A Theory for Polar Amplification from
a General Circulation Perspective

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Abstract

Records of the past climates show a wide range of values of the equator-to-pole temperature gradient, with an apparent universal relationship between the temperature gradient and the global-mean temperature: relative to a reference climate, if the global-mean temperature is higher (lower), the greatest warming (cooling) occurs at the polar regions. This phenomenon is known as polar amplification. Understanding this equator-to-pole temperature gradient is fundamental to climate and general circulation, yet there is no established theory from a perspective of the general circulation. Here, a general-circulation-based theory for polar amplification is presented. Recognizing the fact that most of the available potential energy (APE) in the atmosphere is untapped, this theory invokes that La-Niña-like tropical heating can help tap APE and warm the Arctic by exciting poleward and upward propagating Rossby waves.
1. INTRODUCTION

In spite of the complexity of the climate system, there is a recurring global-scale phenomenon known as polar amplification. Polar amplification refers to the phenomenon that warming or cooling trends are strongest over high latitudes, particularly over the Arctic (e.g., Manabe and Wetherald 1975; Huber et al. 2000; Rigor et al. 2000; Johannessen et al. 2004). Geological data suggest that during the warm periods of earth history, the equator-to-pole temperature gradients were much smaller than the present-day value. Fossilized remains of frost-averse plants and animals around the Arctic Ocean (e.g., McKenna 1980; Tarduno et al. 1998) suggest that above-freezing temperatures were not uncommon during the Cretaceous and early Cenozoic. Estimates of tropical temperatures during these warm periods vary, ranging from below to above the present-day values (Bralower et al. 1997; Douglas and Savin 1978; Pearson et al. 2001).

The evidence collectively suggests that the surface equator-to-pole temperature gradients were weaker during warm periods (Huber et al. 2000). Similarly, CLIMAP (Climate: Long range Investigation, Mapping, and Prediction) reconstruction data show that the meridional surface temperature gradient during the Last Glacial Maximum (LGM) was greater than that of the present-day climate. Based on this paleoclimate evidence, Budyko and Izrael (1991) hypothesized that there may be a universal relationship between changes in the surface meridional temperature gradient and global-mean temperature change.

This hypothesis was tested by Hoffert and Covey (1992), and their key figure is reproduced here as Fig. 1. The top panel of Fig. 1 shows the latitudinal distribution of the deviation of surface temperatures from the present-day temperature, normalized by the
global mean of the temperature deviations. Supporting the hypothesis, the latitudinal
profiles are remarkably similar for the three different warm periods. As a way of testing of
the idea further, Hoffert and Covey (1992) constructed a least square fit to the data shown in
Fig. 1a (shown as a solid line), and then the resulting ‘universal’ relationship was applied to
the global mean temperatures of the middle Cretaceous and LGM. As can be seen in the
lower panel, the latitudinal distributions of the temperature predicted by this relationship
agrees well with the data from both time periods. This apparent universality is also evident
in Fig. 2 which is from more recent work by Miller et al. (2010). Across four different periods
(LGM, Holocene Thermal Maximum, Last Interglaciation, and middle Pliocene), there is a
nearly constant linear relationship between the global temperature change and the
 corresponding Arctic temperature change.

Polar amplification is also evident in the current-day climate. Figure 3 shows that
fluctuations in surface temperature are small in the tropics, but they increase with latitude,
with largest values in the polar latitudes. Climate models in general show polar amplification
in response to enhanced greenhouse gas (GHG) forcing (e.g., Manabe and Stouffer 1980;
Hansen et al. 1984; Winton 2006; Meehl et al. 2007). The models, however, deviate rather
substantially in their prediction of the magnitude of the Arctic warming (Masson-Delmotte
et al. 2006; Walsh et al. 2008). This indicates that key physical processes behind the polar
amplification are not well simulated by the models.

Why is this phenomenon of polar amplification interesting? There are several
reasons. On the practical side, there are some obvious biological and socio-economical
consequences. For instance, the melting of sea ice will open up new, shorter passages for
ships between Asia and Europe. Meteorologically, it can have a global scale impact. Recent studies on sea ice and snow cover indicate that the melting of Arctic sea ice during the summer and snow over land areas during the fall can influence the hemispheric scale circulation during the following winter. These changes in the circulation are associated with fluctuations in winter precipitation, blocking frequency, cold-air outbreaks, and snow cover over a substantial fraction of the middle latitude Northern Hemisphere (NH) (e.g., Singarayer et al. 2006; Honda et al. 2009; Petoukhov and Semenov 2010; Overland and Wang 2010; Liu et al. 2012).

