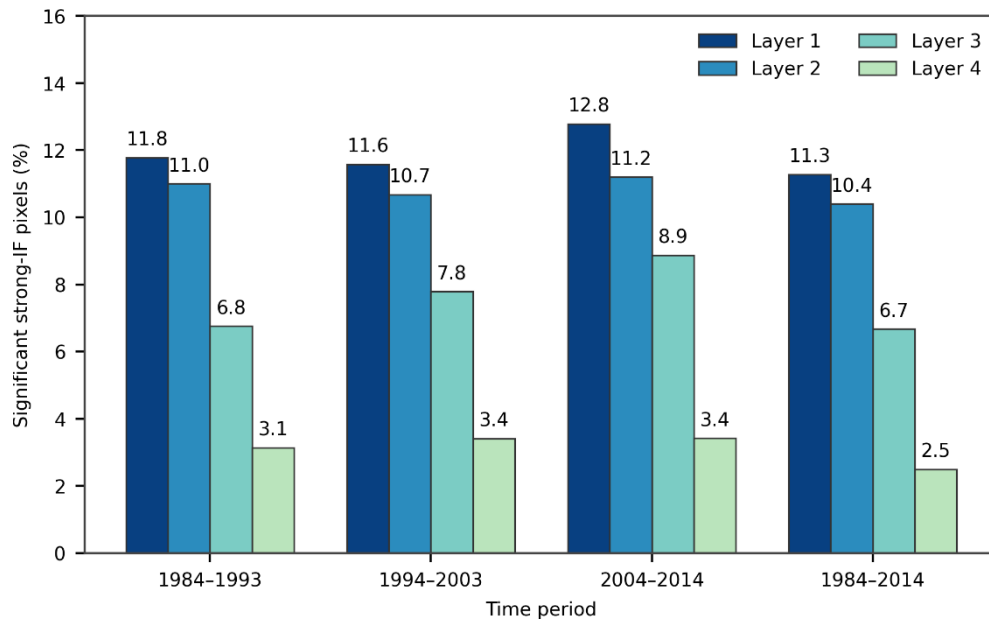


Fig. 5 Fraction of valid land grid cells with significant SSM→T information flow across soil layers and time periods. Percentages of valid land grid cells with significant SSM→T information flow ($p < 0.05$) and an absolute information-flow magnitude $|IF| > 0.2$ nats month⁻¹ are compared across Layers 1–4 and the full-year periods 1984–1993, 1994–2003, 2004–2014, and 1984–2014.

