



Brief Communication: Assessing theoretical frameworks for thermodynamic and dynamic responses to atmospheric warming: application to shallow cumulus clouds over the tropics and in the Polar regions

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Abstract. Clouds exert a major influence on Earth's radiative balance, yet the net radiative feedback from different cloud types remains one of the largest uncertainties in climate science. Tropical shallow cumulus and stratocumulus clouds are particularly influential for Earth's mean climate state and are expected to contribute a positive feedback to future warming, with stratocumulus clouds playing the dominant role. The key objectives of this study are (i) to analyze how shallow cumulus clouds in the subtropics and polar regions change in a warming climate using high-resolution CM1 simulations, and (ii) to identify suitable theoretical approaches to disentangle thermodynamic and dynamic contributions to climate variability and change. We introduce novel thermodynamic and dynamic variants of the Dynamic State Index (DSI) that are defined via energy and vorticity quantities and indicate deviations from thermodynamic or dynamic equilibrium conditions. Therefore, these DSI variants provide a suitable framework to investigate cloud processes.

Shallow cumulus clouds are simulated with the high-resolution Cloud Model 1, and DSI variants are subsequently calculated to address three key research questions: (1) How do shallow clouds in the subtropics and polar regions respond to warming?, (2) Can the DSI identify shallow cumulus clouds?, (3) How do their thermodynamic and dynamic states change with temperature increase? The simulations reveal clear regional contrasts. In the subtropics, a warming of up to +4 K at the surface causes a slight reduction in the vertical and horizontal extent of shallow clouds, whereas in the polar region, significant cloud deepening and densification occur. All DSI variants successfully detect shallow cumulus clouds, confirming their suitability for further analysis of long-term changes in thermodynamic and dynamic processes and for advancing process-based understanding of cloud responses to climate warming.

1 Introduction

Clouds play a critical role in Earth's climate system by influencing the planet's radiative balance. Understanding the net radiative feedback from all cloud types remains a central challenge in climate science. The IPCC Fifth Assessment Report



(2013) concluded that the *net radiative feedback due to all cloud types is likely positive*. This means that, overall, clouds are expected to amplify global warming rather than damp it. The IPCC Sixth Assessment Report further solidified this finding, assessing the net cloud feedback to be positive at $+0.42 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ and concluding that a net negative cloud feedback is very unlikely (Forster et al., 2021). However, the report also emphasises that *the mechanisms behind this positive feedback are not well understood*. The complexity arises from the diverse ways clouds interact with radiation and the atmosphere, as well as the difficulty in representing these processes accurately in climate models. Myers et al. (2021); Sherwood et al. (2020); Zelinka et al. (2017) highlight uncertainties in cloud feedbacks, especially regarding their regional variations and physical mechanisms. Chalmers et al. (2022) point out that *many existing studies have used suboptimal methods* for quantifying radiative forcing and feedbacks. These studies often focus on global mean climate responses, potentially overlooking important regional differences and/or neglect regional patterns and processes that can significantly influence the climate system.

Shallow cumulus clouds and stratocumulus clouds over tropical oceans play a vital role in shaping earth's average climate state due to their albedo, its present-day variability, and its response to rising greenhouse gas concentrations. Studies indicate that they will contribute positive feedback to global warming, primarily as a direct reaction to increasing sea surface temperatures (Myers et al., 2023). Comparing stratocumulus (Sc) and cumulus (Cu) feedbacks, the Sc feedback appears to be the dominant contributor to the tropical low-cloud feedback, whereas the Cu feedback plays a comparatively smaller role, see, e.g., Cesana and Del Genio (2021), Myers et al. (2021). So far, only a few studies consider the impact of atmospheric warming on clouds. Investigating polar clouds and radiation in satellite observations, reanalyses, and climate models, Lenaerts et al. (2017) state that *climate models exhibit strong, but partly inconsistent, biases in their simulation of clouds and radiation over the polar regions*.

Central aims of this research are the analysis of changes of shallow cumulus clouds in the subtropics and polar regions with a warming climate and the identification of suitable approaches to disentangle thermodynamical and dynamical contributions to climate variability and change. The distinction between these two aspects has become increasingly important in climate science, as it helps to clarify the underlying processes that drive changes in weather extremes and overall climate behaviour. This conceptual approach can be traced back to the pioneering work of O’Gorman and Schneider (2009); Sugiyama et al. (2010) and Emori and Brown (2005), who highlighted the need to separate and analyse these contributions individually. Dynamical contributions generally refer to changes in the magnitude and frequency of weather patterns, such as shifts in atmospheric circulation or the occurrence of certain synoptic situations. In contrast, thermodynamic contributions are associated with changes in local and global exchanges of temperature, moisture, and entropy that directly influence the energy and water cycles of the atmosphere. These two types of contributions are not independent; rather, they are closely interconnected and often interact in complex ways to shape the climate system. Building on this framework, Pfahl et al. (2017) provided a quantitative approach to disentangle the dynamical and thermodynamical contributions to changes in extreme precipitation events in a changing climate. Their methodology was based on analysing the vertical pressure velocity and specific humidity, which allowed them to attribute changes in extreme precipitation to either dynamical or thermodynamical factors.

Using developments from theoretical meteorology, the Dynamic State Index (DSI) will be considered as an alternative approach to disentangle dynamic and thermodynamic contributions to cloud changes in a changing climate. Névir (2004)



introduced the DSI as a scalar quantity defined by the Jacobian determinant of the potential temperature, the Bernoulli stream function, and the potential vorticity. In this way, the DSI is composed of derivatives of energy and vorticity quantities, which are conserved individually. The DSI can be derived directly from the primitive equations and thus represents a physically-derived quantity that indicates the activity of essential dynamical processes of the atmosphere. So far, the DSI has been applied especially to identify and diagnose precipitation (Claussnitzer et al., 2008; Müller et al., 2018; Müller and Peter, 2019), indicate moist processes (Hittmeir et al., 2021), analyse wind balances (Gaßmann, 2014) and show that the DSI can be applied to identify hurricanes (Weber and N  vir, 2008). Three research questions are targeted in the study;

1. How do shallow cumulus clouds in the subtropics and in the polar region change with a warming atmosphere?
2. Does the Dynamic State Index (DSI) indicate the presence of shallow cumulus clouds?
3. Can novel variants of the DSI be used to disentangle the thermodynamically-induced and dynamically-induced changes of shallow cumulus clouds in a warming atmosphere?

Addressing this last question is crucial for improving our understanding of the mechanisms behind climate extremes. The theories of the classical DSI concept, as well as those of the novel polytropic DSI variants that will be used to indicate thermodynamic and dynamic activity levels are introduced in Sec. 2. The setup of the high-resolution Cloud Model 1 (CM1) simulations is explained in Sec. 3. In Sec. 4, two cases of cloud changes in the tropics and in the polar region with different warming scenarios are shown. Moreover, thermodynamic and dynamic DSI variants for Shallow Cumulus Clouds in (i) the (Sub-) Tropics and (ii) the polar regions are depicted and analysed. These results are discussed in Sec. 5 and summarized in Sec. 6.

