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Inconsistencies Between Pangean Reconstructions and Basic Climate Controls

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Abstract: The supercontinent Pangea dominated our planet from the Permian into the Jurassic. Paleomagnetic reconstructions have been used to estimate the latitudinal position of Pangea during this 100-million-year period. Atmospheric circulation, recorded by eolian sandstones in the southwestern United States, shows a broad sweep of northeasterly winds over their northernmost extent, curving to become northwesterly in the south. This evidence is consistent with paleomagnetic reconstructions of the region straddling the equator in the Early Permian but is at odds with its northward movement to about 20°N by the Early Jurassic. At least one of the following scenarios must be true: the latitude based on paleomagnetism is incorrect; the interpretation of how winds shaped the dunes is mistaken; the basic climate controls in the Jurassic were different from those of today; or the paleogeographic reconstructions available are insufficient to adequately reproduce the wind fields responsible for dune formation.

From the Permian into the Jurassic—100 million years of Earth history—the supercontinent Pangea dominated our planet. Detailed maps of this pole-to-pole landmass, with paleomagnetic data from each continental block, were published in the 1980s, establishing paleomagnetism as the method *par excellence* of estimating paleolatitude (1). Geologic work delineating the extent of climate-sensitive sedimentary rocks (*e.g.,* coal, glacial till, evaporites, and carbonate sediments) has often helped to reduce uncertainties in the quality of paleomagnetic data and has sometimes led the way to important reinterpretations (2, 3).

Atmospheric circulation is driven by the latitudinal distribution of solar heating, which is modified by the rotation of the planet and the distribution of landmasses. Eolian dunes conclusively provide direct evidence of atmospheric circulation (4, 5). Opdyke and Runcorn (6) were the first to recognize the planetary-scale winds that deposited the Late Paleozoic eolian cross-strata of Wyoming and northern Utah. The markedly consistent dip directions of Early Permian through Early Jurassic cross-strata in the western United States (7, 8) are accurate indicators of paleowind direction (Figure 1), because they were deposited by transverse dunes that migrated downwind by repeated avalanching (9). We have extended the trade-wind explanation for the Wyoming rocks southward by interpreting eolian strata of the Colorado Plateau (southern Utah and Arizona) as records of northwesterly winds lying south of the trades in Pangea's monsoonal wind regime (10) (Figure 2).

The Paleozoic formations that contain the most abundant evidence of life in the ancient dunefields (Cedar Mesa and Esplanade sandstones) were deposited by the northwesterly winds; the formations deposited farther north in the trade-wind belt (*i.e.,* Tensleep, Weber, Casper, and DeChelly) contain comparatively fewer signs of life. These wind and biotic patterns persisted through the Early Jurassic (11). During the entire interval, the dominant winds in the north came from the northeast, curving to become northwesterly over the southern portion of the outcrops. Jurassic dunes in the south were seasonally drenched with rain, whereas weaker southeasterly winds reversed the dry-season slip faces (12).

Conventional wisdom, largely based on paleomagnetic evidence, places the plateau along or just north of the equator during the Early Permian and then moves the plateau north through the Triassic to lie near 20°N by the Early Jurassic, as calculated from published mean poles. Best estimates for the global mean poles for ~200 million years ago vary between 70°N, 96°E and 66°N, 91°E (in North American coordinates), with the variations being minor and depending on methodology (13). These mean poles yield paleolatitudes for a location in southeast Utah (40°N, 110°W) ranging between 17°N and 28°N. We do not know of any published paleomagnetic syntheses that placed the area south of the equator during the Early Jurassic. Yet the constancy of the wind regime indicated by the dip directions of the cross-strata suggests that the sand dunes and the plateau stayed within the same climatic zone during the entire time span. Furthermore, the inferred northward migration appears to be inconsistent with basic qualitative concepts of climate. Northeasterly winds changing southward to northwesterlies would be out of place near 20°N but would fit well near and just south of the equator, where northwesterly winds represent cross-equatorial flow induced by a strong summer monsoonal circulation in the southern hemisphere (SH). The wind regimes recorded by the rocks are consistent with paleogeographic reconstructions and climate simulations (14) of the Late Permian, with the Colorado Plateau straddling the equator, but are very much at odds with a northward movement to about 20°N by the Early Jurassic. Given our understanding of basic climate controls, as supported by climate model results, the wind regime that formed the eolian sandstones of the Colorado Plateau must have occurred on or south of the equator rather than at the generally accepted paleomagnetic latitude of about 20°N (15).