In addition to the reasons described above, polar amplification is a fascinating phenomenon from a theoretical point of view. Regardless of the initial cause of the warming or cooling of the Arctic, the two temperature profiles (one for the Cretaceous period and the other for the LGM) in Fig. 1 raise a fundamental question as to how the different equator-to-pole temperature gradients were maintained. Consider the idealized global energy balance at the top of the atmosphere (TOA), as depicted in Fig. 4a. In the tropics and subtropics, there is surplus of net radiation since absorbed solar radiation exceeds outgoing long wave radiation (OLR). The opposite holds in high latitudes, producing a deficit of net radiation. In equilibrium, this TOA energy imbalance is compensated by poleward energy transport. During the cold season when solar radiation does not reach polar latitudes, the TOA deficit in polar regions is determined almost entirely by the OLR. Thus, in so far as the OLR responds positively to an increasing surface temperature, the warming of the Arctic implies a stronger
poleward energy flux\(^1\) (Fig. 4b). [Of course, it is possible that Arctic OLR may actually decrease as the surface warms if the Arctic becomes covered by tall, convective clouds. However, this does not occur at least in the present-day climate.] This leads to the following question. How does the poleward energy flux increase as the climate warms? In this essay, this question is addressed from the perspective of the general circulation. For a recent review of observational and modeling work on the Arctic warming, readers are referred to Serreze and Barry (2011). As their review paper recounts, most studies on the Arctic climate have focused on local processes such as ice-albedo feedback (Budyko 1969). While these authors also discuss heat transport by the large-scale atmospheric circulation, a theoretical treatment of this topic in the context of polar amplification is lacking in the literature. This essay is an attempt to advance such a theory.

2. THEORIES OF EQUABLE CLIMATES

a. The flux-gradient relationship and baroclinic adjustment

Until recently, proposed mechanisms on equable climates that have considered poleward heat transports include a Hadley cell which occupies the entire hemisphere (Farrell 1990), an enhanced poleward oceanic heat transport (e.g., Barron et al. 1993; Sloan et al. 1995), and an intensification of the thermohaline circulation due to driving by tropical cyclones (Sriver

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\(^1\) One may argue that a weak temperature gradient is caused by an enhanced poleward energy transport which is in turn triggered by an initial state with a strong temperature gradient. However, in a steady state (or over time scales longer than the energy transport processes), since the poleward energy transport is not solely dependent on this presumed initial state, one is still left with the conclusion that a stronger poleward energy flux must be required to maintain an equable climate.
and Huber 2007; Korty et al. 2008). There are other proposed mechanisms that do not involve poleward heat transports. These include a convection-cloud radiative forcing feedback (Sewall and Sloan 2004; Abbot and Tziperman 2008a,b), a vegetation-climate feedback (Otto-Bliesner and Upchurch 1997; DeConto et al. 2000), and decreased cloud reflectivity due to a reduction in the number of cloud condensation nuclei (Kump and Pollard 2008). But again, as was discussed above, an equilibrium climate requires an increased poleward energy flux. Therefore, a mechanism that can account for the increased poleward energy flux is still needed.

Given the fact that the present-day extratropical (i.e., poleward of 30°) poleward heat transport is carried out mostly by atmospheric baroclinic eddies (here eddies are defined as motion that deviates from a zonal mean), it is interesting to note that none of the above theories involve baroclinic eddies. There is a good reason for this. To a very good approximation, the baroclinic eddy heat flux is negatively proportional to the gradient of the mean temperature:

\[ [v'T'] = -D \delta[T]/\delta y, \]

where \( v \) is meridional wind, \( T \) the temperature, the square bracket an appropriately defined mean, and prime the deviation form the mean. According to this flux-gradient relationship, if the meridional temperature gradient were to decrease, a new equilibrium state would be achieved through a weaker poleward eddy heat flux. Therefore, a downgradient (poleward)
baroclinic eddy heat flux cannot account for the poleward heat transport which must increase in order to maintain the weak temperature gradient of a warm climate. Based on a scaling argument relevant for an idealized two-layer atmosphere of differing densities, Held and Larichev (1996) suggested $D \sim U \lambda \xi^2$ where $U$ is the velocity wind shear which is proportional to the meridional temperature gradient, $\lambda$ the internal Rossby radius of deformation, and $\xi$ the supercriticality which can be thought of as the meridional temperature gradient of a radiative equilibrium state. Under equable climate conditions, both $U$ and $\xi$ decrease. According to Fig. 1, these values during the Cretaceous are roughly 50% of the present-day values. Assuming that $\lambda$ does not change the diffusivity would actually be smaller under equable climate conditions. (Even if $\lambda$ increases by 50% so as to maintain a constant interfacial slope between the two layers – for the continuous atmosphere this slope is equivalent to the isentropic slope between the equator and the poles – $D$ would still decrease.)

There is also the view that the statistical equilibrium state of the atmosphere corresponds to the marginal state for baroclinic instability. This equilibration process, known as baroclinic adjustment (Stone 1978; Lindzen et al. 1980; Cehelsky and Tung 1991), is based on Charney-Stern-Pedlosky stability criterion (Charney and Stern 1962; Pedlosky 1964). That is, if baroclinic adjustment is applicable, the atmospheric state exhibits neutrality with respect to a spontaneous growth of eddies from arbitrarily small perturbations in a stratified rotating fluid. This implies that an increase in the eddy heat flux cannot take place beyond that of the neutral state. Therefore, in this theory, which excludes further poleward heat flux
by finite-amplitude disturbances, the reduced meridional temperature gradient of the
equable climate cannot be realized.