2 The Dynamic State Index

The Dynamic State Index (DSI) is a scalar diagnostic field that indicates deviations from a steady, adiabatic and inviscid atmospheric basic state. It is defined as Jacobian determinant of the potential vorticity, the Bernoulli stream function and the potential temperature. By combining those three components in its definition, the DSI unifies spatial changes of the energy, vorticity and thermodynamic information into one scalar (N  vir, 2004). The DSI is zero for an adiabatic inviscid, steady basic state and non-zero DSI values signalize imbalances from this basic state, as depicted in Fig. ???. Several works have demonstrated that the DSI provides a suitable parameter to indicate diabatic processes across all scales. So far, DSI variants for different atmospheric models have been derived and applied to diagnose e.g. the onset and presence of precipitation or the organization of storms, see e.g. Weber and N  vir (2008), Claussnitzer and N  vir (2009), Weijenborg et al. (2015), M  ller and Peter (2019). One example of a front captured by the DSI field and the corresponding radar image is shown on the l.h.s. in Fig. 1. The DSI is strongly correlated with diabatic processes and also reproduces cloud bands on a larger scale. To enable a process-based understanding of clouds, the following chapter develops additional DSI variants alongside the classical DSI in order to disentangle thermodynamic and dynamic deviations from balanced states.



2.1 The classical Dynamic State Index (DSI) variant

Mathematically, the original DSI is derived from the primitive equations and given by the Jacobian determinant of the potential temperature Θ , the Bernoulli stream function B , and Ertel's potential vorticity Π :

$$90 \quad \text{DSI} := \frac{1}{\rho} \frac{\partial(\Theta, B, \Pi)}{\partial(x, y, z)}, \quad (1)$$

where Π is given by

$$\Pi = \rho^{-1} \xi_a \cdot \nabla \Theta, \quad (2)$$

$\xi_a = \nabla \times \mathbf{v} + 2\boldsymbol{\omega}$ denotes the 3D absolute vorticity vector with 3D velocity $\mathbf{v}$, angular velocity of the earth $\boldsymbol{\omega}$, and ρ is the density of the air. The Bernoulli stream function is defined by

$$95 \quad B = \frac{1}{2} \mathbf{v}^2 + \phi + h, \quad (3)$$

where h is the enthalpy expressed by $h = e + pv$ with internal energy e , pressure p and specific volume v .

The $\text{DSI} \neq 0$ indicates deviations from a basic state that is, in its original definition, characterised by the three-dimensional, steady, adiabatic, inviscid wind $\mathbf{v}_{st}$. Mathematically, the steady wind is given by:

$$\mathbf{v}_{st} = \frac{1}{\rho \Pi} \nabla \Theta \times \nabla B, \quad (4)$$

100 see Schär (1993). If the flow satisfies the basic state conditions, the DSI is zero, and non-zero DSI signals indicate non-steady, diabatic, and viscous conditions of a fluid. Therefore, the DSI provides a tool for the diagnosis of dynamical atmospheric processes at different scales, as sketched in Fig. ???. For a detailed derivation of the original DSI from the primitive equations see the original work of N  vir (2004).

2.2 Polytopic DSI variants - The DSI as thermodynamic and dynamic state indicator

105 In order to consider the polytopic DSI to identify and investigate cloud regimes and to use it as an alternative tool for disentangling thermodynamic and dynamic responses, we start with polytopic processes in general in Subsec. 2.2.1 and summarise the definitions and physical meanings of the polytopic DSI variants in Subsec. 2.2.2.

2.2.1 Polytopic process

A general polytopic process is a thermodynamic process that satisfies the following relation:

$$110 \quad pv^n = \text{const.} \quad (5)$$

with the pressure p , volume v and the polytopic index n . Distinguished cases are $n = 0$ (isobaric state), $n = 1$ (isothermal state), $n = \pm\infty$ (isochoric state), and $n = \gamma = \frac{c_p}{c_v}$ (isentropic state) with the heat capacity at constant pressure c_p and the heat capacity at constant volume c_v . For the latter two cases $n = 1$ and $n = \gamma$ the ideal gas law needs to hold. The different

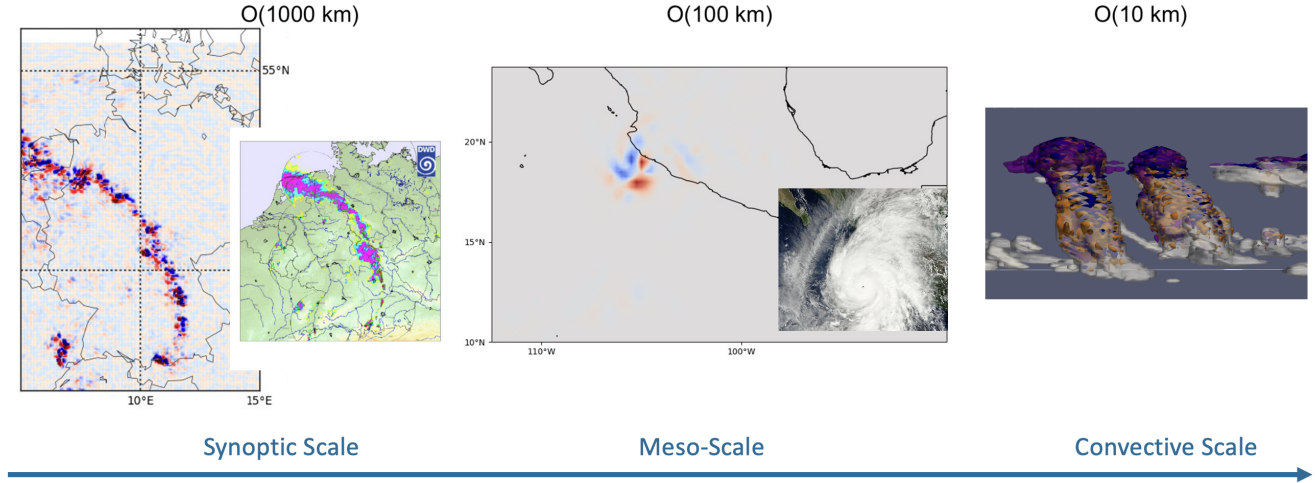


Figure 1. The isentropic DSI (blue: negative DSI values, red: positive DSI values) indicating a front on the synoptic scale (adapted from Müller et al. (2018)), one example of the isobaric DSI variant diagnosing hurricane Patricia (blue: negative DSI values, red: positive DSI values) on the meso-synoptic scale and in this study clouds on the convective scale will be investigated to untangle thermodynamic and dynamic contributions (purple: (thermodynamic DSI variants, orange: dynamic DSI variants)

polytropic states, i.e., different values of n , are characterised by different physical processes. For example, in the case $1 < n < \gamma$ and assuming that the ideal gas law holds, the heat and work flows are directed in opposite directions, while for $\gamma < n < \infty$ the heat and work flows go in the same direction.