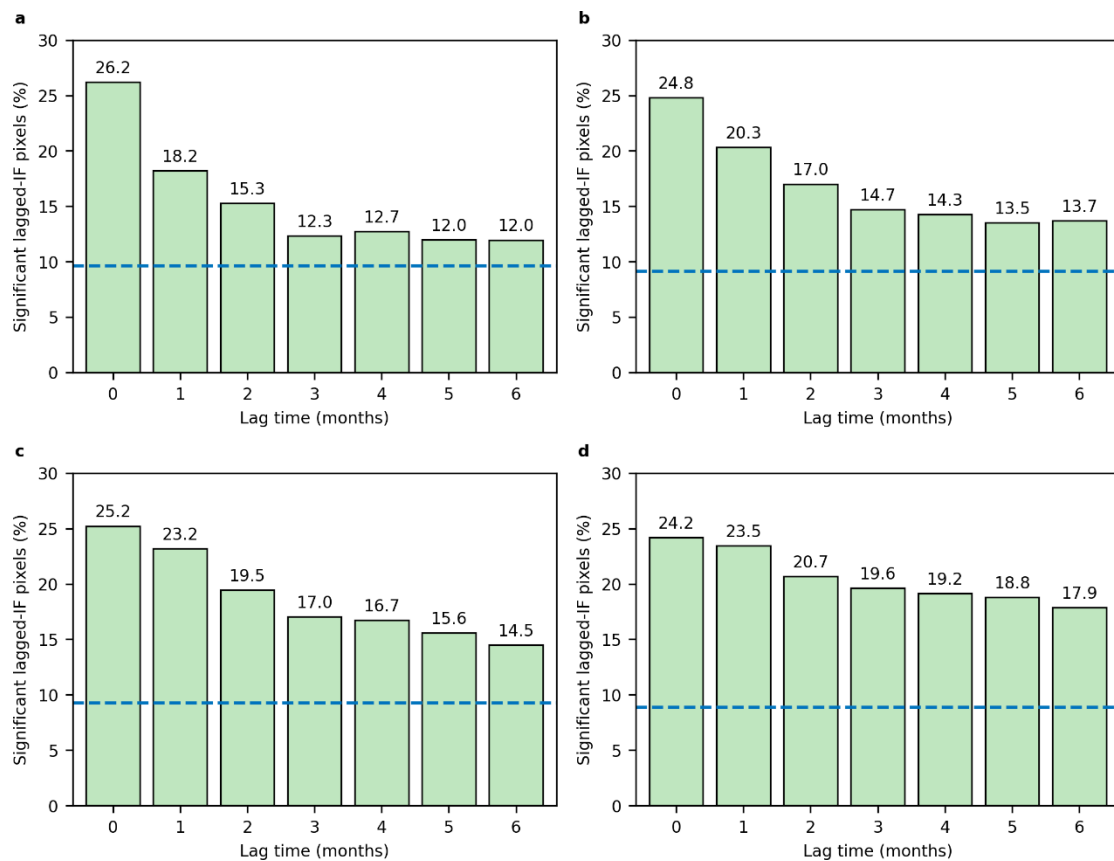


Fig. 6 Persistence of SSM–T causality across soil layers and lag times. (a–d) Percentage of grid cells showing significant $SSM \rightarrow T$ causality for Layer 1 (a), Layer 2 (b), Layer 3 (c), and Layer 4 (d) at lag times of 0 to 6 months. The horizontal dashed line indicates $1/e$ of the zero-lag significant fraction for each layer and is used here as a reference threshold for persistence.

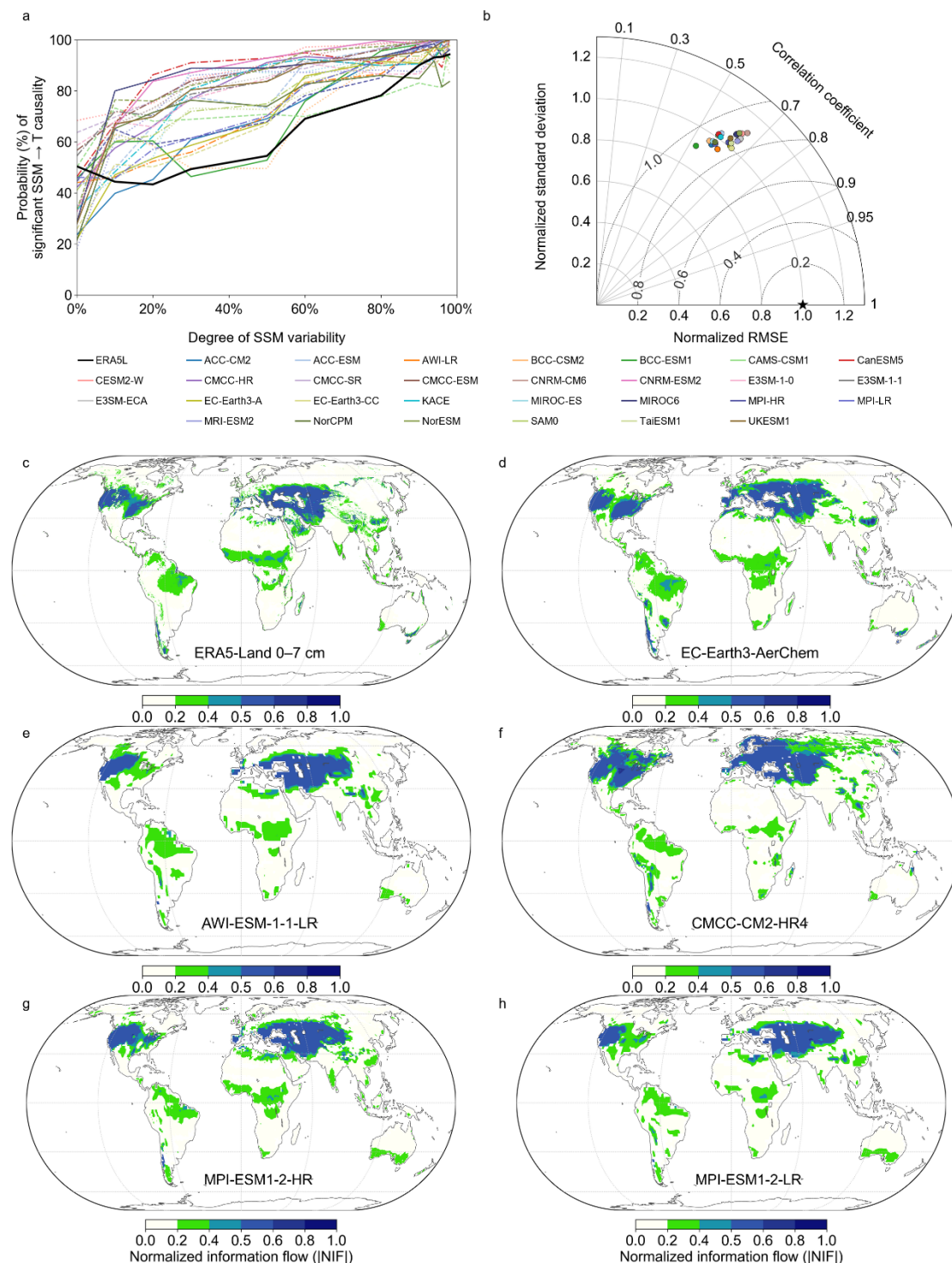


Fig. 7 CMIP6 model evaluation for SSM–temperature causal coupling. (a) Causal

probability versus SSM variability in ERA5-Land (0–7cm) and CMIP6 models. (b) Taylor diagram of model performance relative to ERA5-Land (black star). (c–h) Global distributions of the absolute normalized information flow for ERA5-Land (c) and five selected CMIP6 models (d–h). Only statistically significant grid cells are shown ($p < 0.05$).

