Energetics of Indian winter monsoon

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The Indian subcontinent is characterized by complex topography and heterogeneous land use-land cover. The Himalayas and the Tibetan Plateau are spread across the northern part of the continent. Due to its highly variable topography, understanding of the prevailing synoptic weather systems is complex over the region. The present study analyzes the energetics of Indian winter monsoon (IWM) over the Indian subcontinent using outputs of mesoscale model (MM5) forced with National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), US, initial and boundary conditions. MM5 modeling framework, designed to simulate or predict mesoscale atmospheric circulations, is having a limited-area, non-hydrostatic and terrain following 12 sigma levels. The IWM energetics is studied using MM5 model outputs. Prior to this model's validity and deviation from the corresponding observations (NCEP/NCAR) is assessed. The model's overestimation/underestimation of wind, temperature and specific humidity at upper troposphere proves that the model has difficulty in picking up corresponding fields at all the model grid points because of terrain complexity over the Himalayas and Tibetan Plateau. Hence, the model fields deviate from the corresponding observations. However, model results match well with the winter global energy budget calculated using reanalysis dataset by Peixoto and Oort (1992). It suggests MM5 model's fitness in simulating large scale synoptic weather systems. And, thus the model outputs are used for calculation of energetics associated with IWM. It is observed that beyond 15°N lower as well as upper level convergence of diabatic heating, which represents continental cooling and sinking of heat from atmosphere to land mass (i.e., surface is cooler than surrounding atmosphere) dominates. The diabatic heating divergence (cooling of continents) is found over ocean/sea and whole of the China region, Tibetan and central Himalayas (because of excess condensation than evaporation). The adiabatic generation of kinetic energy depends on the cross isobaric flow (north to south in winter, i.e., the present study shows strong circulation during IWM). It is found that wind divergence of model concludes lower level convergence over study region (i.e., strong winter circulation in the model fields).

Keywords. Indian winter monsoon; topography; budget; mesoscale model; synoptic weather system.

List of abbreviations

K_M	Mean flow kinetic energy	H_1	Horizontal flux of eddy flow
K_T	Eddy flow kinetic energy	ω	Vertical wind
V	Mean Flow of Horizontal Wind (u, v)	ϕ	Geopotential energy
V'	Eddy flow of horizontal wind (u, v)	P	Pressure dimension
H_0	Horizontal flux of mean flow	F	Frictional force
		ζ	Relative vorticity
		β	Rosby number

v'	Eddy flow meridional wind
v	Meridional wind
Z	Dissipation
M	Angular momentum
f	Coriolis factor
a	Radius of Earth
φ	Latitude
λ	Longitude
C_P	Specific heat capacity at constant pressure of atmosphere
T	Temperature
L	Latent heat
q	Specific humidity
α	Specific volume
Q_L	Latent heat loss
Q_H	Heat loss
t	Time
D	Horizontal divergence

1. Introduction

The Indian winter monsoon (IWM) generated by the seasonal shifting results in changes in atmospheric energy budget. The atmospheric energy budget is studied in the form of energetics, i.e., study of energy transfers and transformations from one form to another. The study of energetics of changing weather phenomena at short time scale is less studied. Most of these studies are reported either at annual or less than 10 years' scale (Kung and Chan 1981; Ding and Krishnamurti 1987; Mohanty and Ramesh 1994; Ramesh *et al.* 1999; Rao 2001). The IWM is governed by north westerlies as well as northeasterlies wind circulation (Wu and Wang 2002; Chen *et al.* 2005), ocean–continent temperature difference and pressure gradient. The perturbation of IWM over north Indian region is controlled by north westerlies at lower troposphere and subtropical westerly jet stream at upper troposphere (Dimri and Mohanty 2009). This jet stream shifts north to south during summer to winter and dampens over the Tibetan high because of ridge during winter (Yin 1949; Chen *et al.* 2005). Also the speed of subtropical westerly jet stream reduces from 120 to 70 m/s at 300 hPa because of the Himalayas and Tibetan Plateau (Krishnamurti 1961) (i.e., because of high pressure surge). The Himalayan orography introduces complexity in understanding the circulation associated with IWM. The presence of Himalayas and Tibetan Plateau introduces obstacle for meridional as well as zonal flows (i.e., delineation of circulation).