2.2.2 Polytropic DSI variants

In general, the DSI signalizes deviations from a system-dependent basic state. The steady wind that characterises the polytropic basic state is of the form:

$$120 \quad \mathbf{v}_{st} = \frac{1}{\rho \Pi_{\psi(n)}} [\nabla \psi(n) \times \nabla E_{\psi(n)}] \quad (6)$$

with the polytropic index n , $\psi(n) = T \left[\frac{p_N}{p} \right]^{\frac{n-1}{n}}$, $E_{\psi(n)}$ denotes the stream function and the corresponding potential vorticity is given by:

$$\Pi_{\psi(n)} = \frac{\boldsymbol{\xi} \cdot \nabla \psi(n)}{\rho}. \quad (7)$$

It follows that the polytropic DSI variants can be summarized as:

$$125 \quad \text{DSI}[\psi(n)] = \frac{1}{\rho} \left| \frac{\partial(\psi(n), E_{\psi(n)}, \Pi_{\psi(n)})}{\partial(x, y, z)} \right|, \quad (8)$$

where the polytropic stream functions and the polytropic potential vorticities are individually conserved.



Table 1. Distinguished polytropic states, the corresponding steady winds and DSI variants. Regarding the notations, ϕ is the geopotential, p the pressure, v the volume, T the temperature, θ the potential temperature, s the entropy, Π the corresponding PV.

State	$n = \frac{c_p - c_v}{c_p - c_v}$	Steady wind	Stream function	DSI representation	Processes
isobaric	0	$\mathbf{v} = \frac{1}{\rho \Pi_p} [\nabla p \times \nabla e_M]$	$e_M = \frac{1}{2} \mathbf{v}^2 + \phi$	$\text{DSI} = \frac{1}{\rho} \frac{\partial(p, e_M, \Pi_p)}{\partial(x, y, z)}$	Dynamic (const. pressure)
isochoric	$\pm\infty$	$\mathbf{v} = \frac{1}{\rho \Pi_v} [\nabla v \times \nabla \mu]$	$\mu = e_M + pv$	$\text{DSI} = \frac{1}{\rho} \frac{\partial(v, \mu, \Pi_v)}{\partial(x, y, z)}$	Dynamic (const. volume)
isentropic	c_p/c_v	$\mathbf{v} = \frac{1}{\rho \Pi_\theta} [\nabla \theta \times \nabla B]$	$B = e_M + pv + e$	$\text{DSI} = \frac{1}{\rho} \frac{\partial(\theta, B, \Pi_\theta)}{\partial(x, y, z)}$	Thermod. (const. entropy)
isothermal	1	$\mathbf{v} = \frac{1}{\rho \Pi_T} [\nabla T \times \nabla g]$	$g = e_M + pv + e - Ts$	$\text{DSI} = \frac{1}{\rho} \frac{\partial(T, g, \Pi_T)}{\partial(x, y, z)}$	Thermod. (const. temp.)

For the four distinguished polytropic states isobaric, isochoric, isentropic and isothermal the corresponding steady wind representations characterizing the basic state as well as the DSI representations are summarized in table 1. We note that the original DSI given in (1) represents the isentropic DSI for the polytropic index $n = c_p/c_v$.

130 The DSI is calculated locally, for every grid box of the underlying data set. In case DSI values are equal to 0, the the atmosphere is locally in its basic state. For the physical explanation of the DSI signals that are unequal to zero, we consider the first law of thermodynamics. Assuming a thermodynamic process without the transfer of matter, the change in internal energy e is equal to the sum of the change in heat and work:

135 $de = Tds - pdv.$ (9)

Regarding the notation, T is the temperature, s is the entropy, p is the pressure, and v is the volume. The performance of work is $\delta w = -p dv$ and the heat transfer is given by $\delta q = T ds$. Regarding the definitions of the *dynamic DSI variants* (isobaric and isochoric) given in table 1, the steady wind representations contain the gradient of the pressure p and of the the volume v . It follows that the non-zero values of the isobaric (constant pressure) and isochoric (constant volume) DSI indicate the performance of work. Therefore, these variants can be classified as dynamical parameters.

140 On the other hand, regarding the isentropic and isothermal states in table 1 the steady wind includes the gradients of the potential temperature θ and the temperature T . The isentropic (constant entropy) and isothermal (constant temperature) DSI values unequal to zero signal heat transfer. Therefore, these parameters can be used to identify dynamical and thermodynamical contributions to the change of cloud regimes.



145 Or, in other words, DSI values equal to zero mean that the atmosphere is locally in its basic state, where the basic state is defined by the corresponding steady wind given in Eq. 6. DSI values unequal to zero indicate variabilities in the underlying processes. From a mathematical perspective, variations in the thermodynamic DSI variants occur if the Jacobian determinant, or equivalently the spat product, of the gradients, e.g., entropy (for the isentropic DSI, temperature for the thermodynamic DSI, volume for the isochoric DSI and, respectively, pressure for the isobaric DSI), with the corresponding potential vorticity
150 (Eq. 7) and the corresponding stream functions is unequal to zero; see Table 1. Fig. 1 shows meteorological examples of the DSI variants of the isentropic (thermodynamic) DSI variant on the synoptic scale, the isobaric DSI on the meso scale and both variants for shallow cumulus clouds on the convective scale.

3 Method for cloud simulations and data

In order to analyse the polytropic DSI variants introduced in the previous section 2.2, we simulate shallow convective clouds
155 in two regions using Cloud Model 1 (CM1), version 21.0 (Bryan and Fritsch, 2002). CM1 is a non-hydrostatic, convection-permitting numerical model that was specifically designed to study idealised atmospheric cloud processes. We perform idealised large-eddy simulations (LES) of low-level clouds under different warming conditions over the subtropical and arctic oceans. The simulations have a horizontal grid spacing of $100\text{ m} \times 100\text{ m}$ and a vertical grid spacing of 40 m with $(128 \times 128 \times 100)$ grid points. The simulations were initially run for 86400 s (1 day). After this settling-in phase, when the clouds and
160 precipitation were fully established, each simulation was restarted to get a higher temporal output of 30 s for a period of 10 minutes (20 timesteps in total). This data was used for the statistical analysis presented in section 4.

For the subtropical cases, we used CM1's pre-configured LES test case (les_ShallowCuPrecip) of precipitating shallow cumulus convection based on observations from the Rain in Cumulus over the Ocean (RICO) campaign (vanZanten et al., 2011). Idealized vertical profiles of the arctic ocean are based on data from the Multidisciplinary drifting Observatory for
165 the Study of Arctic Climate (MOSAiC) expedition 2019/20 which represents a blended product of meteorological measurements combined with radiosondes launched from aboard the Polarstern (Dahlke et al., 2023). We specifically searched for mixed-layer vertical profiles allowing only for small variations in potential temperature difference of less than 1 K between 65 and 535 m (criterion 1). Additionally, we only considered thermodynamical profiles with temperatures above 0°C , more precisely $T(z = 65\text{ m}) > 0^\circ\text{C}$ (criterion 2). Out of the 1518 blended profiles, six profiles satisfied these two criteria (Fig. 2). As a starting
170 point we choose profiles of temperature and moisture as indicated by the black lines in Fig. 2, that are on the drier side of the observed profiles. For the wind profile, we used the mean wind.