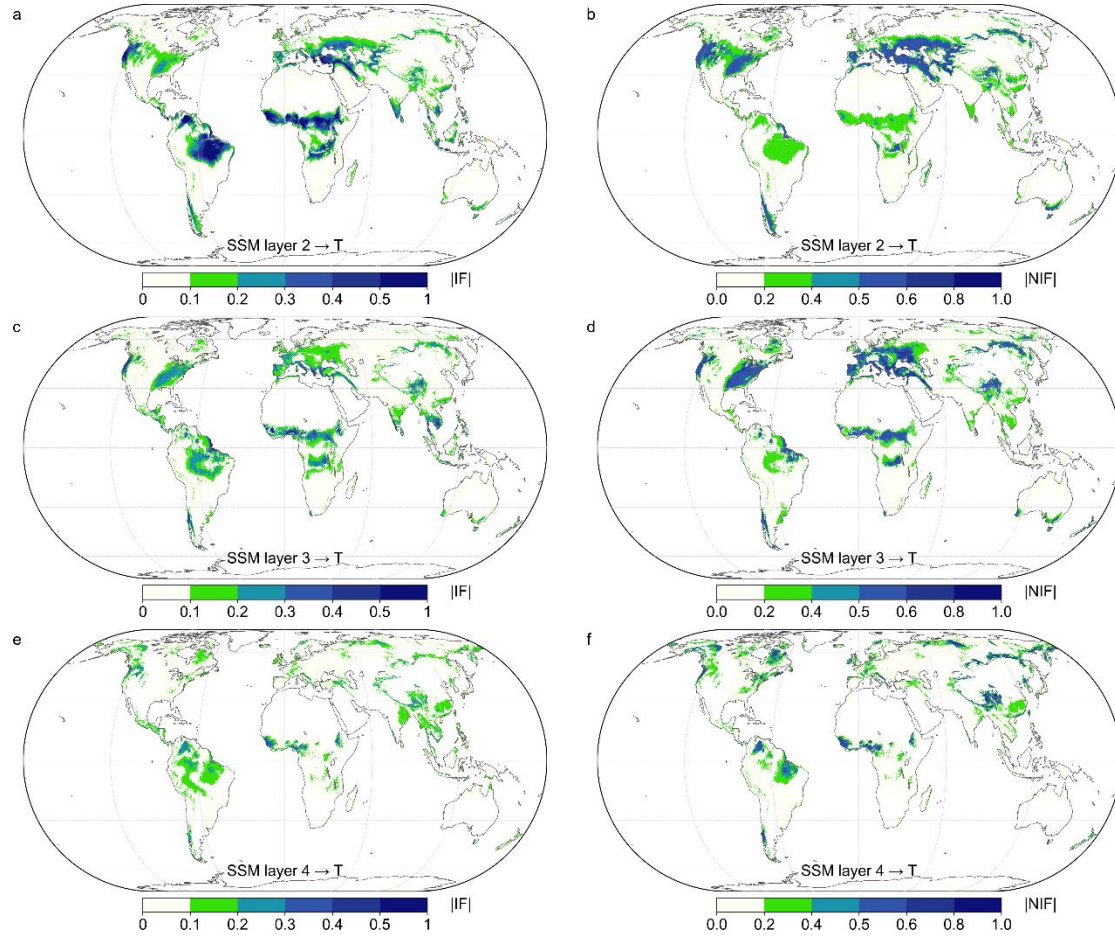


Fig. S2 Causal effects of soil moisture in different layers on air temperature. (a, b) Global distribution of the causal effects of Layer 2 soil moisture (7–28 cm) on air temperature during 1984–2014 based on ERA5-Land, quantified by the absolute information flow (IF, a) and the absolute normalized information flow (NIF, b). Only statistically significant regions are shown. (c, d) Same as in (a, b), but for Layer 3 (28–100 cm). (e, f) Same as in (a, b), but for Layer 4 (100–289 cm).