An earlier attempt at paleogeographic interpretation (10) was partially based on the wind regime simulated by a Jurassic climate model (16) and on paleomagnetic data collected from Colorado Plateau strata (17–19). The climate model showed trade winds during December, January, and February turning to become westerly a few degrees north of the equator. This corresponded reasonably well to estimates of paleolatitude for the Colorado Plateau (17, 20) but did not fit well with paleomagnetic data from the eastern United States (which placed the center of the plateau at about 18°N) nor with the Pangean reconstruction shown by the Paleomap Project (21). Moreover, the Jurassic climate model had extremely low resolution (8° in latitude by 10° in longitude) and was simplistic by current standards. More recently, geophysicists have called attention to the importance of sediment compaction to paleomagnetic interpretations, especially for rocks in which the paleomagnetic signal is carried by detrital hematite. Comparisons of paleomagnetic data from such sedimentary rocks with those from igneous rocks (which do not compact) indicate that sedimentary rocks are likely to yield paleolatitudes that are too low (22, 23). Because the sedimentary rocks from the plateau that provided the evidence for a low-latitude position contain detrital hematite, most paleomagneticists would now favor the higher-latitude interpretation for the plateau, thereby aggravating the discrepancy with our earlier climate-based interpretation.

In an attempt to resolve the discrepancy between winds that appear to have been constant over 100 My and the paleomagnetic evidence for northward movement of the Colorado Plateau, we made a series of climate simulations for the Early Jurassic using the latest version of the Community Climate System Model (24, 25) from the National Center for Atmospheric Research. We made four model simulations with atmospheric CO_2 at present-day levels; two of these runs used "conventional wisdom" for Early Jurassic paleogeography based on Paleomap (21), and two were made with Paleomap-derived paleogeography shifted 30° southward along the nominal 150°E meridian to put the Colorado Plateau under a favorable SH wind regime. For each pair of runs with a given paleogeography, one was made with prescribed sea surface temperatures (SSTs) for the Early Jurassic derived from Chandler *et al.* (16) and the other was made with SST computed *via* a slab ocean model component. We conducted additional model runs using the unshifted paleogeography with constant 100-m topography and with uniform vegetation to exclude these factors as major influences on atmospheric circulation. Finally, to investigate the impact of increased CO_2, we conducted two additional model runs using the shifted paleogeography, the slab ocean model, and, respectively, four times and eight times present-day CO_2 levels. All model runs were at T31 (3.75° in latitude by 3.75° in longitude) resolution, and the last 10 model years were averaged to produce climatologies for analysis.