For the different warming scenarios we assumed an increase in surface temperature by $+2\text{ K}$ and $+4\text{ K}$ for both regions and region-dependent vertical warming (e.g., Lee et al., 2021, their Fig. 4.22). E.g., under the Shared Socioeconomic Pathway SSP3-7.0 scenario, the annual, zonal mean atmospheric temperature of the subtropical region (30°N) increase between $+1\text{ K}$
175 to $+3\text{ K}$ at the surface level and ca. $+4\text{ K}$ to $+5\text{ K}$ at the 500 hPa level in 2081–2100 relative to 1995–2014. In comparison, the annual, zonal mean of the arctic region increases by $+5\text{ K}$ to $+6\text{ K}$ at the surface, while the temperature at the upper levels

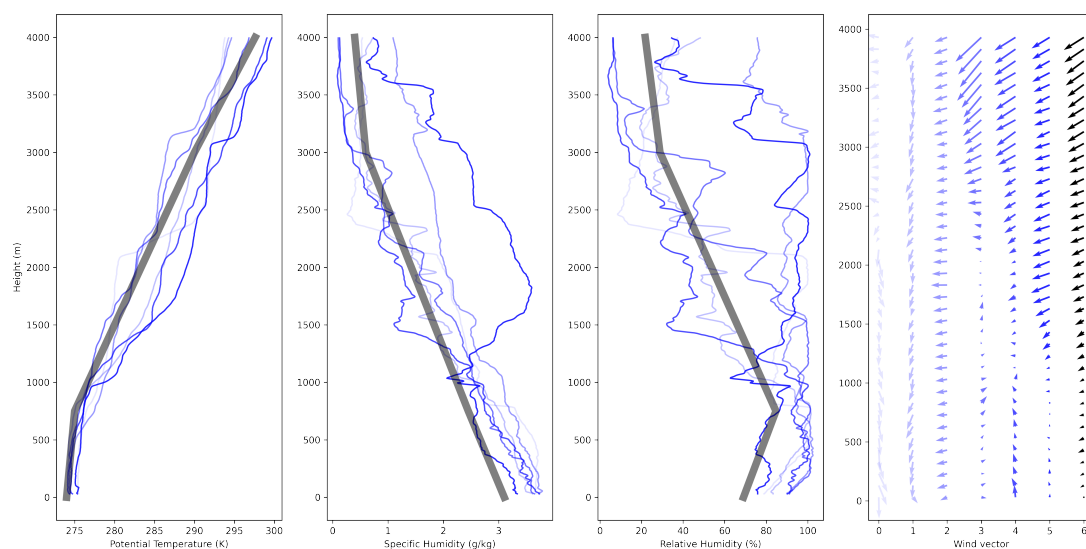


Figure 2. Vertical profiles of potential temperature, specific humidity, relative humidity and wind vector (from left to right). Dates of the MOSAiC profiles that satisfy the two criteria mentioned in the text are Sep. 22, 2019 at 3:53Z and 10:58Z, Sep. 24, 2019 at 1:56Z, June 9 at 2:03Z, 4:56Z and 7:54Z (indicated by different shades of blue starting from light blue to dark blue). Black lines of temperature and moisture variables indicate the profiles used to initialize the polar_0K (original) CM1 simulation. Black wind vectors indicate the mean wind profile.

increases less strongly (ca. $+4K$ at 500 hPa). The idealized soundings used in this study mirror this pattern (see Table 2 and Figs. A1,A2). Furthermore, we assume that the relative humidity stays constant in all warming scenarios.

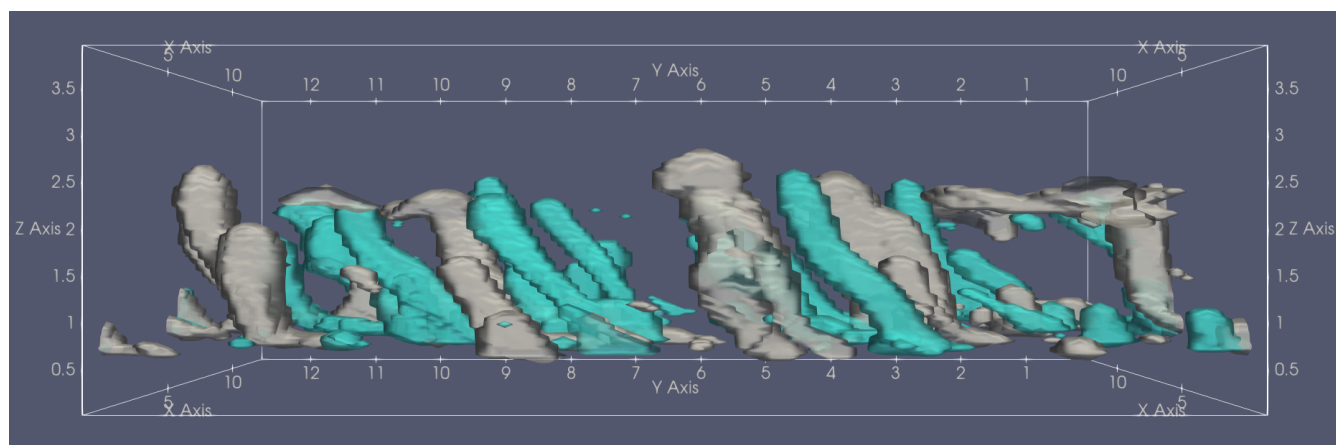


Figure 3. The shallow cumulus clouds (the mixing ratios of cloudy air $q_c = 5e - 8$ [kg/kg]) of case 1 for (i.) the original temperature (grey) and (ii.) the warming scenario of plus 4 Kelvin (turquoise).

Table 2. Idealized vertical profiles over subtropical oceans for different warming scenarios with surface temperature anomalies of $+2K, +4K$. CM1 uses a fixed ocean surface temperature assumption with a sea surface temperature that is 2K warmer than the atmospheric surface temperature, where z is the height given in m. Surface pressure is 1015.4 hPa (subtropical), and 1006.0 hPa (polar). Potential temperature θ is given in K; specific humidity q_v is given in g/kg, relative humidity (rh) is given in percent. Original data is based on vanZanten et al. (2011, subtropical), and Dahlke et al. (2023, polar), respectively. The according vertical profiles are plotted in Figs. A1 and A2.