The study of regional energetics of IWM is necessary for understanding the formation and dissipation of kinetic energy, vorticity, angular momentum, heat and moisture. Previous studies reveal that the East Asian winter monsoon dominates strong northwesterlies and controlled by durable Siberian high as well as strong Aleutian Low in the east of it (Wu and Wang 2002). It is also reported that the East Asian winter circulation is controlled by northerly wind and pressure surges (Compo *et al.* 1999). The IWM circulation over the Indian subcontinent region and its adjacent ocean/sea lying between 10°S–50°N latitude and 30°–120°E longitude is triggered by divergence of moisture in lower troposphere and convergence in upper troposphere (Dimri 2007). Comparative heating of the ocean and cooling of Tibetan or Siberia, due to rapid radiative cooling (dry and dense air over the cold continent vicinity, i.e., Tibetan and Siberian high), is the source region for the heat budget of the IWM over the Indian subcontinent (Ding and Krishnamurti 1987; Ramesh *et al.* 1999). In the atmosphere, amount of kinetic energy is small, but matters. Whole part of potential energy can never be converted into kinetic energy, thus the remaining part of potential energy as eddy flow or turbulence is called available potential energy (Kang and Fringer 2010) (i.e., a source of different kinematics in the atmosphere). This available potential energy explains about rising/sinking motion as well as rotation of air mass (vorticity and circulation). The balance of advection of relative and planetary vorticity reveals the vorticity budget (Peixoto and Oort 1974). The study of Asian summer monsoon energetics explained by Rao (2001) and of winter monsoon focused on the Himalayan region by Dimri (2007), reveals uplifting motions and kinetic energy convergence in the tropics. Both the authors used National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis database for their studies. However, the study of IWM energetics using dynamical model outputs is still unreported and needs to be discussed. It will help in assessing future state of energetics, if results are found within uncertainty limits (though not discussed here). Thus, in this study, comprehensive discussion on energetics of IWM circulation in terms of kinetic energy, vorticity, angular momentum, heat and moisture budget of seasonal mean is provided using model outputs.

The objective of the present study is to report and address the mesoscale modeling framework

version-3 (MM5) model compatibility for the energetics of IWM circulation, thus, to introduce the MM5 model data application for energetics of IWM over the Indian subcontinent. This model is chosen as other models, including Weather Research and Forecasting (WRF) model (Rögnvaldsson *et al.* 2011). There is long-term data available in Coordinated Regional Climate Downscaling Experiment (CORDEX) simulations, but again not available at each pressure levels and only few of the variables are available at 850, 500 and 200 hPa. It would be of help to use model data for further study of atmospheric energy budget with the corresponding observations and its dynamics and hence MM5 model is considered.

Thus the objectives of the study are:

1. To briefly discuss the validity and fitness of the model (MM5) for the study of IWM dynamics and energetics.
2. To comprehensively discuss the IWM energetics using MM5 model outputs.

In the following paragraphs, section 2 gives a brief description of the model and datasets used. Section 3 gives the results and discussion of model based energetics. Section 4 provides conclusion of the study.

2. Data and model details

2.1 Data used

For model validation, a comparative study with observational data is performed. NCEP/NCAR 2004–2007 daily, seasonal (DJF) reanalysis data is used for model initial and boundary conditions. The different model outputs (temperature, wind climatology at different altitudes) with corresponding observations are validated. For better representation of topography (figure 1) GTOPO30 data having resolution of 30'' (~1 km) of United State Geological Survey (USGS) is used.

2.2 Model details

The IWM circulation over the Indian subcontinent is analyzed using mesoscale model-fifth generation version three (MM5) forced with large-scale field from NCEP/NCAR (Kalnay *et al.* 1996). It is designed to simulate mesoscale atmospheric circulation, having a limited-area, non-hydrostatic and terrain-following sigma-coordinates developed at

Figure 1. Topography (m) over study region (10°S–50°N, 30°E–120°E).

the Pennsylvania State University/National Center for Atmospheric Research, US (PSU/NCAR) (Michalakes *et al.* 1998; Dimri and Mohanty 2009). It will serve as a good tool for providing data at finer scale for atmospheric dynamical information. In this model pressure perturbations and temperatures are used as prognostic variables (Dudhia 1993; Chen and Dudhia 2001). For the comprehension four years (2004–2007) seasonal (December, January, February – DJF) daily MM5 outputs are used for the energetics of IWM circulation over Indian subcontinent. Since this work does not focus on modeling framework, model simulation and corresponding validation is discussed in very brief.

2.3 Energetics model description

The equations of budget used are derived from the conservation laws of mass, momentum, heat and the equations of motion. The budget equation is composite of mean part and eddy part. In the mean part, the zonal averaged atmospheric circulation consisting of interaction of longitudinally averaged flow or time averaged atmospheric circulation remains constant or changes very slowly with time. In eddy part, however, this circulation changes very rapidly over a time period (Peixoto and Oort 1992). The most of eddy flow occurs over extratropical region and most of the mean flow over the tropical region (Rao 2001), hence the IWM circulation is predominantly controlled by

the mean part. The atmospheric energetics budget equations are denoted in the flux form and vertical pressure coordinate system (λ, φ, p, t) . For detailed derivation of budget equations and their explanation reader can refer to Peixoto and Oort (1992), Rao (2001) and Dimri (2007). In brief, following discussion is provided.