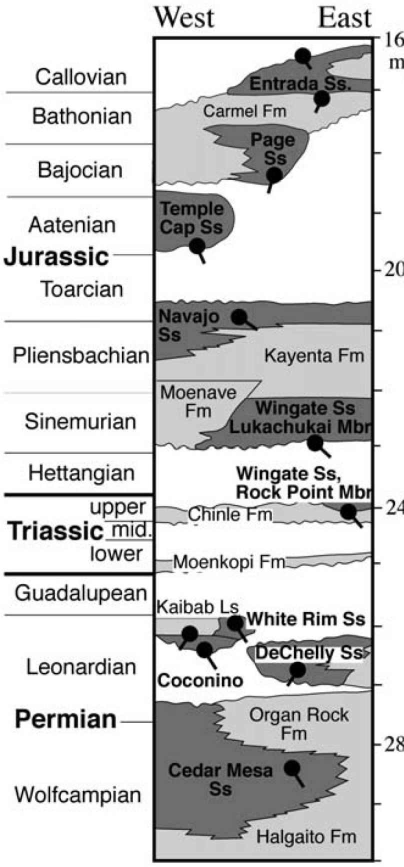

Figure 1. The eolian sandstones of the Colorado Plateau (dark shading) reach an aggregate of 2500 m in thickness and span about 140 My of Earth history. The tails of the black "tadpoles" (circles with extending lines) point in the mean dip direction of dune cross-strata and, therefore, point in the downwind direction of the paleowinds that drove the dunes. From the base of the Cedar Mesa Sandstone (Ss) (bottom) to the top of the Temple Cap Ss, the rocks show northwesterly winds (interpreted as the belt of tropical westerlies situated south of the trade winds). The DeChelly Ss is somewhat anomalous, showing northeasterly winds. Northern exposures of the Coconino Ss, however, record northeasterly winds (interpreted as trade winds); to the south, it records winds from the northwest. West-to-east variations in rock strata are depicted across the diagram; unshaded areas show major unconformities (gaps in the rock record). Fm, formation; Mbr, member; Ls, limestone. [Modified from Blakey *et al.* (26) and Peterson (7)]

Every model configuration yielded a strong monsoon that is hemispherically symmetric—that is, with strong low pressure in the summer hemisphere and strong high pressure in the winter hemisphere (Figure 3). Low-latitude winds over western Pangea during SH summer curve from northeasterly trades in the northern hemisphere (NH) to northwesterlies after crossing the equator. These simulated winds are physically reasonable and consistent with trade-wind flow in the winter hemisphere and strong monsoonal heating in the summer hemisphere. This is the only wind regime with the large, concave-to-the-east, north-to-south sweep in agreement with the winds recorded by the eolian sandstones of the western United States. This is also consistent with current concepts of the atmospheric general circulation and would indicate a low-latitude SH location for the Colorado Plateau during the Jurassic. Furthermore, every model configuration yielded the necessary countervailing southeasterly winds during SH winter, which are consistent with the key characteristics of the southernmost paleodunes. In addition, every simulation exhibits seasonally dry periods for the region of the Colorado Plateau, which is consistent with the rock record (12). Finally, although the atmospheric concentration of CO_2 for the Early Jurassic is uncertain, the model results obtained to date show that the winds are insensitive to a range of CO_2 values from the present-day concentration (355 parts per million) to eight times that amount. However, increased atmospheric CO_2 does change modeled precipitation, with possible impacts on the migration of the dunes (Figure S1).

Results from our simulations (Figure 3), like those of the low-resolution model (16), show that although the trade winds turned while north of the equator in eastern Pangea, these winds turned 5° to 10° south of the equator in western Pangea. Thus, we could infer that this was the position occupied by the Colorado Plateau (1 or 2 grid points south of the placement in the earlier study). Our model would then indicate that the Jurassic sandstones were deposited between 10°S and 20°S, not 10°N to 20°N as suggested by paleomagnetism-based reconstructions. Assuming that winds inferred from the sandstones should correspond to the winds shown by the model, either the climate model is incorrect or the northward movement of the Colorado Plateau occurred much later than suggested by current paleogeographic reconstructions. This result is independent of whether topography representative of the Jurassic is imposed or if the geography is shifted such that the Colorado Plateau is centered at 10°S. Furthermore, the simulations are robust regardless of whether SSTs are prescribed or calculated *via* a slab ocean model.

If we assume that the winds inferred from the paleodunes are correct, the climate model results and the paleomagnetism-based paleogeographic reconstructions cannot both be correct, though both can be wrong. We are left with the following possibilities: (i) The paleomagnetism-based paleogeographic reconstructions are incorrect in moving the Colorado Plateau from around the equator to about 20°N between the Early Permian and the Early Jurassic; (ii) the Early Jurassic climate model results are incorrect in simulating a pattern of northeasterly trade winds north of the equator, arcing just south of the equator into monsoonal-driven northwesterlies; or (iii) the circulation patterns inferred for the dunes represent an extreme climate state that is far removed from the mean state that we have simulated thus far.