Region	z	$\theta(\text{original})$	$\theta(+2K)$	$\theta(+4K)$	$q_v(\text{original})$	$q_v(+2K)$	$q_v(+4K)$	rh
subtropical	0	297.90	299.90	301.90	16.00	17.89	19.96	65.7%
	740	297.90	299.95	301.90	13.80	15.48	17.33	85.5%
	3260	312.66	315.22	317.73	2.40	2.81	3.29	39.9%
	4000	317.00	319.71	322.37	1.80	2.14	2.53	26.9%
polar	0	275.00	277.00	279.00	3.10	4.49	5.12	69.3%
	750	275.00	277.10	279.10	2.45	3.35	3.86	84.7%
	3000	290.00	291.54	293.05	0.60	0.62	0.69	29.0%
	4000	297.60	298.64	299.65	0.40	0.35	0.39	21.8%



4 Results

180 4.1 The impact of atmospheric warming on shallow cumulus clouds in the tropics and in the polar region

Two case studies of high resolution CM1 cloud simulations in the (sub-) tropics and the polar region are investigated with several scenarios of atmospheric warming. In the first case study, we consider shallow cumulus clouds in the subtropics, where the temperature of the atmosphere is increased by 2 and 4 degrees Kelvin. The initial conditions of the mixing ratio and the relative humidity are adapted as described in Sec. 3, and shown in the appendix in Fig. A1 and in Fig. A2.

185 To address the first research question, *How do shallow clouds in the subtropics and in the polar region change with a warming atmosphere?* the shallow cumulus clouds from the different climate scenarios 2nd time step, are shown in Fig. 3. For a better comparison, both scenarios are shown in one figure, where the grey clouds represent the clouds for the original temperature profiles, and the turquoise clouds depict the scenario of an increase of +4 Kelvin. For all scenarios, the same mixing ratio of cloudy air $5e - 8$ is [kg/kg] considered for a fair comparison. The turquoise clouds of the warmed atmosphere
190 are thinner and lower than the clouds in their original state.

In the second case study, the polytropic DSI variants for shallow cumulus clouds in the polar region are investigated for the original state and two warming scenarios: +2 K and +4 K. Fig. 4 a)-f) show the shallow cumulus clouds for the three simulated scenarios: *original*, +2K, and +4K. The figures on the l.h.s. show the horizontal extent, and the figures on the r.h.s. show the vertical profiles. a) and d) represent original conditions; b) and e) show the shallow cumulus clouds for warming by +2 K; c)
195 and f) show the clouds at warming by +4 Kelvin. In Fig. 4 a)-c), an increase in the horizontal extent and in Fig. 4 d)-e) a strong vertical increase with warming can be observed, especially comparing the original state to a warming of 2 degrees Kelvin, but also to the additional warming.

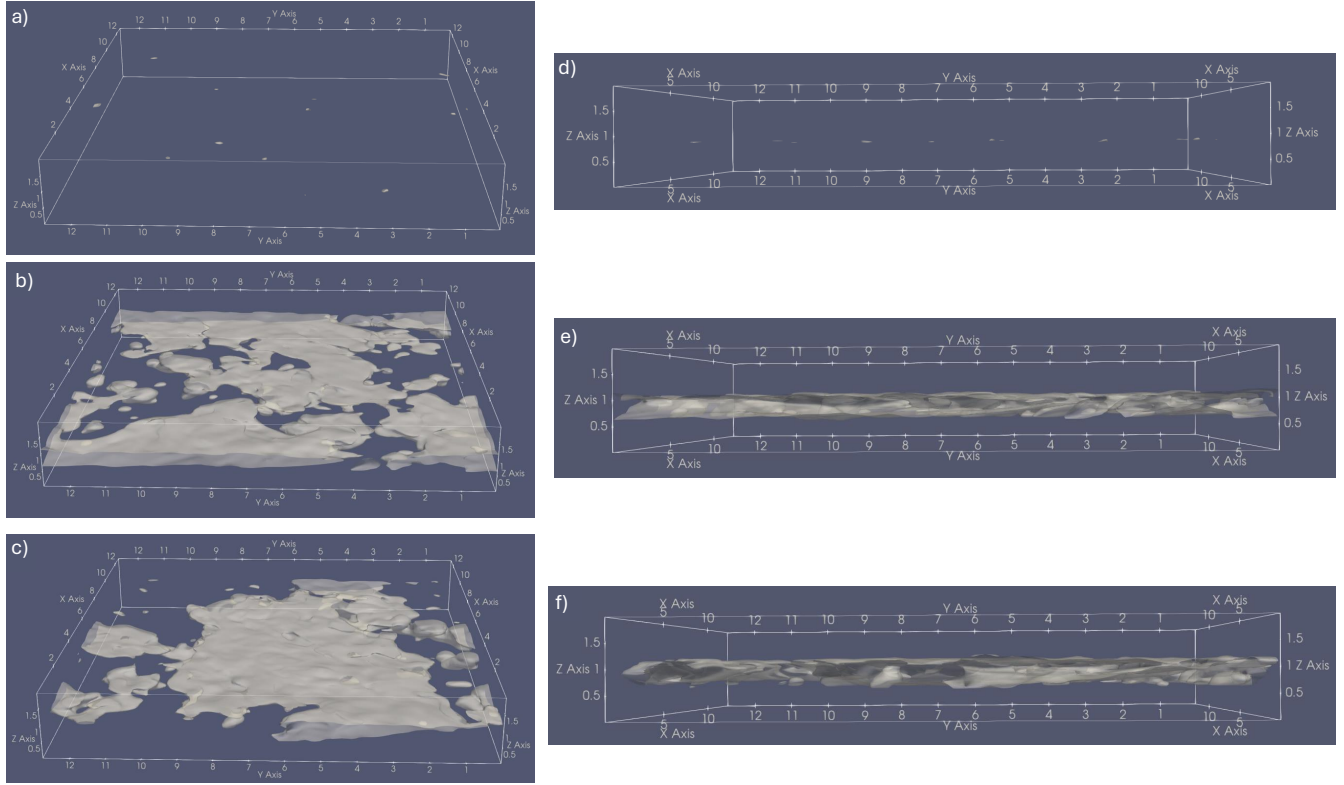


Figure 4. Shallow cumulus clouds (mixing ratio of cloudy air $q_c = 5e - 8$ [kg/kg]) in the polar region (case 2) for the original state and two warming scenarios, where the figures on the l.h.s. show the horizontal extent and the figures on the r.h.s. show the vertical profiles. a) and d) original conditions, b) and e) warming by +2 K, c) and f) warming by +4 Kelvin.

4.2 Thermodynamic and Dynamic DSI variants for shallow cumulus clouds in the original state

To address the second research question, *Does the Dynamic State Index (DSI) indicate shallow cumulus clouds?*, the thermodynamic and dynamic DSI variants, as defined in Table 1, are calculated from the CM1 output. The clouds and thermodynamic (isothermal) DSI variant and the dynamic (isobaric) DSI variants for the first case study at time step 2 are depicted in Fig. 5 a)-d). The colours indicate the 99.7th percentile of the corresponding DSI variants. Fig. 5a) shows the isothermal (thermodynamic) DSI variant. Fig. 5b) indicates the isobaric (dynamic) DSI variant; and 5c) reflects both DSI variants for case study 1, time step 1. In Fig. 5d), all four DSI variants, as defined in Table 1, are shown for time step 17. The thermodynamic DSI variants are depicted in darker colours (blue: DSI isentropic, purple: DSI isothermal), and two dynamic DSI variants are illustrated in lighter colours (orange: DSI isobaric, yellow: DSI isochoric). All DSI variants detect developing shallow cumulus clouds, which means that the second research question can be confirmed. Only very small clouds are not identified by the DSI variants. It can be noticed that the thermodynamic DSI variants dominate near the cloud top, whereas the dynamic DSI variants are more pronounced during the updraft, which will be discussed more in detail in Sec. 5.