The expression of kinetic energy budget equation is given as:

$$\begin{aligned} \frac{\partial \overline{K_M}}{\partial t} + \nabla \cdot (H_0 + H_1) + \frac{\partial}{\partial P} (K_M + \bar{V} \cdot V') \omega \\ = -\bar{V} \cdot \nabla \Phi - C(K_M, K_T) + \bar{V} \cdot \bar{F} \end{aligned} \quad (1)$$

where kinetic energy of mean flow, $K_M = \frac{1}{2} \bar{V}^2$, kinetic energy of eddy flow, $K_T = \frac{1}{2} V'^2$, horizontal flux of kinetic energy of mean flow, $H_0 = K_M \bar{V}$, horizontal flux of kinetic energy of eddy flow, $H_1 = (\bar{V} \cdot V') V'$ and $C(K_M, K_T) = C_H(K_M, K_T) + C_v(K_M, K_T)$, C_H = horizontal component, and C_v = vertical component.

In equation (1), first term on the left hand side (LHS) represents the local rate of change of kinetic energy, the second and third term represents horizontal and vertical divergence of kinetic energy fluxes, respectively. First term on the right hand side (RHS) represents conversion of available potential energy to kinetic energy, the second and third term represents mutual conversion of K_M and K_T , and frictional dissipation of kinetic energy due to turbulence, respectively.

The expression of vorticity budget equation is

$$\begin{aligned} \frac{\partial \bar{\zeta}}{\partial t} + \nabla \cdot (\bar{\zeta} \bar{V}) + \beta \bar{v} + \frac{\partial}{\partial P} (\bar{\zeta} \bar{\omega}) \\ = -(\bar{\zeta} \bar{D}) - k \cdot \left(\nabla \omega \times \frac{\partial v}{\partial P} \right) + \bar{Z}. \end{aligned} \quad (2)$$

In equation (2), the first term on LHS gives the local rate of change of relative vorticity, the second, third and fourth term represents horizontal flux of relative, planetary and vertical flux of relative vorticity, respectively. The first and second term on RHS represents generation of vorticity due to stretching and tilting respectively; the last term depicts residue of vorticity due to frictional dissipation/generation.

The expression of angular momentum budget equation is given by

$$\begin{aligned} \frac{\partial \bar{M}}{\partial t} + \nabla \cdot (\bar{M} \cdot \bar{V}) + \frac{\partial}{\partial P} (\bar{M} \bar{\omega}) \\ - f \bar{v} a \cos \phi = -\frac{\partial}{\partial \lambda} \Phi + \delta \Phi + \bar{F}_\lambda. \end{aligned} \quad (3)$$

In this equation, the first term on the LHS represents local rate of change of relative angular momentum, the second, third and fourth terms represent horizontal flux of relative angular momentum, vertical flux of relative angular momentum and horizontal flux of Ω angular momentum (solid Earth's rotation part) respectively. The first term on the RHS describes pressure torque (Earth's surface and atmospheric drag), the second and third terms represent mountain torque (pressure gradient opposite to the mountain, east-west) and dissipation of angular momentum due to frictional forces, respectively.

The expression of sensible heat budget equation is

$$\begin{aligned} \frac{\partial (C_P \bar{T})}{\partial t} + \nabla \cdot (C_P \bar{T} \bar{V}) \\ + \frac{\partial}{\partial P} (C_P \bar{\omega} \bar{T}) - \bar{\omega} \bar{\alpha} = Q_H \end{aligned} \quad (4)$$

where the first term on the LHS represents local rate of change of sensible heat, the second, third and fourth terms represent horizontal flux of sensible heat, vertical flux of sensible heat and adiabatic conversion of available potential energy to kinetic energy, respectively. The RHS explains diabatic sensible heat transfer to the atmosphere.

The equation of latent heat budget can be written as:

$$\frac{\partial (L \bar{q})}{\partial t} + \nabla \cdot L \bar{q} \bar{V} + \frac{\partial}{\partial P} (L \bar{\omega} \bar{q}) = Q_L. \quad (5)$$

In equation (5) in LHS the first term delineates the local rate of change of latent heat, the second and third term represents horizontal and vertical latent heat flux. RHS represents diabatic latent heat transfer to the atmosphere (moisture source or sink), i.e., Clausius-Clapeyron part. The latent heat part also explains the moisture content in the atmosphere, Earth's surface and vicinity of ocean/sea. This also conveys the moisture budget in the latent heat budget equation (5).

3. Results and discussion

The comprehensive study of results of IWM energetics over Indian subcontinent are discussed

in the following subsections. Prior to that the validity of the MM5 model fields is explained by assessing model biases of the basic parameters that are used in the calculation of the energetics. The sensitivity of the model is discussed with comparative study of wind and temperature and their respective biases at different pressure level in very brief (as not the focus of the present study).