The paleomagnetic reconstructions appear to be tightly constrained by data (23); so, if paleomagnetic interpretations are indeed the cause of this conundrum, a basic assumption of the paleomagnetism model would have to be questioned; given the

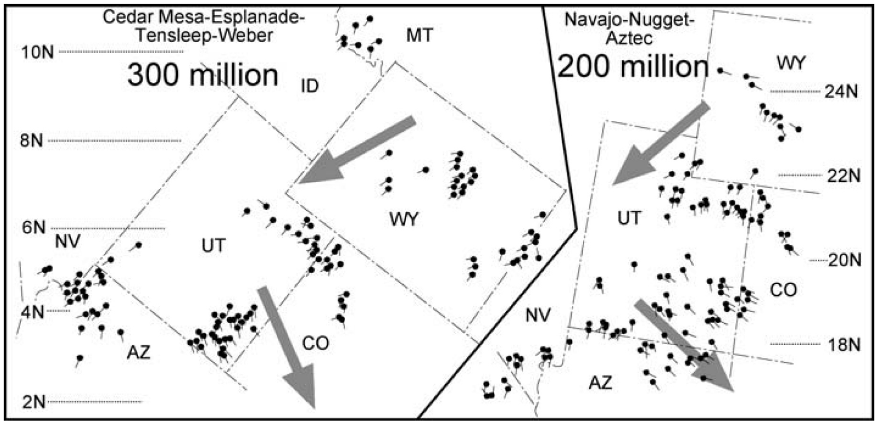

Figure 2. Dip directions of cross-strata of Late Paleozoic (left) and Early Jurassic (right) eolians and stones. Tails of "tadpoles" point downwind; each represents scores of measurements. Large gray arrows show the flow of trade winds (top arrows) and tropical westerlies (bottom arrows). Paleomagnetic data indicate that, during the Permian, Utah was near the equator but that, by the Jurassic, it had drifted to 20°N. [Modified from Peterson (7)]

consistency of Early Jurassic paleomagnetic poles from the Atlantic Ocean–bordering continents (13) and the convincing paleolatitude determinations from the Newark sediments (23), we are not ready to argue that the paleomagnetic field model must be wrong. However, the climate model results appear to be very robust based on our understanding of fundamental climatic controls. Indeed, the basic qualitative nature of these results could have been inferred just from this understanding, without the use of a climate model. Our modeling work to date suggests that atmospheric CO_2 is not likely to have a substantial impact on the orientation and migration of paleodunes, in large part because of the spatial and seasonal homogeneity of this gas (which means that it warms or cools more-or-less uniformly around the globe). The most relevant potential climate control that we have not yet considered is changing orbital states. Orbital cyclicity is known to strongly affect both the latitudinal and seasonal distribution of solar radiation and could therefore affect the monsoonal circulations that prevailed over Pangea. Furthermore, the amplitudes and periodicities of obliquity, precession, and eccentricity cycles in the past could have differed from those at present.

During the past two decades, climate models have been increasingly used to simulate atmospheric circulations of the past. Slipface orientations of modern dunes coincide well with the pattern of modern circulation (4), and we have shown that the dip directions of avalanche-dominated eolian cross-strata can, in conjunction with model simulations, be used to accurately delineate ancient atmospheric circulation. Past climate reconstructions are important in their own right, and they have previously provided strong constraints on paleogeographic reconstructions based on paleomagnetic data. Although proxy records such as coal and evaporite deposits are subject to uncertain interpretation of paleoclimatic conditions (*e.g.*, temperature, precipitation, and evaporation), wind directions preserved in eolian sediments relate directly to the atmospheric circulation. Furthermore, atmospheric circulation patterns can be a more profound indicator of a given climatic state than temperature and precipitation alone. Because the atmospheric general circulation is strongly linked to latitude, this information has great value as an independent check on magnetism-based paleogeographies.