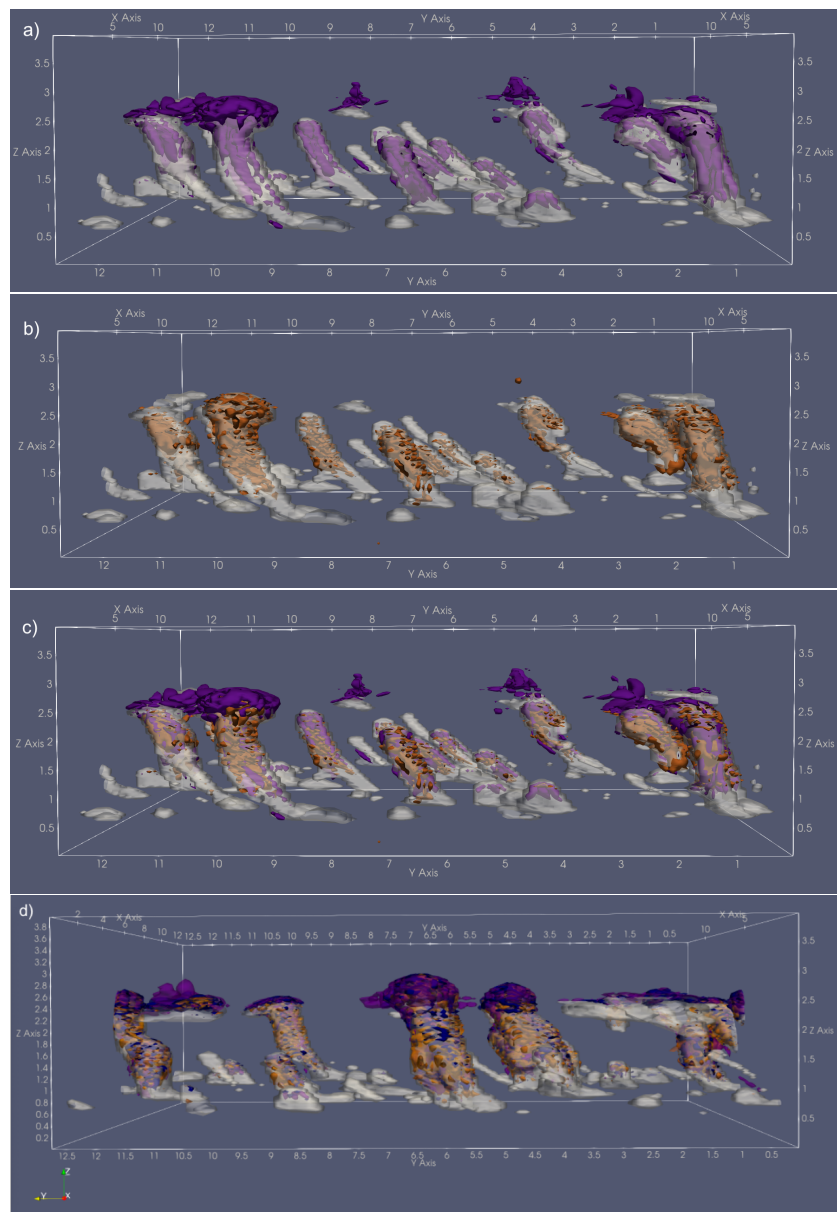


Figure 5. a) Thermodynamic (isothermal) DSI variant, time step 2 b) Dynamic (isobaric) DSI variant, time step 2, c) isothermal and isobaric DSI variants for shallow cumulus clouds in the tropics, time step 2, d) All four DSI variants for time step 2, the thermodynamic DSI variants (blue/purple) are dominant on the top of the cloud, where the cooling plays a crucial role. The dynamic DSI variants (orange/yellow) are prominent in the inside of the clouds reflecting the up- and downstreams. The colours indicate the 99.7th percentile of the corresponding DSI variants and the clouds are represented by the mixing ratio of cloudy air at $q_c = 5e - 8$ [kg/kg].



210 4.3 Thermodynamic and dynamic DSI variants in climate warming scenarios.

Answering the first research question in Subsec. 4.1 it is shown that warming scenarios lead to: (i) a decrease in the height and width of tropical clouds; and (ii) an increase in the horizontal and vertical extents of polar shallow cumulus clouds. After confirming the suitability of the DSI parameter for identifying clouds in the previous subsection, the third and final research question can be addressed: *Can a novel variant of the DSI be used to disentangle the thermodynamically-induced and*
 215 *dynamically-induced changes of shallow cumulus clouds in a warming atmosphere?*

The results regarding the first case study (shallow cumulus clouds in the tropics) are summarised in Table 3, where the 99.7th percentile for all four DSI variants for the original state and for the two warming scenarios (+2 K and +4 K) is listed. Due to the different dimensions of the DSI variants, see the definitions in Table 1), the absolute value is not comparable. Therefore, in addition to the absolute values of the 99.7th percentiles DSI variants, the (percentage) growth rates and decline rates are
 220 additionally calculated for the warming scenarios and shown in brackets in columns four and five of Table 3.

Table 3. The 99.7 percentiles of the four DSI variants for the two case studies for the original state and two warming scenarios +2 K and +4 K are listed. The numbers in the brackets denote the growth rates of the corresponding DSI percentiles.

Process	DSI variant 99.7% Percentile	Tropics original (T_{2m})	Tropics ($T_{2m} + 2\text{ K}$)	Tropics ($T_{2m} + 4\text{ K}$)
Thermodynamic	DSI isentropic	2.00e-10	2.07e-10 (+3,5%, 1,035)	9.32e-11 (-53,4%, 0,466)
Thermodynamic	DSI isothermal	1.53e-07	1.57e-07 (+2,6%, 1,026)	5.75e-08 (-62,4%, 0,376)
Dynamic	DSI isobaric	9.01e-14	8.02e-14 (-11,0%, 0,890)	4.36e-14 (-51,6%, 0,484)
Dynamic	DSI isochoric	1.70e-11	1.64e-11 (-3,5%, 0,965)	7.73e-12 (-54,5%, 0,455)
→ Decrease				
Process	DSI variant 99.7% Percentile	Polar region original (T_{2m})	Polar region ($T_{2m} + 2\text{ K}$)	Polar region ($T_{2m} + 4\text{ K}$)
Thermodynamic	DSI isentropic	5.39e-13	7.09e-13 (+31,45%, 1,315)	1.31e-12 (+143%, 2,430)
Thermodynamic	DSI isothermal	4.97e-09	5.22e-09 (+5,0%, 1,050)	6.01e-09 (+20,9%, 1,209)
Dynamic	DSI isobaric	2.05e-15	2.12e-15 (+3,4%, 1,034)	2.63e-15 (+28,3%, 1,283)
Dynamic	DSI isochoric	1.83e-13	2.07e-13 (+13,1%, 1,131)	2.79e-13 (+52,5%, 1,525)
→ Increase				

Regarding the first case study, a warming of + 2 K results in only slight changes in thermodynamic and dynamic processes, where stronger thermodynamic DSI signals and a decrease in dynamic DSI signals can be observed. Increasing the temperature of the atmosphere by a total of +4 K leads to a decrease in the height and width of the clouds in the tropics; see Sec. 4, Fig. 3. These results are confirmed by the overall decrease in the absolute values of all the DSI variants in Table 3.