3.1 Basic fields

The wind bias at 300 hPa shows stronger westerlies in model from 15° to 50°N (figure 2a) (Hanna and Yang 2001; Tinis *et al.* 2006). A core of maxima is noted at and around 35°N over the northern Africa

Figure 2. Wind bias climatology for DJF (December, January and February) during 2004–2007 over the study region; (a) at 300 and (b) at 900 hPa, shaded region corresponds to values >10 m/s, (a) has contour interval of 5 m/s, but (b) has contour interval of 3 m/s.

and west of Asia (i.e., the model has drawback in capturing upper level circulation because of topographic intervention; Colle *et al.* 2003). Because of the Himalayas and Tibetan Plateau, model westerly gets enhanced as model could not pick up all the grid points (figure 1). Similarly, at 900 hPa, model has stronger westerly from 25° to 50°N and stronger easterlies and/or south to southeasterlies from equator to northward (figure 2b). The wind bias shows strengthening of westerlies in upper as well as lower levels (Giorgi and Bates 1989; Hanna and Yang 2001; Dobler and Ahrens 2010). The wind bias is basically controlled by zonal wind part in the model environment, i.e., influencing magnitude as well as direction of the wind. The vertical distribution of zonal wind shows presence of mid latitude westerlies from 25°N to beyond 50°N dominating from lower to upper troposphere (figure 3a) and it shows that in the presence of Himalayas and Tibetan Plateau deviation and damping of westerly is delineated (i.e., presence of topographic complexity in the model environment). A small easterly bias at upper troposphere is clearly delineated (figure 3a). In case of meridional wind (figure 3b), from 25°N to beyond 45°N stronger southerly wind from lower to upper troposphere is seen, while from 10°S to 25°N stronger northerly wind is seen. The meridional wind bias shows maximum deviation due to the Himalayan terrain (i.e., zonal wind splits into two parts, one northerly and another one southerly because of topography). Therefore, from figure 3(a and b), presence of stronger lower tropospheric northeasterlies (equator to 25°N; tropics) and stronger southwesterlies (beyond 25°N; mid-latitude) are seen. The maximum of wind bias is seen at 250 hPa over 40°–45°N corresponding to subtropical westerly jet stream (i.e., influenced by turbulence generated through rough terrain) (Palmer *et al.* 1986; Bacmeister *et al.* 1994; Uchida and Ohya 2003). The vertical velocity (ω) (figure 3c) reveals strong rising motion from 10° to 45°N up to middle troposphere, while from 10°S to 10°N sinking motion in lower troposphere level is seen. This rising motion reveals evaporation over oceanic region, i.e., cumulus convection (Rao 2001). Apart from this, a strong subsidence core is seen at 900 and 500 hPa (figure 3c). The lower level of tropics shows stronger convergence at equator and stronger divergence at 10°S. But beyond 30°N, a stronger divergence is observed at lower level and stronger convergence is seen at upper level. It explains the orographic downwelling. Whole upper troposphere has cascading

Figure 3. Sectorial (over 30°–120°E) mean of pressure-latitude cross section of (a) zonal wind bias, (b) meridional wind bias, (c) omega (vertical wind), and (d) wind divergence for DJF during 2004–2007 over the study region; (a), (c) and (d) have contour interval 5, (b) has contour interval 1 (Unit: (a), (b), (c) and (d) m/s, m/s, 10^{-5} hPa/s and 1/s, respectively) the gray shading in (a), (b), (c) and (d) is longitudinal (over 30°–120°E) averaged topography.

convergence (figure 3d). The strong divergence over 10°S at 500 hPa is followed by strong subsidence in vertical velocity. The rising motion from the equatorial sea descends/sinks over the foothill of Himalayas and moves towards the oceans from the Himalayas at surface level, thus completing the Hadley circulation (i.e., winter circulation) (Chang and Lau 1982). In the model, due to biases, this strengthened circulation dominates. The mean sea level pressure (mslp) is lower (1011 hPa) over ocean and higher over continent (1032 hPa) (figure 4a). This means that it continuously increases from ocean to land (northward) and steeply rises over Tibetan Plateau revealing a pressure surge (figure 4a). The geopotential height at 900 hPa is maximum over the Himalayan region (figure 4b). Due to winter/dry conditions, planetary boundary

layer (PBL) comes closer to the surface; the specific humidity at 500 hPa shows negative bias with maxima over southern Indian Ocean (figure 4c). It reveals that the evaporation from Indian Ocean gets added to the air with rising motions. But the continent has lesser moisture as well as weak transportation. At 900 hPa higher specific humidity from west Himalayas to east Himalayas is seen, figure 4(d). Over west of Indian subcontinent, positive bias is observed. The transportation of moisture depends upon the kinetic energy of air mass (moisture), that is balanced by the kinetic energy budget and heat budget. The temperature bias at 300 hPa shows that the model is colder than the corresponding observation and similar is found at 900 hPa (figure 5a and b) (Lu *et al.* 2011). However, at 900 hPa over east of Asia and at 300 hPa over the

Figure 4. Sea level pressure (SLP), geopotential height and specific humidity bias for DJF during 2004–2007 over the study region; (a) SLP has contour interval of 3 hPa, (b) geopotential height (900 hPa); contour interval of 30 m, (c) specific humidity bias at 500 hPa; contour interval of 0.5 g/kg and (d) specific humidity bias at 900 hPa; contour interval of 1 g/kg.

Russian region warm bias is seen. This delineates that model has colder bias from lower to upper troposphere which is main weakness of the MM5 modeling framework (Horvath2012). However, the advantage of MM5 model is that it has various variables at each pressure levels, which is necessary for energetics computations. While other models, as WRF and others, have not all the variables and not at each levels of the troposphere. The broad kinematics of the IWM seems to be similar in model environment though with some weaknesses.