None of the above two equilibration processes is caused by an exhaustion of zonal-
mean available potential energy (ZAPE; Lorenz 1955). In the present-day atmosphere, eddy
available potential energy is only about 10% of the zonal-mean available potential energy
(Peixoto and Oort 1994; Li et al. 2007). According to the above equilibration theories, the
baroclinic eddy heat flux is either saturated with respect to linear instability or constrained
in the context of homogeneous baroclinic turbulence (Salmon 1980; Vallis 1988; Held and
Larichev 1996). In reality, however, the atmosphere is neither devoid of finite amplitude
disturbances nor does it resemble homogeneous turbulence: for example, the atmosphere is
almost always subject to finite-amplitude disturbances from the tropics (think of El Niño-
Southern Oscillation or the Madden-Julian Oscillation (MJO)), and there is inhomogeneity
introduced by orography and the land-sea distribution. Thus, if, somehow, the mostly
untapped ZAPE can be released through these forcings, in principle, enhanced poleward
heat transport, required to maintain the equable climates, can be realized.

Of course, this is not to say that the contributions from oceanic heat transport can be
ignored. The point is that shortcomings in the above equilibration theories should not
prevent us from searching for other atmospheric processes that can contribute to the
maintenance of an equable climate. Such a theory is needed because oceanic heat transport
alone cannot explain the high-latitude continental winters of above-freezing temperatures
of the Cretaceous and early Cenozoic. In fact, the hemisphere-wide Hadley cell (Farrell
1990), whose sinking branch occurs in the Arctic, can warm high-latitude continental interior.
However, this theory requires a tropopause height of ~ 30 km, 2-3 times that of the present-day value. In this essay, we present another plausible theory for equable climates which involves a circulation that is more similar to that of the present-day climate.

b. Criteria for an alternative mechanism

Is there an alternative mechanism that (1) can help explain equable climates, but (2) does not require a radically different atmospheric state, (3) does not involve either the flux-gradient relationship or baroclinic adjustment, and possibly (4) accounts for the apparent universal relationship? As was mentioned earlier, given the fact that only a small fraction of the ZAPE is being tapped, processes that can tap the remaining vast storage of ZAPE may potentially satisfy all of the four conditions. Is there such a process?

A hint can be seen from present-day stationary waves. During the boreal winter, poleward of ~40°N, the poleward transport of moist static energy is dominated by its stationary wave contribution (Oort and Peixoto 1992). This can be accounted for by linear wave theory: vertically propagating Rossby waves, as signified by upward and westward tilt in the pressure (or geopotential) field, transport heat poleward. According to the linear theory of Charney and Drazin (1961), vertical wave propagation is possible for waves with large horizontal scales embedded in a weak westerly wind. The NH winter circulation is in fact most favorable to this vertical propagation.

Stationary waves are forced by both orography and heating, although these two forcings are not independent of each other. For example, orographic forcing is dependent on pressure difference across the orography, and the pressure field may be influenced by a
heat-induced circulation. Likewise an orographically-forced circulation can influence heating by affecting air temperatures over the ocean, hence the ensuing convection and convective heating. Since these `forced tapings’ of ZAPE are independent of baroclinity and instability, this mechanism satisfies the condition (3).

Stationary waves are not the only agent of a forced tapping. For instance, the 30-60 day tropical convective system, known as Madden-Julian Oscillation (MJO; Madden and Julian 1971, 1972), can excite poleward propagating Rossby waves (Matthews et al. 2004). Sardeshmukh and Hoskins (1986) showed that waves excited by tropical convective heating can escape into the extratropics through a subtropical Rossby wave source. In the NH, this subtropical Rossby wave source is located over southeast Asia and the adjacent western subtropical Pacific Ocean where the convective divergent flow from the Indo-western Pacific warm pool (simply `warm pool’ hereafter) interacts with the tight absolute vorticity gradient associated with the subtropical jet. The wave that emanates from the Rossby wave source can propagate poleward until it encounters a turning latitude. The larger the zonal scale of the wave, the farther it can propagate into high latitudes (Hoskins and Karoly 1981).

Therefore, when MJO convection is over the warm pool region, the Rossby wave excited by this MJO heating constructively interferes with the stationary wave forced by climatological warm pool convection (Garfinkel et al. 2010; 2012). This constructive interference can strengthen the forced tapping, hence enhance poleward heat transport. Thus, stationary or non-stationary, large horizontal scale (zonal wave numbers 1 or 2) tropical convective heating can tap ZAPE. This possibility is depicted in Fig. 5a. (Figure 5a also shows the transient baroclinic eddy heat flux. This will be discussed in Section 3.)
The forced tapping of ZAPE can also arise from an eddy momentum flux which is strongest in the upper troposphere. Since the potential vorticity gradient is positive in the upper troposphere, in the latitude of the wave source, or wave stirring, there is eastward acceleration by an eddy momentum flux convergence. Likewise, in the latitude of a wave sink or wave dissipation, there is a westward acceleration by an eddy momentum flux divergence. Thus, in the stirring (dissipation) region, the vertical shear of zonal wind increases (decreases). To maintain thermal wind balance, the meridional temperature gradient must increase (decrease) across the stirring (dissipation) region. Thus, poleward (equatorward) of the dissipation region, there must be a sinking (rising) motion so as to bring adiabatic warming (cooling). In the atmosphere, the Hadley cell is driven in part by wave dissipation in the subtropics (Pfeffer 1982; Kim and Lee 2002; Walker and Schneider 2006); by the same token, in midlatitudes where most of the stirring occurs (due to baroclinic eddies), there is the thermally indirect Ferrel cell.