225 In the second case study, the polytropic DSI variants for shallow cumulus clouds in the polar region are investigated for two
warming scenarios +2 K, +4 K. The 99.7 percentiles of all four DSI variants are shown in Table 3, lower block. In contrast to
the first case study, a strong increase in the values of all thermodynamic and dynamic DSI variants can be recognised. While
the percentiles of the dynamic DSI variants increase by up to +52% (isobaric DSI) and +157% for a warming of +4K, the
thermodynamic isentropic DSI variant shows an increase of 143% for the +4K warming scenario. These results correspond
230 with the cloud simulations in Subsection 4.1, where a strong horizontal extent, but also a vertical extent of the clouds could be
observed.

5 Discussion

The high-resolution cloud model 1 (CM1) is applied to address the three research questions: 1. *How do shallow clouds in
the subtropics and in the polar region change with a warming atmosphere?* 2. *Does the Dynamic State Index (DSI) indicate*
235 *shallow cumulus clouds?* and 3. *How does the thermodynamic and dynamic state of shallow cumulus clouds change with a*
warming atmosphere? For both regions and all atmospheric warming scenarios, the same mixing ratio threshold of $5e-8$ for
the cloud representation in all figures is considered for a fair comparison.

Regarding case 1, the tropics, comparing the CM1 simulations of the shallow cumulus clouds for the original state and
a warming of +4 K, a slight vertical and horizontal reduction of the cloud extent can be recognised, as depicted in Fig. 3.
240 This result is expected because the imposed subtropic warming profile exhibits stronger temperature increases in the mid-
troposphere than near the surface, which results in enhanced stability. The strengthened inversion suppresses vertical mixing
and limits cloud-top growth, leading to a reduction in cloud vertical extent. Furthermore, the simulated reduction in cloud extent
is consistent with studies indicating a positive low-cloud feedback in subtropical marine regions (?). In contrast, the simulations
of shallow cumulus clouds for the warming atmosphere in the polar regions indicate a distinct increase in horizontal and vertical
245 extent of the clouds with warming, as shown in Fig. 4.

Fig. 5 shows that the thermodynamic and dynamic DSI variants do indicate shallow cumulus clouds. Only very small clouds,
which are presumably associated with very low dynamic and thermodynamic processes, are not detected. This can be explained
by the high threshold used by the DSI. The animation in the supplementary material shows that these clouds are in the early
state of their generation and will be detected by the DSI at later stage of their development. Therefore, we can answer the
250 second research question positively.

It can be recognized that the thermodynamic DSI variant is dominant at the top of the clouds, where the temperature gradient
is large due to the cooling of the air. By definition, high temperature/entropy gradients are reflected in the thermodynamic DSI
variants. Because of the strong relationship between the entropy (gradient) and temperature (gradient), both thermodynamic
DSI variants reflect similar structures. Therefore, we focus in Fig. 5 a)-c) on one thermodynamic (isothermal) DSI variant.
255 Additionally, the two dynamic DSI variants are strongly correlated; thus, we only depict one dynamic (isobaric) DSI variant.
The dynamic DSI variants that are not equal to zero indicate deviations from the isochoric and isobaric basic states, see Eq.
6. More precisely, the isochoric DSI variant equal to zero indicates an incompressible basic state. Therefore, signals of the



isochoric DSI indicate incompressible changes, i.e., local variations in density. These, in turn, are related to local variations in pressure, which are reflected by the DSI isobaric. Therefore, the dynamic DSI variants have similar structures. Since the pressure gradients are related to the wind, the signals of the dynamic DSI variant are more dominant during the updrafts, where the vertical motion is strongest. The smaller scale structures of the dynamic DSI variants in Fig. 5a)-d) can be explained by the wind induced turbulence within the clouds that is reflected by the dynamic DSI variants.

In general, all four DSI variants show congruent structures because they all depict rotational motions by the corresponding PV variants, including the vorticity vector. But while the thermodynamic DSI variants pronounce the regions of dominating thermodynamic processes, such as the cooling at the top of the clouds, the dynamic DSI variants emphasize the dynamic processes, such as the vertical updrafts. Comparing the DSI concept with the analysis of the basic variables directly, the DSI concept has two advantages: (1.) The DSI is derived directly from the set of primitive equations. (2.) The DSI is defined to describe local deviations from the corresponding basic states. That means DSI values measure *anomalies* with respect to zero. Commonly regarded anomalies of variables such as wind, temperature, or pressure need reference values for every vertical level. Regarding the DSI concept, the reference value (which is given by the basic state) for each level is zero.

From the physical perspective, temperature and pressure represent intensive quantities, yet their equilibrium behavior differs markedly. Pressure equilibrates almost instantaneously in the atmosphere, leading to only minor deviations from the reference state; consequently, the values of the isobaric DSI remain consistently small. In contrast, temperature adjusts more slowly toward equilibrium, resulting in larger deviations and higher thermodynamic DSI values. Entropy and volume—both extensive quantities—exhibit intermediate responses between these two extremes. Their exchange processes reflect the system's tendency to restore equilibrium over longer timescales. The thermal equilibrium of the atmosphere is therefore characterized by inertia, as temperature, being an intensive quantity, responds sluggishly to external forcing.

The results of addressing the third research question are in accordance with the findings of the first research question. Answering the first research question, we observed a slight reduction in shallow cumulus clouds in the tropics and a strong densification of shallow cumulus clouds in the polar region. These observations are confirmed by the absolute values of the DSI variants as shown in Table 3. Regarding the first case study, the tropics, a warming of +2 K leads to a slight increase in thermodynamic DSI values and a decrease in dynamic DSI values. That means that the variability of the thermodynamic processes related to heat transfer increases, while the variability of the dynamic processes decreases. At a warming scenario of +4 K, the signal is clear for all thermodynamic and dynamic DSI variants. The variability and intensity of dynamic and thermodynamic atmospheric processes become less pronounced with higher temperature increases, as already indicated by the analysis of the clouds in research question one. The decrease in cloud horizontal and vertical extent seems to be related to less dynamic and thermodynamic processes. Running the simulations for different resolutions ranging from 100m to several km does not change our results w.r.t the DSI variants.

In contrast, regarding the warming climate scenarios in the polar region in case study 2, a strong increase in thermodynamic and dynamic shallow cumulus cloud processes is observed. This corresponds to the impact of atmospheric warming on the clouds, as shown in Fig. 4, where a distinct increase in the vertical and horizontal densification of the clouds can be recognised. Therefore, stronger thermodynamic processes, such as heat transfer, as well as more intense dynamic processes, including the



performance of work, vortex-related motions, and increased turbulence, can be expected in a warming scenario of +4 K in the polar region.