3.2 Kinetic energy budget

The energetics of IWM is controlled by the kinematics of the air parcel formation or dissipation of kinetic energy and transformation of kinetic energy to available potential energy and vice-versa. The sectorial pressure-latitude cross section (30°–120°E) distribution of horizontal flux of kinetic energy delineates very weak convergence over whole lower troposphere over the study region

and strong convergence at upper troposphere from 10°S to 25°N (figure 6a). This explains weaker horizontal movement of air mass at lower level, but stronger movement at upper level due to presence of the jet stream. The horizontal flux of kinetic energy is dissipated in two forms, i.e., mean and eddy flow. Available potential energy conversion to kinetic energy governs the air mass to rise/sink. The adiabatic generation and destruction of kinetic energy occurs through meridional and zonal motion of air masses. At tropics (lower latitude), the kinetic energy is produced by meridional motion, and is destroyed by zonal motion of air masses (Kung 1971; Rao 2001). The general circulation of atmosphere is controlled by balance between generation and destruction of kinetic energy. The convergence of adiabatic generation of kinetic energy from 10°S to 30°N depicts at lower troposphere and strong convergence over equator from 1000 to 700 hPa (figure 6b), implying destruction/weak generation of kinetic energy. On the other hand, divergence of adiabatic generation of kinetic energy shows production of kinetic energy

Figure 5. Temperature bias climatology at 300 and 900 hPa for DJF during 2004–2007 over the study region, (a) and (b); each has contour interval of 3°C.

from the available potential energy over the region that emphasizes to the winter circulation. The zonal adiabatic generation of kinetic energy displays strong convergence over 10°S to 20°N that suggests strong destruction of kinetic energy (figure 6c) from 20° to 40°N and a strong divergence from lower to upper troposphere (figure 6c) indicates production of kinetic energy. The opposite is found in the meridional adiabatic generation of kinetic energy (figure 6d). This makes air parcel to move southward (north to south) until reaches the Inter Tropical Convergence Zone (ITCZ) and completes the Hadley circulation.

The vertical integrated geographical distribution of horizontal kinetic energy flux divergence is extended over whole China region, while

convergence is seen over central to western Himalayan region (figure 7a). The adiabatic generation of kinetic energy depends on the cross isobaric flow (north to south in winter, i.e., study shows strong circulation during IWM) (Kung 1971; Rao 2001). It has a strong convergence over central Himalayas and western India implying the destruction of kinetic energy, while the remaining region shows divergence with strong divergence over Tibetan Plateau and China (figure 7b) (i.e., subtropical westerly jet stream component causes strong divergence). The zonal and meridional adiabatic generation of kinetic energy opposes each other. Zonal flux over the Himalayan to Tibetan region illustrates strong divergence that represents generation of kinetic energy, but the opposite is found in case of meridional generation of kinetic energy (figure 7c and d). The peak value of the total kinetic energy (eddy and mean) is found from 30°N to beyond 50°N, which delineates the kinetic energy balance. The kinetic energy budget variation of area averaged study region is shown along vertical pressure levels (figure 8). The kinetic energy generation is completely balanced by destruction of the kinetic energy from lower to upper troposphere (i.e., explanation of good Hadley circulation during winter over the study region). The residue of kinetic energy contribution is significant. The study region is characterized by convergence flux at lower troposphere, but strong divergence flux at upper troposphere. The adiabatic generation of kinetic energy is maximum at upper troposphere, which is similar to the earlier studies (Kung 1971; Savijarvi 1980; Rao 2001). Because of strong westerly, dissipation of zonal adiabatic generation of kinetic energy is observed over the study region from lower to upper troposphere. The model shows that the study region is source of kinetic energy and adiabatic generation occurs by meridional wind and is dissipated by zonal wind (Ananthakrishnan and Keshavmurthy 1973).

3.3 Vorticity budget

Vorticity is a localized microscale air mass rotation phenomenon. The IWM circulation is characterized through analysis of vorticity budget. Earlier studies have explained about the horizontal transportation and production of vorticity by stretching and tilting terms and cumulus convection (Holton and Donald 1972; Chu *et al.* 1981; Holopainen and Oort 1981; Yanai *et al.* 1982; Rao 2001). The

Figure 6. Same as figure 3, but for kinetic energy, (a) horizontal flux of kinetic energy, (b) adiabatic generation of kinetic energy, (c) zonal adiabatic generation of kinetic energy and (d) meridional adiabatic generation of kinetic energy. (a), (b), (c) and (d) have contour interval of 1.5, 3, 3 and 1, respectively (Unit: 10^{-4} Watt/kg).

horizontal flux of absolute vorticity of model is discussed as sectorial mean cross section along pressure-latitude (over 30° – 120° E) (figure 9a). A strong flux is observed at 15° – 25° and 35° N in lower troposphere exhibiting reduced atmospheric stability over the region (i.e., strong flux leads to a decrease in absolute vorticity) (Holton 1992). This flux then transforms into clockwise rotation due to Coriolis force (Peixoto and Oort 1992). But at 10° S, 10° N and beyond 25° N opposite distribution is observed. The destruction/weak generation of vorticity due to stretching is observed over the study region, which suggests anticyclonic circulation at lower troposphere (figure 9b). However, a strong flux (generation) at 40° N and a strong flux (destruction) beyond 40° N in the upper

troposphere is possibly attributed to the zonal component of the subtropical westerly jet stream.