In the same way, if a forced wave, say, excited by tropical convective heating, manages to propagate into the extratropics and dissipates in mid-to-high latitudes, there should be adiabatic warming poleward of these latitudes. Figure 5b illustrates this possibility: A tropical convective heat source excites a Rossby wave, and as this Rossby wave propagates poleward, westerly momentum is transferred into the wave source region (indicated by the symbol, ⊙, in Fig. 5b). If this momentum flux convergence is sufficiently strong, the equatorial wind becomes westerly, i.e., the circulation evolves into a superrotating state. If the angular momentum of the atmosphere is to be conserved, the eastward acceleration in the tropics must be balanced by a westward acceleration elsewhere.
From the arguments presented above, this westward acceleration will take place in the region of wave dissipation. This region is indicated by the symbol, $\otimes$, in Fig. 5b. As mentioned above, thermal wind adjustment requires that this momentum sink produce downward motion on its poleward side. The downward motion compresses the air and warms it adiabatically. Therefore, if this downward motion occurs in polar regions, a localized tropical heat source can warm high latitudes. In the atmosphere, such a localized heat source can be found over the warm pool. If this process were to intensify as the climate warms, then the Rossby wave response could be an important contributor toward polar amplification. Thus, if this tropical stirring mechanism is responsible for polar amplification, one can expect that the resulting equable climate must be accompanied by an equatorial upper tropospheric wind which is less easterly or even superrotating.

Indeed, one of the most spectacular examples of such a forced wave effect can be found in a modeling study of equatorial superrotation. With an idealized two-layer GCM, Saravanan (1993) examined the transition from a ‘normal’ state to a superrotating state by subjecting the model atmosphere to zonal-wavenumber-two heating on the equator. The transition takes place as the heat source is gradually strengthened. Because the zonal mean of the heat source is zero, the zonal mean ‘radiative equilibrium’ temperature field is identical between the normal and superrotating states. In spite of their identical radiative equilibrium temperature field, Fig. 1e of Saravanan (1993) shows that the midlatitude eddy heat flux of the superrotating state is only about half that of the normal state. Although not discussed in that study, according to the flux-gradient relationship, this implies that the meridional temperature gradient of the superrotating state should be weaker than that of
the normal state. This, in turn, implies that there must be a process, other than the eddy heat flux, that warms high latitudes and/or cools the tropics in that model. Because there is no ocean in the model, the high-latitude warming must take place through an atmospheric process, most likely through adiabatic warming. Although this result is from a highly idealized model, it nevertheless alludes to the possibility that an increase in strength and a localization of tropical convection may contribute toward polar amplification.

Now turning our attention to condition (4), if these forced tapping processes were to explain the universal relationship between the global mean temperature and the meridional temperature gradient, there must be a process where localized warming (cooling) promotes (hinders) the forced tapping. Given the theoretical expectation that an enhanced large-scale, localized tropical convection (acting as wave stirring) can cause winter Arctic warming, if GHG warming can intensify the existing zonally localized convection (currently the strongest convection occurs over the warm pool), then condition (4) can be satisfied. In other words, if the GHG warming intensifies the existing east-west gradient in tropical convection, according to the theory presented here, poleward heat transport will intensify, hence the Arctic will warm more than the tropics. Here, the zonal localization is emphasized because the zonally symmetric part of the tropical heating does not excite the forced waves.

c. Does the west-east gradient in the tropical convection increase with warming?

In the current climate, it is uncertain whether or not the zonal asymmetry in convective heating over the tropical Pacific would intensify in a warming world. In fact, this has been a subject of debate in the climate science community in the context of the Walker
Circulation which is characterized by rising motion over the warm pool region and sinking motion over the eastern tropical Pacific. Most climate model simulations of the twentieth century show a weakened Walker circulation (Vecchi et al. 2006; Vecchi and Soden 2007), and this model response has been attributed to GHG warming (Held and Soden 2006).

However, the opposite trend has been found in satellite data analysis (Sohn and Park 2010), and also in reanalysis, reconstruction, and in-situ measurements (L’Heureux et al. 2013). Since a trend toward rising (sinking) motion coincides with increased (decreased) SST and active (inactive) convection, the Walker Circulation trend has often been equated with trends in SST trend and/or convective precipitation. However, this is not necessarily the case.

The experiment by Clement et al. (1997) shows that when their model’s SST is uniformly raised, while keeping the trade wind (the surface branch of the Walker circulation) speed constant, the model responds by increasing the east-west SST contrast, producing a La-Niña-like SST field. Similarly, based on the thermodynamic energy balance in the tropics, one can expect that the Walker circulation may weaken while the east-west contrast in convective heating increases; this is possible if the fractional increase in static stability is greater than that of the convective heating.