295 In a separate study, the authors are currently examining the precise relationships between the variables defining each DSI variant (potential vorticity, stream function) and the resulting output variables (wind, pressure, temperature, etc.) for a selected case study in order to gain deeper physical insights. Future work may extend the analysis to additional cloud types and regions, including the application of spatial smoothing of the DSI field across multiple grid boxes. In each context, it is sufficient to consider one thermodynamic and one dynamic DSI variant. Moreover, the DSI framework could be applied to long term studies
300 of precipitation events.

As illustrated in Fig. 5, the ability to identify clouds using the DSI opens up several avenues for future application. On the one hand, DSI variants can be utilized to detect clouds in datasets that lack explicit cloud resolution, or to quantify uncertainties. Given that Crnivec et al. (2023) found that CMIP6 models underestimate cloud cover in both Sc- and Cu-dominated tropical ocean regions, DSI variants could provide a valuable tool for constraining uncertainties in the feedback mechanism. On the
305 other hand, the DSI offers an alternative approach to the ridge-regression-based cloud controlling factors (CCF) framework introduced by Ceppi and Nowack (2021).

6 Conclusions

Studies on the effect of warming on shallow cumulus clouds are becoming increasingly important. Shallow cumulus feedback seems to be the most important contributor to the tropical low-cloud feedback (Myers et al., 2021; Cesana et al., 2023). To gain
310 a better understanding of cloud feedbacks, it is crucial to better understand the impact of warming on the physical processes governing cloud structures. We are introducing new DSI variants based on the basic atmospheric equations that identify the thermodynamic and dynamic states of the atmosphere. The applicability of this new methodology is demonstrated using case studies of shallow cumulus and stratocumulus clouds in the polar region and the subtropics. This approach provides an alternative view to cloud controlling analysis. Four DSI variants (dynamic: isobaric and isochoric; thermodynamic: isentropic and
315 isothermal) were applied to high-resolution CM1 simulations to address the three research questions posed in the introduction. The simulations revealed distinct regional responses of shallow cumulus clouds to atmospheric warming. In the subtropics, a warming of up to +4 K resulted in a slight reduction in cloud extent, while in the polar region, significant cloud deepening and densification were observed.

All DSI variants successfully identified shallow cumulus clouds, confirming the DSI as a reliable diagnostic for diabatic and
320 dynamic processes. Thermodynamic variants highlighted strong temperature and entropy gradients, particularly near cloud tops, whereas dynamic variants emphasized updrafts and turbulent motion. Due to their strong inter-correlation, one thermodynamic (isothermal) and one dynamic (isobaric) variant are sufficient to characterize the key processes efficiently. The DSI-based analysis further reveals contrasting process responses to warming: tropical scenarios exhibited a weakening of thermodynamic and dynamic variability, while polar scenarios showed intensification of both. These findings align with the simulated structural
325 cloud changes and illustrate the DSI's utility for quantifying local deviations from atmospheric equilibrium.



The high correlation shown here between the DSI variants and clouds opens up opportunities to study the physically based causes of dynamic and thermodynamic processes in greater depth. With DSI analyses of climate projections, the contributions from atmospheric thermodynamics and dynamics to changes in (extreme) precipitation could possibly be better understood, providing a complementary or alternative approach to a previously used physical diagnostic method (Pfahl et al., 2017). Furthermore, because the DSI is defined in terms of variables from the atmospheric governing equation system rather than directly in terms of clouds, the DSI variants can be applied to datasets in which clouds cannot be directly resolved which will be tackled in future works. Moreover, future work will aim to extend the framework to long-term analyses of precipitation and climate variability and in further regions.

Appendix A: Appendix: Method for cloud simulations and data

A1 Initial states

Figures A1, A2 show the vertical profiles of input variables that reflect the initial states of the atmosphere for the Cloud Model One, where a) potential temperature, b) specific humidity, c) relative humidity.

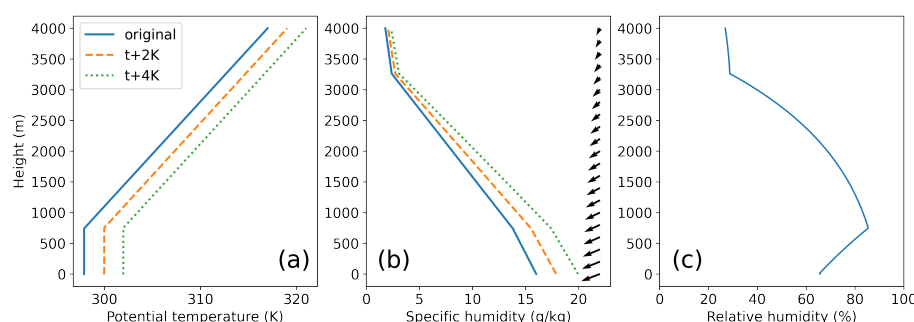


Figure A1. Vertical profiles of the initial states for the CM1 simulation of case study 1 (tropics)

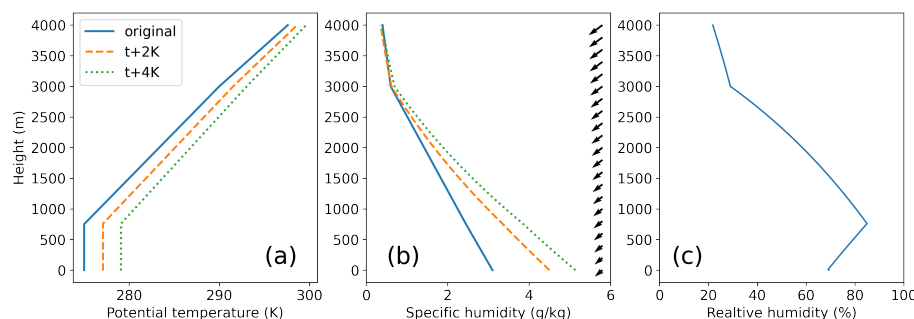


Figure A2. Vertical profiles of the initial states for the CM1 simulation of case study 2 (polar region).



Code and data availability. The Code for the DSI calculations is available in the following github repository <https://github.com/AR12358/DSI>. Cloud Model 1 is used to generate the Data to calculate the Dynamic State Index. Please contact the authors. They will provide you the data.

Video supplement. For the animation of case study 1, tropics, original temperature, see the github repository <https://github.com/AR12358/DSI>

Author contributions. AR, LS, NV, TS, PN have designed the study and discussed the results. AR has written the manuscript, calculated and simulated the DSI variants, LS provided the CM1 simulation data and wrote Sec. 3 *Method for cloud simulations and data*, PN derived the DSI variants, NV enabled the network and has improved the manuscript.

Competing interests. No competing interests are present.

Acknowledgements. This work was supported by the German Academic Exchange Service (DAAD) through a research fellowship for postdoctoral junior researchers, no. 57607681, at the University of Oslo.



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