The geographical distribution of vertically integrated vorticity advection is computed over the study region to see spatial variation of vorticity transportation. Strong flux of relative vorticity advection is observed over Siberia, Tibetan Plateau, Pakistan, Afghanistan and Iran. It is because of subtropical westerly jet stream and anticyclonic divergence in upper troposphere (figure 10a). However, Arabian Sea, Indian peninsula and Bay of Bengal region have weaker flux of relative vorticity advection that explains trough and cyclogenesis condition at lower troposphere. Because of Coriolis force, the planetary vorticity advection is opposite to the relative vorticity

Figure 7. Geographical distribution of vertical integrated kinetic energy for DJF during 2004–2007 over the study region for the model (MM5/NCAR); (a) horizontal flux of kinetic energy, (b) adiabatic generation of kinetic energy, (c) zonal adiabatic generation of kinetic energy, and (d) meridional adiabatic generation of kinetic energy. (a), (c) and (d) have contour interval of 15, but (b) has contour interval of 10 (Unit: Watt/m^2).

advection (figure 10b), i.e., presence of stronger flux of planetary vorticity advection over Siberia and Tibetan Plateau. Except Pakistan and southern Iran, whole study region shows generation of vorticity due to stretching with maxima over Iraq, Turkey and Syria that maintains IWM circulation.

The area averaged vertical distribution of vorticity budget over the study region is depicted in figure 11. A weak horizontal flux of vorticity advection at lower level and stronger flux at upper level is seen. The horizontal transportation of vorticity of IWM region is not only balanced by generation of vorticity due to stretching and tilting terms (i.e., horizontal to vertical turbulence term), but it also depends on cumulus convection at sub-grid scale (Chu *et al.* 1981; Rao 2001). The generation of vorticity due to stretching is balanced from lower to upper level troposphere. But strong flux in generation of vorticity due to tilting is observed from lower to upper troposphere insinuating dissipation of vorticity through advective tilting.

3.4 Angular momentum budget

The sectorial pressure-latitude cross section of angular momentum budget over the study region is depicted in figure 12. The horizontal flux of omega momentum beyond 30°N is found to have strong flux at lower level, while it has weak flux at upper level (figure 12a). This variation explains lower atmospheric mass movement northwards with the help of surface westerlies because of zonal component from west through the action of Coriolis force (Peixoto and Oort 1992). From equator to 10°N and at 25°N , at lower level strong flux is observed that describes strong trade wind in the Hadley cell during winter (Peixoto and Oort 1992). The horizontal flux of relative angular momentum is nearly opposite to the omega momentum flux (figure 12b). This balances the angular momentum budget and equals to sum of torques (Driscoll 2010). The angular momentum of any region can be exchanged by another region, which is controlled by pressure torque and it is basically sum of friction torque

and mountain torque. From 5° to 40°N , a strong flux of pressure torque is observed (figure 12c) from lower to upper troposphere in a periodic manner which shows that the mountain torque dominates in the lower level and friction torque in the

Figure 8. Vertical distribution of area averaged kinetic energy budget for DJF during 2004–2007 over the study region for the model (MM5/NCAR), where red, green, blue, purple, black and yellow lines denote zonal generation of KE (kinetic energy), meridional generation of KE, adiabatic generation of KE, diabatic generation of KE (mean and eddy) horizontal flux of KE and residue of KE, respectively (Unit: Watt/m^2).

upper levels (figure 12c) (i.e., the Himalayas and Tibetan Plateau's perturbation part of the angular momentum is due to complex terrain).

The local angular momentum budget is controlled by balance terms – horizontal flux of omega momentum, relative momentum and pressure torque. All these terms are depicted as the vertically integrated geographical distribution in figure 13(a–c). The strong divergence is located with horizontal flux of omega momentum, which is observed over Kazakhstan, Mongolia and west China (Gobi Desert). This attributes to an intense high pressure region in the winter season and a net poleward transport of omega momentum (figure 13a) that delineates the strong circulation in the model output. A weak convergence over India, Burma, Bangladesh and south China is found, which leads to easterlies losing its omega angular momentum due to friction with surface (i.e., due to complex terrain). In summer, the horizontal flux of relative angular momentum is opposite to the horizontal flux of omega angular momentum (Peixoto and Oort 1992; Rao 2001; Dimri 2007). But it is observed that the horizontal flux of relative momentum is nearly same as the omega momentum over Tibetan Plateau and Gobi Desert. However, the opposite pattern is found over India, Burma, Bangladesh and south China (figure 13b). The geographical distribution of pressure torque over Jammu & Kashmir, Thar desert, Maharashtra, Odisha, West Bengal and Bay of Bengal areas have weak flux, but strong flux is found over Iran and north Arabian Sea. The dissipation/generation

Figure 9. Same as figure 3, but for vorticity; (a) horizontal flux of absolute vorticity and (b) generation of vorticity due to stretching. (a) and (b) both have contour interval of 3 (Unit: $10^{-4}/\text{s}^2$).