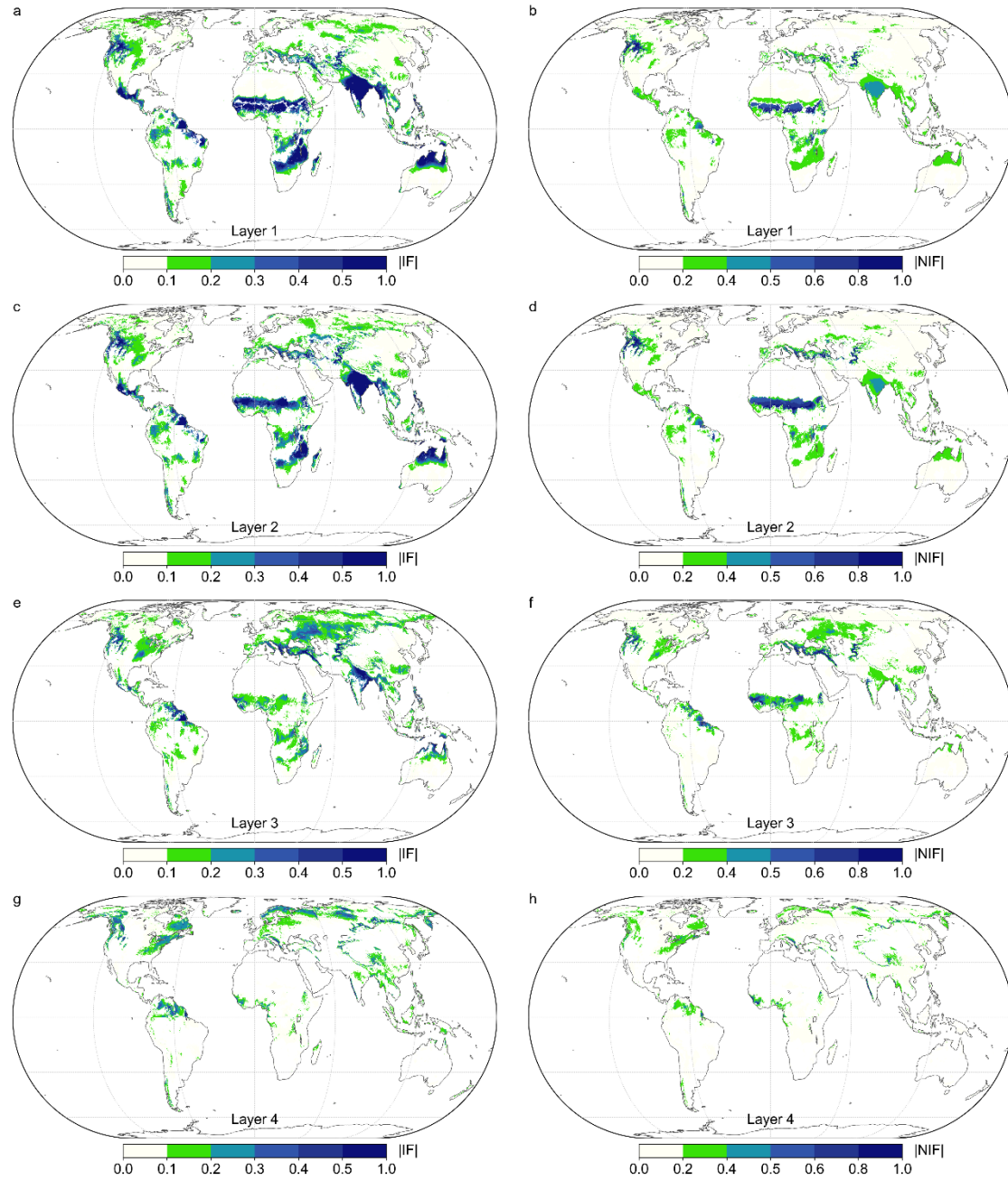


Fig. S13 Causal effects of soil moisture at different depths during the warm season of each hemisphere. (a, b) Global distribution of the warm-season causal effects of surface soil moisture (Layer 1, 0-7 cm) on air temperature during 1984-2014 based on ERA5-Land, quantified by the absolute information flow (IF, a) and the absolute normalized information flow (NIF, b). The warm season is defined as April–September in the Northern Hemisphere and October–March in the Southern Hemisphere. Only statistically significant regions are shown. (c, d) Same as in (a, b), but for Layer 2 (7-28 cm). (e, f) Same as in (a, b), but for Layer 3 (28-100 cm). (g, h) Same as in (a, b), but for Layer 4 (100-289 cm).