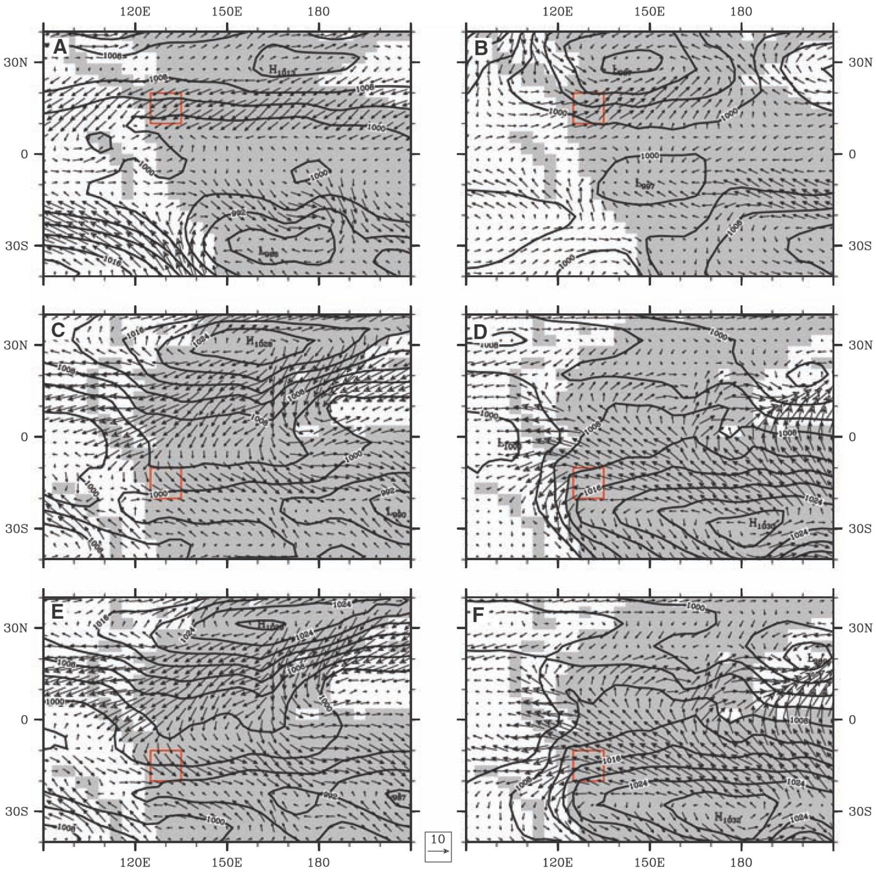

Figure 3. Simulation results for NH winter [December, January, February (DJF), left column] and NH summer [June, July, August (JJA), right column] for unshifted paleogeography with prescribed SST (**A** and **B**), shifted paleogeography with prescribed SST (**C** and **D**), and shifted paleogeography with slab ocean (**E** and **F**). Sea-level pressure (hPa) is contoured at 4-hPa intervals, and winds at the lowest model level are given as vectors, with a 10 ms^{-1} reference vector shown at bottom. The Colorado Plateau is outlined in red.

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Supporting Material follows.