In paleoclimate studies, there is emerging evidence that during times when the climate was warm (cold), the tropical SST took on a La-Nina-like (El-Nino-like) spatial structure. Stott et al. (2002) analyzed seawater temperature and salinity reconstruction data for the late Pleistocene, and found that during interstadials (periods of warm high latitudes) the tropical Pacific warm pool was fresher, implying enhanced convection, while the stadials (periods of cold high latitudes) coincide with a saltier warm pool, suggestive of suppressed convection.
This finding is at odds with the conclusions of an earlier study by Lea et al. (2000), but Stott et al. (2002) pointed out that the site used by Lea et al. (2000) may be too far to the east to be considered as representative of the western warm pool. The association of a warm (cold) climate with La-Niña-like (El-Niño-like) conditions is reported in other studies such as Koutavas et al. (2002) who showed that the LGM coincided with El-Niño-like conditions in the tropical Pacific, and Visser et al. (2003) who found that warm pool SST increased by 3.5-4.0°C during the last two glacial to interglacial transitions.

3. TESTING OF THE FORCED TAPPING MECHANISM

The forced tapping mechanism was tested with a GCM experiment (Lee et al. 2011a) in the context of the equable climate of the Mesozoic and Cenozoic when high-latitude continental winters are believed to have undergone above-freezing temperatures (Huber 2008; Spicer et al. 2008). In a series of model runs, a localized heat source was prescribed in the western corner of the tropical Pacific ocean (see the red box in Fig. 6a) where warm pool convection was postulated to have existed by the authors; elsewhere in the tropics, the same amount of heating is subtracted (see the blue box in Fig. 6a) so that the zonal mean net heating in the tropics is zero. Figure 6a shows the difference in January surface temperature between a run with 150 W/m² contrast (between the red and blue regions) and a run with no heating contrast. Although the zonal mean diabatic heating is identical between the two runs, the run with the tropical heat perturbation produces Arctic temperatures that are as large as 16°C warmer. Figure 6b shows evidence of poleward

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2 The Mesozoic and Cenozoic range from about 145 to 50 million years ago.
propagating Rossby wave trains emanating from the heating region in the tropics, supporting
the hypothesis that large-scale, localized tropical heating can warm the winter Arctic by
exciting poleward propagating Rossby waves.

As the tropical heat perturbation intensifies, the Arctic surface air temperature
exhibits a marked increase (Fig. 7b), yet the temperature in the equatorial region (Fig. 7a)
remains close to being constant. This behavior is reminiscent of the ‘universal’ relationship
depicted in Figure 1. It is unknown whether there was a warm pool during the Mesozoic and
Cenozoic, nor how strong was the convective heating. However, this proof-of-concept
calculation shows that stirring of the tropical atmosphere (by way of a heat perturbation)
can produce cold season polar amplification with a muted equatorial temperature change.

Does this polar amplification occur as was theorized in Section 2b? Lee et al. (2011b)
found that between 40°N and 60°N, the warming is due to the stationary eddy heat flux (the
prescribed tropical heating is stationary); between 60°N and 80°N the warming is by the
transient eddy heat flux (see Fig. 5a; since the imposed heat perturbation is stationary, the
transient eddy heat flux should be regarded as a response to the stationary eddy heat flux),
and between 70°N and 80°N, it is caused by adiabatic warming driven by stationary wave
momentum flux. It turned out that poleward of 80°N, the warming is caused by downward
infrared radiation (IR) associated with increased cloud cover. Because the ultimate driver of
these responses is the stationary tropical heat perturbation, the logical conclusion is that
dynamical processes - meridional heat flux and adiabatic warming - first warms the Arctic
Ocean, and the transport of water vapor and cloud liquid water (by the tropically forced
Rossby wave, and perhaps by the transient eddies that respond to the heat flux convergence
by the forced wave) into the Arctic leads to further warming through enhanced downward IR; once it encounters the cold Arctic air, because of the low saturation vapor pressure, the water vapor condenses (latent heat release) to form clouds, and as cloud cover increases, radiative forcing by the clouds can take over the warming. This final step in the process is sketched in Fig. 5c. This physical process is found to contribute to the present-day warming trend in the Arctic winter, and this is consistent with the La-Niña-like trend of intensified tropical convection over the warm pool region. Lee et al. (2011b) found with global European Center for Medium-Range Weather Forecasts reanalysis data (ERA-40) that winter Arctic warming between 1958-2001 is contributed by increases in the frequency of occurrence of a few teleconnection patterns; these patterns grow and decay at intra-seasonal time scales where the growth of aggregation of these patterns is preceded by enhanced warm pool convection and the decay is followed by downward IR over the Arctic Ocean. Poleward eddy heat flux and adiabatic warming also contribute to the Arctic warming trend. Because it takes 7-10 days for a Rossby wave to propagate from the tropics to high latitudes (Hoskins and Karoly 1981), the mechanism described here, if it is relevant, should be operating on intraseasonal time scales. This is found to be the case in Lee et al. (2011b).

The connection between localized tropical convection and Arctic warming at intraseasonal time scales is highlighted by the findings of Yoo et al. (2011). Using ERA-Interim data, they showed that when the MJO convection enhances (suppresses) the warm pool convection, Arctic warming (cooling) follows. Here, it was again found that the positive warm pool convection anomaly is followed by dynamic warming, then by moisture transport
into the Arctic, and an increase in downward IR (Yoo et al. 2012a). The implied causal relationship between the convection and the Arctic warming was supported by model calculations (Yoo et al. 2012b). This warm pool convection-Arctic warming linkage is also present at interannual time scales, since La-Niña (El-Niño) years are accompanied by enhanced (suppressed) poleward moist energy flux in the extratropics and warmer (cooler) Arctic (Lee 2012). To emphasize the linkage between the tropical convection and Arctic warming, Lee (2012) named this forced tapping process as the Tropically Excited Arctic warming (TEAM) mechanism.