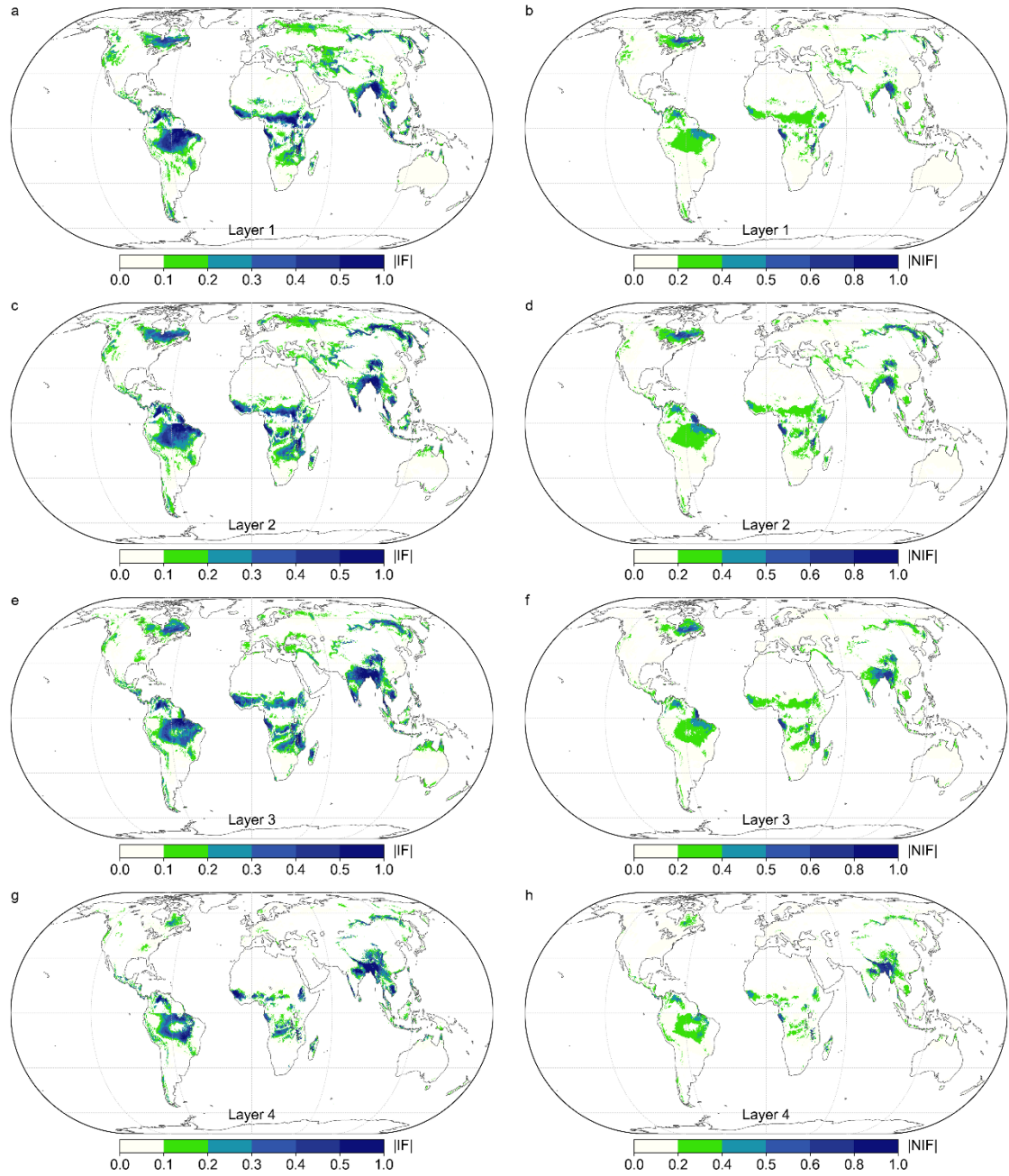


Fig. S14 Causal effects of soil moisture at different depths during the cold season of each hemisphere. (a, b) Global distribution of the cold-season causal effects of surface soil moisture (Layer 1, 0–7 cm) on air temperature during 1984–2014 based on ERA5-Land, quantified by the absolute information flow (IF, a) and the absolute normalized information flow (NIF, b). The cold season is defined as October–March in the Northern Hemisphere and April–September in the Southern Hemisphere. Only statistically significant regions are shown. (c, d) Same as in (a, b), but for Layer 2 (7–28 cm). (e, f) Same as in (a, b), but for Layer 3 (28–100 cm). (g, h) Same as in (a, b), but for Layer 4 (100–289 cm).