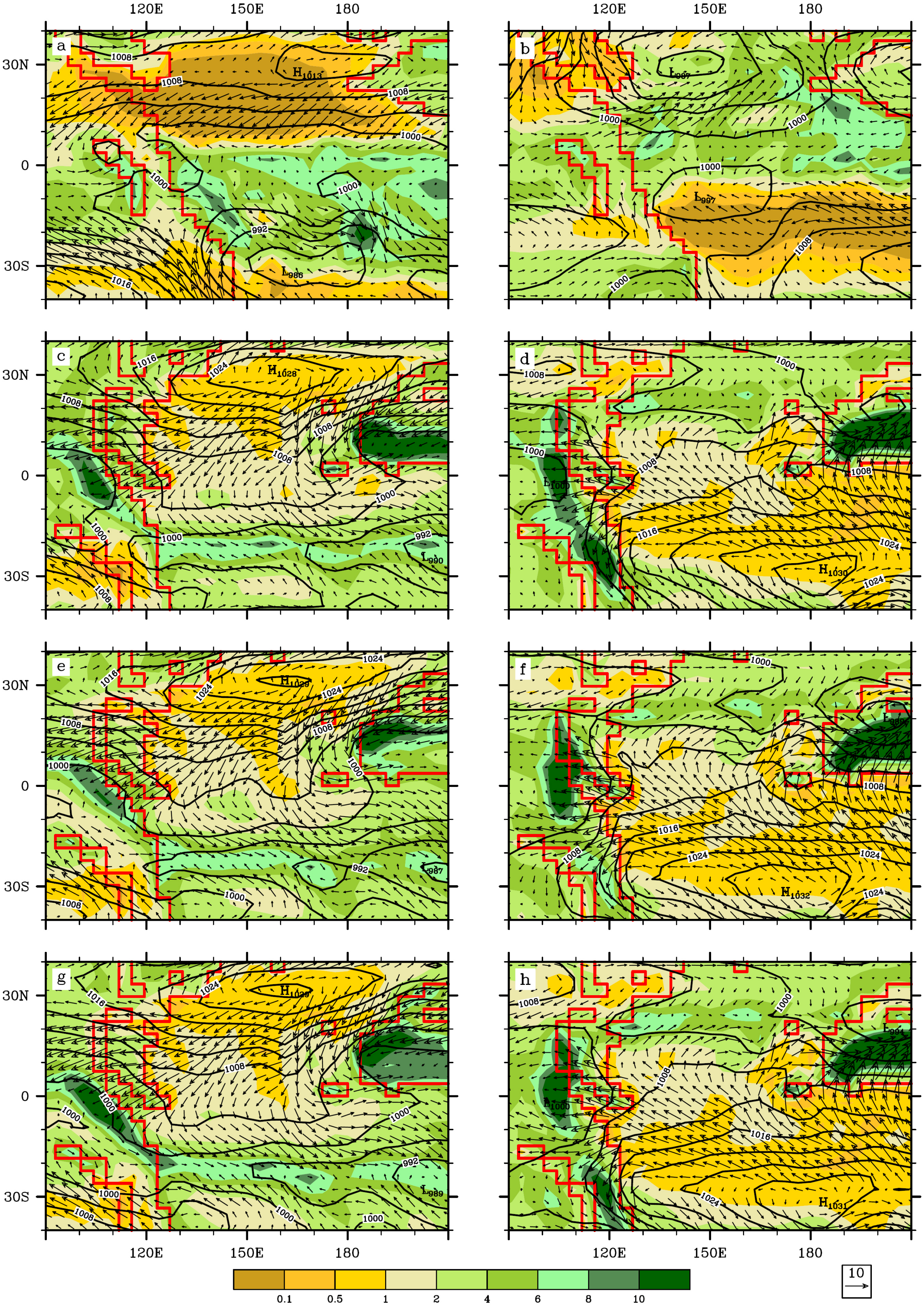

Figure S1. Simulation results for NH winter (DJF, left column) and NH summer (JJA, right column) for (**a**,**b**) unrotated paleogeography with prescribed SST; (**c**,**d**) rotated paleogeography with prescribed SST; (**e**,**f**) rotated paleogeography with slab ocean; and (**g**,**h**) rotated paleogeography with slab ocean and 4× CO_2. Precipitation (mm day^{-1}) is shaded according to the color bar; sea-level pressure (hPa) is contoured at 4hPa intervals; and winds at the lowest model level are given as vectors, with a 10 m s-1 reference vector shown. The continental outline is shown in red.