4. MORE ON POLEWARD HEAT FLUX AND DOWNWARD IR

Without invoking the TEAM mechanism, some recent studies have questioned the importance of the ice-albedo feedback, and have instead stated that a poleward atmospheric heat (or moist static energy) transport may be the key process behind the Arctic amplification (Alexeev 2005; Lu and Cai 2010; Graversen 2007; Graversen and Wang 2009).

Held and Soden (2006) showed that the fourth IPCC assessment report (AR4) models, under Special Report on Emissions Scenarios (SRES) A1B forcing scenario, produce an increase in the poleward atmospheric heat flux, while the changes in the oceanic heat transport are negligible. Consistent with this increase in poleward heat flux, Wu et al. (2010) and Zelinka

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3 The Pacific Decadal Oscillation (PDO) may be regarded as another phenomenon which can be used to test the TEAM mechanism since the associated SST pattern shares a resemblance with that of El Nino. However, care needs to be taken in doing so because it is the tropical convection pattern that matters in the TEAM mechanism; during the positive phase of the PDO (El-Nino-like SST) which started in late 1970s, the hydrographic salinity record indicates a continued freshening in the western warm pool region (Durack and Wijffels 2010), suggesting that there has been a La-Nina-like trend in convective precipitation.
and Hartmann (2012) showed that the equator-to-pole gradient in the TOA net radiation strengthens in response to GHG-driven warming. Analyzing the time mean states of the models, both studies found that the increase in the TOA radiation gradient is caused by water vapor and cloud feedbacks.

Wu et al. (2010) interpreted that these feedback processes increase the baroclinicity, and that the transient eddies respond to this increase in baroclinicity. However, their Fig. 5 shows that the match between baroclinicity and the poleward eddy flux is poor: the increase in baroclinicity occurs mostly in the upper troposphere, yet the increase in eddy heat flux is largest in the lower troposphere. Recognizing this discrepancy, they suggested that eddies are influenced by the upper tropospheric baroclinicity. Even though the mechanism that drives this process remains unclear, it appears that this view, that an increase in the poleward eddy heat transport is a response to a strengthening of the equator-to-pole gradient in the TOA net radiation, or upper tropospheric baroclinity, is shared by others (Lu and Cai 2010; Zelinka and Hartmann 2012).

The prevalence of this view is understandable, given the importance of baroclinic instability and the flux-gradient relationship in our understanding of the atmospheric circulation. However, it is not feasible to tease apart causal relationships from time mean states. Instead of the causality proposed by the above studies, it is also possible that a strengthening of the poleward energy flux, for instance, driven by tropical stirring (through localized convection), i.e., the TEAM mechanism, causes the TOA net radiation gradient to increase. If one were to diagnose the two model runs in Lee et al. (2011a), without
knowledge of how the model was perturbed, one may conclude that the clouds, by
influencing the TOA net radiation gradient, caused the energy transport to strengthen.
The AR4 model studies also found that downward IR, caused by increased moisture
and cloud cover, plays an important role for warming the Arctic (e.g., Winton 2006). Two
different processes can contribute to this increase in downward IR: a local moisture
feedback process (Abbot et al. 2009) and remote process which invokes moisture transport
from outside of the Arctic. The increase in poleward latent heat flux in the AR4 models (Held
and Soden 2006; Wu et al. 2010) suggests that the remote process plays an important role
for enhancing the downward IR.

5. SUMMARY, CAVEATS AND FURTHER QUESTIONS

From the perspective of the atmospheric general circulation, this article advances a
conjecture that an equable climate, which is characterized by a weak meridional
temperature gradient, can be realized if the vast storage of zonal available potential energy
(ZAPE) can be tapped with a forcing which relies on neither baroclinic instability nor the flux-
gradient relationship. Under usual circumstances, localized tropical convection is perhaps
the most viable candidate for such a forcing. From this perspective, a theory, referred to as
the TEAM (Tropically Excited Arctic warMing) mechanism, has been put forward (Lee 2011a,
b; Yoo et al. 2011, 2012a, b; Lee 2012) where the main thesis is that an enhancement in the
warm pool tropical convection strengthens and/or more frequently excites poleward
propagating Rossby waves, and that the wave dynamics and subsequent increase in
downward infrared radiation lead to warming over the Arctic.
This general-circulation based theory can help explain: (1) an enhanced poleward heat transport, conforming to the TOA energy balance; (2) that Arctic warming occurs during the winter when solar radiation does not reach the Arctic; (3) the paleo-equable climate warmth in the high-latitude continental interior; (4) the apparent universal relationship between global-mean temperature and the meridional temperature gradient; (5) the apparent invariance of equatorial temperature in the widely varying climatic conditions (Fig. 1); (6) the tendency of models to produce equatorial superrotation when the model climate is warmed (Lee 1999; Huang et al. 2001; Cabarello and Huber 2010).