Figure 10. Same as figure 7, but for vorticity; (a) relative vorticity advection, (b) planetary vorticity advection, and (c) generation of vorticity due to stretching. (a), (b) and (c) have contour interval of 10, 2 and 5, respectively (Unit: 10^{-7} N/m^3).

Figure 11. Same as figure 8, but for vorticity budget, where black, blue and red lines denote horizontal flux of vorticity advection, generation of vorticity due to tilting and generation of vorticity due to stretching, respectively (Unit: N/m^3).

of atmospheric angular momentum due to friction torque (air mass lose/gain angular momentum to Earth's surface) and mountain torque (air mass lose/gain its angular momentum because of east-west side pressure difference of the terrain) is discussed. It is difficult for the model to separate mountain torque, friction torque and any other torque, e.g., gravity wave torque, which is inadequate in the model (figure 13c). The Himalayas have very irregular terrain that makes it difficult for model to pick up variables at all grids and that is the reason why model shows over-/under-estimation from the observation (Egger *et al.* 2007; Driscoll 2010).

The area averaged vertical distribution of angular momentum budget is also computed over the study region (figure 14). The horizontal flux of relative angular momentum shows convergence at lower troposphere, being nearly constant in middle troposphere and a small flux in upper troposphere is seen. Whereas, omega angular momentum behaves nearly in similar manner in lower troposphere and opposite in the middle and upper troposphere. The residue of angular momentum follows a constant pattern at lower troposphere, but a strong divergence from middle to upper troposphere is noted. This explains weak generation of angular momentum in lower troposphere and strong generation in the middle and upper troposphere. However, mountain and pressure torque opposes each other. On the whole, angular momentum budget from lower to upper atmosphere reveals balance and is constant.

3.5 Heat and moisture budget

The temperature and moisture climatology are not sufficient for discussion of heat and moisture budget. Hence, the studies are needed for distribution of heat and moisture fluxes along horizontal as well as vertical component. The transportation of moisture from warm ocean to cold land mass in winter is smaller than that in summer and therefore causes less precipitation during winter and maximum during summer over the Indian subcontinent region. The vertical distribution of horizontal moisture, heat fluxes and diabatic heating are illustrated as sectorial pressure-latitude cross section in figure 15 along with longitudinal (over 30° – 120°E) average. The horizontal flux of moisture convergence extends from lower to middle troposphere over 5°S to 5°N (figure 15a). A strong divergence

Figure 12. Same as figure 3, but for angular momentum; (a) horizontal flux of omega momentum, (b) horizontal flux of relative momentum, and (c) pressure torque. (a), (b) and (c) have contour interval of 5, 5, 2, respectively (Unit: $10^{-4} \text{ m}^4/\text{s}^2$).

Figure 13. Same as figure 7, but for angular momentum; (a) horizontal flux of omega momentum, (b) horizontal flux of relative momentum, and (c) pressure torque. (a), (b) and (c) have contour interval of 5, 3 and 2, respectively (Unit: $10^6 \text{ kg}/\text{s}^2$).

is observed at 700 and 400 hPa over the equator (figure 15a). From lower to middle troposphere over 15° to 20°N , a small convergence delineates the evaporation. Beyond 30°N a weak divergence is found from lower to upper troposphere (figure 15a). The vertical presentation of adiabatic conversion of available potential energy to kinetic energy illustrates divergence in the whole region except beyond 40°N in upper level. This explains the generation of kinetic energy, i.e., vertical rising motion over the whole study region (figure 15b) (Ramesh *et al.* 1999) (i.e., this area is leeward side of the Himalayan terrain, causing orographic lifting or rising motion during IWM). However, the diabatic heating divergence is found over 5°S to 15°N , at lower level and 600 hPa, explaining evaporation and latent heat transfer to atmosphere from Indian ocean, Arabian Sea and Bay of Bengal, (Ding and Krishnamurti 1987; Ramesh *et al.* 1999;

Rao 2001). Beyond 15°N , lower as well as upper level convergence of diabatic heating is observed, which represents continental cooling and sinking of heat from atmosphere to land mass (figure 15c).