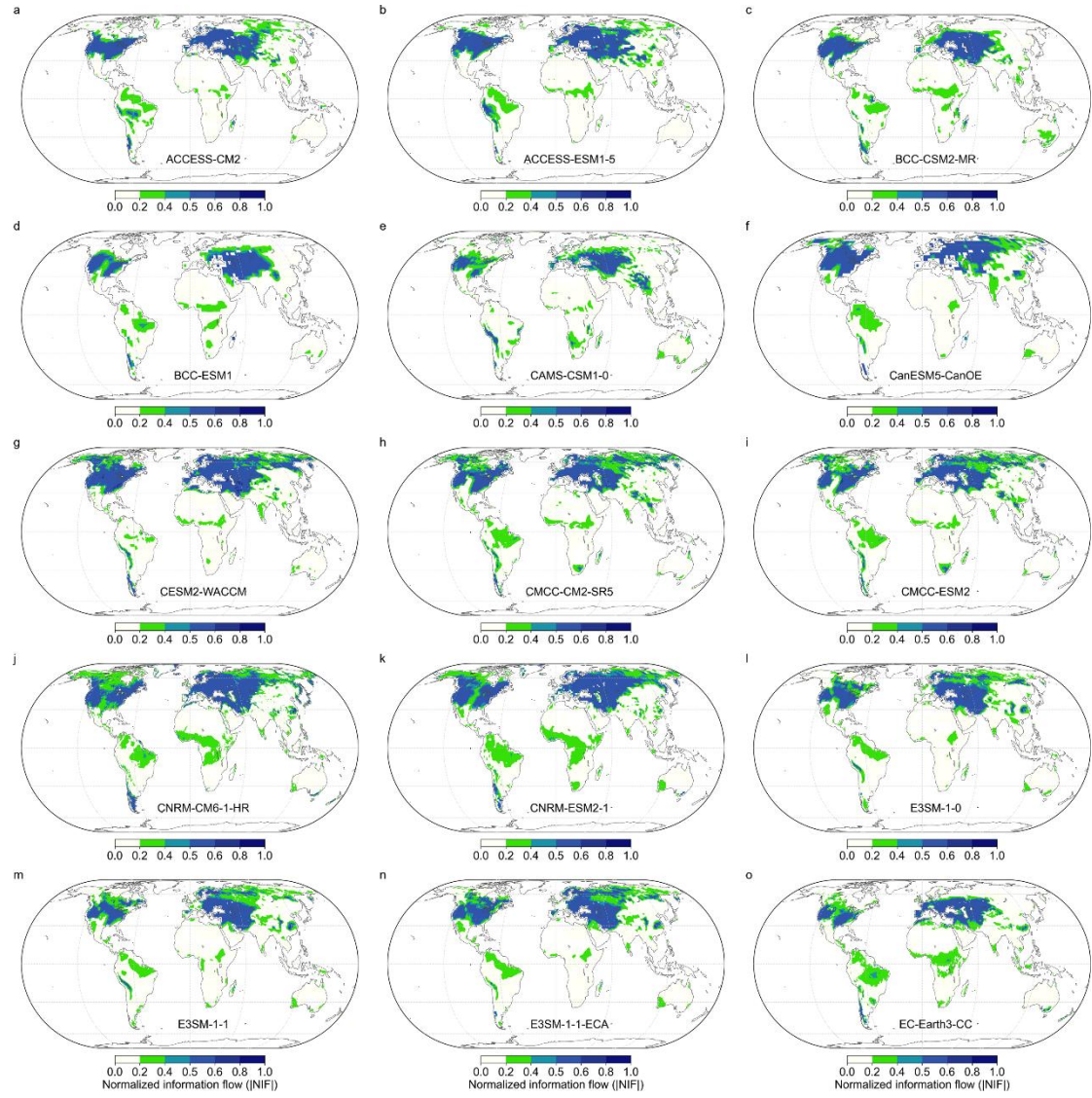


Fig. S15 Global distribution of significant causal effects simulated by climate models (1/2).
(a–o) Global distribution of the causal effects of surface soil moisture on air temperature simulated by 15 CMIP6 models not shown in Fig. 7, quantified by the absolute normalized information flow (NIF). The model name is labeled in each panel. Only statistically significant regions are shown ($p < 0.05$).