Regarding (2), the leading theory has been that the ice-albedo feedback process (Budyko 1969) warms the Arctic Ocean during the warm season and then release the heat during the following winter (Serreze and Barry 2011). Figure 8a is adopted from Stroeve et al. (2011), and shows a schematic description of the ice-albedo feedback process in more detail. In this framework, the GHG-driven warmer air thins the spring sea ice and melts the summer sea ice, with latter process being amplified by ice-albedo feedback. The warmer ocean then releases the stored heat in the following fall and winter, a process which hinders sea ice formation and thickening. However, recent studies have raised questions on this picture: Over regions covered by sea ice, the surface during the cold season is actually warmed by a heat flux from the atmosphere (Graversen and Wang 2009; Lee et al. 2011a); Park et al. (2013) and Flourney et al. (2013) found that during winter and early spring, positive downward IR anomalies over the Arctic are preceded by anomalously strong warm pool convection, and followed by a statistically significant reduction in Arctic sea ice; Persson (2012) analyzed measurements from the Surface Heat Flux of the Arctic Ocean (SHEBA)
experiment and found that melt onset is preceded by springtime free-tropospheric warming, and is punctuated by atmospheric synoptic events.

The autocorrelation of Arctic sea ice further suggests that winter processes such as the TEAM mechanism may play more active role than was previously thought. Figure 9 shows that the April sea-ice area (its lag correlations are highlighted by the first vertical line in Fig. 9) is uncorrelated with the previous melting season (May-September), but is correlated with the previous cold season (November – March). The April sea-ice area is also correlated with the sea-ice area for much of the following year, until the month of March. In contrast, the September sea-ice area (highlighted by the second vertical line in Fig. 9) is significantly correlated with all of the previous months’ sea-ice area, but for those months with positive lags, statistically significant correlations are found only until the following March. One possible explanation for these lag correlations is that winter climate conditions may be more important than summer conditions. In fact, Persson (2012) reports for a synoptic weather event that during the SHEBA experiment the ice-albedo feedback effect was much weaker than warming by downward IR. Graversen and Wang (2009) also found in their model experiment that the ice-albedo effect is weaker than the downward IR effect. They pointed out that this is consistent with the fact that the Arctic is covered by clouds most of the time (Wang and Key 2005). Therefore, contrary to the view that summer season warming is the main driver, it is possible that the winter warming, perhaps driven by the TEAM mechanism, may act as the main player by its hindering of the formation of sea ice, and thus by promoting summer sea ice melting. This possibility is presented schematically in Fig. 8b.
Point (4) above also needs further discussion. As indicated by Miller et al. (2010), the apparent universal relationship (Figs. 1 and 2) may be misleading since the forcing mechanisms vary among the different time periods. On the other hand, there is emerging evidence that La-Nina-like conditions prevailed during warm periods such as Pliocene (Rickaby and Halloran 2005), interglacial periods (Visser et al. 2003), and interstadials during late Pleistocene (Stott et al. 2002); whereas El-Nino-like conditions were present during cold periods such as stadials (Stott et al. 2002), glacial periods (Visser et al. 2003), and LGM (Koutavas et al. 2002). Therefore, it is possible that the Arctic amplification, whether it is ultimately caused by GHG or by orbital forcing (e.g., HTM and LGM were forced by variations in orbital parameters), may be realized through the influence of these forcings on tropical convection.

There are also caveats to the TEAM mechanism. Although the premise of the theory hinges on the forced tapping of ZAPE by dynamical warming, it turns out that the tropical warm pool convection also causes downward IR to increase over the Arctic, and this process appears to have an even greater impact on the Arctic surface temperature than does the dynamic warming (Lee et al. 2011a,b; Yoo et al. 2012b). Hence, for the TEAM mechanism to be effective, moisture transport into the Arctic (and subsequent condensation into cloud liquid water droplets) is critical. Since the moisture content is higher in warm air than in cold air, it is to be expected that poleward sensible heat flux caused by the forced tapping would be also accompanied by an enhanced moisture flux. Nevertheless, this downward IR is not part of the untapped ZAPE in the sense of Lorenz (1955), although it is in the sense of available energy formulated by Bannon (2012).
Secondly, it is unclear whether dynamic warming can occur over the Arctic under different climatic conditions. Adiabatic warming is an element of the TEAM mechanism, but the location of the downward motion (thus the adiabatic warming) depends on where the westward acceleration occurs (the location indicated by ⊗ in Fig. 5b), and also on the horizontal scale of the overturning circulation which depends on Rossby radius of deformation. Therefore, there is no guarantee that the downward motion would occur over polar regions under a different basic state or during a different time period. Similarly, even though poleward propagating waves can also transport heat poleward, since the poleward heat flux can occur only if waves can propagate upward and poleward, and since this in turn depends on the background state (meridional and vertical refractive indices for Rossby waves are dependent on the background state), it is uncertain whether eddy heat flux convergence, driven by tropical convection, would occur under a different basic state and time period.