The vertically integrated fluxes of heat and moisture are depicted in figure 16. The vertically integrated horizontal flux of moisture shows moisture convergence over Indian Ocean, Bay of Bengal and Arabian Sea region implying evaporation and addition of mass to the atmosphere. A small convergence is found over the Ganges River basin and the Tibetan Plateau. A strong divergence concurrent with dry and cold condition is observed over Thar desert, Jammu & Kashmir and Himalayas (figure 16a). The available potential energy is described in the earlier studies for explanation of perturbation of internal wave energetics (Kang and Fringer 2010). A strong divergence of the available potential energy conversion is

observed over Tibetan Plateau, northern Pakistan and Afghanistan that introduces generation of kinetic energy due to rising motion of air mass. Whereas the adjacent areas of central to western Himalayas, southern Pakistan and Bay of Bengal are showing convergence (figure 16b), i.e., destruction of kinetic energy because of meridional (northerly) motion of air mass (Kung 1971). The

Figure 14. Same as figure 8, but for angular momentum budget, where black, green, purple, blue and red lines denote horizontal flux of relative angular momentum, horizontal flux of omega angular momentum, residue of angular momentum, mountain torque and pressure torque, respectively (Unit: kg/s^2).

rest of the area over ocean shows weak divergence and over the continent shows convergence. The continental region convergence is because of cold continent and its vicinity atmosphere. Similarly, ocean region divergence is because of comparative warm ocean (i.e., because of high specific heat capacity of water than continent) and its vicinity atmosphere (figure 16b). The diabatic heating divergence (cooling of continents) is illustrated over ocean/sea and whole of the China region, Tibetan and central Himalayas (because of excess condensation than evaporation) (figure 16c). But over Pakistan, Jammu & Kashmir, Ganges River basin and Bay of Bengal, diabatic heating convergence dominates. It causes moisture convergence over the region.

Area averaged vertical distribution of heat and moisture budget over the study region is illustrated in figure 17. A strong divergence of the horizontal flux of moisture is manifested from 1000 to 250 hPa that reveals winter with dry air mass. But strong convergence dominates at 150 hPa. However, the adiabatic conversion of available potential energy to kinetic energy leads to divergence from lower to upper troposphere manifesting to substantial kinetic energy in that area. An alternating pattern of convergence and divergence is noted in the troposphere with convergence maxima at 700 hPa and divergence maxima at 100 hPa. The heat and moisture budget have crucial role to play in the atmospheric dynamics such as cumulus convection, advection, condensation, precipitation and

Figure 15. Same as figure 3, but for heat and moisture; (a) horizontal flux of moisture, (b) adiabatic conversion of available potential energy to kinetic energy, and (c) diabatic heating. (a), (b) and (c) have contour interval of 5, 2 and 2, respectively (Unit: Watt/kg).

Figure 16. Same as figure 7, but for heat and moisture; (a) horizontal flux of moisture, (b) adiabatic conversion of APE to KE, and (c) diabatic heating. (a), (b) and (c) have contour interval of 10, 20 and 10, respectively (Unit: 10^2 Watt/m^2).

Figure 17. Same as figure 8, but for heat and moisture budget, where red, blue and green lines denote horizontal flux of moisture, adiabatic conversion of APE to KE and diabatic heating, respectively (Unit: Watt/m^2).

kinetics. They govern the synoptic weather system. The over-/under-estimation of temperature is possibly due to the diabatic heating as well as heat budget or vice-versa.

4. Conclusions

The energetics of IWM over Indian subcontinent region is studied using MM5 model data and observational data. The primary finding of the current study is that the model derived winter energy budget over the Indian subcontinent region matches well with that of the observational

analysis done by Peixoto and Oort (1992). A cold model bias is attributed to the irregular terrain of the Himalayas and Tibetan Plateau, which makes it difficult to pick it up at each model grids. The temperature deals with horizontal and vertical heat fluxes as well as heat budget. The moisture flux and moisture budget (latent heat, evaporation and condensation, i.e., Clausius-Clapeyron part of the model) are directly governed by the heat budget. The wind circulation transports mass (moisture) and controls the moisture budget over the study region (ocean as well as land). The model shows bias in zonal as well as meridional wind. The model shows stronger upper level westerlies, which influences the fluxes, vorticity and angular momentum. But the vertical wind (omega) implies good estimation of vertical fluxes of mass, momentum and heat (evaporation, convection and available potential energy). The wind divergence of model concludes lower level convergence in 10°S to 25°N region (i.e., strong winter circulation in the model fields). Specific humidity shows small negative bias in lower as well as upper troposphere over Arabian Sea, Bay of Bengal and southern India. It also justifies the under estimation of specific humidity and temperature in the model. Over-estimation in wind, apart from zonal and meridional components, is because of orographic forcing in the model. Topographical phenomena like orographic lifting, downwelling, turbulences, vorticity and circulation is overestimated in the model. The sea level pressure and geopotential height are justifying the winter condition of the study region and validity of the model at lower troposphere. However, the MM5 model has bias, but model has various kinematical variables for the regional forecast and modeling for atmospheric dynamics and energetics. The pressure torque shows the periodic variation

from lower to upper troposphere during the winter season. The vertically integrated horizontal flux of angular momentum shows divergence, justifying the IWM angular momentum balance of atmosphere. The IWM consists of divergence at lower level and convergence at upper level. The kinetic energy advection over the study region is small, due to high pressure or strong ridge over the Himalayas and Tibetan Plateau. The energy budget terms – kinetic energy, vorticity, angular momentum, heat and moisture show overall balance from lower to upper atmosphere for the IWM.

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