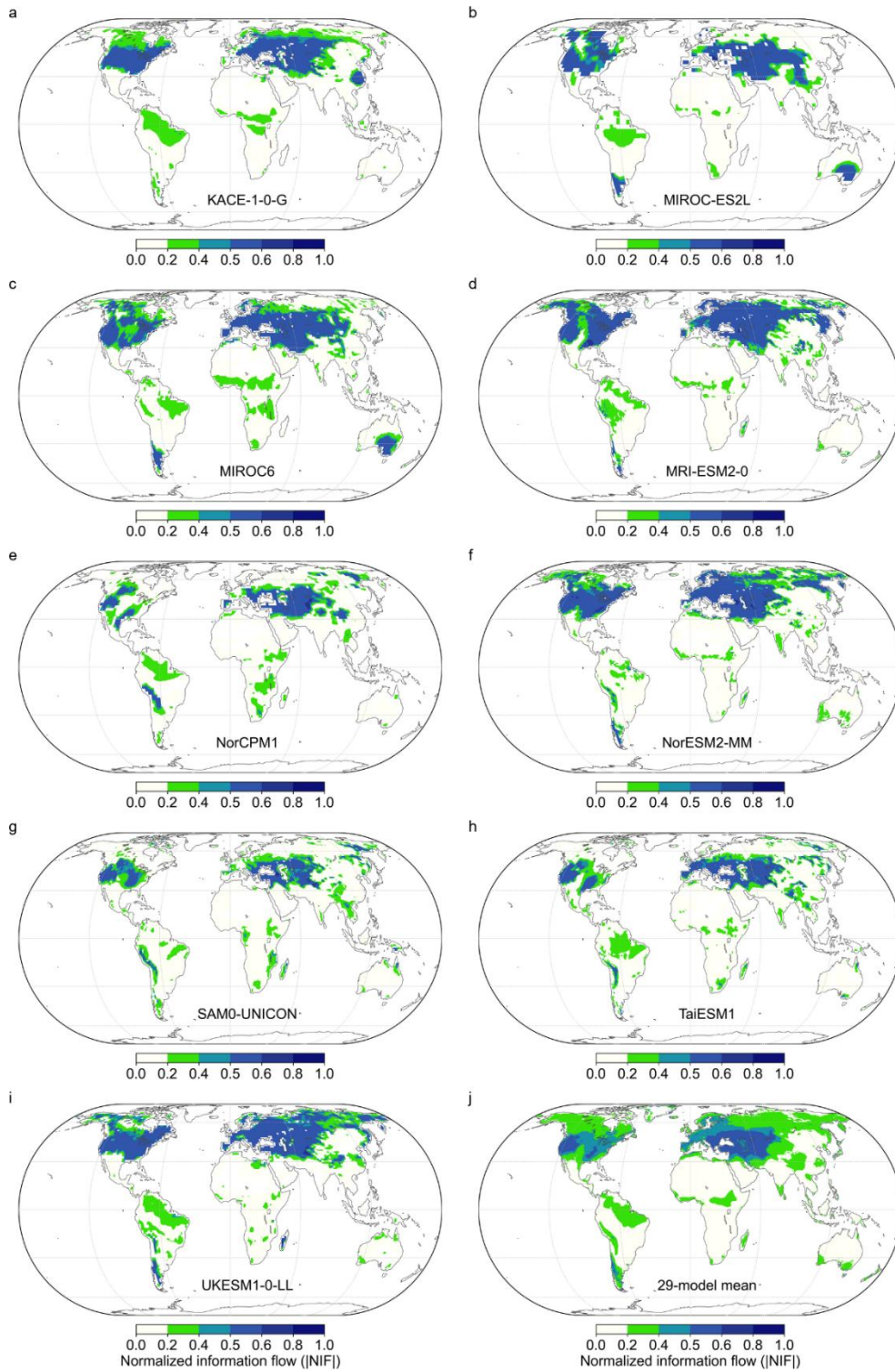


Fig. S16 Global distribution of significant causal effects simulated by climate models (2/2). (a–i) Same as in Fig. S15, but for nine additional CMIP6 models not shown in Fig. 7. (j) Multi-model mean NIF of the 29 CMIP6 models, including the five models shown in Fig. 7.