Thirdly, the TOA energy balance of equable climates warrants further discussion. One premise of the TEAM mechanism is that an equable climate arises in part from a greater Rossby-wave-driven poleward water vapor and cloud liquid water transport which leads to an increase in cloudiness and thus a larger outgoing IR in polar regions. The resulting increase in the meridional gradient of the TOA net radiative flux by these waves requires that there be a stronger poleward energy transport. However, this may not be the case if the Arctic is covered by optically thick, tall clouds, similar to the convective clouds in the tropics. In this case, the cloud tops may be sufficiently cold that the TOA radiative deficit over the Arctic may be small enough for the meridional gradient in the TOA radiative flux to
be greater than that of a colder climate. It could be that in the initial stage of warming, Arctic amplification occurs through an enhanced poleward energy flux, such as the TEAM mechanism, and that as the warming continues and sea ice melts away, convection may ensue as shown by Abbot et al. (2009).

In closing, we reiterate that the TEAM theory is incomplete, but that progress can be made in the topic of polar amplification and equable climates by going back to basics and considering the general circulation. Theoretical pursuit of the polar amplification problem also points to the need for a more accurate understanding and better simulation of tropical convection in climate models. The current level of understanding is apparently inadequate (Stevens and Bony 2013). The following quote by Visser et al. (2003) from a paleoclimate perspective underscores the need to further develop such a general-circulation based theory: “A new view of the importance of the tropics in controlling global climate change is beginning to emerge, although the nature of the linkage between tropical and extra-tropical regions still needs to be resolved.”

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Figure 1: (a) Zonal-mean surface temperature deviations ($\Delta T$) from the present-day climate divided by $<\Delta T>$, where $<$ denotes a global average. The solid line is a least-squares fit to the data displayed for a fourth-order polynomial in the sine of latitude; $NT(x) = \Delta T(x)/<\Delta T> = 0.36+3.21x^4$, where $x = \sin(\text{latitude})$. (b) $\Delta T$ for the mid-Cretaceous maximum warming and LGM cooling. Points are derived from paleodata and lines indicate the best-fit $NT(x)$ shown in (a) multiplied by the corresponding $<\Delta T>$. [From Hoffert, M. I., and C. Covey, 1992].
Figure 2: Paleo data estimates of Arctic summer surface temperature deviations from the present-day values (ordinate), their NH or global mean values (abscissa), and their uncertainties. The time periods shown are: the last Glacial Maximum (LGM), Holocene Thermal Maximum (HTM), Last Interglaciation (LIG), and middle Pliocene (MP). [From Miller et al., (2010)]
Figure 3: Time series of the seven-year running mean of the anomalous zonally averaged surface temperature (°C). [From Bekryaev et al., 2010].
Figure 4: Schematic diagram of top of the atmosphere (TOA) net radiation and poleward energy flux. According to Fig. 1, under equable climates, warming is much greater in high latitudes. This implies that the increase in outgoing long wave radiation (OLR) is greater in the high latitudes, hence strengthening the equator-to-pole gradient in TOA net radiation. This implies that the poleward energy flux must be stronger under equable climates. Note that this balance between the TOA radiation gradient and the poleward energy flux, on its own, cannot be used to infer a causal relationship.
(2) eastward acceleration at the wave source; if strong enough, generates equatorial superrotation

(4) Storm track eddies may respond, and transport heat farther poleward

(3) Poleward and upward propagating waves transport heat poleward

(5) Partial wave absorption serves as a wave sink, causing westward acceleration

(6) Thermal wind balance requires adiabatic warming (sinking motion) poleward of the wave sink
Figure 5: Schematic diagram of the TEAM mechanism. The storm track eddy response in step (4) and the cloud cover increase in step (8) are found to accompany the forced tapping (of ZAPE) mechanism (Lee et al. 2011a). Step (7) is shown by Yoo et al. (2012a, 2012b), and (8) by Yoo et al. (2012b). It is worth noting that the equatorial superrotation can be a byproduct of the TEAM mechanism.
Figure 6: January difference in (a) surface temperature and (b) 250-hPa geopotential height and wind fields between a run with 150 W/m² contrast (between the red and blue regions) and a run with no heating contrast. The model is a coupled atmosphere-mixed-layer ocean GCM. The CO₂ level in this model is 4 × PAL (Preindustrial Atmospheric Level, 1 PAL = 280 ppmv). [Adopted from Lee et al. 2011a.]
Figure 7: January zonal mean surface air temperature simulated by a coupled atmosphere-mixed-layer ocean GCM. In the legend, the values indicate the imposed heating difference between the red and blue boxes (W/m$^2$) shown in Figure 6a.

[Adopted from Lee et al. 2011a.]
Figure 8: (a) Adopted from Stroeve et al. (2011), and shown here to be compared with (b). (b)
Supported by the sea-ice-area autocorrelation shown in Fig. 9, the physical processes
described by the TEAM mechanism suggest that winter Arctic conditions may influence
summer Arctic sea ice. The question marks indicate that the causal relationship may not be
as solid as previously suggested (e.g., by Stroeve et al. 2011) for the present warming. These
processes may become more important as sea ice continues to melt.
Figure 9: Lagged autocorrelation of monthly mean Arctic sea-ice area from 1979-2010. The data is from National Snow and Ice Data Center. The abscissa is the reference month and the ordinate is the corresponding lag month. For instance, (4,-7) is for correlation between April and the previous September sea-ice area. Except for the dotted area, all values are statistically significant (p < 0.05). To aid visualization, the abscissa shows double of the twelve-month period.