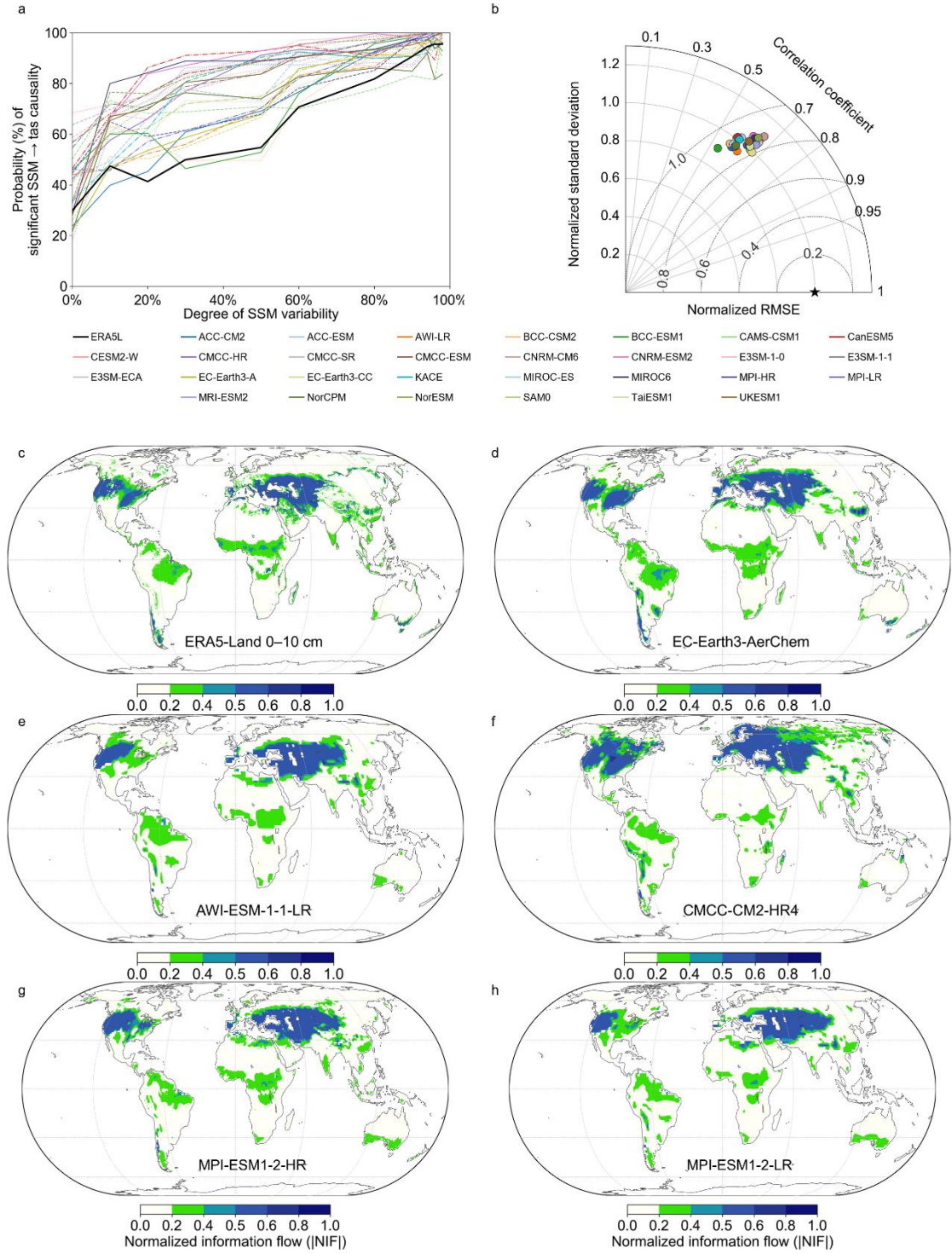


Fig. S17 CMIP6 model evaluation for SSM–temperature causal coupling (ERA5-Land 0–10 cm). (a) Probability of significant SSM→T causality versus SSM variability in ERA5-Land (0–10 cm) and CMIP6 models. (b) Taylor diagram of model performance relative to ERA5-Land (black star). (c–h) Global distributions of significant causal influence for ERA5-Land (c) and five selected CMIP6 models (d–h). Causal effects are measured by information flow; only statistically significant regions are displayed.

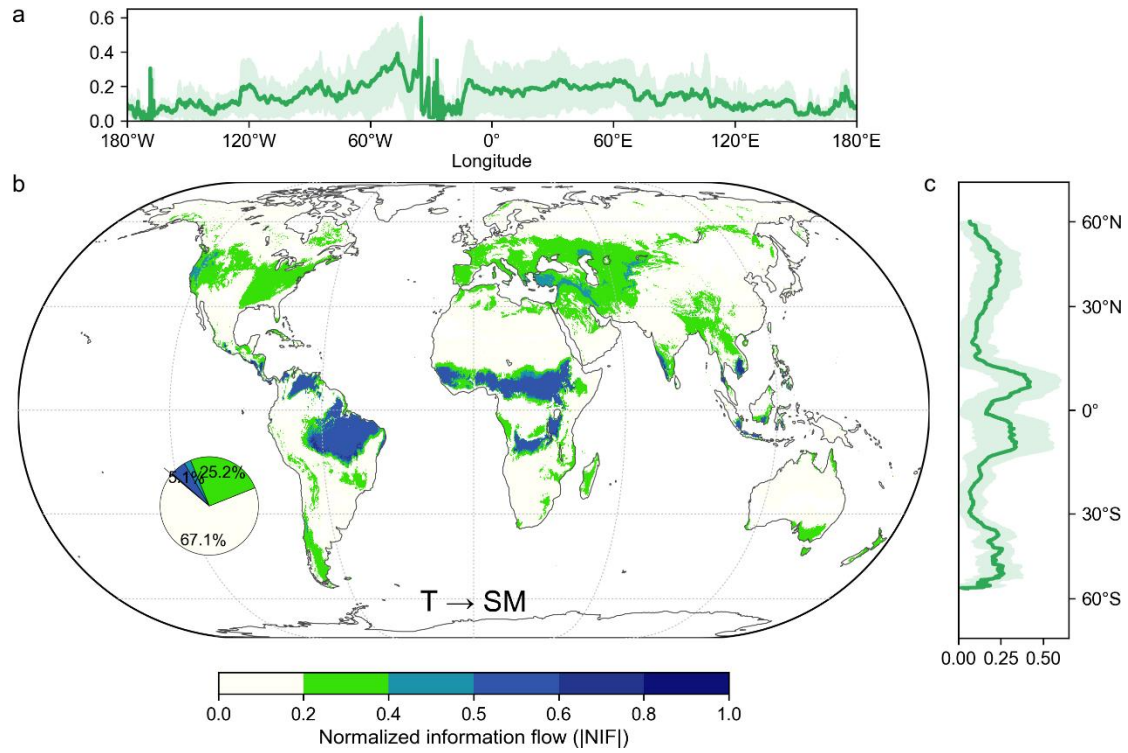


Fig. S19 Significant effects of near-surface air temperature on surface soil moisture based on normalized information flow. (a) Longitudinal mean of the absolute normalized information flow from T to SSM based on ERA5-Land, with shading indicating ± 1 standard deviation. (b) Global distribution of the absolute normalized information flow from temperature to surface (0-7 cm) soil moisture during 1984-2014 ($p < 0.05$). The pie chart shows the proportions of statistically significant grid cells within different absolute normalized information flow strength classes. (c) Same as in (a), but for latitudinal means.